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REPORT ON THE ASSESSMENT OF THE POSSIBILITIES OF THE USE OF HYDROGEN AND OTHER INNOVATIVE TECHNOLOGIES AND CARBON CAPTURE AND UTILIZATION (CCU), CARBON CAPTURE AND STORAGE (CCS) TECHNOLOGIES IN INDUSTRIAL ENTERPRISES, AND ON THE LEGAL ANALYSIS

Project name:

FEASIBILITY STUDY ON THE USE OF CO₂ CAPTURE AND STORAGE, HYDROGEN, AND OTHER
INNOVATIVE TECHNOLOGIES IN LITHUANIAN INDUSTRIAL ENTERPRISES OPERATING IN THE
MOST ADVERSELY AFFECTED AREA

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List of acronyms

Acronym	Description
°C	Degree centigrade or degree Celsius
€	European euro
ϕ	Average aquifer porosity
ρCO_2	CO_2 density at saline aquifer conditions
£	Sterling Pound
μm	Micrometers
3D	Three-dimensional
A	Area
ADB	Asian Development Bank
AI	Artificial intelligence
Al	Aluminium
APS	Announced Pledges Scenario
AR5	Sixth Assessment Report
Art.	Article
ASU	Air separation unit
B	Oil or gas formation volume factor
BALTICSEAH2	Baltic Sea Hydrogen Valley project
BECCS	Bioenergy with Carbon Storage
BMBF	Federal Ministry of Education and Research (Bundesministerium für Forschung, Technologie und Raumfahrt)
BOS	Burned oil shale
BREEAM	Building Research Establishment Environmental Assessment Method
C_2F_6	Hexafluoroethane
$\text{C}_4\text{H}_6\text{O}_3$	Propylene carbonate
Ca	Calcium
CaCO_3	Calcium carbonate
CaL-LP	Calcium-looping lime production
CaO	Calcium oxide
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CCC	Cryogenic carbon capture
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CDM	Clean Development Mechanism
CEE	Central and Eastern Europe
CEF	Connecting Europe Facility
CF_4	Tetrafluoromethane
CfD	Contract for Difference
CH_3OH	Methanol
CH_4	Methane

Acronym	Description
CLC	Chemical looping combustión
CLFR	Compact linear Fresnel reflector
cm	Centimetre
CMP	Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol
CNG	Compressed natural gas
CO(NH ₂) ₂	Urea
CO ₂	Carbon dioxide
COP	Coefficient of Performance
COVID-19	Coronavirus disease 2019
CRA	Corrosion-resistant allow
CSP	Concentrated solar power
CSR	Corporate Social Responsibility
DAC	Direct air capture
DKK	Danish Krone
DME	Dimethyl ether
DOGF	Depleted oil and gas field
DRI	Direct reduction of iron
DRL	Deep reinforcement learning
DRVs	Digital Rock Volumes
EAF	Electric arc furnace
EBRD	European Bank for Reconstruction and Development
ECR	Electrochemical CO ₂ reduction
EER	Energy Efficiency Ratio
EFSI	European Fund for Strategic Investments
EHR	Enhanced hydrocarbon recovery
EIA	Environmental Impact Assessment
EIB	European Investment Bank
EIC	European Innovation Council
ELD	Environmental Liability Directive
EOR	Enhanced oil recovery
ERDF	European Regional Development Fund
ESG	Environmental, Social, and Governance
ESIF	European Structural and Investment Funds
ETC	Evacuated tube collector
ETS	Emissions Trading System
EU	European Union
EU BEC	Breakthrough Energy Catalyst
EU ETS	The European Union Emissions Trading System
EUA	European Emission Allowance
EUDP	Energy Development and Demonstration Program
F&A	Facilities and Administrative
FDI	Foreing direct Investment
FEZ	Free Economic Zone

Acronym	Description
Fm.	Formation
FNO	Fourier Neural Operator
FOAK	First-Of-A-Kind
FP	Framework Programme for Research and Technological Development
FPC	Flat plate collector
FSRU	Floating Storage and Regasification Unit
g	Grams
GBS	Global Business Service
GDP	Gross Domestic Product
GET	Green Economy Transition
GHG	Greenhouse Gas
GRA	Global Research Alliance on Agricultural Greenhouse Gases
GSR	Green Strategic Reserve
GT	Gigatonnes
GW	Gigawatt
GWh	Gigawatt-hour
GWP	Global warming potential
H	Average thickness of trap multiplied by the net-to-gross ratio
H ₂	Hydrogen
ha	Hectare
HCOOH	Formic acid
HDR/EGS	Hot Dry Rock/Enhanced Geothermal System
HELCOM	Helsinki Commission
HFC	Hydrofluorocarbon
ICC	Internalization of Carbon Compounds
ICCS	Illinois Industrial Carbon Capture and Storage
ICM	Industrial Carbon Management
ICT	Information and Communication Technologies
IEA	International Energy Agency
IMO	International Maritime Organisation
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Use
IRENA	International Renewable Energy Agency
IT	Information Technology
ITER	International Thermonuclear Experimental Reactor
K	Kelvin
kg	Kilogram
KKJ	Kaunas Cogeneration Plant
km	Kilometre
km ²	Squared kilometre
KPI	Key performance indicator
ktoe	Kilotonnes of oil equivalent
KTU	Kaunas University of Technology

Acronym	Description
l	Litre
LAMMC	Lietuvos agrarinių ir miškų mokslų centras (Lithuanian Research Centre for Agriculture and Forestry)
LCO ₂	Liquified carbon dioxide
LCOE	Levelized cost of energy
LCOH	Levelized cost of hydrogen
LDL	Leak detection log
LED	Light-emitting diode
LEED	Leadership in Energy and Environmental Design
LNG	Liquified natural gas
LOHC	Liquid Organic Hydrogen Carrier
LTG	Lietuvos Geležinkeliai
LTOU	Lietuvos oro uostai, Lithuanian Airports
LULUCF	Land Use, Land-Use Change and Forestry
m	Metre
m ²	Squared meter
m ³	Cubic meter
MAOP	Maximum operating pressure
MCH	Methylcyclohexane
MCO ₂	Effective storage capacity of CO ₂
mD	Millidarcy
MDEA	Methyl diethanolamide
MEA	Ethanolamide
mg	Milligram
Mg ₂ NiH ₄	Magnesium-nickel hydride
ML	Machine Learning
mm	Millimetre
MNDWI	Modified Normalized Difference Water Index
MoU	Memorandum of Understanding
MPa	Megapascals
MSI	Multispectral imaging
Mt	Megatonnes
Mtoe	Megatonnes of oil equivalent
mtpa	Million tonnes per annum
MW	Megawatt
mW	Milliwatt
MWh	Megawatt.Hour
MXCT	Micro X-ray Computed Tomography
N ₂ O	Nitrous oxide
NaHCO ₃	Sodium bicarbonate
NCCMA	National Climate Change Management Agenda
NCS	Norwegian Continental Shelf
NDTI	Normalized Difference Tillage Index
NDVI _{re}	Red-Edge Normalized Difference Vegetation Index

Acronym	Description
NECP	National Energy and Climate Plan
NF ₃	Nitrogen trifluoride
NGO	Non-governmental organization
NGPP	Natural gas processing plant
NGR	Neutron Gamma Ray
NH ₃	Ammonia
NOK	Norwegian Krone
Nox	Nitrogen oxides
NRC	Nature Research Center
NZE	Net Zero Emissions
NZIA	Net-Zero Industry Act
OECD	Organisation for Economic Co-operation and Development
OGCI	Oil and Gas Climate Initiative
OSPAR	Convention on the Protection of the Maritime Environment of the North-East Atlantic
P	Pressure
P2X	Power-to-X
PaM	Policies and measures
PCFC	Proton conductive fuel cell
PCI	Project of Common Interest
PDC	Polycrystalline diamond compact
PEM	Proton Exchange Membrane
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoate
PLA	Polylactic acid
PM	Particulate matter
PPPIRC	Public-Private Partnership in Infrastructure Resource Center for Contracts, Laws and Regulations
PPPLRC	Public-Private Partnership Legal Resource Center
PPPRC	Public-Private Partnership Resource Center
PV	Photovoltaics
PVC	Polyvinyl chloride
Pz	Piperazine
R&D	Research and Development
R&D&I	Research, development and innovation
RBMK	Reaktor Bolshoy Moshchnosti Kanalny, high-power channel-type reactor
RED	Renewable Energy Directive
REV	Representative Element Volume
RFNBO	Renewable fuels of non-biological origin
RNNP	Risk Level Norwegian Petroleum Activity
ROZ	Residual oil zone
RPA	Robotic Process Automation
SA	Saline aquifer
SACS	Saline Aquifer CO ₂ Storage

Acronym	Description
SAF	Sustainable Aviation Fuel
SAR	Synthetic aperture radar
SCM	Supplementary cementous materials
SDG	Sustainable Development Goal
SEA	Strategic Environmental Assessment
S_{eff}	Sweep efficiency
SET	Strategic Energy Technology
SF ₆	Sulphur hexafluoride
Si	Silicon
Sm ³	Standard cubic meter
SME	Small and medium-sized enterprise
SMR	Steam methane reforming
SO ₂	Sulphur dioxide
SOFC	Solid oxide fuel cell
SO _x	Sulphur oxides
SPE	Society of Petroleum Engineers
SRCSS	Special Report on Carbon Dioxide Capture and Storage
SRMS	Storage Resources Management System
STEM	Science, Technology, Engineering and Mathematics
STEPS	Stated Policies Scenario
SVM	Support vector machines
S_{Wir}	Irreducible water saturation
T	Temperature
tclk	Tonne of clinker
tCO ₂	Tonne of carbon dioxide
TEN-E	Trans-European Network for Energy
TEN-T	Trans-European Transport Network
TESZ	Trans-European Suture Zone
TEU	Twenty-foot equivalent unit
TGR-BF	Top Gas Recycling Blas Furnace
TJTP	Territorial Just Transition Plan
TRL	Technology readiness level
TV	Television
TWh	Terawatt hour
UI	User interface
UK	United Kingdom
UNCLOS	United Nations Convention on the Lay of the Sea
UNFCCC	United Nations Framework Convention on Climate Change
URp	Volume of proven ultimate recoverable oil or gas
US	United States
US\$	United States dollar
UX	User experience
VCS	Verified Carbon Standard
VCU	Verified Carbon Unit

Acronym	Description
VER	Verified Emission Reduction
VIP	Very important person
VKJ	Vilnius Cogeneration Plant
VU	Vilnius University
WAG	Water-alternating-gas
WP	Work Package
WtE	Waste-to-energy
ZEN	Zero Emission Network
ZEP	Zero Emission Platform

1. Introduction

In response to the urgent need for industrial decarbonization and alignment with the European Union's climate neutrality targets, Inovacijų Agentūra initiated the project "Feasibility study on the use of CO₂ capture and storage, hydrogen and other innovative technologies in Lithuanian industrial enterprises operating in the most adversely affected areas". It mainly targets the companies that operate in one of the following counties regions: Kaunas, Šiauliai, and Telšiai; however, we expect that the project will bring important technological and legal regulation messages and insights for the government, industrial, business, academic communities, and society in general in Lithuania. The project focuses on assessing the technical and economic feasibility of deploying carbon capture, utilization, and storage (CCUS) technologies and hydrogen-based solutions, particularly within the ammonia, cement, glass, thermal power plants, and other industries. These sectors are recognized as significant contributors to industrial greenhouse gas emissions and are central to Lithuania's broader strategy to reach net-zero emissions by 2050.

During the project implementation, four documents should be prepared:

1. The feasibility study preparation plan.
2. The report on the assessment of the possibilities of the use of hydrogen and other innovative technologies and carbon capture and utilization (CCU), carbon capture and storage (CCS) technologies in industrial enterprises, and on the legal analysis.
3. The action plan for the transition of industrial enterprises to zero emissions by 2050.
4. The final report.

The present text constitutes the second document "2. The report on the assessment of the possibilities of the use of hydrogen and other innovative technologies and carbon capture and utilization (CCU), carbon capture and storage (CCS) technologies in industrial enterprises, and on the legal analysis." (Assessment Report). This Assessment Report has been developed following the formal requirements provided by Inovacijų Agentūra in technical conditions for the project implementation for evaluating the potential deployment of hydrogen, innovative low-carbon technologies, and carbon capture, utilization, and storage (CCUS/CCS) in Lithuanian industrial enterprises.

The Assessment Report applies a multidisciplinary methodology that integrates emission source mapping, technology benchmarking, infrastructure evaluation, regulatory alignment, and economic assessment to achieve it. Emission sources are characterized by volume, CO₂ concentration, and operating profile. Benchmarking against international best practices enables a comparative analysis of low-carbon technologies, including post-combustion CO₂ capture, blue and green hydrogen integration, oxy-fuel processes, and carbon mineralization. Each technology is evaluated in terms of maturity, compatibility with existing infrastructure, and potential for deployment under Lithuanian industrial conditions. The analysis also explores capture and transport configurations, estimating the technical feasibility of extracting CO₂ from specific units, conditioning it for pipeline transport, and storing it either temporarily or permanently. The best international practices from at least five advanced countries and literature from the OECD, the World Bank, the European Commission, and peer-reviewed high-level scientific publications are reviewed.

The potential for CO₂ storage, particularly geological storage within or near Lithuania, is thoroughly examined, including infrastructure needs, injection conditions, monitoring, and storage site feasibility under national and EU legal frameworks. A dedicated legal analysis is conducted to identify existing regulatory barriers and propose legislative amendments to support CCU, and CCS integration into

Lithuania's industrial sector. Recommendations are also outlined for improving national support measures, enabling infrastructure reuse, and enhancing international R&D collaboration.

Given Lithuania's position within the European regulatory landscape, the Assessment Report ensures compatibility with key legislation such as the EU Emissions Trading System (EU ETS), the Carbon Border Adjustment Mechanism (CBAM), the Renewable Energy Directive (RED III), the CCS directive, the proposed Net-Zero Industry Act, and other vital documents. Integrating these regulatory instruments is essential for compliance and access to EU-level funding mechanisms, such as the Innovation Fund, Horizon Europe research and innovation programme and Connecting Europe Facility (CEF).

The findings and recommendations will be discussed with the Working Group, with feedback incorporated before final approval. The completed Assessment Report will serve as the basis for the following documents: "The action plan for the transition of industrial enterprises to zero emissions by 2050" and "The final report". It will help make strategic decisions at the national level, including proposals to the National Industrial Competitiveness Commission "Industry 4.0", ensuring alignment with Lithuania's commitment to climate neutrality by 2050.

2. Executive Summary

This report is a feasibility study about the use of carbon dioxide capture, utilization and storage in the Republic of Lithuania. The report is mainly focused on the application of these technologies, as well as other innovative technologies, such as renewable energies and hydrogen, in the whole country, and specifically in the areas of the country which have a more important carbon intensive industrial sector, this is, the counties of Kaunas, Šiauliai, and Telšiai.

The document assesses carbon dioxide capture, utilization and storage technologies from a technical, social, economic and environmental point of view, evaluating the use feasibility in Lithuania.

In the first chapter, a complete overview of the economy, industrial structure, energy sector and business and scientific background is offered. In the chapter, a continuous growth of the gross value added of Lithuania can be observed during the period 2010-2024, of 32.68%. It can be also remarked that the industry sector is reducing its importance, making 18.7% of the Lithuanian economy in 2024. This sector also creates 18% of the total employment in the Lithuanian economy.

Another important conclusion from this chapter is the reduction in the greenhouse gas emissions in the Republic of Lithuania during the analyzed period. Specifically, greenhouse gas emissions have been reduced by 65.8% during the period 1990-2023, if LULUCF are considered, and 62.2% if LULUCF are not considered. The total value without LULUCF in 2023 was the minimum of the evaluated period.

As for energy, it is remarkable that Lithuania does not produce coal, or natural gas, and oil production is very reduced, so it depends on imports from these sources of energy. In general terms, consumption of these three energy sources has been quite constant during the last six years approximately, although in 2023, coal consumption went down by 37.0%. On the other hand, the energy sector is evolving to a higher participation of renewable energies during the last years. In particular, onshore wind power capacity has grown by 165% from 2023 to 2025, from 947 MW in 2023 to 2,510 in 2025. Even more relevant, the solar PV capacity in Lithuania is in 2025 more than four times larger than in 2023, having grown from 572 MW in 2023 to 3,128 MW in 2025. As of the third quarter of 2025, 81% of the total power capacity in the country is decarbonized. The electricity generation is characterized by an important reduction, by two thirds, in 2010, derived from the shutdown of the nuclear power plant of Ignalina. Since that year, the Lithuanian power system relies highly on imports from third countries, with a net import of around 8,600 GWh per year during the 2016 to 2023 period. Electricity generation from renewable energy sources is growing, making 87% in 2023.

The first chapter also offers an overview of the transport and business infrastructure, as well as the scientific potential of Lithuania.

The second chapter offers a review of the main technologies which can reduce greenhouse gas emissions in Lithuania, different from carbon dioxide capture, utilization and storage. In particular, options for the use of hydrogen to decarbonize industry are analyzed. Hydrogen has relevant advantages, such as its potential use as fuel, and to produce useful derivatives such as synthetic methane, green ammonia or green methanol. However, as per now, most hydrogen is produced from fossil fuels, and it is necessary to make green hydrogen (such as that produced with electrolysis based on renewable energies) economically attractive.

Other technologies which are considered include renewable energies, such as solar PV, concentrated solar power, onshore wind power, offshore wind power, hydropower, biomass, solar water heaters, or geothermal energy. Material and energy efficiency technologies are also a good option, which focuses on the reduction of the demand for energy and materials, instead of energy production with renewable

energies. Related to this, the reduction of waste and recycling is also key. Finally, the role of digitalization and artificial intelligence to automate and optimize processes is also key.

Some of these technologies are currently economically profitable, such as solar PV or onshore wind energy. However, it is advisable to offer public support to other ones, such as hydrogen production, until they have evolved and become commercially viable, such as hydrogen.

Focusing specifically on the main objective of the report, carbon capture is analyzed. Carbon can be captured from the atmosphere, using three main approaches: enhanced weathering, ocean carbon removal and direct air capture. However, these technologies are still not fully developed, so it is more effective to capture carbon dioxide produced from industrial processes and from the combustion of fossil fuels. Among these methodologies, it is possible to mention the post-combustion capture, including absorption, adsorption, membrane separation, calcium looping and cryogenic carbon capture. Pre-combustion, which tries to remove CO₂ from fossil fuels before they are burnt, and oxyfuel combustion, which uses pure oxygen to burn fossil fuels instead of air, are also considered.

The cost of carbon capture depends on the process and the approach used to do it. Post-combustion shows costs ranging from US\$30 to US\$50 per tonne of CO₂, while pre-combustion costs between US\$120 and US\$140 per tonne of CO₂, and oxy-fuel combustion is slightly more expensive, reaching between US\$130 and US\$150 per tonne of CO₂. However, the specific costs of each process depend heavily on the process, varying mostly according to the concentration of CO₂ in the gas flux. In this sense, sectors such as cement and petrochemicals, which can reach a concentration of 30% of carbon dioxide in the gas flux, show capture costs below US\$60 per tonne of CO₂, using post-combustion and pre-combustion. Ammonia and fertilizer production are also appropriate sectors to apply carbon capture, with costs ranging from US\$25 to US\$35 per tonne.

Once captured, carbon dioxide can be either utilized, or stored. Both options are regarded as alternatives to reduce greenhouse gas emissions to the atmosphere from hard-to-abate sectors, although it should be always preferred to reduce in origin carbon dioxide emissions, by increasing the use of renewable energies or using energy efficiency measures.

Carbon utilization focuses on the use of captured carbon dioxide as an input to produce other useful raw feedstock, or in other processes. For example, carbon dioxide can be used to produce concrete, or synthetic hydrocarbons, such as methanol, formic acid, methane, polymers or carbonates. Carbon utilization is a good way to give value to what is in principle regarded as waste, carbon dioxide. However, the use of carbon dioxide as a raw material to produce new products is still considerably more expensive than the use of original raw materials. For example, the cost of using captured carbon dioxide to produce methanol can vary from €300 to €2,500/tonne of CO₂. These technologies can be further used with subsidies, with a high carbon allowance price, or focused on hard-to-abate sectors.

If carbon utilization is not an option, it can be sequestered. Although there is a variety of carbon storage processes, such as geological storage into deep rock formations, mineral carbonation or ocean-based carbon storage, only geological storage is being considered as a feasible option at the moment. Carbon capture in Lithuania is currently hampered by the national regulation, which forbids it.

The cost of storing carbon dioxide consists of two different processes: transport and storage itself. There are three main alternative ways to transport carbon dioxide: onshore pipeline, offshore pipeline, and shipping. Cost per tonne of CO₂ depends highly on the distance to which the gas is transported, as well as the amounts of carbon dioxide which has to be transported.

As for pipelines, offshore pipelines cost between 50% to 100% more than onshore pipelines. The cost of transport by pipeline depends on distance and amounts of transported amounts of carbon dioxide.

There are important economies of scale, which make that transporting 2.5 million tonnes of CO₂ per year at a distance of 1,500 km, for example, using offshore pipelines can cost around twice the cost of transporting 10 million tonnes of CO₂, in terms of cost per transported tonne of CO₂.

Pipelines can be chosen when there are high amounts of carbon dioxide to be transported, or for short distances. The selection between onshore and offshore pipelines depends on the location of the geological storage.

In general terms, shipping is more appropriate for small amounts of carbon dioxide, or for long distances. As liquefaction is an important part of the cost per tonne of transporting carbon dioxide by boat, and it is unavoidable, costs per tonne of CO₂ do not depend heavily on distance.

Although transport costs depend on the distance and the amount of carbon dioxide which has to be transported, it is possible to use the following approximate figures: between €5 and €25/tonne of CO₂ for pipelines, between €10 and €50/tonne of CO₂ for boat, from €10/tonne of CO₂ to €60/tonne of CO₂ for railway, and finally between €15/tonne of CO₂ and €42/tonne of CO₂ for truck.

As a reference, storage costs in the USA, range from €1 to €20 per tonne of CO₂, being higher for deep saline aquifers than for oil fields.

The assessment also includes a geological assessment of Lithuania to find the most appropriate geological formations to store carbon dioxide. Two different formations are considered:

1. Saline aquifers: There are two main formations in Lithuania: Cambrian reservoir (consisting of the Middle Cambrian Daimena Sandstone Formation) and Pärnu-Kemeri reservoir (Lower Devonian and Lower-Middle Devonian). Cambrian reservoir has two main structures: Syderiai and Vaškai. Syderiai has a storage capacity varying from 21.5¹ to 232² Mt of CO₂, and Vaškai, with 8.7¹-106² Mt of CO₂. On the other hand, the Devonian Pärnu-Kemeri reservoir consists of sedimentary materials (sandstones) but it reaches the depths necessary for retaining CO₂ in its supercritical state only in Western Lithuania (Gargždai area) and therefore, do not seem to be appropriate³.

Finally, there is another structure in the Baltic Sea, D11, with a total storage capacity of 11.3¹-69² Mt of CO₂.

2. Oil fields: The main existing oil field area in Lithuania is the Gargždai zone of uplifts, located 110 km to the Southwest. It has a depth of around 2,000 m. There are five different sandstone reservoirs which can be suitable for carbon dioxide storage: Giruliai, Ablinga, Pajuris (I), Pajuris (II) and Vargale. The total storage capacity of the Gargždai zone of uplifts is 31.3⁴ to 267² Mt of CO₂.

¹ ŠLIAUPIENĖ, R., ŠLIAUPA, S. *Prospects for CO₂ Geological Storage in Deep Saline Aquifers of Lithuania and Adjacent Territories*. 2012. Geologija. Vol. 53, 121–133.

² Source: MALIK, S., MAKASUSKAS, P., KARALIUTE, V., PAL, M., SHARMA, R. *Assessing the geological storage potential of CO₂ in Baltic Basin: A case study of Lithuanian hydrocarbon and deep saline reservoirs*. 2024. International Journal of Greenhouse Gas Control. Vol 133 <https://doi.org/10.1016/j.ijggc.2024.104097>

³ Source: SHOGENOVA, A., ŠLIAUPA, S., SHOGENOV, K., ŠLIAUPIENĖ, R., POMERANCEVA, R., VAHER, R., UIBU, M., KUUSIK, R. *Possibilities for geological storage and mineral trapping of industrial CO₂ emissions in the Baltic region*. 2009. Energy Procedia. Vol. 1, 2753-2760

⁴ Source: ŠLIAUPA, Saulius; MICHELEVIČIUS, Dainius; ŠLIAUPIENĖ, Rasa; LIUGAS, Jonas. *Assessment of the Potential for CO₂ Storage and Utilization in the Fractured and Porous Reservoir of the Cambrian Sandstones in*

Besides, there are options to develop shared carbon storage projects with other Baltic countries, focusing mainly on four closed structures: North Blidene, Blidene, Dobeles and E6-E (Latvia). It has been estimated that the average available capacity is 220.4 Mt of CO₂, with an optimistic estimate of 767.6 Mt of CO₂.

Carbon storage is, as mentioned before, currently forbidden under the Lithuanian regulation. For this reason, if any carbon was captured in the country, it should be transported to be stored in third countries. However, the draft updated National Energy and Climate Plan of the Republic of Lithuania for 2021-2030 (NECP) considers that it is necessary to evaluate carbon capture and storage in the country.

On the European side, carbon capture, utilization and storage are considered in the European Green Deal and the European Climate Law as technologies which can contribute to mitigate climate change. The European Union supports these projects through different instruments, such as the Just Transition Funds. The Connecting Europe Facility (CEF) also supports the development of large international projects to develop trans-European networks in the field of transport, energy and digital services. Part of this budget can be allocated to carbon transport and storage projects.

The European Union also supports R&D&I international projects, through instruments such as the Horizon Europe, the LIFE Climate Change Mitigation and Adaptation and the Innovation Fund. These funds have a total combined budget of € 140,930 million, from which, €701 million are allocated to carbon removal projects.

Besides, funds can be provided by multilateral institutions, such as the World Bank, the European Bank for Reconstruction and Development, the European Investment Bank or the Asian Development Bank.

Recommendations for the development of carbon capture, utilization and storage projects in Lithuania are also offered. The most important recommendation is the development of a regulation which encourages investment in carbon storage projects, as well as the offsetting of captured carbon dioxide emissions with allowances in the European Trading System. International cooperation with other countries is also highly encouraged, due to the large costs of these projects, and the need to use geological structures which can be shared by more than one country.

As for regulation, the European Commission has developed the CCS Directive, which creates a comprehensive legal framework to store CO₂ in the European Union in an environmentally safe way. According to this Directive, each Member State has to evaluate the best geological formations for carbon storage, and their risks. The European Commission has also published Guidance documents to offer some best practices and technical advice on the implementation of the CCS Directive.

On the other hand, the Environmental Impact Assessment Directive makes it compulsory, for carbon storage projects, to carry out environmental impact assessments.

In Lithuania, Art. 14 of the Law on Subsurface explicitly forbids carbon dioxide injection and storage in geological formations. However, Lithuania is totally committed to climate objectives aligned with the Paris Agreement and the European objectives, and carbon storage is considered as an option in other countries which do support this technology.

Carbon transport is also considered by different regulations. Particularly, the CCS Directive establishes that access to CO₂ transport networks should be granted to any potential user in a transparent and

non-discriminatory way, as long as the pipeline or the storage has available capacity. The Net Zero Industry Act describes different means of transport, including pipelines shipping, road, and rail. The CCS Directive is pending from being fully transposed to the Lithuanian regulatory framework.

For carbon capture and utilization, it is necessary to develop regulation which explicitly considers these technologies. Currently, the Emission Trading System considers stored CO₂ as non-emitted, and some carbon capture and utilization products are recognized as contributing to achieving permanent carbon storage.

Finally, the Lithuanian National Energy Independence Strategy focuses on the valorization of biogenic CO₂, to produce high value-added products, such as synthetic green fuels, as well as the need for the development of CO₂ terminals in Klaipėda.

3. An overview of the current situation in terms of industrial decarbonization

3.1. Lithuania's industrial structure and their CO₂ emissions

Industrial structure In Lithuania

Lithuania is the largest economy in the three Baltic States, in 2024 the country ranked 22nd in terms of gross value added out of the 27 countries in the European Union, with €₂₀₂₄ 70,221.1 million in that year⁵. It can be remarked that the gross value added in Lithuania has grown importantly during the last years, specifically, by 32.68% in the last 10 years.

The following figure shows the evolution of the gross value added in Lithuania during the period from 1995 to 2024.

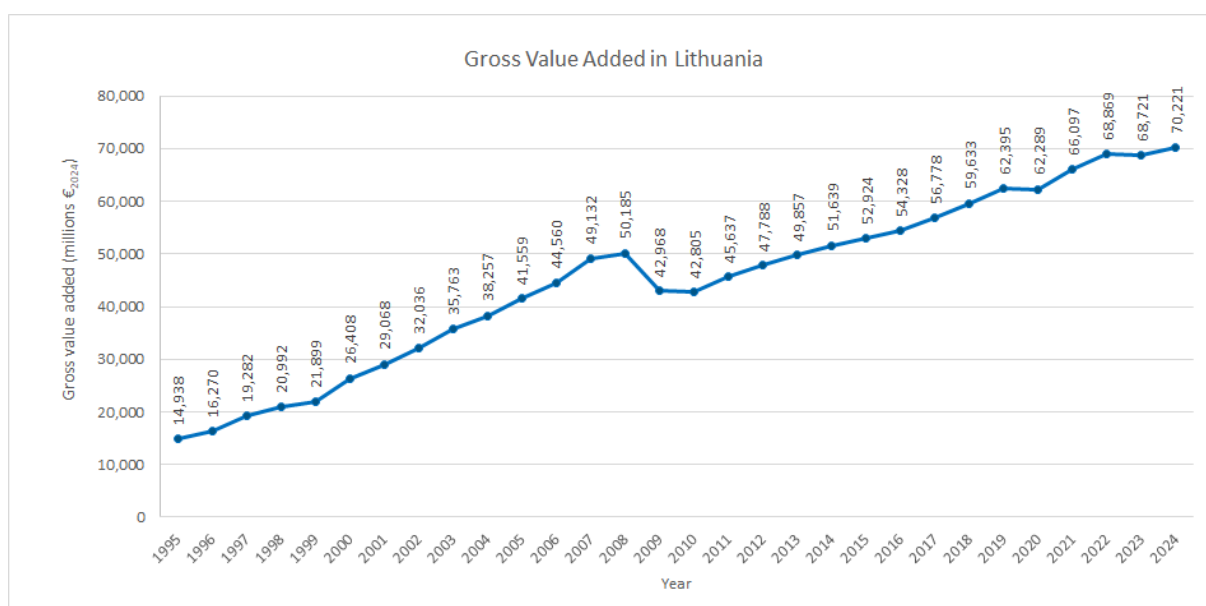


Figure 1: Evolution of the gross value added in Lithuania, period 1995-2024

As a comparison, the gross value added in the whole European Union-27 only grew by 13.47% during the same period. Indeed, Lithuania is one of the economies in the EU with the highest growth rates. It can be mentioned that the reduction in the GDP in the European recession in 2009 was high, around 14%, but the gross value-added levels was recovered in 2013.

From Figure 1, the recession derived from the COVID-19 pandemics had very little effect on the gross value added of the country, which was only contracted by 0.17% in 2020. The fast growth rate was recovered in 2021.

If the gross value added in Lithuania is divided into economic subsectors, the following chart can be obtained:

⁵ Source: Eurostat. Gross value added and income by main industry (NACE Rev. 2). Extracted on July 23rd, 2025.

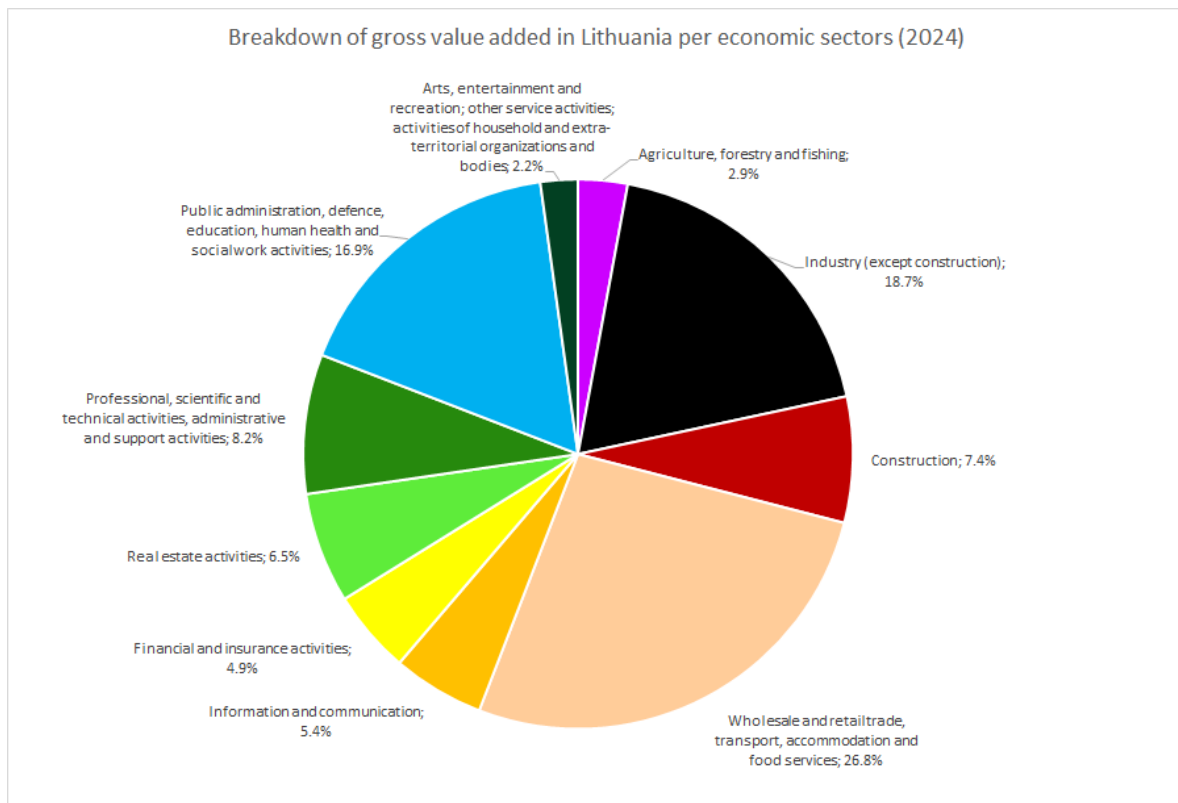


Figure 2: Breakdown of the gross value added in Lithuania, 2024

As can be seen from the previous figure, the most relevant economic sector in Lithuania is the services sector (70.9% of the Lithuanian economy in 2024) which includes the Wholesale and retail trade, transport, accommodation and food services, which was 26.8% of the whole Lithuanian economy, followed by the public sector, with a 16.9% and other services making up the remaining 27.2%.

On the other hand, its Industry represented 18.7%, Construction amounted to 7.4%, and Agriculture, forestry and fishing was just 2.9% of the Lithuanian economy.

The importance of the agriculture sector has been greatly reduced since the 90s, when it reached between 11% and 12%. Instead, the services sector has grown, from 57.4% in 1995 to 70.9% in 2024. The industry sector relative weight in the economy has slightly reduced, from 31.7% in 1995 to 26.1% in 2024.

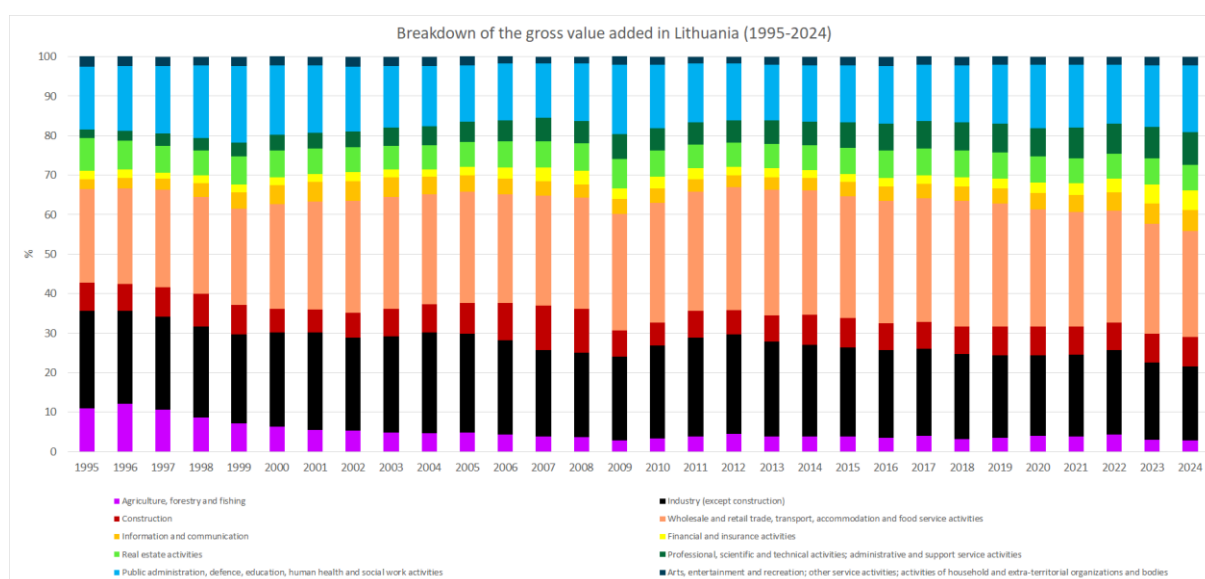


Figure 3: Evolution of the breakdown of the gross value added in Lithuania, period 1995-2024⁸

Similarly to the assessment about the evolution of the gross value added in Lithuania, the evolution of employment in the Republic of Lithuania can be examined. In 2024, there were 1.501 million people working in the country, with an unemployment rate of 7.1%⁶.

The following figure shows the evolution of the employment in Lithuania, classified per economic sectors.

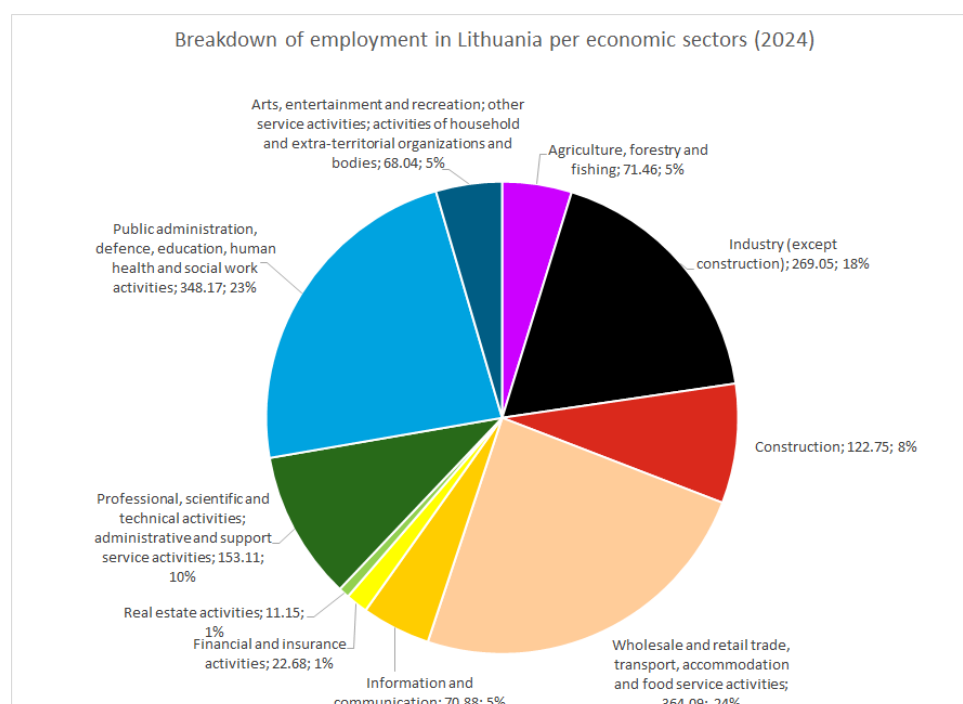


Figure 4: Breakdown of employment in Lithuania, year 2024⁷

⁶ Source: Eurostat. Unemployment by sex and age- annual data.

⁷ Source: Eurostat. Employment by main industry.

As can be seen from Figure 4, the sectors which create the most employment are: Industry and Construction, with a 26%, Wholesale and retail trade, transport, accommodation and food services, with 24%; and Public administration, defence, education, human health and social work activities, with 23%.

These percentages are comparable to the importance of each economic activity in terms of gross value added, although there are some activities which can create a very high value with less employment, such as Real estate activities or Financial and insurance activities.

The following figure shows the evolution in the employment, per sector, during the period 1995-2024, in absolute values⁸.

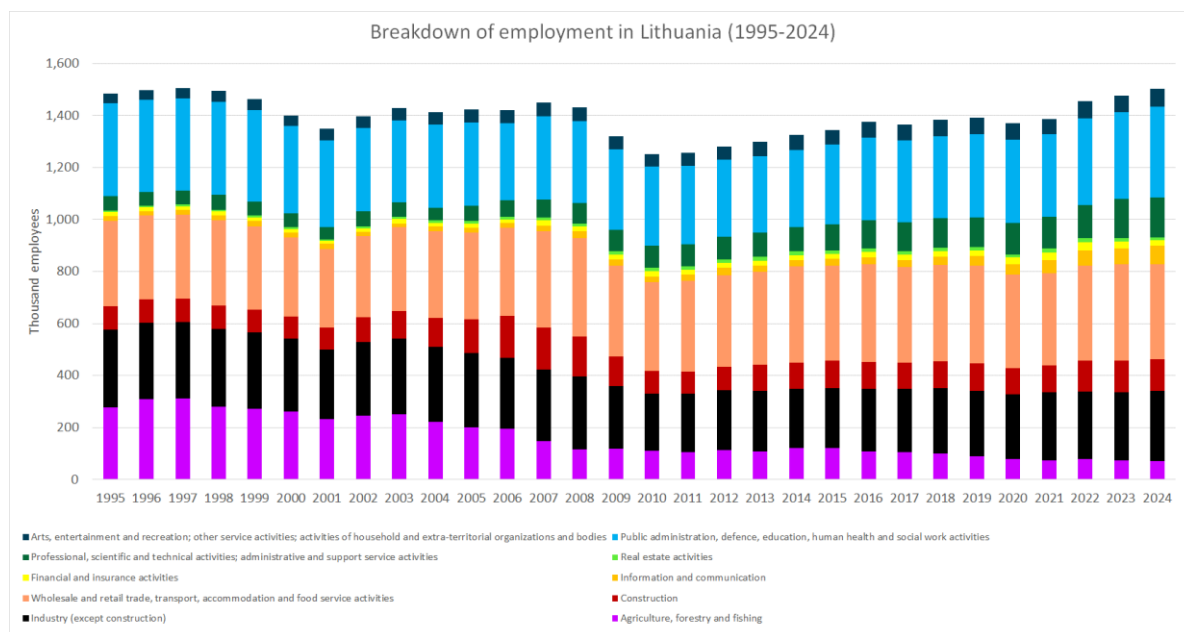


Figure 5: Evolution of the breakdown of the employment in Lithuania, period 1995-2024

As can be seen from this figure, the total number of professionals working in Lithuania went down in the period 2008-2010, with the financial crisis, but it has grown importantly in the last years, reaching 1.50 million people in 2024. Therefore, employment in 2024 was very near the employment in 1997, the maximum of the historical series.

It is important to remark the differences in the relative importance of some sectors: while the Agriculture, forestry and fishing sectors made around 20% in 1995, their importance has been reduced to 5% as the Lithuanian economy has been modernized. The importance of Industry is now slightly lower (from 20% to 18%), but the sector which has grown the most is Professional, scientific and technical activities, administrative and support service activities. These sectors were around 3.5%-4% in 1995, and now they create around 10% of the total employment.

Focusing specially on the industrial sector, Lithuania has a well-developed Industry, which created 18.7% of the gross value added and 17.9% of the employment in 2024.

The strongest industrial sectors are wood processing, chemicals, electronics, machine tool manufacturing, metal processing, construction materials, biotechnology, food processing, and light industries, including textile, clothing, furniture and household appliances manufacturing.

⁸ Source: Eurostat. Employment by main industry (NACE Rev.2) - national accounts

Lithuania's industry is a recognized worldwide leader in the laser technology industry, producing around 80% of the high-energy pico-second lasers worldwide. It is also the world leader in ultra-fast parametric light generator production.

Some of the most important industrial sectors in Lithuania are:

- **Automotive sector:** This sector has grown during the last years and is taking advantage of the good skills of the country in engineering. In the last years, major players at a worldwide level have established their operations in the country, such as Hella and Continental.
- **Industrial Machinery:** Lithuania has large amounts of skilled professionals in software development, IT and mechanical and electronics engineering, what makes the country an important player in the region in Industrial machinery and Equipment manufacturing. Besides, the country has a high-developed infrastructure, a strong hardware supply chain, and good ratios quality/cost.

On the other hand, Lithuania has developed some financial incentives to encourage the growth of the industrial sector, and to attract new companies to the country. The most important incentives are⁹:

- **Free Economic Zones (FEZ):** There are seven Free Economic Zones in different parts of the country, in some cases, located near airports: Klaipėda FEZ, Kaunas FEZ, Šiauliai FEZ, Kėdainiai FEZ, Akmenė FEZ, Marijampolė FEZ and Panevėžys FEZ.

Free Economic Zones offer investors good conditions to develop businesses, including large amounts of area available to install infrastructures and factories, with good connections, as well as facilities to lease. Besides, these zones offer support services and attractive tax incentives.

Companies which develop businesses in these zones can benefit from 0% tax on corporate profits during the first 10 years of operation, and only 7.5% tax over the corporate profits in years 11-17. These businesses are also exempt from tax on dividends and real estate taxes. As a comparison, the standard corporate tax rate is 16% in the country.

- **Green Corridor:** This is a support programme for large-scale investment projects. Projects asking for this support must be valued at more than €20 million in capital expenditures and create more than 150 jobs. In this case, the tax benefits for the companies include 0% of corporate tax during the first 20 years of operation, and simplified processes for land purchase, planning, and migration.
- **FDI Invest LT+:** To attract foreign direct investment in Lithuania, the Lithuanian government offers to cover a percentage of the total capital investment. The rate can reach up to 50%, although the specific subsidy is negotiated with each company and for each opportunity.

On the other hand, the 10 counties in which the Republic of Lithuania is divided have a strong industrial activity¹⁰:

- **Telšiai county** is characterized for the presence of the oil refinery ORLEN Lietuva, in Mažeikiai. This refinery, which is the biggest petrol product producer in the Baltic States,

⁹ Source: General Lithuania's Manufacturing Sector talking points. Invest Lithuania. 2022.

¹⁰ Source: Invest Lithuania.

demands for metalworking and machinery industries in the zone. For example, the **county** produces starters, alternators, agriculture machinery, household equipment, polished wire, nails, and fitting parts. Additionally, there is an important food industry, with some relevant brands, along with furniture manufacturing and wood (solid oak and veneered oak) processing.

- **Klaipėda county** is the third largest county in Lithuania. It is a significant hub for higher education, particularly through Klaipėda University. Klaipėda University specializes in maritime and marine sciences, IT, regional studies, and social sciences. Its strategic location near the Baltic Sea has allowed it to develop a reputation in maritime education, maritime logistics, environmental sciences, and regional development. The university has a directly contributing role by providing skilled professionals in maritime navigation, logistics, port management, and marine engineering. These graduates support Lithuania's port activities, maritime trade, and shipping industries, boosting efficiency and innovation. The university conducts research in marine sciences, environmental protection, renewable energy, and regional development, fostering innovations that benefit the maritime and environmental sectors. It acts as a catalyst for economic growth in the Klaipėda region, attracting research projects, investments, and fostering partnerships with industry stakeholders, including port authorities, shipping companies, and environmental organizations. The Klaipėda county's industrial activity is based on its port, the only ice-free one in the Baltic region. Besides, the county has the largest shipyard of the country, being able to offer services such as design and turnkey projects. Moreover, testing and component manufacturing is also carried out in the county, along with small-scale extraction of oil and natural gas. The zone is also the largest PET products supplier in Europe, and has a strong chemical and plastic industry, producing lubricants, engine oils and plastic plumbing pipes. Finally, other strong industries in the Klaipėda zone are pet food, beer, fish and meat processing, confectionery, tobacco products, soft furniture and wooden components. The county is also well connected by air, with the Palanga International Airport 20 minutes far.
- **Tauragė county** is a production zone for the key industries of food processing, agriculture, rubber and plastic, as well as textile and protective clothing production. There is also a strong furniture and wood industry, producing construction timber, wood pellets, standard and custom designed solid wood, and clipboard furniture. Besides, there is a well-developed private industrial park, where there are more than 15 international companies. The county produces renewable energy, including biomass, wind power, hydro energy and solar energy. It has the largest wind farm in the Baltic States (which also extends to the Pagėgiai Municipality), two solar PV plants and the second biggest hydroelectricity plant in Lithuania.
- **Šiauliai county** has experience in the television production and technical manufacturing, in industries such as heating, ventilation equipment, furniture components and building materials. It also has mechanical and electrical engineering, producing electric and regular bicycles, and retail equipment, metal components, electrical distribution equipment and household appliances. The county also produces construction materials, notably cement in factories like the one belonging to Naujoji Akmenė, but also roofing sheets and tiles, façade/interior boards and panels, and fibre-reinforced composite.
- **Panevėžys county** is specialized in metal working and electrical engineering, having been the largest colour TV screen and compressor producer in the Baltic zone. The county has also a relevant heavy vehicle industry, including metal and electric components, which are used by vehicle manufacturers such as Volvo, Scania, MAN, Rolls-Royce and Bombardier. The county

also has an important Norwegian industrial park, “Scan Investment”, developed by the Norway government, and where many Norwegian investors develop businesses, mainly in the furniture industry. The county is also making efforts in the transition to the Industry 4.0 and process robotization. Finally, other relevant industrial sectors are glass manufacturing (with an important factory, AB Panevėžio stiklas), textile, mattresses, and food and beverages (wheat processing, starch modification, meat processing, dairy products and milk proteins).

- **Utena county** has the largest brewery of Lithuania, the Carlsberg-owned Švyturys-Utena brewery. Besides, the presence of the now-decommissioned Visaginas nuclear power plant made this region have a large amount of highly skilled professionals in the energy sector. Other strong industries are textiles (apparel, work wear, suits and knitwear), meat and wine, and metal processing and machinery, as well as heating equipment and R&D medical devices.
- **Kaunas county** takes benefit of being home of the Kaunas University of Technology (KTU), the largest engineering university in Lithuania. Besides, Kaunas is easily reachable by road, rail, and air. The Kaunas Free Economic Zone is the largest one in the country. The main industries in the county are advanced electric and mechanic engineering, including automotive components, electric vehicles, charging points and parts, computer vision systems, electronic components and industry automation solutions. Along with it, the county produces medical products, such as pharmaceuticals, medical devices, clinical trials management, healthcare software, embedded software and imaging software. The county also has experience in IT solutions, including mobile development, UI and UX design, e-commerce solutions, web development platform, software solutions for engineering, F&A software and IT security solutions. Additionally, the county has an established fertilizer industry with two factories located in Jonava and Kėdainiai.
- **Marijampolė county** is one of the less industrialized counties in Lithuania. However, it benefits from the Mockava Terminal, the only railway station in Lithuania which is directly connected to the Poland railway network, and which connects Poland and the Baltic states. The main industrial activity in the Marijampolė county is centred on wood and furniture (including windows, glued plywood, particle boards, wooden pallets, soft furniture, and timber products), food (frozen bakery products, confectionery, meat and fish processing, condensed milk and sugar), as well as metal processing and machinery (such as metal structures, containers, machined and forged components, packaging machines, and automation solutions).
- **Vilnius county** has the largest city of Lithuania, and many activities related to IT, such as software development, R&D, and computer game development. The Santara Valley Science and Technology Park and the Vilnius University are able to attract activity in the industries of life sciences (manufacturing of enzymes, medical devices for respiratory support, molecular biology products, generic and innovative pharmaceutical preparations, and food supplements), fintech, electronics and optics (manufacturing of scientific and industrial lasers, optical parametric amplifiers, solar cells and modules, metering equipment, wireless controllers and remote fleet management systems).
- **Alytus county** is specialized in technical textile and ventilation solutions, home textile, knitwear, sportswear, upholstery manufacturing. It also has wood processing and furniture production including prefabricated wood houses, timber processing, wood pellets, upholstered and wooden, furniture components, mattresses and foam production. Besides, in Alytus there is the only refrigerator manufacturing in the Baltic Sea Region, and produces

electrical appliances, stainless steel products, storage tanks and pressure vessels, and electronic components.

CO₂ emissions in Lithuania

Lithuania is one of the 195 countries which have ratified the United Nations Framework Convention on Climate Change (UNFCCC), which entered into force on March 21st, 1994. Lithuania also signed the Kyoto Protocol in 1998 and ratified it in 2002.

In December 2015, 195 countries agreed to develop a global action plan to avoid climate change, by limiting global warming to well below 2°C. This agreement was reached in the Paris climate conference and is called the Paris Agreement. Lithuania signed the Paris Agreement on April 22nd, 2016, and ratified it on December 30th, 2016.

Lithuania has the following targets regarding the reduction of greenhouse gas emissions, which are related to the targets of the European Commission, and the international commitments of the whole European Union and the individual country. These objectives are included in the National Climate Change Management Agenda:

- 2030: 70% reduction of greenhouse gas emissions in all the economy, compared to 1990, or 30% reduction compared to 2005. In the EU Emission Trading Systems (ETS), the reduction should be 50% compared to 2005, while the non-EU ETS sectors should reduce their emissions by 25% compared to 2005.
- 2040: 85% reduction of greenhouse gas emissions in all the economy, compared to 1990.
- 2050: Become carbon-neutral, this is, reduction by 100% compared to 1990.

These objectives have been increased compared to the Lithuanian National Energy and Climate Plan submitted in 2019, which included a target of reducing the greenhouse gas emissions in all the economy by 40% compared to 1990 in 2030, 70% in 2040 and 80% in 2050.

The following table shows the evolution of these targets:

Lithuania GHG emission reduction targets						
	EU Climate and Energy Framework and 2019 National Energy and Climate Plan			Update Climate Targets (European Green Deal and National Climate Change Management Agenda)		
	2030	2040	2050	2030	2040	2050
	(compared to 1990)	(compared to 1990)	(compared to 1990)	(compared to 1990)	(compared to 1990)	(compared to 1990)
Economy-wide	-40%	-70%	-80%	-70%	-85%	-100%
EU ETS sectors	-43% (compared to 2005)			-50% (compared to 2005)		
Non-ETS sectors	-9% (compared to 2005)			-25% (compared to 2005)		

Table 1: Evolution of the greenhouse gas emission reduction targets in Lithuania

According to the United Nations Framework Convention on Climate Change (UNFCCC) and to the Kyoto Protocol, Lithuania prepares regularly, and updates, the greenhouse gas emissions inventories. The following table includes the Lithuania's emissions by sectors during the period 1990-2023:

GHG emissions/removals in kt CO ₂ eq., using IPCC AR5 GWPs							
GHG source and sink categories	Energy	Industrial Processes and Product Use	Agriculture	LULUCF	Waste	Total without LULUCF	Total with LULUCF
1990	33,145.2	4,299.9	8,626.7	- 4,031.0	1,340.5	47,412.3	43,111.2
1991	35,203.8	4,324.3	8,470.6	- 4,893.9	1,368.4	49,367.1	44,473.2
1992	19,937.0	2,526.3	6,535.2	- 4,193.6	1,341.1	30,339.5	26,145.9
1993	16,065.2	1,600.5	5,179.8	- 5,726.0	1,371.3	24,216.8	18,490.8
1994	15,137.5	1,816.7	4,534.3	- 5,448.7	1,347.2	22,835.7	17,387.0
1995	14,186.8	2,096.7	4,169.0	- 4,231.9	1,352.6	21,805.1	17,573.2
1996	14,669.6	2,459.3	4,295.9	1,089.4	1,352.0	22,776.9	23,866.3
1997	14,217.6	2,413.3	4,325.2	- 316.5	1,372.6	22,328.6	22,012.1
1998	14,914.7	2,789.2	4,163.4	- 8,031.9	1,355.5	23,222.8	15,190.8
1999	12,473.7	2,717.9	3,884.2	- 7,434.5	1,346.5	20,422.2	12,987.8
2000	10,945.0	2,849.1	3,687.0	- 9,777.3	1,355.4	18,836.5	9,059.2
2001	11,624.2	3,078.5	3,523.9	- 7,619.7	1,398.9	19,625.4	12,005.7
2002	11,688.4	3,235.2	3,668.6	- 6,741.5	1,404.2	19,996.4	13,254.9
2003	11,701.9	3,309.7	3,757.8	- 6,074.1	1,413.7	20,183.1	14,109.0
2004	12,320.6	3,476.6	3,807.8	- 5,626.0	1,391.8	20,996.8	15,307.8
2005	13,172.8	3,504.1	3,825.4	- 4,843.2	1,359.9	21,862.3	17,019.1
2006	13,222.6	3,803.7	3,829.3	- 4,354.7	1,343.2	22,198.8	17,844.1
2007	13,447.8	5,443.0	3,926.0	- 6,079.4	1,317.7	24,134.5	18,055.1
2008	13,326.2	4,865.8	3,849.1	- 6,644.3	1,211.0	23,252.1	16,607.8
2009	12,147.0	2,005.8	3,906.1	- 7,432.5	1,195.5	19,254.3	11,821.8
2010	13,131.7	2,007.3	3,863.0	- 10,671.2	1,185.7	20,187.6	9,516.4
2011	12,273.1	3,265.9	3,898.8	- 10,632.4	1,118.7	20,556.5	9,924.1
2012	12,312.4	3,183.8	3,947.2	- 10,038.3	1,098.5	20,541.9	10,503.6
2013	11,688.2	2,735.4	3,922.1	- 9,319.5	1,072.2	19,417.9	10,098.4
2014	11,307.6	2,872.3	4,116.0	- 8,420.9	1,024.7	19,320.6	10,899.7
2015	11,278.2	3,179.2	4,190.4	- 7,412.7	980.8	19,628.6	12,215.8
2016	11,587.7	3,037.8	4,094.4	- 6,498.8	969.1	19,689.0	13,190.2
2017	11,539.3	3,276.9	4,046.0	- 5,846.3	962.4	19,824.5	13,978.2
2018	11,883.1	2,844.8	3,920.5	- 4,761.6	851.9	19,500.3	14,738.6
2019	11,896.5	3,072.3	3,932.5	- 5,079.5	813.6	19,714.9	14,635.4
2020	11,807.7	2,878.4	4,133.2	- 5,141.0	788.9	19,608.2	14,467.2
2021	12,222.4	2,745.4	4,047.3	- 5,381.6	751.1	19,806.5	14,384.7
2022	11,710.4	2,276.2	3,754.9	- 6,477.5	706.7	18,486.8	11,970.8
2023	11,398.7	2,091.1	3,687.1	- 3,144.0	711.7	17,927.2	14,744.6
2023/1990%	-65.6%	-51.4%	-57.3%	-22.0%	-46.9%	-62.2%	-65.8%

Table 2: Evolution of the greenhouse gas emissions in Lithuania¹¹

As can be seen, the greenhouse gas emissions in the country have been reduced by 62.2% if LULUCF¹² are not considered, and by 65.8% if they are taken into account, during the period from 1990 to 2023. The sectors with the largest reductions are Energy (-65.6%), Agriculture (-57.3%) and Waste (-51.4%).

The main reason for the decrease in the greenhouse gas emissions during the period from 1990 to 2023 is related to the change in the Energy sector, the decline in industrial production and the use of fossil fuels.

Going into a higher detail, as will be detailed in chapter 3.2, the energy consumption in Lithuania went down very importantly between 1900 and 1992. Until 1991, Lithuania made part of the Soviet Union. Once the Soviet Union disappeared, there was an important economic crisis in Lithuania, what led to a

¹¹ Source: Ministry of Environment. Republic of Lithuania. Environmental Protection Agency. State Forest Service. *Lithuania's National Inventory Report 2025. Greenhouse Gas Emissions 1990-2023*. Vilnius, 2025.

¹² LUCUCF is Land Use, Land-Use Change and Forestry, and is referred to the carbon dioxide that is stored as carbon in the vegetation and soil in land.

very high reduction of energy consumption. As can be seen, greenhouse gas emissions from the Energy sector in 1992 were only 57% of the emissions in 1991.

Greenhouse gas emissions in other sectors, such as Industry and Agriculture, also went down when Lithuania left the Soviet Union. Since then, emissions have been reduced thanks to the improvement in energy efficiency in processes, the use of more renewable energies, and measures to reduce greenhouse gas emissions. Between 1993 and 2023, the total greenhouse gas emissions reduction has reached 26%.

If the importance of each economic sector in terms of greenhouse gas emissions is considered, in 2023, the sector which accounted for the largest emissions was Energy, with 63.6%. Agriculture was responsible for 20.6% of the emissions, and thirdly, Industry produced around 11.7%.

Included in the Energy sector, the main subsectors are Transport, with 34.4%, and Energy industries, with 13.5%, followed by Manufacturing industries and construction (6.1%).

The following graph shows the evolution of the greenhouse gas emissions per sector, during the period 1990-2023:

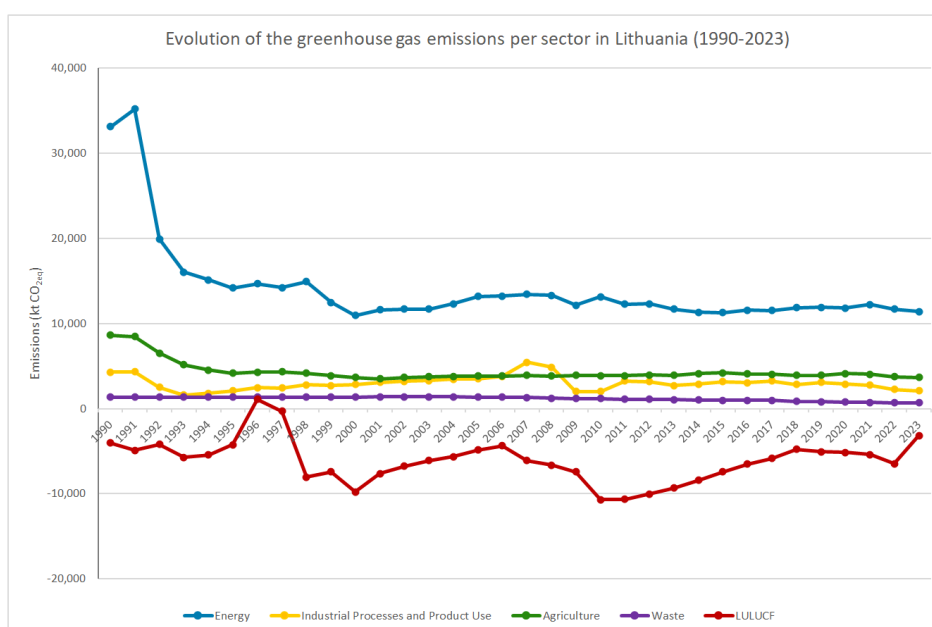


Figure 6: Evolution of the greenhouse gas emissions, per economic sector, for the period 1990-2023¹¹

Besides, the following figure shows the breakdown of greenhouse gas emissions, per greenhouse gas, during the period from 1990 to 2023:

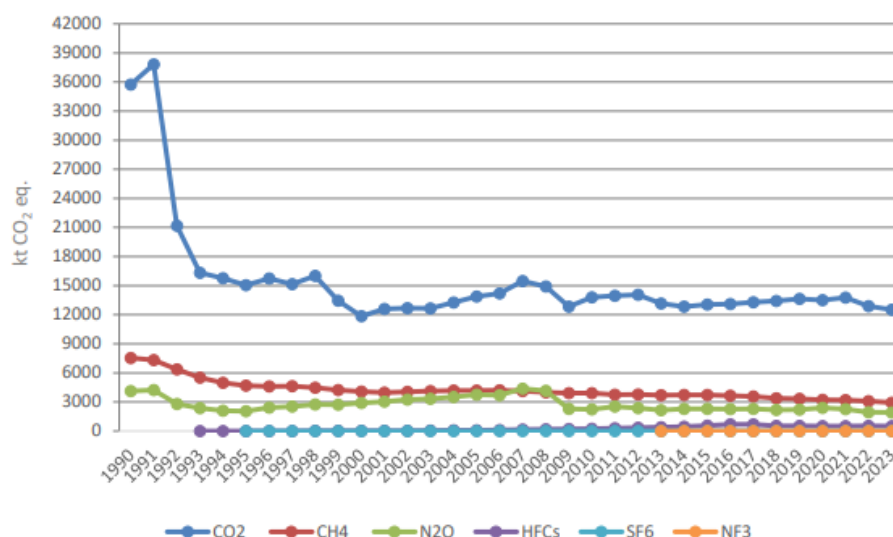


Figure 7: Evolution of the greenhouse gas emissions, per gas, for the period 1990-2023¹¹

As can be seen, the most important greenhouse gas is carbon dioxide. Other gases have lower absolute emissions, but due to the large values of their global warming potential (GWP), they make an important effect in terms of global warming, such as methane (CH₄) and nitrous oxide (N₂O).

Global Warming Potential (GWP) is an index developed by the Intergovernmental Panel on Climate Change (IPCC), to consider that not all greenhouse gases have the same impact on global warming. The GWP is a measure of how much heat is absorbed the emission of 1 tonne of a greenhouse gas, compared to the heat absorbed by 1 tonne of carbon dioxide (CO₂). This means that, if a greenhouse gas has a larger GWP, this gas will have a larger impact in terms of warming the earth's atmosphere. For example, if a gas has a GWP of 27, 1 tonne of that gas will absorb as much heat as 27 tonnes of CO₂.

Global Warming Potential depends on the time horizon, as some gases decay as years go by, while the effect of other gases multiplies after some years in the atmosphere.

The following table offers the Global Warming Potentials of some of the main greenhouse gases:

Greenhouse gas	Expected lifetime (years)	Global Warming Potentials in different time horizons		
		20 years	100 years	500 years
Carbon dioxide (CO₂)	N/A	1	1	1
Methane (including indirect) (CH₄)	12 years	82.5 ± 25.8	29.8 ± 11	10.0 ± 3.8
Nitrous oxide (N₂O)	109 years	273 ± 118	273 ± 130	130 ± 64
CFC-11 (R-11) (CCl₃F)	52 years	8,321 ± 2,419	6,226 ± 2,297	2,093 ± 865
CFC-12 (R-12) (CCl₂F₂)	100 years	10,800	10,200	
HCFC-22 (R-22) (CHClF₂)	12 years	5,280	1,760	
HFC-32 (R-32) (CH₂F₂)	5 years	2,693 ± 842	771 ± 292	220 ± 87
HFC-134a (R-134a) (CH₂FCF₃)	14 years	4,144 ± 1,160	1,526 ± 577	436 ± 173
Tetrafluoromethane (R-14) (CF₄)	50,000 years	5,301 ± 1,395	7,380 ± 2,430	10,587 ± 3,692
Hexafluoroethane (C₂F₆)	10,000 years	8,210	11,100	
Sulfur hexafluoride (SF₆)	3,200 years	17,500	23,500	
Nitrogen trifluoride (NF₃)	500 years	12,800	13,700	

Table 3: Global Warming Potentials of some relevant greenhouse gases, in different time horizons^{13, 14}

It can be mentioned that the importance of CH₄ emissions has gone down through the analysed period, as well as CO₂ emissions. However, HFCs emissions have grown during the last 10 years.

As this report focuses on the use of carbon dioxide capture, sequestration, use and storage in industrial zones of Lithuania, it is important to specifically review emissions in the industry sector.

In 2023, four sectors of interest were identified, which combine an absolute relevant amount of carbon dioxide emissions, with a reduced number of emission points: fertiliser production, cement production, oil refining, and heating and electricity production.

In addition to the main industry emitters, a significant part (38%) of total emissions in Lithuania comes from heat and power generation.

Out of the industrial players, five companies emit 23% of the total CO₂ emissions in Lithuania, and 87% of the total emissions in the sectors which were registered in the GHG Emission Allowance Registry in 2023¹⁵.

¹³ Source: Intergovernmental Panel on Climate Change. MASSON-DELMOTTE, V., P. ZHAI, A. PIRANI, S.L. CONNORS, C. PÉAN, S. BERGER, N. CAUD, Y. CHEN, L. GOLDFARB, M.I. GOMIS, M. HUANG, K. LEITZELL, E. LONNOY, J.B.R. MATTHEWS, T.K. MAYCOCK, T. WATERFIELD, O. YELEKÇİ, R. YU, AND B. ZHOU(eds). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. 2021. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

¹⁴ Source: Intergovernmental Panel on Climate Change. MYHRE, G., D. SHINDELL, F.-M. BRÉON, W. COLLINS, J. FUGLESTVEDT, J. HUANG, D. KOCH, J.-F. LAMARQUE, D. LEE, B. MENDOZA, T. NAKAJIMA, A. ROBOCK, G. STEPHENS, T. TAKEMURA AND H. ZHANG, 2013. *Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

¹⁵ Source: Ministry of Environment. Republic of Lithuania. Environmental Protection Agency. State Forest Service. *Lithuania's National Inventory Report 2025. Greenhouse Gas Emissions 1990-2023*. Annexes. Vilnius, 2025.

They are the following:

- AB “ORLEN Lietuva”, an oil refinery factory located 200 km North from Vilnius. The total emissions in 2023 reached 1.65 million tonnes of CO₂.
- AB “Achema”, a producer of nitrogen fertiliser and other chemical products, located in Jonava District, 100 km Northwest of Vilnius. This plant had total emissions of 1.36 million tonnes of CO₂ in 2023.
- AB “Akmenės Cementas”, a cement production factory, located in Šiauliai. AB “Akmenės Cementas” is the largest cement manufacturer in Lithuania, and had emissions of 0.78 million tonnes of CO₂ in 2023. It is located 270 km Northwest of Vilnius.
- UAB "Vilniaus Šilumos Tinklai". Vilniaus šilumos tinklai is Lithuania's largest provider of heating and hot water, and emitted around 0.23 million tonnes of CO₂ in 2023.
- AB "Ignitis gamyba". It is a relevant power producer in Lithuania, and one of its plants produced 0.13 million of tonnes of CO₂ in 2023.

The following table includes a list of the 20 main emitters in Lithuania, in year 2023:

N	Plant name	Region	Emitters	NACE code	Verified emissions of CO ₂ produced in 2023, tonne
1	AB "ORLEN Lietuva"	Telšiai	Oil refinery factory	19.20- Manufacture of refined petroleum products	1,646,257
2	AB "Achema"	Kaunas	Chemicals, boilers and CHP	20.15- Manufacture of fertilisers and nitrogen compounds	1,363,398
3	AB "Akmenės Cementas"	Šiauliai	Cement production furnace	23.51- Manufacture of cement	783,849
4	UAB "Vilniaus Šilumos Tinklai"	Vilnius	Vilnius Power Plant No 2 (E-2)	35.30- Steam and air conditioning supply	233,200
5	AB "Ignitis gamyba"	Vilnius	Power plant	35.11- Production of electricity	128,564
6	UAB "Kauno kogeneracine jėgainė"	Kaunas	Power plant	35.10- Electric power generation, transmission and distribution	119,661
7	UAB "Gren Klaipėda"	Klaipėda	Power plant	35.10- Electric power generation, transmission and distribution	100,151
8	AB "KN Energies"	Klaipėda	LNG terminal FSRU	52.24- Cargo handling	94,023
9	UAB "Paroc"	Vilnius	Plants producing stone-wool	23.99- Manufacture of other non-metallic mineral products n.e.c.	49,235
10	AB "Nordic Sugar Kėdainiai"	Kėdainiai	Sugar manufacturing	10.81- Manufacture of sugar	28,052
11	AB "Panevėžio stiklas"	Panevėžys	Glass melting furnace	23.13- Manufacture of hollow glass	18,531
12	UAB "Neo Group"	Klaipėda	Polyethene and plastic sheet supplier	20.16. - Manufacture of plastic raw materials	18,203
13	UAB "Lietuvos cukrus fabrikas"	Marijampolė	Boiler	10.81- Manufacture of sugar	15,763
14	AB "Panevėžio energija"	Panevėžys	Kėdainiai region boiler house	35.30- Steam and air conditioning supply	15,127
15	UAB "IKEA Industry Lietuva"	Kazlų Rūdos	Fuel combustion plants	16.21- Manufacture of veneer sheets and wood-based panels	14,226
16	AB "Šiaulių energija"	Šiauliai	Šiauliai southern boiler house	35- Electricity, gas, steam and air conditioning supply	14,056
17	UAB "Kauno stiklas"	Kaunas	Glass melting furnace	23.13- Manufacture of hollow glass	13,695
18	AB "Grigeo Klaipėda"	Klaipėda	Paper and cardboard manufacturing plant	17.12- Manufacture of paper and paperboard	8,865
19	AB "Amber Grid"		Natural gas transmission operator	49.50- Transport via pipeline	8,089
20	AB "Grigeo"		Paper and cardboard manufacturing plant	17.12- Manufacture of paper and paperboard	7,786
21	Other installations registered in the GHG Emission Allowance Registry, 2023				71,322
Total CO₂					4,752,053

Table 4: List of the twenty large emitter plants in Lithuania in 2023¹⁶

¹⁶ Source: Ministry of Environment. Republic of Lithuania. Environmental Protection Agency. State Forest Service. *Lithuania's National Inventory Report 2025. Greenhouse Gas Emissions 1990-2023. Annexes*. Vilnius, 2025. The emitter number 8 has been changed from UAB „Hoegh LNG Klaipėda" to AB "KN Energies", as the LNG terminal FSRU was acquired by this company in December 2024.

3.2. Energy infrastructure

Primary energy production and demand

The following figure shows the data for the primary energy production, imports and exports for the period between 1990 and 2023¹⁷:

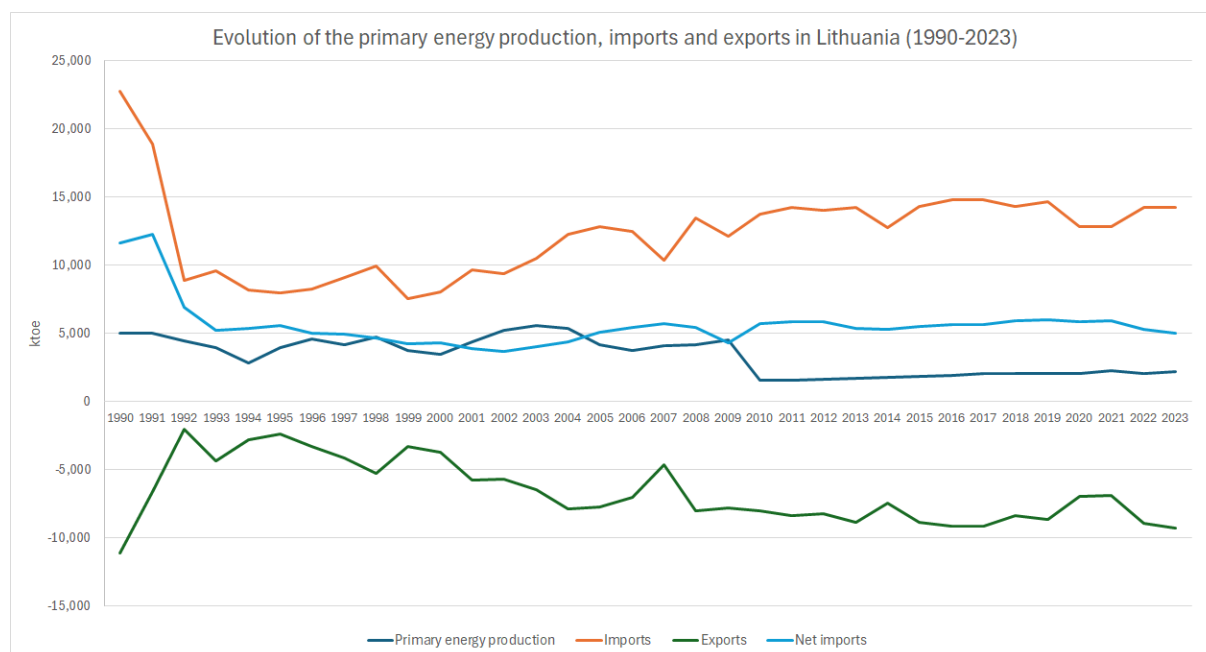


Figure 8: Evolution of the primary energy production, imports and exports in Lithuania, period 1990-2023

Regarding the primary energy production in the country, during the period from 1990 to 2009, it remained quite constant, around 4,300 ktoe approximately. An important reduction can be noticed in 1994, of 29%. This is mainly related to an important decrease in the electricity generation in that year, specifically from nuclear power, and with oil and natural gas, compared to previous years.

Since 2009, the shutdown of the Ignalina Nuclear Power Plant, led to a sharp reduction of the primary energy production of the country, which in 2010 was 1,563 ktoe. Since then, it grew to around 2,000 ktoe until 2017, and it has kept constant around 2,000-2,200 ktoe since then.

Regarding primary energy imports and exports, they reached their maximum in 1990 and 1991, when Lithuania remained in the former Soviet Union. As the Soviet Union disappeared, the country suffered an economic crisis, what led to a reduction of both energy imports and exports. Specifically, energy imports went down from around 23,000 ktoe in 1990 to around 9,000 ktoe in 1992, while energy exports were reduced from around 11,000 ktoe in 1990 to around 2,000 ktoe in 1992. Since then, the curves of energy imports and exports have been approximately symmetrical about axis X: what involves that most of the energy imported is transformed in Lithuania and then exported. During the last 20 years, energy imports have been around 13,500 ktoe, and energy exports around 8,000 ktoe.

The following figure shows the evolution of the total energy supply, the primary energy consumption and the final energy consumption. The comparison between the primary and the final energy consumption is interesting to evaluate the improvement of the performance of the energy system in Lithuania.

¹⁷ Source: Eurostat. Complete energy balances. Last update May 2nd, 2025.

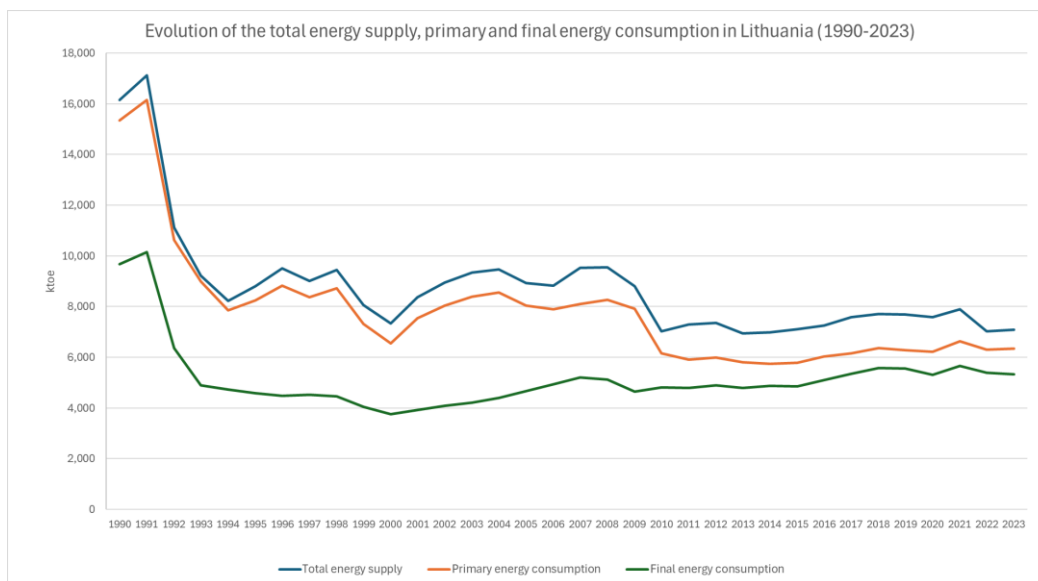


Figure 9: Evolution of the total energy supply, primary and final energy consumption in Lithuania, period 1990-2023¹⁸

The evolutions of the total energy supply and the primary energy consumption are similar and have been discussed before. However, it is interesting to note that the primary energy consumption and the final energy consumption are getting closer. During the period since 1990 to 2009, the ratio between primary and final energy consumption ranged from 50% to 64%, and since 2009, it has grown to around 84%. This shows an improvement in the efficiency of the energy utilization by the country.

Coal production and consumption

The following figure shows the coal production, consumption, exports and imports, along the period 1990-2024:

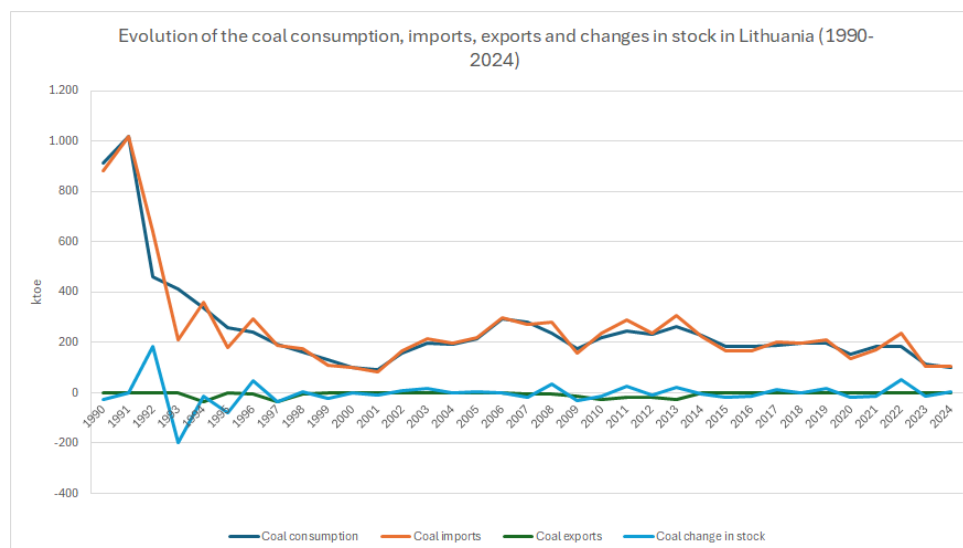


Figure 10: Evolution of the coal consumption, imports, exports and changes in stock in Lithuania, period 1990-2024¹⁹

¹⁸ Source: Eurostat. Complete energy balances. Last update May 2nd, 2025.

¹⁹ Source: Eurostat. Supply, transformation and consumption of solid fossil fuels. Last update June 25th, 2025.

Firstly, it is important to note that Lithuania has never produced coal, so the coal consumed by the country is approximately the coal that is imported. There are, however, some differences, derived from changes in stock, and very small coal exports which are produced in some years of the series.

Coal consumption and imports were higher in the first year of the series, 1990 and 1991, when they reached around 900 ktoe in 1990 and around 1,000 ktoe. As described for the energy consumption, when Lithuania left the Soviet Union, the coal consumption was reduced importantly, especially in 1992, when it reached 460.6 ktoe. Coal consumption continued going down to a minimum in 2001, with 91 ktoe. Then, it grew until 2006, when it almost reached 300 ktoe, and since then it has remained almost constant, around 200 ktoe. Imports have evolved quite similarly, except for the stock changes and very small exports.

Regarding the sectors with higher coal consumption, in the 90s, the most important sectors were households (46% in 1990, or 422.8 ktoe) and commercial and public sectors (38% in 1990, 344.4 ktoe). Both sectors reduced their coal consumption during the 90s, the commercial and public sector consumption in 2000 was only 17% of the consumption in 1990, and the household consumption was only 5%. Since then, both consumptions have been, altogether, around 100 ktoe.

The coal consumption in the industry sector was reduced from around 50 ktoe in the first years of the 1990 decade to only 9.8 ktoe in 2001. Since then, the coal consumption grew again, to an average of 120 ktoe per year.

Oil production and consumption

The following figure shows the evolution of the oil production, consumption, imports, exports, and change in stock in Lithuania, during the period 1990-2023.

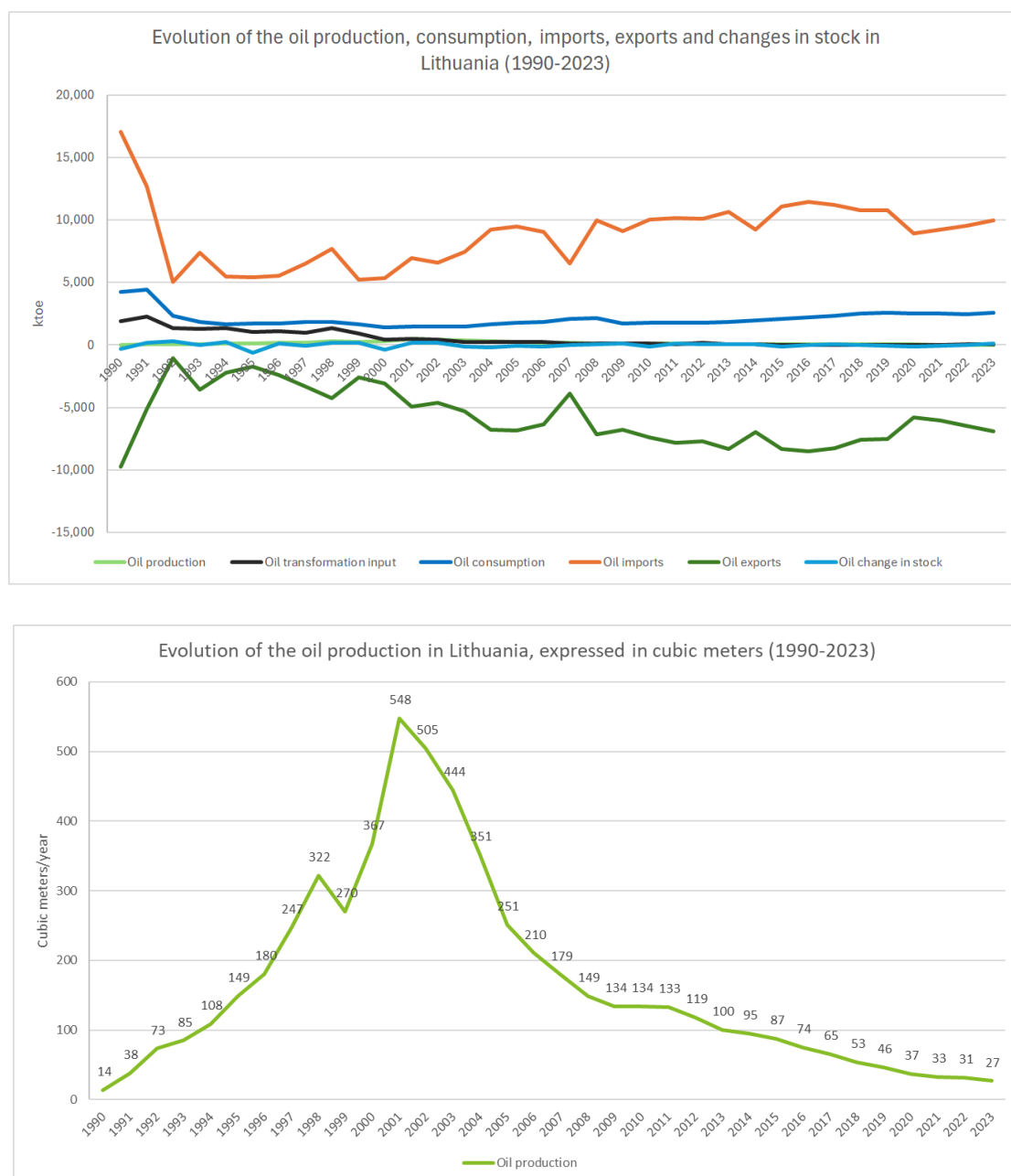


Figure 11: Evolution of the oil production, consumption, imports, exports and changes in stock in Lithuania, period 1990-2023. Graphic below: Detail of oil production in Lithuania in m³/year. ²⁰

Firstly, it should be noted that the oil production in Lithuania is very low, around 20 ktoe in the last three years. It reached a maximum of 471 ktoe in 2001, year when it was 32% of the country's oil consumption. During the 21st century, there have been some attempts, by oil drilling companies in

²⁰ Source: Eurostat. Supply, transformation and consumption of oil and petroleum products. Last update June 25th, 2025.

Lithuania (AB LOTOS Geonafta, UAB Genčių nafta, UAB Manifoldas, UAB Minijos nafta, LL Investicijos, Achema, Tethys Oil AB, Orlen Lietuva, Oilead) to explore new resources and produce oil.

Oil consumption, as happens with energy consumption in general, reached a maximum in 1990 and 1991 with around 4,500 ktoe. After the disappearance of the Soviet Union, oil consumption fell to 2,300 ktoe. It continued falling, until 1,400 ktoe in 2000. Since 2001 to 2008, it grew until 2,164 ktoe. With the financial crisis of 2009, oil consumption went down to 1,713 ktoe, with a reduction of about 21%. Since then, it has grown until 2018 with 2,552 ktoe. In the last 6 years, oil consumption has remained constant, with around 2,500 ktoe.

Oil imports and exports have been, as primary energy imports and exports, symmetrical about the axis X. The maximum imports took place in 1990, with around 17,000 ktoe, while the maximum exports were 9,800 ktoe, another maximum. Then, they reached their minimum in 1992, with 5,066 ktoe for the exports and 1,076 ktoe for the imports. During the period 1994-2000, exports were 2,800 ktoe on average, and imports were 5,900 ktoe. Both grew until 2006, with 9,000 ktoe for exports and 6,360 ktoe for imports, to fall again in 2009 with the economic crisis. In the period from 2010 to 2023, they have been constant on average, with 10,200 ktoe for oil imports and 7,400 ktoe for oil exports.

Natural gas production and consumption

The following figure shows the evolution of the natural gas consumption, imports, exports and changes in stock in Lithuania, during the period from 1990 to 2023.

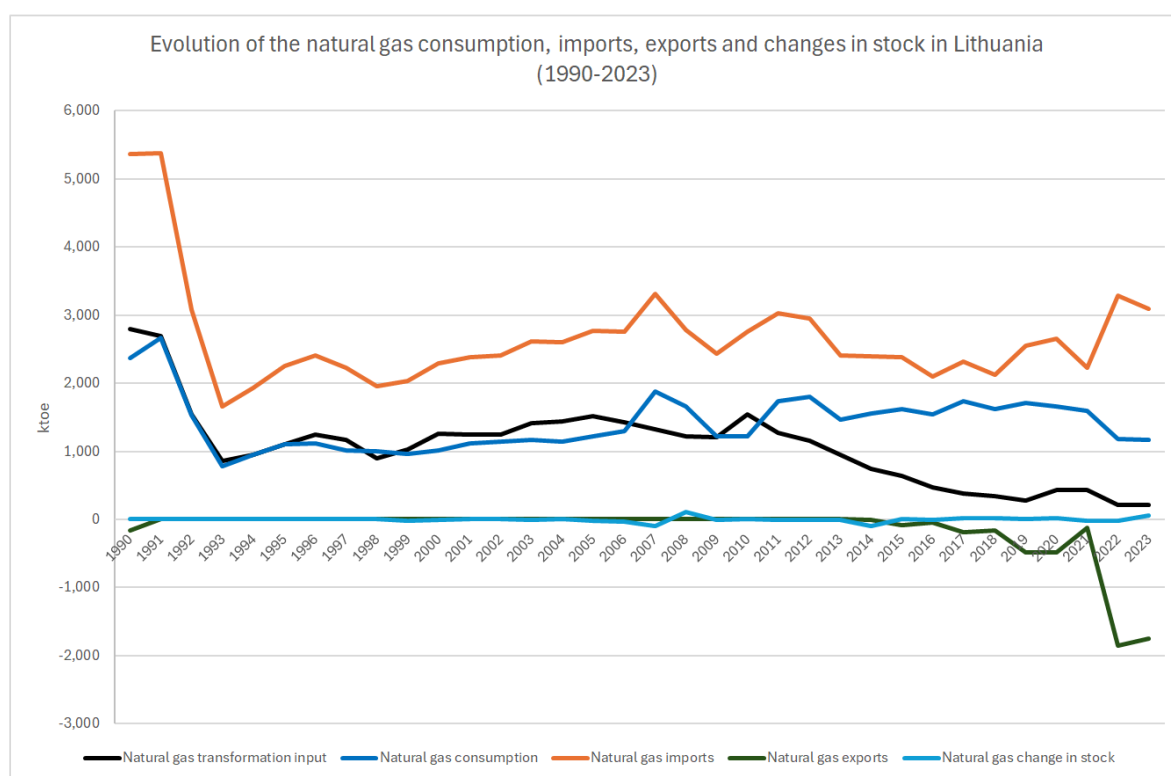


Figure 12: Evolution of the natural gas production, consumption, imports, exports and changes in stock in Lithuania, period 1990-2023²¹

²¹ Source: Eurostat. Supply, transformation and consumption of gas. Last update June 25th, 2025.

First of all, Lithuania does not produce any natural gas domestically, as the country lacks commercially viable gas accumulations. This is due to the natural geological conditions in the region, including the insufficient thermal maturity of the organic matter, the type of kerogen, and suboptimal temperature and pressure regimes, which are not conducive to the generation of dry natural gas. As a result, all natural gas consumption in Lithuania is covered through imports. In the figure before, the total natural gas consumption of the country, which includes the consumption itself and the transformation input, reached a maximum of 5,156 ktoe in 1990 and 5,350 ktoe in 1991. As has happened with other energy sources, consumption went down in 1992, reaching only 3,068 ktoe in that year. It has grown steadily until 2007, with 3,212 ktoe, and then went down in 2008 with the economic crisis. They grew again to around 3,000 ktoe in 2009 until 2012. However, since then, and due specially to the reduction in the use of natural gas as a transformation input, consumption has been reduced, until 1,371 ktoe in 2023.

Natural gas imports were almost equivalent to consumption and transformation input until 2017, with some small differences due to changes in stock. However, in 2017, Lithuania began to export natural gas, and for this reason imports grew more than consumption. Imports have been above 3,000 ktoe in 2022 and 2023. Natural gas exports were low until 2021, below 500 ktoe, with no exports until 2014. However, in 2022 and 2023, exports were around 1,800 ktoe.

Power capacity in Lithuania

The structure of the power generation mix in Lithuania has radically changed in the past decade. The following figure shows the evolution of the installed electricity power capacity in the country, for the period 1990-2025.

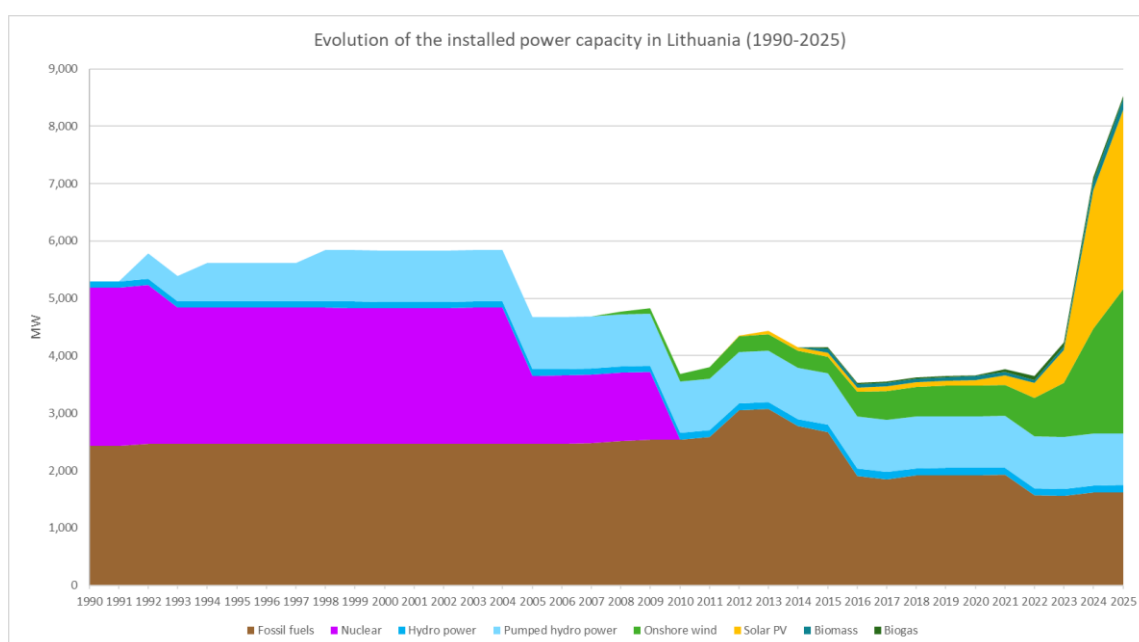


Figure 13: Evolution of the installed power capacity in Lithuania, period 1990-2025²²

²² Source: Eurostat. Electricity production capacities by main fuel groups and operator (last update August 21st, 2025) and U.S. Energy Information Administration until 2015. Since 2015, the source is Litgrid- Power System- Power system information- Generation capacity. The data for the pumped hydro power capacity in Eurostat is based on the average generation power capacity of the Kruonis Pumped Storage Power Plant (4 units with an average generation power capacity of 190 MW each) but has been corrected to consider the maximum generation capacity: 4 units of 225 MW each.

Along the 1990s, the electricity production capacity was based on nuclear, with 2,760 MW, and fossil fuels, with 2,426 MW.

The nuclear capacity of the country was made up by two RBMK (Reaktor Bolshoy Moshchnosti Kanalny, or high-power channel-type reactors) which made the Ignalina Nuclear Power Plant. The construction of these nuclear reactors began in 1978, and they started their operation in 1983. However, the first Ignalina power unit was shut down in 2004, and the second reactor in 2009. The reasons for closing the nuclear reactors were the lack of safety of the power plants, whose design like that used at Chernobyl. This was an exigence to join the European Union, and Lithuania also received a subsidy of US\$36.8 million from the European Bank for Reconstruction and Development's Nuclear Safety Account to improve the safety of the nuclear power plants. The installed power of the two Ignalina reactors were 1,380 MW each until 1992 (a total capacity of 2,760 MW), but in 1993, it was reduced to 1,185 MW each (a total nuclear capacity of 2,367 MW).

As for fossil fuels, there are several power plants, of which, the most important is the Elektrėnai power plant, commissioned in 1972. The total power capacity of this plant is 1,055 MW. The fossil fuel electricity generation capacity kept stable at 2,470 MW during the period from 1990 to 2007. New capacity was added until 2013, when a maximum of 3,075 MW was reached. Since then, some plants have been closed, and by the end of 2025, the total fossil fuel installed capacity was 1,620 MW.

The hydro power installed capacity has kept constant during all the period, around 100 MW, which were provided mainly by the 100.8 MW Kaunas Hydroelectric Power Plant, located on the Nemunas River, and commissioned in 1960.

There is a pumped hydro power plant in Lithuania, the Kruonis Pumped Storage Power Plant, located in Kruonis. It has four 225 MW generators, with a total installed capacity of 900 MW, although the different generators were commissioned in different years. The total capacity was operative in 1998.

The solar PV capacity has experienced a sharp increase during the last 3 years. In 2023, the total solar PV capacity was 572 MW, more than doubling the installed capacity in 2022, which was 259 MW. Then, in 2024, the country installed more than 1,800 MW, reaching a total installed solar PV capacity of 2,408 MW. From this amount, more than one half has been developed by the residential market. The fast-growing path of this technology has continued in 2025: by the end of the third quarter of the year, the total solar PV installed capacity reached 3,128 MW.

The onshore wind installed capacity is also growing very quickly. In 2025, it reached 2,510 MW, having installed 678 MW only in the three first quarters of the year. Indeed, since 2023, the installed capacity has multiplied by 1.65, from 947 MW to 2,510 MW.

Finally, since 2016, a reduced power capacity of biomass and municipal waste-based power plants has been installed, including 190 MW of biomass, 3 MW of biogas and 46 MW of waste incineration (figures as of the third quarter of 2025).

By the end of the third quarter of 2025, around 81% of the total cumulative installed capacity in Lithuania was based on renewable energy sources, including hydro power. The total installed capacity in that year reached 8,527 MW, from which, the most relevant technologies were solar PV, with 3,128 MW, wind with 2,510 MW and fossil fuels with 1,620 MW.

Electricity generation in Lithuania

As for the electricity generation mix in Lithuania, the following figure shows the evolution in the electricity generation, per technology, during the period from 1990 to 2023:

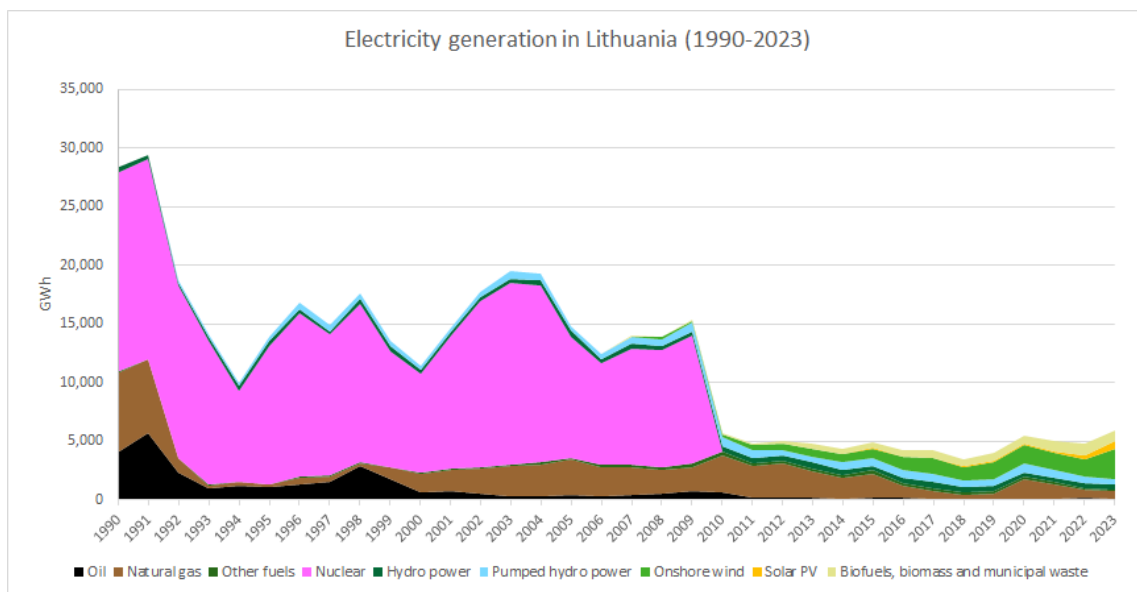


Figure 14: Evolution of the electricity generation in Lithuania, period 1990-2023²³

As can be seen from the figure, Lithuania produced large amounts of electricity during the first years of the analysed period, specially, in 1990 and 1991. This was due, mainly, to the use of the nuclear power plant of Ignalina, whose two reactors produced up to 17,000 GWh yearly. However, the shutdown of this power plant in 2009 reduced the country generation by around two thirds, to around 4,000 GWh per year.

Oil was an important electricity source until 1999, making between 7% and 19% of the electricity mix, depending on the year. It was more relevant in 1990 and 1991, and since then, the total electricity generation with oil has been below 3,000 GWh per year. Since 2000, it has been a marginal electricity source, with a maximum of 735 GWh in 2009. Since 2011, the generation has been always below 300 GWh.

Regarding natural gas, it was important in 1990 and 1991, with a generation higher than 6,000 GWh, what made around 20-25% of the generation. Natural gas became then marginal during the period 1992-1999, with less than 10%. Since then, the electricity generation with natural gas was between 1,500 and 3,000 GWh per year, until 2015, being 58% of the power generation in 2012. Since 2016, generation with natural gas has been between 10% and 30%, depending on the electricity imports. For example, in 2020, electricity imports were lower, and then generation with natural gas was higher.

Besides, the Lithuanian power system also uses small amounts of other fuels (mainly peat), which makes between 0% and 1% of the total power generation. Generation with these fuels peaked during the period 2005-2021, ranging from 200 to 300 GWh.

Electricity generation with hydro power, coming from the Kaunas Hydroelectricity Power Plant, has kept constant during the last 30 years, around 400 GWh per year. Regarding the pumped hydro power, this plant has a variable production, although, in general terms, electricity generation has grown during the 21st century: in years 1992-2000 the average electricity generation was 360 GWh/year, while since 2001, it has grown to 580 GWh/year.

²³ Source: Eurostat. Production of electricity and derived heat by type of fuel. Last update on May 2nd, 2025.

The increase in the installed solar PV capacity, which was described before, can be also observed in the electricity generation with this technology. In 2023, solar PV generated 688 GWh, a 14% of the total electricity generation in the country, what doubled the 342 GWh in 2022.

Electricity produced with onshore wind began to grow on 2011, when it represented 11% of the generation, or 475 GWh, with 202 MW. Since then, it has grown along with the installed capacity, reaching 2,536 GWh with an installed capacity of 1,287 MW in 2023. In that year, onshore wind made 24% of the total electricity generation in Lithuania.

Finally, biofuels, biomass and waste-to-energy are becoming a relevant source of power generation, having reached around 20% by 2022, with 954 GWh.

It can be mentioned that, in 2023, 86% of the total of the total electricity generation came from sources without greenhouse gas emissions.

Electricity consumption, imports, exports and generation

Additionally, the evolution of the electricity generation, consumption, exports and imports in Lithuania during the period 1990-2024 has been analysed. The following figure shows how they have changed over the time.

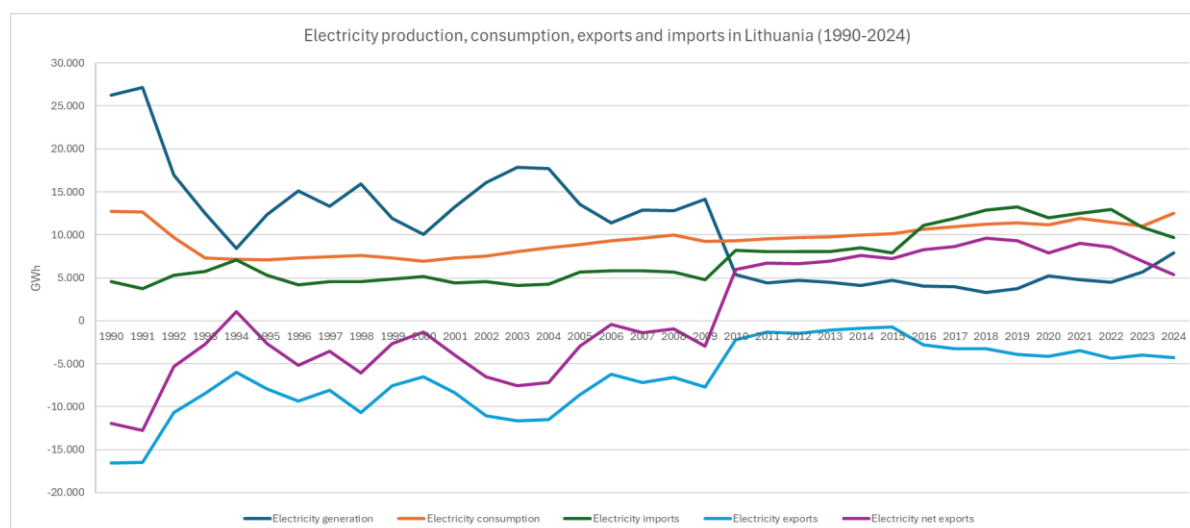


Figure 15: Evolution of the electricity generation, consumption, exports and imports in Lithuania, period 1990-2024²⁴

As already described, the electricity generation reached its maximum in 1990 and 1991, with 27,158 GWh in 1991. This is related to the use of large amounts of fuel oil and natural gas, along with the two reactors of the Ignalina nuclear power plant. It varied with the years according to the availability of the nuclear power plant, but was reduced to around 4,000 GWh since 2010, first year when the nuclear power was not available. In 2024, electricity generation, however, went up to almost 8,000 GWh.

Electricity consumption went down importantly in the first years of the series: in 1990 and 1991, it was around 12,700 GWh, and by 1993 it had gone down by 42%, keeping around 7,000 GWh until 2003, when it reached 8,000 GWh. Since then, it has grown slowly, only by 56% during the period since 2003 to 2024.

It is interesting to analyse the evolution of the imports and exports. During all the period when the nuclear power plant was available, Lithuania was a net electricity exporter, except for the year 1994.

²⁴ Source: Eurostat. Supply, transformation and consumption of electricity. Last update on August 21st, 2025.

Electricity imports keep constant around 5,000 GWh per year until 2009. Electricity exports in the period 1990-2009 depended on the generation, as Lithuania exported the electricity which was not needed to cover the demand.

However, once the nuclear power plant was closed, Lithuania has become a net electricity importer, with a net import of around 8,600 GWh per year during the period from 2016 to 2023. The increase in the electricity generation in 2024 led to a reduction in net electricity imports to around 5,400 GWh in that year.

3.3. Transport infrastructure

Lithuania's transport infrastructure plays a crucial role in the nation economic vitality, strategic regional positioning, and commitment to sustainable development. Geographically situated at the crossroads between Western Europe, the Baltic region, and Eastern Europe, Lithuania is strategically important as part of the Trans-European Transport Network (TEN-T). It hosts a portion of the North Sea-Baltic core transport corridor, significantly influencing trade and transit flows between the EU, the Baltic States, and Eastern neighbours²⁵ (Lietuvos transporto infrastruktūros plėtros iki 2030 m. planas, 2022).

The Lithuanian Road network is notably dense, one of the highest densities in Europe. The network encompasses approximately 21,237.6 km of state roads, including 1,750.7 km of main roads, and 4,927.7 km of regional roads (Lithuanian Road Administration, 2022). The total length of roads reached 84,503 km in 2023.¹¹ Major European routes (E-roads) traverse Lithuania, such as the Via Baltica corridor, crucial for north-south traffic connecting the Baltic countries with Western Europe. Lithuania continuously invests in upgrading this network, aiming to comply fully with the TEN-T requirements by 2030, involving approximately 177.5 km of strategic road segments and estimated investments of around 788 million euros²⁵.

Rail transport infrastructure in Lithuania primarily features broad gauge (1,520 mm) lines, with significant infrastructure supporting connections with Eastern countries. However, with the Rail Baltica project, a standard gauge (1,435 mm) railway line is under construction, enhancing direct connections with the broader EU rail network. Rail Baltica is pivotal for developing a high-speed rail link from the Baltic states to Central and Western Europe, representing a major investment of approximately 2.5 billion euros for 392 km of new track. Additionally, electrification of railways, which currently covers only 8% of the network, remains a strategic priority, with plans to electrify an additional 652.6 km by 2030, costing around 427.6 million euros²⁵.

In 2023, the total length of railways in Lithuania reached 3,463 km, from which, there were 1,924 km in operation. The electrification rate remains very low, only 152.4 km. The national and state-owned railway company of Lithuania is Lithuanian Railways ("Lietuvos Geležinkeliai", LTG), which operates freight and passenger trains, and is also in charge of maintaining the public railway infrastructure.

The maritime sector is centered around Klaipėda Port, Lithuania's only major seaport, and a critical node in the country's transport and logistics ecosystem. In 2024, the Port of Klaipėda achieved a record handling volume of 35.5 million tons of cargo, surpassing the one million TEU²⁶ mark for the third consecutive year. It leads among Baltic States ports with a 39% market share in cargo volumes. The port handled 5,478 vessels and welcomed 381,000 passengers and tourists during the year. The Port

²⁵Source: PATVIRTINTA Lietuvos Respublikos susisiekimo ministro 2022 m. vasario 9 d. įsakymu Nr. 3-86. *Lietuvos transporto infrastruktūros plėtros iki 2030 m. planas*.

²⁶ TEU is Twenty-Foot Equivalent Unit, a standard unit to quantify the capacity of container ships and ports. 1 TEU is equivalent to one 20-foot-long shipping container.

continues to develop through projects like the reconstruction of breakwaters, the construction of the Southern port area, and the creation of infrastructure to support Lithuania offshore wind energy ambitions. Klaipėda has also positioned itself as one of the greenest ports in Europe, with projects such as LNG bunkering, electrification of quays, and green hydrogen production infrastructure. These initiatives underscore the transformation of the port into a hub for innovation, sustainability, and regional competitiveness²⁷.

Lithuania inland waterways, primarily used for local freight and passenger traffic, remain underutilized, representing untapped potential. TEN-T includes an inland waterway E41, connecting Kaunas to Klaipėda via the Nemunas River and Curonian Lagoon. Investments, such as a 28.3 million euros modernization project, are aimed at enhancing this waterway's navigability, addressing current infrastructure inadequacies, and fostering economic use of this transport mode. In 2023, inland waterways transported 1.47 million tonnes, and 2.8 million passengers.

Lithuania has three major international airports—Vilnius (VNO), Kaunas (KUN), and Palanga (PLQ)—each playing a critical role in the national and regional air transport system and integrated into the TEN-T network. Lithuanian Airports (Lietuvos oro uostai, LTOU) has committed to ambitious environmental goals, including achieving climate neutrality by 2030 and zero emissions from operations under its control by 2050. In recent years, all three airports have implemented a wide range of CO₂ reduction measures such as the introduction of electric and hybrid vehicles, replacement of diesel ground power units with electric ones, increased use of LED lighting, and installation of solar power plants. Notably, Vilnius Airport has introduced a comprehensive energy efficiency program, reconstructed runways to reduce CO₂ emissions during operations, and installed a solar power plant covering 20% of the VIP terminal needs. Kaunas and Palanga airports have also embraced energy efficiency, renewable energy, and modern equipment upgrades. These efforts are part of the broader LTOU NET ZERO Strategy 2023–2050, which aligns with Lithuania's international commitments under the Paris Agreement and the EU Green Deal²⁸.

Intermodal terminals in Vilnius and Kaunas play a pivotal role in enhancing Lithuania's logistics efficiency and multimodal connectivity. Operated by LTG Infra, these terminals are integral to the country's sustainable freight transport strategy, facilitating seamless cargo transfers between rail and road. Aligned with LTG Group sustainability commitments, the terminals support the shift towards greener logistics solutions, contributing to reduced carbon emissions and improved environmental performance in the transport sector²⁹.

CO₂ emissions from Lithuania's transport sector present a significant environmental challenge. Transport is among the largest contributors to greenhouse gas emissions in the country, primarily due to the heavy reliance on fossil fuels, particularly diesel and petrol, in road and rail transport. In 2019, transport accounted for approximately one-third of total national greenhouse gas emissions, and projections indicate that without substantial interventions, these emissions could continue to rise. Consequently, Lithuania has adopted stringent national and EU targets to reduce these emissions by promoting alternative fuels, electrification of the transport sector, and enhancing transport efficiency. Strategic initiatives such as Rail Baltica and the ongoing electrification of railways are vital in

²⁷ Source: Management Report 2024. Financial Statements 2024. Port of Klaipėda.

<https://portofklaipeda.lt/wp-content/uploads/2025/04/KVJUD-VA-and-FA-2024-EN-1.pdf>

²⁸ Source: Lithuanian Airports. LTOU Net Zero Strategy 2023-2050.

<https://www.ltou.lt/uploads/documents/files/LTOU%20NET%20ZERO%20Strategy%202024.pdf>

²⁹ Source: LTG Group. <https://ltg.lt/en/sustainability/>

significantly curbing emissions. Additionally, expanding infrastructure for electric vehicles and alternative fuel usage aligns with the country's commitment to reducing CO₂ emissions and transitioning towards a sustainable and low-carbon transport system.

It can be mentioned that greenhouse gas emissions in the transport sector are increasing. According to the Lithuania's National Inventory Report 2025¹¹. Greenhouse Gas Emissions 1990-2023, the Transport sector contributed in 2023 54.0% of the total emissions in the Energy sector, this is, 32.7% of the total greenhouse gas emissions in Lithuania. At the same time, the Transport sector consumed in 2023 41.7% of the total final energy consumption.

In particular, road transportation is the most relevant means of transport in terms of fuel consumption and greenhouse gases. This sector used 89,262 TJ of energy in 2023, and emitted 6,146 thousand tonnes CO₂ in that year, compared to 4.194 thousand tonnes of CO₂ in 2005. Road transportation made 94.4% of the total fuel consumption in the Transport sector.

Meanwhile, the railway transport sector used only 1.44% of the total fuel consumption, and off-road transport made 2.4%. It can be noted that emissions have fallen importantly in 2022 and 2023, below 100,000 tonnes of CO_{2eq}, while in 1990 it was above 400,000 tonnes of CO_{2eq}. There are two reasons for this. Firstly, when the Soviet Union broke up, the overall freight transport decreased. Secondly, from the year 2008, when there was an important economic crisis, emissions went down again.

Finally, in 2022 and 2023, emissions have decreased by 45.4% to 92,200 tonnes of CO₂ in 2022, when the loading and transport of all the company's common-use wagons to or from Belarus and Russia was banned.

Regarding domestic navigation, emissions were 9,700 tonnes of CO₂ in 2022. This is a reduction of 53.5% compared to emissions in 2005, which were above 20,000 tonnes of CO₂. This is derived from the lower use of fossil fuel consumption in inland waterways.

Finally, around 0.03% of the total fuel consumption was used from civil aviation sector.

3.4. Business infrastructure

Lithuania's business infrastructure is dynamic, internationally oriented, and evolving rapidly in line with global sustainability and technological trends. Anchored by a growing Global Business Services (GBS) and ICT sector, Lithuania now hosts 96 investor companies employing over 26,000 professionals, with that number expected to surpass 30,000 by the end of 2023³⁰. The sector continues to expand both in volume and sophistication, offering multifunctional services across areas such as IT, finance, cybersecurity, AI, and supply chain management. The GBS hubs in Vilnius and Kaunas are central to this growth, supported by robust infrastructure, world-class office facilities, and access to an internationally oriented talent pool.

Vilnius, the largest city in the Baltics, and Kaunas, a growing innovation centre, are connected by strong digital and physical infrastructure and benefit from proximity to two international airports. The country's appeal is bolstered by a resilient and multilingual workforce, where 92% of GBS employees have tertiary education and 47% of centres support ESG or CSR activities. Educational collaboration is strong, with 73% of centres partnering with universities and institutions to co-create industry-specific programs.

³⁰ Source: Invest Lithuania. *Lithuania's Business Services Report*. 2023. <https://investlithuania.com/wp-content/uploads/LT-GBS-Report-2023.pdf>

The ecosystem is further reinforced by Lithuania's supportive investment climate, including competitive labour costs, attractive financial incentives for RPA/AI deployment, and long-term partnerships facilitated by Invest Lithuania. The country also stands out in diversity, ranking 1st in the CEE region for gender parity in the GBS sector and being a top location in the EU for young professionals with STEM backgrounds. With continuous investments in digital infrastructure and innovation, Lithuania's business ecosystem provides a fertile foundation for deploying advanced industrial technologies like hydrogen production, CO₂ capture and storage, and climate-friendly innovations crucial to transitioning high-emission sectors towards sustainability³¹. These business infrastructure assets provide a fertile environment for deploying cutting-edge technologies, including hydrogen, CO₂ capture and storage, and other climate-friendly industrial solutions vital for advancing green transition goals in Lithuania's most affected regions.

3.5. Scientific potential

Lithuanian institutions are currently leading comprehensive research and development initiatives in the fields of hydrogen and synthetic fuels, spanning from fundamental research to practical demonstrations. These initiatives encompass multiple technological readiness levels, ensuring both theoretical insights and applicable technological advancements. A major research area includes hydrogen production and storage technologies. The Lithuanian Energy Institute has been particularly active, exploring innovative hydrogen generation through hydrolysis reactions involving aluminium (Al) and magnesium-nickel hydride (Mg₂NiH₄). They are also developing advanced materials for solid-state hydrogen storage solutions and leveraging metal hydrides to produce synthetic fuels. Furthermore, Mg₂NiH₄ thin films have garnered attention due to their potential applications in hydrogen storage, hydrogen production systems, smart windows, and biofuel technologies. Fuel cell technologies represent another critical area of investigation. At Kaunas University of Technology, research predominantly focuses on solid oxide fuel cells (SOFC) and proton conductive fuel cells (PCFC). Significant efforts are dedicated to developing thin-film proton-conducting ceramics and catalytically active membranes. Concurrently, Vilnius University contributes vital insights into the sintering processes and electrical properties of oxygen-conducting electrolytes, essential for SOFC operation, as well as researching the transport mechanisms of ions in various superionic materials. Vilnius Gediminas Technical University expands the applicability of hydrogen by researching its utilization in transportation. They are specifically investigating mixtures of compressed natural gas (CNG) and hydrogen for use in spark ignition internal combustion engines, supported by comprehensive experimental validations utilizing advanced engine testing equipment. Beyond technological and material sciences, research at Vytautas Magnus University addresses critical socio-economic and regulatory dimensions. Their studies revolve around renewable energy prosumers, analysing their roles within the frameworks of energy justice theory and the broader implications for energy security at regional and national levels. Klaipėda University conducts research in the fields of energy, transport, and hydrogen technologies, with a strong focus on sustainable development and innovation. In the energy sector, their work includes integrating renewable sources such as wind, solar, and bioenergy into regional power grids, as well as improving energy efficiency in maritime and industrial processes, particularly around port operations. The university also explores marine renewable energy options, such as harnessing wave and tidal energy from the Baltic Sea. In terms of transport, their research emphasizes enhancing maritime logistics, shipping safety, and port efficiency, alongside developing smart transportation systems aimed at reducing emissions and optimizing traffic flow in Klaipėda and the wider region. Regarding hydrogen, Klaipėda University investigates hydrogen production, storage, and distribution technologies, assessing how hydrogen can be integrated into maritime fuel systems

³¹ Source: Invest Lithuania. *Lithuania's Business Services Report*. 2023.

and industrial processes to lower carbon emissions. They also conduct pilot projects and feasibility studies focused on hydrogen applications in the Baltic region, supporting Lithuania's transition toward cleaner energy options. Through collaborations with industry stakeholders, government agencies, and EU programs, the university is actively advancing research that promotes sustainable energy solutions and positions hydrogen as a vital element in the future of energy and transportation. Lithuania is also actively participating in significant projects aimed at scaling up hydrogen infrastructure and utilization. Notably, the Baltic Sea Hydrogen Valley project (BALTICSEAH2), scheduled from 2023 to 2029, aims to substantially increase hydrogen production capacity, projecting an annual output of 48,500 tonnes by 2030. This project is strategically focused on supplying industries such as methanol, ammonia, chemical production, and refining processes. Through international cooperation, including collaborations with international partners and engagement with broader European Union initiatives, Lithuania is positioning itself at the forefront of hydrogen technology advancements. The breadth of these activities underscores the significant potential for hydrogen and synthetic fuels to contribute to Lithuania's sustainable energy transition, bolstering energy security and fostering significant environmental and economic benefits.

Talking about research on CCUS technologies in Lithuania is rather fragmented and touches specific challenges. For example, Vilnius Tech researchers investigate how remote sensing technologies—particularly the fusion of multispectral (MSI) and synthetic aperture radar (SAR) satellite data—can enhance the monitoring of carbon farming practices in Lithuania. Given the frequent cloud cover in the region, the authors emphasize the advantage of integrating SAR (which is not limited by atmospheric conditions) with MSI for more accurate and continuous observation. The research focuses on identifying and classifying three key agricultural practices that contribute to carbon sequestration: permanent meadows, intermediate crops, and stubble fields. SAR fusion proved effective in tracking permanent meadows by detecting areas with minimal temporal change. For intermediate crops and stubble, MSI imagery supplemented with spectral indices (NDVI_{re}, MNDWI, NDTI) and classified via Random Forest algorithms yielded high accuracy, particularly for intermediate crops (F1-score = 0.84, Kappa = 0.86). Despite promising results, challenges remain in distinguishing visually similar vegetation types and in fully capturing the dynamics of land cover changes³².

Kaunas University of Technology (KTU) is at the forefront of sustainable cement research, focusing on the integration of CO₂ into cementitious materials to significantly reduce the carbon footprint of construction. One of the key areas of research involves the development and application of rankinite-based concrete, a novel binder that offers a promising alternative to traditional Portland cement. Rankinite, a low-lime calcium silicate, requires significantly lower synthesis temperatures and less calcareous material, leading to substantial reductions in CO₂ emissions during production. More importantly, this material actively incorporates CO₂ during the curing process, forming stable calcium carbonates that not only sequester carbon but also enhance the mechanical strength of the final product—compressive strengths exceeding 100 MPa have been reported after CO₂ curing³³. Complementing this work, KTU is also leading the LIMECEM project, which is pioneering a two-step synthesis approach for low-lime cement. This method enables a reduction of energy use and CO₂ emissions by up to 30% compared to traditional methods. It involves modifying calcium aluminate and

³² Source: METRAIKAITYTĖ GUDELĖ, G.; SUŽIEDĖLYTĖ VIŠOCKIENĖ, J. *Remote sensing data application to monitor carbon farming practices*. The International Society for Photogrammetry and Remote Sensing. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLVIII-4/W9-2024, 257–265, <https://doi.org/10.5194/isprs-archives-XLVIII-4-W9-2024-257-2024>, 2024.

³³ Source: ŠMIGELSKYTĖ, Agnė. *Synthesis, properties, and application of rankinite in the production of CO₂ cured concrete*. PhD thesis. Kaunas University of Technology. 2019.

silicate systems via the intercalation of sulphate ions under controlled conditions, producing reactive Ca/Si/Al compounds. This approach supports the use of secondary raw materials, contributing to a more circular and environmentally friendly cement manufacturing process³⁴. Beyond these alternatives, KTU has made significant advances in the use of alkali-activated materials derived from industrial by-products such as fly ash, bottom ash from biomass combustion, and silica-rich waste from aluminium fluoride production. These materials are processed to create concrete with performance characteristics comparable to conventional cement—achieving compressive strengths of around 55 MPa—while offering enhanced durability against acidic environments and thermal fluctuations. Importantly, this strategy not only mitigates CO₂ emissions but also supports waste valorisation, aligning with broader sustainability and circular economy goals³⁵. KTU's integrated research approach demonstrates a holistic commitment to decarbonizing construction materials by harnessing CO₂ as a resource, rather than treating it solely as a pollutant, thereby contributing meaningful solutions to the global climate challenge.

Vilnius University and Nature Research Center (NRC) have played a pivotal role in advancing scientific understanding of carbon capture, utilization, and storage (CCUS) in the Baltic region, particularly through its early and detailed work on subsurface geological assessment. In foundational studies, VU and NRC researchers gathered and analysed an extensive archive of geological data from more than 600 deep wells spanning the Baltic Basin. The work of researchers encompassed critical parameters such as stratigraphy, petrophysical characteristics, hydrochemistry, and in situ pressure-temperature conditions. Through this comprehensive approach, the university significantly contributed to identifying and characterizing key storage formations—including the Cambrian and Pärnu-Kemeri aquifers—by assessing their porosity, permeability, and overall capacity for long-term CO₂ sequestration. These insights laid the groundwork for evaluating Lithuania's geological suitability for secure and effective carbon storage³⁶.

The Lithuanian Research Centre for Agriculture and Forestry (LAMMC) together with Vytautas Magnus University Agriculture Academy are an active participant in the Global Research Alliance on Agricultural Greenhouse Gases (GRA), contributing to research groups focused on livestock, croplands, and integrative systems. Through this collaboration, LAMMC develops and implements strategies to reduce greenhouse gas emissions in agriculture, including methodologies for measuring and enhancing soil carbon sequestration³⁷.

Despite the promising foundations laid by Lithuanian institutions, the country's current R&D landscape in hydrogen and CCUS technologies faces several systemic challenges that must be addressed to fully unlock its innovation potential. Most research remains concentrated on lower technology readiness levels (TRLs), particularly up to TRL 4 (laboratory prototypes), with limited progression toward pilot-scale demonstrations or commercialization. To align with global best practices and accelerate the path

³⁴ Source: Šiaučiūnas, RAIMUNDAS. *Two-step synthesis of low-lime cement, its structure and properties (LIMECEM)*. Research Council of Lithuania. Project No.: P-MIP-21-256. 2024. <https://en.ktu.edu/projects/two-step-synthesis-of-law-lime-cement-its-structure-and-properties-limecem/>

³⁵ Sources: Kaunas University of Technology. *Lithuanian scientists: alkali-activated concrete from industrial waste is as strong as traditional and more environmentally friendly*. October 30th, 2018. <https://en.ktu.edu/news/lithuanian-scientists-alkali-activated-concrete-from-industrial-waste-is-as-strong-as-traditional-and-more-environmentally-friendly>

³⁶ Cited extensively in special chapter related to geological studies of this Report.

³⁷ Source: Global Research Alliance on Agricultural Greenhouse Gases. Lithuania. <https://globalresearchalliance.org/country/lithuania>

from lab to market, Lithuania must adopt a more balanced R&D evaluation framework that not only values academic publications but also prioritizes patents, industrial partnerships, and applied technological outputs. The national funding and assessment mechanisms should explicitly encourage collaborative projects targeting higher TRL developments and emphasize innovation outcomes, mirroring approaches seen in Germany's "Kopernikus Projects"³⁸ as it represents one of the largest coordinated research initiatives in Europe focused on the energy transition, with a strong emphasis on bridging the gap between academic research and industrial application. Funded by the Federal Ministry of Education and Research (BMBF), these projects address system level challenges across energy storage, sector coupling, grid flexibility, and process decarbonization. Of special relevance are subprograms like P2X (Power-to-X), which explore hydrogen production, CO₂ utilization, and production of synthetic fuels beyond TRL 4 through extensive demonstration and industry collaboration. The Kopernikus model offers a blueprint for how countries like Lithuania, by choosing their own priorities and project scale, could structure mission-driven R&D to accelerate clean technology deployment while strengthening innovation ecosystems.

Furthermore, there is an absence of dedicated CCUS and hydrogen industrial scale demonstration projects, which are open for business, academia, and general society in Lithuania. These are essential not only for validating technology performance under real-world conditions but also for building public trust, industry awareness, and practical skills among technicians, engineers, and scientists. Establishing living labs or testbeds, such as industrial clusters or university-industry pilot plants, would allow stakeholders to gain knowledge and competencies and build local capacity. Strategic investments could be modeled after, for example, Norway's Longship project³⁹, which integrates R&D, infrastructure development, and workforce training. In addition, in the CCUS domain, Lithuania still lacks sufficient research focus on critical areas such as post-combustion capture, mineral carbonation, subsurface storage integrity, and biogenic CO₂ derived material synthesis. To close these gaps, coordinated support through national research programs and EU partnerships should be expanded.

Finally, integrating CCUS and hydrogen research into broader industrial and climate policy through mission oriented and public-private partnerships can help ensure that scientific advancements directly contribute to Lithuania's decarbonization and economic goals. With targeted science policy goals, smart funding instruments, and stronger international collaboration, Lithuania can evolve from mostly academic developments and excellence to technological leadership in the green transition on an EU scale.

3.6. Evolution of climate neutral technologies for Lithuania's industrial decarbonisation

The Net-Zero Industry Act (NZIA) is an initiative developed by the European Commission, based on the Green Deal Industrial Plan, which has the objective of increasing the manufacturing capacity of the European Union for technologies which are related to the clean energy transition (produce low, zero, or negative greenhouse gas emissions when they are used). The NZIA is fighting the barriers which prevent the European industry from producing these technologies.

³⁸ Source: Federal Ministry of Research, Technology and Space of Germany. Kopernikus Projects. <https://www.kopernikus-projekte.de/en/home>

³⁹ Source: Gassnova. CCS Norway. *The Longship CCS Project*. <https://ccsnorway.com/the-project/>

The European Parliament and the Council came to an agreement on the NZIA on February 6th, 2024, and the Act entered into force.

The NZIA is aimed at attracting investments in developing these manufacturing capabilities and creating better conditions and market access for clean technologies. The objective of the NZIA is that the European Union's overall strategic net-zero technologies manufacturing capacity approaches or reaches at least 40% of annual deployment needs by 2030. This will create predictability, certainty and long-term signals to manufacturers and investors.

Having appropriate local manufacturing capacities for the key clean technologies is an important factor to help the European Union fulfil with its commitments in terms of greenhouse gas emission reduction and to reach carbon neutrality by 2050. Besides, it can create good quality jobs, improve the industrial capacities of the European Union, and contribute to make an energy independent European Union.

The NZIA also considers the need for simplifying the regulatory framework for the manufacturing of these technologies, increasing the competitiveness of the net-zero technology industry in Europe, and accelerating the capacity of CO₂ emissions storage.

For this reason, the NZIA has the objective of creating a European Union market for CO₂ storage services. An obligatory EU-level objective of reaching an annual CO₂ storage capacity of at least 50 million tonnes of CO₂ has been set.

The main clean technologies which are under the scope of the NZIA are:

- Solar photovoltaic and solar thermal technologies.
- Onshore and offshore renewable technologies.
- Battery and energy storage technologies.
- Heat pumps and geothermal energy technologies.
- Hydrogen technologies, including electrolyzers and fuel cells.
- Sustainable biogas and biomethane technologies.
- Carbon capture and storage (CCS) technologies.
- Grid technologies.
- Nuclear fission energy technologies, including nuclear fuel cycle technologies, and small modular reactors.
- Sustainable alternative fuel technologies.
- Hydropower technologies.
- Other renewable energy technologies.
- Energy system-related energy efficiency technologies, including heat grid technologies.
- Renewable fuels of non-biological origin technologies.
- Biotech climate and energy solutions.

- Other transformative industrial technologies for decarbonisation.
- CO₂ transport and utilisation technologies.
- Wind propulsion and electric propulsion technologies for transport.
- Other nuclear technologies.
- Energy-intensive industries that produce components used in net-zero technologies and invest in decarbonisation, such as steel, chemicals, and cement.

The NZIA also establishes the creation of Net-Zero Industry Academies, to train professionals specialized in Net-Zero technologies. The courses will be standardised to allow that professionals can easily work in every European country. Each academy should focus on one net-zero industry technology and aim to train 100,000 professionals each within three years of creation.

Another objective of the NZIA is the identification and development of suitable geological CO₂ storage sites. For this reason, the NZIA tries to coordinate the effort of EU oil and natural gas producers in investing in the identification and development of geological CO₂ storage sites.

The NZIA also selects some net-zero strategic projects, which are aligned with the NZIA objectives. These projects can be given advantages, including “priority status” at national level, faster permitting, support in the Net-Zero Europe Platform (including advice on financing); and urgent treatment in judicial and dispute resolution procedures. Projects can ask to obtain this status using an application process, which has been available since the end of July 2024.

The NZIA will reduce the administrative burden for developing net-zero manufacturing projects and will develop simpler and faster permitting procedures.

Besides, mandatory non-price criteria must be considered in public selections, including sustainability, resilience, cybersecurity and other qualitative factors:

- In public procurement and contracting procedures, sustainability is a minimum mandatory requirement. Besides, other criteria (excluding price) are considered in the selection, such as diversifying supply sources, social sustainability, cybersecurity and timely delivery.
- In renewable energy auctions (solar PV, wind), auctions need to be designed to consider the contribution to sustainability, resilience, cybersecurity, responsible business conduct and ability to finish the projects on time. At least 30% of the volume auctioned annually in each EU country (6 GW) need to consider these criteria.
- The public administrations can also develop actions such as support schemes to promote the purchase of net-zero products by households and businesses, or to encourage the development of renewable energies.

Finally, the Net-Zero Europe Platform is the governance body which is made up by the European Commission and the European countries, to monitor and foster the application of the Net-Zero Industry Act. Besides, this platform offers advice about financing net-zero strategic projects, and the engagement in international net-zero industrial partnerships.

The Net-Zero Europe Platform, along with the European Hydrogen Bank, are expected to attract investment in net-zero technologies. Besides, regulatory sandboxes will be developed to test innovative net-zero technologies.

The European Hydrogen Bank was created in 2022, to foster private investments in the hydrogen value chain in the EU and globally, creating a global hydrogen market, and connecting renewable energy supply and demand. It covers part of the initial investments in hydrogen projects. The first auction was carried out from November 2023 to February 2024, and nearly €720 million were given to 7 renewable hydrogen projects in the European Union. A second auction was carried out from December 2024 to February 2025. In this auction, 15 projects were selected, and the grant awarded was €992 million, with individual subsidies between €8 million and €246 million. The subsidy is offered as a grant per kilogram of renewable hydrogen produced, granted for a maximum duration of 10 years.

Besides, the Republic of Lithuania has allocated a €36 million State Aid scheme⁴⁰, for the production of hydrogen through the before mentioned hydrogen auctions carried out by the European Hydrogen Bank. These funds have been specifically created by the country, to complement the auctions opened to all the European Union by the European Hydrogen Bank, and are expected to support the production of up to 13,000 tonnes of renewable hydrogen, and avoid around 61,000 tonnes of CO₂ emissions. The subsidy is open to any company which intends to build new electrolyzers in Lithuania.

The Republic of Lithuania has also taken steps to the Net-Zero economy. In this sense, the Net-Zero Government Roadmap of Lithuania is the vision to make the public sector in Lithuania climate neutral. The main instrument to reach this objective is the use of green public procurement, which will make the public administration in Lithuania lead with the example.

Green public procurement includes:

- Development of a long-term renovation strategy for the existing building stock. As of 2021, all new buildings should meet the highest energy efficiency standard (A++).

Besides, from November 2024, wood and organic materials must make up at least 50% of construction materials in newly built public buildings. Finally, from 2025, all new public buildings must be built according to a sustainable building scheme, including BREEM, LEED or FITWEL.

- As of 2023, all public authorities must buy 100% electricity from renewable energy sources.
- According to the Alternative Fuels Act, of 2021, Lithuanian public authorities must shift towards clean vehicles (this is, light vehicles which emit less than 50 g CO₂/km and heavy vehicles which use alternative fuels).
- Public authorities must apply mandatory environmental criteria for priority product groups when implementing public procurements, for textile, electronic equipment, food and catering, furniture and packaging.

⁴⁰ Source: European Commission. Press corner. *Commission approves a €400 million Austrian State aid scheme, and a €36 million Lithuanian state aid scheme, to support renewable hydrogen production.* March 10th, 2025.

Currently, Lithuania has not developed any project which has been classified as strategic under the NZIA. On the other hand, it can be mentioned that there is not any relevant wind energy manufacturing plant or research centre⁴¹.

There are some small solar PV panel and cell manufacturing companies, listed in the following table:

Name of the company	Activity	Production capacity (MW)
Valoe Oyj	Cell production	60
Solitek OOO	Module production	120
Intelligent Solar	Module production	60
Viaasolis- Solar glass	Module production	<100
Solet PV	Module production	<100
Metsolar	Module production	<100

Table 5: List of solar PV module and cell production plants in Lithuania⁴²

On the other hand, the relevance of Lithuania in terms of patent production in the fields of climate neutral technologies is limited. According to the IRENA INSPIRE Renewable Energy Patents Database, since 2020 to 2023, Lithuania had published 2,553 patents, while leading countries, such as Germany, have published that number of patents in a year.

From them, the most important categories are “Enabling technologies”, with 249 patents, and “Bioenergy” with 210 patents.

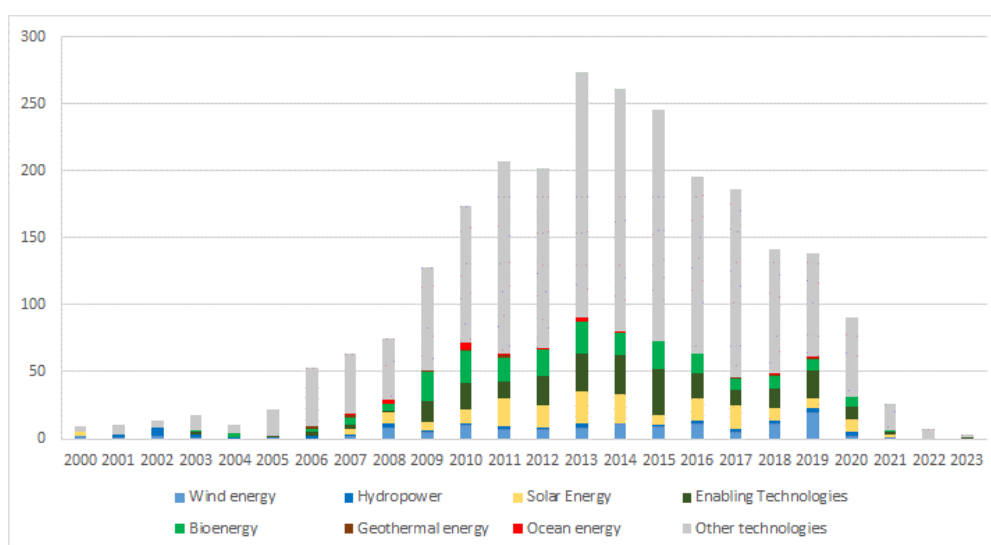


Figure 16: List of patents in the fields of climate neutral technologies published by Lithuania, years 2000-2023⁴³

⁴¹ Source: WindEurope.

⁴² Source: Own research.

⁴³ Source: IRENA INSPIRE (www.irena.org/Inspire) based on EPO PATSTAT 2024 Autumn edition, and on the Climate Change Mitigation Technologies (Y02) classification by EPO.

4. Reducing CO₂ emissions in technological processes

4.1. Possibilities for the use of hydrogen and other innovative technologies in industry

Overview of hydrogen in industrial decarbonization

Hydrogen is increasingly recognized as a key solution for industrial decarbonization, particularly in sectors where direct electrification is not feasible. While electrification is the preferred option for many applications, hydrogen is seen as a viable alternative in industries like steel manufacturing, chemicals, and high-temperature processes. Its role is gaining momentum due to climate change policies, net-zero commitments, and the growth of renewable energy infrastructure, which supports the production of green hydrogen through electrolysis powered by wind and solar energy. However, hydrogen still faces significant challenges, including low volumetric energy density, which complicates its storage and transportation, and high costs that limit its use to traditional applications like ammonia production and refining.

Despite these hurdles, hydrogen remains essential in achieving global decarbonization, particularly in hard-to-abate industries. While projections often overestimate the economic viability of hydrogen in various applications, it is crucial to balance its development with other decarbonization technologies to avoid misallocating resources. Ensuring that hydrogen production, transport, and utilization align with economic and environmental goals will be key to unlocking its full potential as a climate solution.

Hydrogen: fundamentals, current production, and role in industrial decarbonization

Hydrogen is the most abundant chemical element in the universe, yet it rarely exists in its pure molecular form on Earth. As a result, hydrogen must be extracted from other compounds, typically through energy-intensive processes. The fundamental properties of hydrogen present both opportunities and challenges. Hydrogen has a high gravimetric energy density, meaning it contains a significant amount of energy per unit of mass. However, its low volumetric energy density creates difficulties in storage and transport. To address this challenge, hydrogen can be stored in compressed gaseous form, liquefied at cryogenic temperatures, or converted into hydrogen carriers. The most common derivatives are:

- **Synthetic Methane:** Produced via the combination of hydrogen with captured CO₂, synthetic methane can be used as a drop-in replacement for natural gas in industrial heating and power generation, reducing dependence on fossil fuels.
- **Green ammonia or e-ammonia (NH₃):** As a hydrogen carrier and direct fuel, ammonia is gaining traction in industries such as maritime transport and power generation. It offers high energy density and does not emit CO₂ when combusted. However, its combustion can produce harmful nitrogen oxides (NO_x) and nitrous oxide (N₂O), which pose challenges for emissions control and environmental safety. Minimization of these harmful emissions is possible through careful system design, combustion control, and after-treatment.
- **Green methanol or e-methanol (CH₃OH):** Hydrogen-derived methanol serves as an alternative feedstock in the production of plastics, chemicals, and fuels, providing a pathway to reducing carbon-intensive processes. It can be used as a versatile fuel, which can be blended with

gasoline, or used directly in internal combustion engines⁴⁴. Specifically, as methanol keeps liquid in room temperature, it can be transported much easier than natural gas or other gaseous fuels, what makes it very appropriate for shipping.

- Sustainable Aviation Fuel (SAF): It is mostly referred to e-kerosene, which is produced with carbon dioxide and green hydrogen as raw materials. It can be produced with the Fischer-Tropsch process, or from methanol. The main advantage of e-kerosene is that it can be directly blended with fossil jet fuels, without need for investing in new infrastructure. Depending on the raw materials used and the production process, the mix of SAF and fossil jet fuels can have levels of SAF from 10% to 50%. Green kerosene is, thus, much more scalable than other biofuels⁴⁵
- Liquid Organic Hydrogen Carriers (LOHCs): These compounds enable safe and efficient hydrogen transport over long distances, facilitating the integration of hydrogen into industrial supply chains. Some examples of Liquid Organic Hydrogen Carriers (LOHCs) are toluene ($C_6H_5CH_3$), methylcyclohexane (MCH, $CH_3C_6H_{11}$), formic acid ($HCOOH$), perhydro-dibenzyltoluene ($C_{21}H_{32}$), or perhydro-N-ethylcarbazole⁴⁶.

Each hydrogen carrier involves trade-offs, notably in terms of infrastructure requirements, overall cost, and conversion losses. Conversion losses are susceptible to technological solutions, the amounts produced, etc. For example, in very qualitative numbers^{47, 48, 49}, compression of hydrogen (it includes the electricity required for compression and heat losses during the process) to 700 bar results in energy losses of approximately 10–15%, while liquefaction (high energy is consumed to cool hydrogen to cryogenic temperatures, and boil-off losses can occur during storage and transport) can incur losses up to 35%. Synthetic methane production (via Sabatier reaction – $H_2 + CO_2 \rightarrow CH_4 + H_2O$; includes energy required, capture CO_2 , and conduct the methanation process, decompose back to H_2) has a conversion efficiency of about 55–65%, implying losses of 35–45%. Ammonia (Haber-Bosch process; producing ammonia from hydrogen requires high pressure and temperature, with additional losses if cracked back into H_2 at the point of use) and methanol synthesis (via $CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$; includes synthesis from hydrogen and CO_2 , and potential reforming losses) show efficiencies of 60–70%, with corresponding losses of 30–40%. Liquid Organic Hydrogen Carriers (LOHCs; energy is lost during both hydrogenation (charging) and dehydrogenation (releasing H_2), often requiring high temperatures),

⁴⁴ Source: SHELTON, Jennifer. *The Case for Methanol in the Hydrogen Fuel Economy*. Power Engineers. February 21st, 2024. <https://www.powereng.com/library/the-case-for-methanol-in-the-hydrogen-fuel-economy>

⁴⁵ Source: State of Green. *Green hydrogen derivatives for deep decarbonisation*. September 1^{9th}, 2023. <https://stateofgreen.com/en/news/green-hydrogen-derivatives-for-deep-decarbonisation/>

⁴⁶ Source: PAPADAPIAS, Dionissios D.; PENG, Jui-Kun; AHLUWALIA, Rajesh K. *Hydrogen carriers: Production, transmission, decomposition, and storage*. International Journal of Hydrogen Energy. Volume 46, Issue 47, 9 July 2021, pages 24169-24189. <https://doi.org/10.1016/j.ijhydene.2021.05.002>

⁴⁷ Source: KUSUMA, Danny. *Hydrogen Hype- A story of energy loss*. February 25th, 2024. <https://dannykusuma.medium.com/hydrogen-hype-a-story-of-energy-loss-f37a592331c8>

⁴⁸ Source: ABDIN, Zainul et al. *Large-scale stationary hydrogen storage via liquid organic hydrogen carriers*. iScience, Volume 24, Issue 9, 102966; DOI: 10.1016/j.isci.2021.102966

⁴⁹ Source: SPATOLISANO Elvira et al. *Liquefied hydrogen, ammonia and liquid organic hydrogen carriers for harbour-to-harbour hydrogen transport: A sensitivity study*. International Journal of Hydrogen Energy Volume 80, 28 August 2024, Pages 1424-1431. <https://doi.org/10.1016/j.ijhydene.2024.07.241>

despite offering transport advantages, have round-trip efficiencies as low as 30–50%, meaning up to 70% of energy can be lost throughout the cycle.

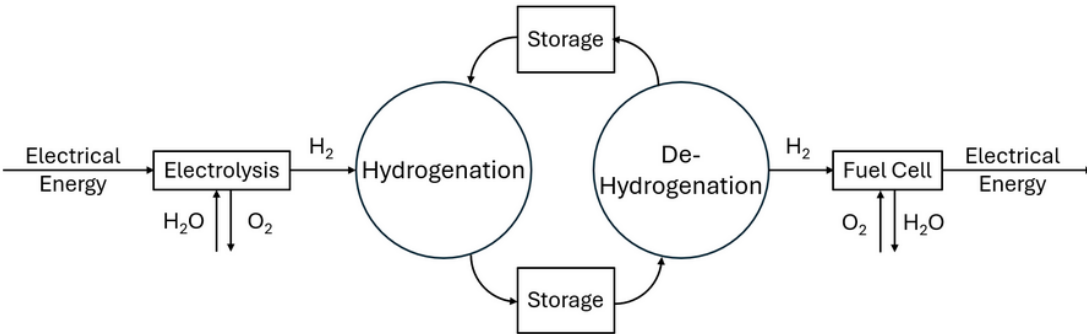


Figure 17: Schematic of a LOHC process for storing electrical energy.

As of today, hydrogen production remains predominantly dependent on fossil fuels. In 2024, hydrogen production reached nearly 100 million metric tonnes, an uptick of 3.0% compared to 2023. Approximately 85% of those are reliant on unabated fossil fuels, primarily through steam methane reforming (SMR). Around 15% was a by-product of processes of refining and the chemistry industry. Finally, less than 1% was produced from low-emissions sources, mostly electrolyzers using low-carbon electricity, as well as fossil fuels with carbon capture, utilisation and storage. Low-emissions hydrogen production reached 0.7 million tonnes in 2024, from which, around 80% was from existing fossil fuel projects retrofitted with CCUS, and 20% from electrolysis.. This hydrogen is typically generated as a secondary output of industrial processes and is often consumed on-site rather than integrated into broader energy markets.⁵⁰

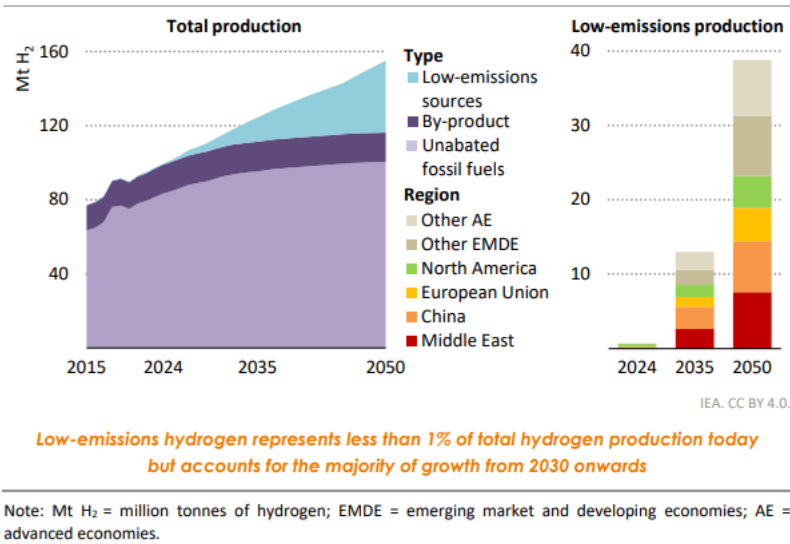


Figure 18: Global hydrogen production by technology in 2024 and the 2035-2050 outlook from different scenarios. STEPS – Stated Policies Scenario, APS – Announced Pledges Scenario and NZE – Net Zero Emissions scenario⁵⁰.

Hydrogen production is responsible for close to 1,000 million metric tons of CO₂ emissions per year⁵¹. To address this issue, various low-carbon hydrogen production methods are being developed,

⁵⁰ Source: World Energy Outlook 2025. International Energy Agency.

⁵¹ Source: International Energy Agency.

categorized primarily as blue hydrogen and green hydrogen. Blue hydrogen refers to hydrogen produced from natural gas with carbon capture and storage (CCS) to mitigate CO₂ emissions. However, the effectiveness of CCS varies, and concerns remain regarding methane leakage and incomplete carbon capture. In contrast, green hydrogen is produced via electrolysis using renewable electricity, offering a zero-emission alternative. While green hydrogen remains expensive compared to fossil-based hydrogen, cost reductions are expected as renewable energy deployment scales up and electrolysis technology advances.

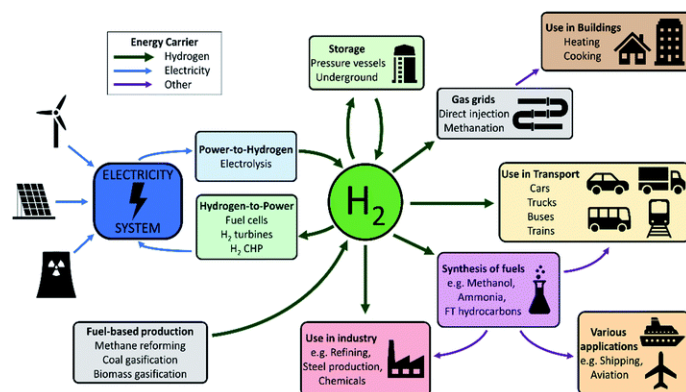


Figure 19: Overview of the key hydrogen production and usage pathways⁵².

Industrial applications represent one of the most promising areas for hydrogen deployment. The steel industry, for example, is actively exploring hydrogen-based direct reduction of iron (DRI) as an alternative to traditional coal-based blast furnaces. If implemented at scale, hydrogen-based DRI could significantly reduce carbon emissions in steel production, which currently accounts for around 7% of global CO₂ emissions⁵³. Similarly, the chemical sector is evaluating the feasibility of replacing conventional hydrogen feedstocks with green hydrogen in ammonia and methanol production. These chemicals serve as essential building blocks for fertilizers, plastics, and other industrial materials.

Hydrogen's role in industrial decarbonization is further reinforced by ongoing policy developments and financial incentives. The European Union, through its Hydrogen Strategy, aims to install at least 140 GW of electrolyser capacity by 2030⁵⁴.

Summarizing, introducing hydrogen technologies to Lithuania's industrial, energy, and transportation sectors is a bold but complicated endeavor. Despite the global enthusiasm surrounding hydrogen's potential for decarbonization, a deeper analysis reveals that significant barriers remain, both systemic and technological, hampering a rapid and economically viable transition.

⁵² Source: QUARTON, Christopher J.; TLILI, Olfa; WELDER, Lara; MANSILLA, Christine; BLANCO, Herib; HEINRICHS, Heidi; LEAVER, Jonathan; SAMSATLI, Nouri J.; LUCCHESI, Paul; ROBINIUS, Martin, SAMSATLI, Sheila. *Sustainable Energy & Fuels - The curious case of the conflicting roles of hydrogen in global energy scenarios*. Sustainable Energy & Fuels. Issue 1, 2020. October 9th, 2019. <https://doi.org/10.1039/C9SE00833K>

⁵³ Source: DEVLIN, Alexandra; KOSSEN, Jannik; GOLDIE-JONES; Haulwen; YANG, Aidong. *Global green hydrogen-based steel opportunities surrounding high quality renewable energy and iron ore deposits*. Nature Communications 14, Article number: 2578 (2023). May 4th, 2023. <https://doi.org/10.1038/s41467-023-38123-2>

⁵⁴ EU's Hydrogen Strategy targets 10 million tonnes of renewable hydrogen produced domestically, 140 GW of electrolysis capacity is estimated to be needed to produce that amount. Source: European Commission. The Joint Research Centre: EU Science Hub - Water Electrolysis and Hydrogen: growing deployment prospects in Europe and beyond. November 24th, 2023.

One of the dominant challenges is economic competitiveness. Hydrogen-powered trucks, as discussed in international practices, currently incur operational costs of approximately 1 euro per kilometer plus an additional 1 euro per kilometer for hydrogen fuel itself, already about 30% more expensive than conventional diesel operations. The situation is further aggravated by high hydrogen production costs, where even the most optimistic near-term targets of 2 €/kg remain elusive for scalable, industrial grade applications. However, the current hydrogen sale price is much higher, around 13 €/kg. Given Lithuania's relatively small market size and lack of economies of scale, achieving cost parity without strong governmental intervention appears unlikely in the next decade.

Infrastructure readiness is another fundamental bottleneck. Hydrogen fueling infrastructure is practically non-existent in Lithuania, mirroring broader European trends where large-scale hydrogen networks are only beginning to materialize. Retrofitting existing natural gas pipelines to hydrogen presents technical uncertainties, especially regarding material fatigue, possible hydrogen embrittlement, and pressure management. Even in mature markets like the Netherlands and Germany, retrofitting has been cautious and gradual. For Lithuania, this suggests a long and expensive path to a national hydrogen backbone, dependent on external technologies and standards.

The technological maturity of hydrogen systems itself introduces operational uncertainties. Electrolyzers, essential for green hydrogen production, are susceptible to performance degradation under stress. Additionally, current membrane technologies, such as PEM electrolyzers, suffer from durability, need for rare and expensive materials (such as iridium), and environmental concerns, such as non-biodegradable materials shedding into ecosystems. Given Lithuania's strategic push towards sustainability, these environmental aspects could present public acceptance issues.

Furthermore, certification and regulatory fragmentation stand as a serious non-technical barrier. Today, more than 20 different hydrogen certification systems exist globally. Without mutual recognition and streamlined regulatory frameworks, Lithuanian hydrogen projects may face severe difficulties integrating into European hydrogen markets, which would stifle both investment and operational scaling.

From a market adoption perspective, the fundamental problem lies in value chain mismatch. Producers, distributors, and users of hydrogen are advancing at different speeds. Automotive manufacturers like Honda and Toyota report technical progress, but these advances remain commercially non-viable without matching hydrogen production and distribution scaling. Lithuania, facing challenges of limited industrial hydrogen demand and fragmented logistics markets, will likely experience these pains even more acutely.

The weight and storage challenges associated with hydrogen, particularly for transportation, cannot be overlooked either. Fuel cell vehicles, even after removing substantial battery weight, still struggle with range and payload issues. Hydrogen storage at required pressures (500 bar and beyond) introduces additional cost and safety complexities, making these systems unattractive for a market sensitive to upfront investments.

In the energy sector, hydrogen is often envisioned as a flexible solution for energy storage, grid balancing, and sector coupling, but significant obstacles remain. Electrolyzers, while technically capable, require cheap and abundant renewable electricity to produce green hydrogen economically—a condition Lithuania currently cannot fully guarantee due to its modest renewable energy capacity. Additionally, scaling hydrogen for seasonal storage introduces questions of efficiency loss, system complexity, and high capital costs. Storing hydrogen in salt caverns, as successfully piloted in larger countries, demands specific geological conditions, which do not occur in Lithuania. Without clear economic incentives and robust demand-side pull from heavy industries or centralized heating systems,

hydrogen is unlikely to compete effectively with more mature battery storage or direct electrification solutions in the Lithuanian energy landscape. Thus, hydrogen's role in the Lithuanian energy system might remain niche rather than transformative, at least until broader European or regional hydrogen corridors mature and economies of scale can be leveraged.

Finally, political and societal inertia cannot be underestimated. Although political support for hydrogen exists in many European countries, real-world examples (for example Darbėnai case with green methanol production facilities) demonstrate how quickly momentum can wane due to shifts in public funding priorities, energy prices, and unforeseen technical hurdles. In Lithuania, where energy policy must also address broader regional security concerns, hydrogen might struggle to maintain consistent prioritization over more established renewable technologies like solar and wind.

The main problem to increase the production and use of green hydrogen is the high cost, compared to alternative fuels. The best option is to reduce to a minimum the electricity supply cost to produce hydrogen. This can be achieved by reducing the grid taxes and costs associated to electricity from the grid. However, the best option is to develop jointly renewable energy power production plants and electrolyzers, to minimize the electricity cost. As the investment cost of an electrolyzer is very high, it is very advisable to use it during as much time as possible along each year. This can be achieved by combining solar PV power and wind energy generation. Solar PV only produces electricity when there is solar irradiation, while wind resources are normally more abundant at night. Combining both sources of energy, it is possible to reach utilization rates for the electrolyzer of 90%.

In conclusion, while hydrogen undoubtedly holds long-term promise for CO₂ reduction in Lithuania's industry, transportation, and energy sectors, the near-to-medium term outlook is clouded by cost inefficiencies, infrastructure immaturity, technological fragilities, regulatory disarray, and market misalignments. Addressing these challenges will require a carefully phased strategy anchored in realistic economics, cross-border cooperation, and robust governmental support mechanisms.

Role of Innovative Technologies

On the other hand, it is important to identify the main technologies which can help the industrial sector reduce the carbon dioxide emissions. Some of them focus on the reduction of greenhouse gas emissions in the energy sector, both to produce electricity or to produce heat, and others are related to the capture, storage, and use of carbon dioxide which cannot be avoided in industrial processes.

- **Use of renewable energies to produce electricity.**

Renewable energies are energy sources which are based on natural resources that cannot be depleted on a human timescale. There is a variety of technologies which produce electricity without carbon dioxide emissions, and that can replace the use of fossil fuels. Renewable energy can be also used to produce heat or as a biofuel, but this is described in another chapter.

Among them, it is possible to mention the following ones:

- **Solar photovoltaics:** Electricity production with solar photovoltaics, or solar PV, is based on the use of solar cells, which transform the energy from photons into electricity, through the movement of electrons.

When the photon hits the metal, an electron is excited, what produces a direct electric current. Solar cells are assembled in solar modules, while a set of modules make a panel. Panels are connected in series to form strings to increase the voltage.

Solar PV plants need also inverters, which are a component which transforms the direct current produced by the solar PV panels into alternating current.

The global installed solar PV capacity reached in 2024 an installed capacity of 1,856,725 MW⁵⁵. On the other hand, Lithuania reached 3,128 MW in the third quarter of 2025⁵⁶.

- **Concentrated solar power or CSP:** This technology uses mirrors or lenses to concentrate the solar light into a receiver. Electricity is generated by converting the concentrated light into heat, which then produces steam, which moves then a power generator.

CSP includes a variety of designs and technologies. Firstly, a parabolic trough is based on a linear parabolic reflector which concentrates light onto a receiver located along the focal line. A working fluid, such as molten salt is heated and used to generate heat, and then electricity.

On the other hand, the solar power tower consists of an array of dual axis tracking reflectors, called heliostats, that concentrate the sunlight in a receiver which is located in the upper part of a tower. The receiver contains a heat-transfer fluid, such as water steam or molten salt. This fluid is heated to 500-1000 °C and used to produce heat and steam.

A compact linear Fresnel reflector (CLFR) consists of many thin and flat mirrors which can concentrate sunlight on one or more tubes which are located above the mirrors at a specific height. The design is similar to the parabolic trough, but mirrors are flat, instead of parabolic.

Finally, dish Stirling or dish engine systems consist of a stand-alone parabolic reflector which concentrates light onto a focal point. The reflector has two axes, which make sure that it can track the Sun. The working fluid is heated to 250-700°C and used then by a Stirling engine to generate power.

However, it can be mentioned that concentrated solar power is, generally, considered as a non-economically feasible technology. Indeed, it is rarely used in Europe, where, as of 2022, almost all the installed capacity was located in Spain (2,304 MW out of 2,321 MW)⁵⁵. This technology is mainly developed in countries with large sun resources, such as the United Arab Emirates (600 MW), or Morocco (540 MW).

- **Onshore wind power:** Wind power is based on transforming the kinetic energy of wind (air in motion) into mechanical power and then electric power. Wind makes the turbine blades turn, and then the motion is transferred to a drive shaft and a gearbox. The movement generates magnetic fields in a generator, and then electricity.

A wind turbine is located on top of a tower. The turbine has a rotor, which is the part that is moved by the wind, and whose main part are three blades. The nacelle is a box which is located on top of the tower and contains, among other components, the gearbox and the generator. The gearbox increases the rotational speed from 5-20 rpm of the rotor to a rotational speed of 1,000-1,800 rpm to produce electricity by the generator.

Onshore wind turbines are those which are located in land and are the most common ones. Onshore wind turbines have usually a limited power capacity, due to the visual and environmental impact of higher wind turbines. The most used onshore wind turbines have now around 6 MW, although the record is a Chinese wind turbine with 15 MW.

⁵⁵ Source: IRENA (2025), *Renewable energy statistics 2025*, International Renewable Energy Agency, Abu Dhabi.

⁵⁶ Source: Litgrid. Power system. Power system information. Generation capacity. Installed capacity of the power plants operating in the Lithuanian power system as of 25 November 2025.

As of 2025, Lithuania's total installed capacity of onshore wind power is 2,510 MW, from which, 885 MW were installed in 2024.⁵⁶

- **Offshore wind power:** Offshore wind technology is based on the same physical principles than onshore wind power. However, the wind turbines are located in the sea, instead of in land.

There are some differences between both technologies. In the case of offshore wind turbines, they are installed in the sea, what affects the foundations. There are two offshore wind power technologies: bottom-fixed and floating.

Bottom fixed offshore wind turbines are directly settled into the seabed. The foundation design depends mostly on the sea depth: monopiles and gravity foundations are preferred for depths until 20-30 meters, while the tripile and jacket foundations are the most appropriate for depths until 60 meters.

On the other hand, floating offshore wind turbines are located in a platform which is floating. The platform is anchored to the seabed with mooring systems. There is a variety of designs, depending on the platform, the mooring and the anchoring systems. The advantage of the floating offshore wind turbines is that they can be placed in deep waters. Specifically, wind resources are especially rich in water depths around 600 m.

In general, offshore wind technology is much more expensive than onshore wind technology, but the wind resource is more abundant, and these turbines can produce electricity for more hours per year. Besides, the environmental and visual impact is lower, and the power capacity can be bigger. As of October 2024, the largest offshore wind turbine was installed in China, and has 20 MW, and a rotor diameter of 292 m. However, these records are being overcome constantly: on September 2025, a 26-MW wind turbine was installed in China, with a rotor diameter exceeding 310 m, and blades with a length of 153 m.

It should be remarked that the average power capacities are, however, lower. In Europe, the average installed offshore wind turbine capacity is around 10 MW⁵⁷.

As of 2024, Lithuania had not developed any offshore wind farm.

- **Hydropower:** Hydropower is based on the use of falling or fast-running water to produce electricity. The gravitational potential or kinetic energy of a water source is converted into power when the water moves a turbine, which generates magnetic fields, which then produce electricity in a generator.

Some hydroelectricity power plants use a dam and a reservoir, what allows them to be flexible, and to adapt to the power demand. An important advantage of these power plants is that they do not emit greenhouse gases, and once built, they do not produce waste. However, the environmental impact derived from the construction of the dam, and the flood of the zone is very important.

Some of these plants have also pumped-storage systems, with reversible turbines, and two reservoirs at different heights. In these plants, the turbine can operate as a pump. When the electricity price and/or the power demand is high, the plant produces electricity, by moving water from the upper reservoir to the lower one. However, when the power demand is lower, and/or the electricity prices are also low, water can be then pumped from the lower reservoir to the upper one and be used again.

⁵⁷ Source: WindEurope. *Wind energy in Europe. 2024 Statistics and the outlook for 2025-2030*. February 2025.

Finally, run-of-the-river hydroelectric plants do not have a reservoir, but they are built in a stream or river with a water flow. These power plants make far less environmental impacts than a reservoir hydropower plant, but they have not storage capacity and cannot adapt generation to demand. Besides, they are vulnerable to droughts and lack of water.

In 2025, Lithuania had a total hydroelectricity installed capacity of 1,030 MW, from which, 130 MW was hydro power and 900 pumped hydropower.

- **Biomass for electricity production:** Biomass is a type of renewable energy which is obtained from dead plants and animals. Among the main sources of biomass, it is possible to mention wood and wood processing waste (firewood, wood pellets, wood chips, furniture mill sawdust), agricultural crops and waste materials (soybeans, sugar cane, switchgrass, woody plants, etc.), biogenic materials in municipal solid waste (paper products, wool and cotton products, food, wood wastes), and animal manure and human sewage (used to produce natural gas).

All kinds of biomass can be burnt to produce heat, which is then used to heat water, what generates water steam. Water steam moves a turbine, which generates electricity, similarly to other power plants such as nuclear, natural gas power plants, wind power plants, or hydroelectric power plants.

It is important to mention that while it is true that burning biomass releases CO₂, it is typically considered carbon-neutral under the assumption that the CO₂ released during combustion was previously absorbed from the atmosphere during the biomass's growth. This concept of biogenic carbon neutrality depends on several factors, including the sustainability of the biomass source, the harvest and regrowth cycle, and supply chain emissions. In climate accounting (e.g., IPCC and EU ETS frameworks), these emissions are often reported separately from fossil emissions. However, accounting for the full life-cycle impacts of biomass fuels, including land use, processing, and transport, is essential to ensure their use leads to actual and measurable CO₂ reductions. Thus, while biomass can be a viable alternative fuel, its carbon impact must be assessed holistically, not simply at the combustion stage.

The total installed power capacity of biomass, to produce electricity in Lithuania, was 190 MW by the third quarter of 2025⁵⁶.

- **Marine energy:** Marine energy is a source of renewable energy derived from the movement of ocean water, utilizing the kinetic energy of waves and tides to generate electricity. Wave energy converters can capture the energy contained in ocean waves and use it to generate electricity. Converters include oscillating water columns that trap air pockets to drive a turbine; oscillating body converters that use wave motion; and overtopping converters that make use of height differences to produce electricity⁵⁸.

However, marine energy remains a very expensive and innovative technology, with only some prototypes developed in the world. Indeed, the total worldwide installed capacity in 2024 was only 494 MW. From this capacity, in the European Union, there are 229 MW installed, mostly in France, with 212 MW⁵⁵.

⁵⁸ Source IRENA and Ocean Energy Europe (2023). *Scaling up investments in ocean energy technologies*, International Renewable Energy Agency. Abu Dhabi.

- **Use of renewable energies to produce heat.**

Renewable energy can be converted into different kinds of energy, such as electricity or heat. The main renewable heat technologies are solar water heaters, geothermal energy, and biomass and other biofuels.

- **Solar water heaters:** Solar water heater systems are designed to harness solar energy for heating water, utilizing solar collectors to absorb sunlight and convert it into heat. The system typically consists of two main components: the solar collector to capture the sunlight and a storage tank to store the heated water for later use.

Solar water heaters are used for industrial processes where large volumes of hot water are required, reducing energy operating costs in those processes. Despite the high upfront installation costs of this technology, it offers long term energy savings with relatively low maintenance costs.

Another technology uses solar irradiation to heat air for space heating. Total solar collectors in operation worldwide, by 2023, reached 559,902 MWth, from which, 559,060 MWth were solar water collectors. This is, almost 100% of the global solar collector capacity were solar water heaters. There are only 842 MWth of solar air collectors worldwide⁵⁹.

In the specific case of Lithuania, only 19 MWth of solar water collectors have been installed. From them, 7.7 MWth are flat plate collectors (FPC), and 11.2 MWth are evacuated tube collectors (ETC). There are not solar air collectors.

- **Geothermal energy:** Geothermal energy is a form of renewable energy that is derived from the heat stored beneath the Earth's surface. The heat is transferred to the surface through conduction and convection. Geothermal energy can be harnessed for electricity generation and direct heating.

In particular, Lithuania's Western region exhibits a significant geothermal anomaly, with heat flows reaching 80–100 mW/m², compared to the ~40–50 mW/m² background of the East-European craton. This is driven by both elevated concentrations of radioactive heat-producing elements in the crystalline basement and increased mantle heat input. Three sedimentary aquifer complexes—Cambrian (~140 m), Middle–Lower Devonian (~400 m), and Upper–Middle Devonian (~200 m)—are recognized in the subsurface. Shallow Devonian sandstone aquifers (1,000–1,500 m) yield temperatures of ~45–46 °C, suitable for district heating. Deeper zones (2000–2500 m) may attain ~96 °C, potentially enabling low-capacity power generation depending on reservoir quality. HDR/EGS exploitation of the Žemaičių Naumištis granitoid (3.5–4 km depth) could reach 150 °C, leveraging heat flows of 80–100 mW/m². Ongoing research by KTU is using numerical modelling of Devonian and Cambrian reservoirs to refine geothermal production forecasts^{60,61}.

⁵⁹ Source: IEA Solar Heating & Cooling Programme. AEE- Institute for Sustainable Technologies (2025). *Solar Heat Worldwide. Global Market Development and Trends 2024. Detailed Market Figures 2023. 2025 Edition.* June 2025.

⁶⁰ Source: SAULIUS, Šliaupa; LAZAUSKIENĖ, Jurga; ŠLIAUPIENĖ, Rasa. *Thermal Maturity of the Silurian "Hot" Shales and Correlation with the Present Geothermal Variations in West Lithuania, Baltic Basin.* Minerals. 2025. <https://doi.org/10.3390/min15050539>

⁶¹ Source: MEMON, Abdul Rashid; PAL, Mayur. *Assessing Geothermal Energy Production Potential of Devonian Geothermal Complexes in Lithuania.* Energies. 2025. <https://doi.org/10.3390/en18030612>

Geothermal energy is a reliable base-load power source, unlike intermittent renewable sources like solar or wind. However geothermal energy is geographically limited to areas near tectonic plate boundaries or geothermal hotspots, making it inaccessible for many regions. The initial costs of drilling wells and building geothermal plants are high, although ongoing operational costs are relatively low.

Total geothermal energy installed worldwide reached 15,412 MW in 2024, with 874 MW in the European Union. The main countries in Europe in terms of installed geothermal energy are Iceland, with 788 MW and Italy, with 772 MW⁵⁵.

- **Biomass and other biofuels:** Biomass refers to organic materials that can be used as a source of energy, being directly burnt for heat or converted into biofuels. Biofuels such as bioethanol, biodiesel, and biogas, serve as cleaner alternatives to gasoline and diesel in transportation.

Biomass is a renewable resource, as it can be replenished through sustainable agricultural and forestry practices. When used for energy, biomass releases CO₂ into the atmosphere as part of a natural carbon cycle, where plants absorb CO₂ during their growth phase, making it considered "carbon neutral" when managed sustainably⁶². Biomass is directly burnt in biomass boilers in domestic and industrial uses.

Biofuels are produced from vegetable oils, animal fats, or recycled cooking grease, serves as a renewable alternative to conventional fossil fuels⁶³. Biomass can be thermochemically converted using processes such as pyrolysis, hydrotreating or gasification to produce biofuels. Besides, biomass can be fermented to produce ethanol, used as a vehicle fuel. Biofuel production exists in Lithuania in plants owned by Mestilla and Rapsoila UAB which utilize locally sourced rapeseed oil to produce biodiesel.

Biogas is produced in anaerobic digesters, in sewage treatment plants and from solid waste in landfills. Biogas is natural gas or methane, similar to the natural gas from geological origin, and has the same uses.

- **Material and energy efficiency measures.**

Material efficiency measures focus on reducing the number and quantities of raw materials used in production processes or increasing the lifecycle of products. One common measure is **additive manufacturing** (3D printing). It enables precise material to use by building products layer by layer, reducing material waste.

Energy efficiency measures aim to reduce the amount of energy required to produce goods and services, leading to lower emissions and operational costs, without a decrease of the quality or amount of produced goods and services. One of the most important energy efficiency measures is waste heat recovery systems⁶⁴. These systems capture and reuse heat generated from industrial processes, such as exhaust gases from furnaces or boilers. This recovered energy can be used for electricity generation or to preheat raw materials.

Other energy efficiency technologies include:

⁶² Source: US Department of Agriculture – Biomass Energy

⁶³ Source European Court of Auditors - *Special report 29/2023: The EU's support for sustainable biofuels in transport. An unclear route ahead.* 2023.

⁶⁴ Source: TLV – Steam Theory – Waste Heat Recovery.

- Heat pumps to produce heating and cooling. They use electricity to transfer heat from a cold place to a warm place (when it is used to produce heat), or to transfer heat from a warm place to a cold place (when it is used for cooling). They have a high performance, being able to produce around 2-5 kWh of heat per kWh of electricity (what is called COP, Coefficient of Performance), and between 2-4 kWh of cooling per kWh of electricity (this is the EER, Energy Efficiency Ratio, which is always lower than the COP).
- Isolation in windows, including the checking of air leaks, the use of solar control films, or the use of double-glazed windows or triple-glazed windows, with two or three sheets of glass, and an air gap in between.
- Improvement of the insulation in buildings, using doors with brush strips, or PVC curtains between spaces, or installing insulation materials in roofs or walls.
- Use of energy efficiency lighting systems, such as LED technology to replace old incandescent, sodium vapour or mercury vapour lightbulbs, both in street and in buildings. Besides, the use of lighting sensors, which adapt the light intensity to the needs, according to the presence of humans, motion or timing, is a good option for energy saving. Another technology are sensors which adapt the light intensity to the outdoor light which enters the building. In the street, dimmers can adapt the power of LED lighting to the night hour and the traffic in the light or the availability of natural light.
- Replacement of old equipment and appliances for newer ones, considering that the technologies have evolved, and new appliances can use less energy than older ones.
- Use of variable speed motor drives, which can adapt the speed and power of the engine to the demand, by adapting the electricity used from the grid. This ensures a smoother operation of the equipment, and also saves energy, by avoiding sharp variations in electricity demand and speed.

- **Carbon Capture**

Carbon capture is a set of technologies aimed at reducing CO₂ emissions by capturing and storing carbon dioxide from the atmosphere and utilizing captured carbon for industrial applications. These technologies will be further explained and expanded upon in later sections of this document.

- **Artificial intelligence and digitalisation.**

Digitalisation refers to the integration of digital technologies into manufacturing and other industrial processes. This integration facilitates real-time data collection, analysis, and informed decision-making. The role of AI in improving efficiency and optimizing resource use has a clear correlation with the industries capacity in reducing their emissions.

Some of the biggest uses of AI in industry are:

- **Predictive Maintenance:** Use of machine learning algorithms to analyse sensor data and predict equipment failures before they occur.
- **Process Optimization:** AI can identify patterns in production data, enabling more efficient use of energy and materials.
- **Supply Chain Management:** AI powered systems can enhance logistics, inventory management, and demand forecasting.

Optimizing these processes specially helps with cost efficiencies, yet, in doing so, also leads to more sustainable operations, studies have shown that the advancements in use of AI technologies in industry have arrived hand in hand with improvements in global emissions⁶⁵. Nonetheless, some concerns still persist arising from the energy needs that AI commands⁶⁶.

Artificial intelligence (AI) and machine learning (ML) have increasingly found significant applications in optimizing carbon capture, utilization, and storage (CCUS) technologies. These advanced computational tools, such as neural networks, support vector machines (SVM), decision trees, random forests, logistic and linear regression, naïve Bayes, nearest neighbor, and hidden Markov models, have been utilized across various stages of the CCUS processes to enhance efficiency, improve reliability and reduce simulation time. In the carbon capture phase, AI algorithms play a pivotal role by optimizing system performance parameters like temperature, pressure, and flow rates. Techniques such as deep neural networks have effectively optimized capture methods involving absorption, adsorption, membrane separation, and cryogenic distillation, significantly enhancing process efficiency⁶⁷. For geological storage, AI's impact is evident in advanced modeling capabilities. For instance, deep learning techniques, including Fourier Neural Operators (FNOs), have been employed to model CO₂ plume migration within subsurface reservoirs. These models dramatically reduce simulation time while maintaining high accuracy, enabling real-time monitoring and assessment of CO₂ storage sites⁶⁸. Real-time monitoring and fault detection within CCUS facilities also benefit significantly from AI integration. Automated monitoring systems leveraging machine learning algorithms can rapidly detect anomalies, ensuring operational safety and system reliability. This proactive approach prevents potential disruptions and maintains continuous operational efficiency. Moreover, AI-driven site selection and risk assessment models have improved the decision-making process for geological storage. Machine learning tools analyze complex geological data to pinpoint optimal locations for CO₂ storage, predicting long-term site stability and reducing associated risks⁶⁹. Another promising application involves the optimization of energy management and process scheduling. Deep reinforcement learning (DRL) methods have been successfully applied to coordinate multi-energy systems integrated with CCUS processes. These methods outperform traditional, rule-based scheduling, enhancing economic

⁶⁵ Source: CHEN, Yixuan; JIN, Shanyue. *Artificial Intelligence and Carbon Emissions in Manufacturing Firms: The Moderating Role of Green Innovation*. Processes 2023, 11(9), 2705. September 10th, 2023. <https://doi.org/10.3390/pr11092705>

⁶⁶ Source: WU, Carole-Jean; RAGHAVENDRA, Ramya; GUPTA, Udit; ACUN, Bilge; ARDALANI, Newsha; MAENG, Kiwan; CHANG, Gloria; AGA, Fiona Aga; HUANG, James; BAI, Charles; GSCHWIND, Michael; GUPTA, Anurag; OTT, Myle; MELNIKOV, Anastasia; CANDIDO, Salvatore; BROOKS, David; CHAUHAN, Geeta; LEE, Benjamin; LEE, Hsien-Hsin S.; AKYLDIZ, Bugra; BALANDAT, Maximilian; SPISAK, Joe; JAIN, Ravi; RABBAT, Mike; HAZELWOOD, Hazel. *Sustainable AI: Environmental Implications, Challenges and Opportunities*. arXiv:2111.00364. Cornell University. January 9th, 2022. <https://doi.org/10.48550/arXiv.2111.00364>.

⁶⁷ Source: SIRI, Dharmapuri et al. *Carbon Capture and Storage Optimization with Machine Learning*. E3S Web of Conferences 581, 01003 (2024). Empowering Tomorrow 2024. <https://doi.org/10.1051/e3sconf/202458101003>.

⁶⁸Source: CHANDRA, Anirban, KOCH, Marius; PAWAR, Suraj; PANDA, Aniruddha; AZIZZADENESHELI, Kamyar; SNIPPE, Jeroen; ALPAK, Faruk O.; HARIRI, Farah; ETIENAM, Clement; DEVARAKOTA, Pandu; ANANDKUMAR, Anima; HOHL, Detlef. *Fourier Neural Operator based surrogates for CO₂ storage in realistic geologies*. arXiv:2503.11031v2 [physics.comp-ph]. Cornell University. March 20th, 2025. <https://doi.org/10.48550/arXiv.2503.11031>

⁶⁹ Source: Saiwa. Machine Learning in Carbon Capture. Advancing Climate Solutions. January 23rd, 2025. <https://saiwa.ai/blog/machine-learning-in-carbon-capture/>

efficiency and maximizing carbon capture effectiveness⁷⁰. Overall, applying artificial intelligence and machine learning in CCUS technologies represents a significant advancement, addressing key challenges such as efficiency optimization, cost reduction, and enhanced monitoring. As these technologies evolve, their integration into CCUS processes is expected to grow, offering more robust and effective solutions for global carbon management.

- **Sustainable transport: electric vehicle, biofuels, hydrogen.**

Sustainable transport refers to the use of transportation systems with minimal environmental impact in terms of carbon emissions. It includes modes of transport that promote energy efficiency, reduce greenhouse gas emissions, and utilize renewable resources. In industries, sustainable transport plays a critical role in reducing carbon footprints through the adoption of low-emission vehicles, including electric and hybrid models, and the integration of alternative fuels such as biofuels and hydrogen:

- **Low-Emission Vehicles:** all-electric and hybrid vehicles produce zero tailpipe emissions in short distance transport⁷¹. The use of these alternatives in warehouses and distribution centres for material handling contribute to efficient internal logistics by providing quiet and emission-free operations.
- **Alternative Fuels:** Alternative fuels are energy sources used to power vehicles and other forms of transportation that are not derived from traditional gasoline or diesel. Biofuels, compressed natural gas, liquefied natural gas, and hydrogen can significantly reduce transportation-related carbon emissions.

- **Waste reduction and recycling**

Waste reduction and recycling involve strategies aimed at minimizing the generation of discarded excess, optimizing resource use, and promoting the recovery of materials. These practices contribute to the sustainability of industrial enterprises by reducing resource consumption and lowering the environmental impact of waste disposal. A review paper published in an Emerald journal in 2024 showed that improvements of the environmental performance of an industrial production have also a positive impact on the productivity (usually considering cost savings) and vice versa.⁷²

Several effective waste reduction and recycling strategies can be applied in the industrial sector, including:

- **Process Optimization:** Improving production processes to minimize material waste involves adapting advanced manufacturing technologies and refining resource management.
- **Material Substitution:** Replacing raw materials with recycled or renewable alternatives.

⁷⁰ Source: ALABI, Tobi Michael; LAWRENCE, Nathan P.; LU, Lin; YANG, Zaiyue; GOPALUNI, R. Bhushan. *Automated deep reinforcement learning for real-time scheduling strategy of multi-energy system integrated with post-carbon and direct-air carbon captured system*. Applied Energy. Volume 333, March 1st, 2023, 120633. <https://doi.org/10.1016/j.apenergy.2022.120633>

⁷¹ Source: US Department of Energy. Alternative Fuels Data Center. Electric Vehicle Benefits and Considerations.

⁷² Source: RÜDELE, Kai; WOLF, Matthias; RAMSAUER, Christian. *Synergies and trade-offs between ecological and productivity-enhancing measures in industrial production – a systematic review*. Management of Environmental Quality: An International Journal. Vol. 35 No. 6, 2024, pp. 1315-1353. Emerald Publishing Limited 1477-7835. July 17th, 2024. <https://doi.org/10.1108/MEQ-07-2023-0195>

- **Closed-loop Recycling:** Implementing systems that allow materials to be collected, processed and reused within the same production cycle. Closed-loop box reuse is a common example of this; recycling one ton of corrugated cardboard saves 24% of the energy required to create new cardboard.⁷³
- **Industrial Symbiosis:** Collaborating with other industrial companies to exchange by-products and waste materials, turning one's waste into another one's material. This is best exemplified by the Kalundborg Eco-Industrial Park located in Denmark, where there are more than 30 exchanges of materials between the partners in the park⁷⁴.

- **Carbon-neutral cement production**

Carbon neutral cement production aims to significantly reduce or entirely eliminate CO₂ emissions associated with cement manufacturing, one of the largest contributors to industrial greenhouse gas emissions. It has to be considered that at least 8% of global emission caused by humans come from the cement industry⁷⁵. Traditional cement production relies on the calcination of limestone, a process that releases significant amounts of CO₂ both from the combustion of fossil fuels and the chemical decomposition of limestone.

Several innovative technologies and methods can be employed to achieve carbon neutrality in cement production, including the following:

- **Alternative Sources of Thermal Energy:** replacing fossil fuels with alternative fuels in the cement industry can reduce the CO₂ emissions up to 30 %. It is because $\frac{1}{3}$ of CO₂ emissions comes from burning the fuel and the other $\frac{2}{3}$ - from calcination process. Variety of alternative fuels, such as agricultural biomass residues, non-agricultural biomass residues, petroleum based wastes, miscellaneous wastes and chemical and hazardous wastes could be used. It is also important to mention that waste-derived fuels reduce CO₂ emissions indirectly, as their use avoids emissions from incineration or landfilling, while also replacing fossil fuels⁵⁴.
- **Alternative Clinker Materials:** Clinker is the primary constituent of cement, and it is notably carbon-intensive to produce. Reducing its proportions in cement formulation is a very effective method in lowering emissions. This reduction is achievable through supplementary cementitious materials (SCMs) such as calcinated clay. Calcinated clay is the most scalable solution because it can use existing equipment and offers the right mechanical qualities⁷⁶.
- **Carbonation curing:** This process involves curing concrete with CO₂ instead of steam, which allows the CO₂ to be absorbed and permanently stored within the concrete structure⁷⁷. While

⁷³ Source: Recycling Facts

⁷⁴ Source: EHRENFELD, John; GERTLER, Nicholas. *Industrial Ecology in Practice: The Evolution of Interdependence at Kalundborg* Journal of Industrial Ecology. International Society for Industrial Ecology. Volume 1, Issue 1. January 1997, pp 67-79. <https://doi.org/10.1162/jiec.1997.1.1.67>

⁷⁵ Source: Nature. *Concrete needs to lose its colossal carbon footprint*. Nature 597, 593-594 (2021). doi: <https://doi.org/10.1038/d41586-021-02612-5>

⁷⁶ Source:–LECAMWASAM, Tharika. *Three emerging technologies for low-carbon concrete*. Climateworks Foundation. July 30th, 2024.

⁷⁷ Source: LIU, Zhuo; MENG, Weina. *Fundamental understanding of carbonation curing and durability of carbonation-cured cement-based composites: A review*. Journal of CO₂ Utilization. Volume 44, February 2021, 101428. <https://doi.org/10.1016/j.jcou.2020.101428>

in principle this method provides clear contributions to reduce emissions, its efficacy can vary and its overall impact over CO₂ emissions is still in question⁷⁸.

- **Mechano-chemical activation** is an emerging technique for producing high-performance supplementary cementitious materials from clays and other aluminosilicates. It combines intensive grinding (mechanical activation) with chemical reactions, often without high-temperature calcination, to significantly increase the reactivity of naturally inert or low-reactivity clays. In this process, mechanical energy is applied—typically via planetary ball mills or attritors—to induce structural disorder, increase surface area, and create defects in clay minerals like kaolinite, illite, or pyrophyllite. These disruptions increase the number of reactive sites, allowing the clay to better participate in pozzolanic reactions when blended into cement. This process not only improves compressive strength and durability of cement composites, but also drastically reduces CO₂ emissions—as high-temperature kilns are avoided and clinker content in the mix is reduced. For instance, replacing Portland cement with mechano-chemically activated clays can result in CO₂ reductions of 40–60% per ton of cementitious material, especially in combination with other supplementary cementitious materials like limestone or fly ash⁵⁸.

- **Carbon neutral fertilizer, chemical products and oil refining**

Fertilizer production, chemical sectors and oil refining are some relevant sectors in Lithuania in terms of carbon dioxide emissions. The main reason for this is that nitrogen and hydrogen is one of the most important components of most fertilizers, while hydrogen is important to produce chemical products such as ammonia, methanol, and in oil refining. Nitrogen can be obtained from air, but the production of hydrogen generates large amounts of carbon dioxide, as most of it is generated from natural gas reforming⁷⁹.

Therefore, to produce reduce greenhouse gas emissions in the fertilizer and chemical industries, as well as in oil refining, it is key to minimize the carbon footprint of the hydrogen production. To do this, there is a number of technologies, such as:

- Use of carbon capture and storage to collect the carbon dioxide emitted in natural gas reforming processes. The advantage of the technology is that the process to produce hydrogen does not need to be changed. However, the development of carbon capture and storage is costly, and also needs energy. Another disadvantage is that this option does not reduce the use of fossil fuels.
- Use of water electrolysis to produce hydrogen⁸⁰. This is a good option if there is a renewable power plant near the plant, using, for example, wind or solar PV. The use of electrolyzers is being extensively explored, however, an important disadvantage is that there is a need for large amounts of electricity. Besides, the space for new wind and solar PV plants is limited, and the

⁷⁸ Source: RAVIKUMAR, Dwarakanath; ZHANG, Duo; KEOLEIAN, Gregory; MILLER, Shelie; SICK, Volker; LI, Victor. *Carbon dioxide utilization in concrete curing or mixing might not produce a net climate benefit*. Nature Communications 12, 855 (2021). February 8th, 2021. <https://doi.org/10.1038/s41467-021-21148-w>.

⁷⁹ Source: ROSA L, GABRIELLI P. *Energy and food security implications of transitioning synthetic nitrogen fertilizers to net-zero emissions*. Environmental Research Letters 2022, doi: 10.1088/1748-9326/aca815.

⁸⁰ Source: U.S. Department of Energy. *Hydrogen Production Processes*. Hydrogen and Fuel Cell Technologies Office.

electricity generated by these plants can be needed by other sectors, even more if economies are tending to electrification.

- Biomass gasification. This technology, which is mature enough, uses heat, steam and oxygen to transform biomass into hydrogen and other products, without combustion. Biomass production does not emit new carbon dioxide emissions, since growing it removes carbon dioxide from the atmosphere.

Gasification is a process which converts organic or fossil fuel-based carbon rich matter into carbon monoxide, hydrogen and carbon dioxide, using high temperatures (above 700°C) and a controlled amount of oxygen and steam.

- Use of biomass to produce hydrogen with microorganisms. This option makes sense if biomass comes from crop residues or urban waste, but should not be considered if it is necessary to produce the biomass, competing with food production. Microbes, such as microalgae and bacteria, can produce biological reactions which transform organic waste into hydrogen. For example, in fermentation-based processes, sugars and raw biomass is transformed into hydrogen, with no need for light. In photobiological processes, microorganisms use water and organic matter to produce hydrogen using the sunlight.

- **Bioplastics**

Bioplastics refer to a range of materials derived from renewable biological resources, such as corn starch, sugarcane, or algae, rather than traditional fossil fuels. The use of bioplastics in industry can potentially reduce CO₂ emissions by lowering the carbon footprint associated with plastic production and disposal. Switching from traditional plastic to bioplastics could cut greenhouse gas emissions by 25%.⁸¹

The most common bioplastics used in industrial applications are Polylactic Acid (PLA), a biodegradable plastic derived from fermented plant starch commonly used in packaging, and Polyhydroxyalkanoates (PHA), a group of biodegradable plastics produced by bacteria through the fermentation of sugars or lipids. PHA is used in medical applications, packaging, and agricultural films. Although PHA is biodegradable in various environments, its high production costs and limited supply pose challenges for large-scale adoption.

- **Electrification**

Electrification refers to the substitution of processes based on fossil fuels by processes powered by electricity. This transition can significantly reduce CO₂ emissions when the electricity is generated from renewable or low-carbon sources. There are several applications of electrification in industrial processes, including the following:

- **Industrial Heat Pumps:** Industrial heat pumps are systems that use electricity to transfer heat from low-temperature sources – such as water or air – to higher temperatures suitable for various industrial processes. This mechanism is inherently more energy-efficient than combustion-based methods, as it relocates existing energy rather than generating it anew. This is especially true for industries requiring low to medium temperature heat. Sectors such as

⁸¹ Source: POSEN, Daniel; JARAMILLO, Paulina; E LANDIS, Amy; GRIFFIN, W Michael. *Greenhouse gas mitigation for U.S. plastics production: energy first, feedstocks later*. Environmental Research Letters 12 034024. March 16th, 2017. DOI: 10.1088/1748-9326/aa60a7

food processing, chemical manufacturing, and textiles can take the most advantage of this technology.

Industrial heat pumps can achieve an operational efficiency that far exceeds the traditional fossil fuel burners, according to the International Energy Agency the coefficient of performance of an industrial heat pump ranges from 3 to 5, indicating that they can deliver three to five units of heat for every unit of electricity consumed.⁸²

- **Electric Boilers:** Electric boilers produce steam or hot water by converting electrical energy into heat, achieving nearly 100% efficiency⁸³. They can be implemented in various industrial sectors to replace fossil fuel-based boilers, especially where there is a need for heat below 200°C such as the paper and textile industry. Electric boilers present a viable solution in areas with high renewable electricity penetration or where the integration of district heating networks is possible.
- **Electric Arc Furnaces (EAF):** Electric arc furnaces are widely used in the steelmaking industry to recycle scrap metal, producing steel with considerably lower CO₂ emissions compared to traditional blast furnaces.⁸⁴ EAFs use high current electric arcs to melt scrap metal, with the process becoming entirely carbon-free when powered by renewable electricity.

The adoption of electrification technologies depends on several factors, including the availability of low-carbon electricity, infrastructure investments, and the specific energy requirements of each industrial process.

4.2. Social, economic, and environmental impact of innovative technologies

The implementation of Innovative Technologies in industrial enterprises presents a range of social, economic, and environmental impacts that must be assessed to evaluate their overall feasibility and contribution to sustainable development. This section provides a comprehensive analysis of these aspects, considering both short-term and long-term effects across different industrial sectors in Lithuanian counties.

Social Aspects

The deployment of innovative CO₂ reduction technologies in industrial operations across places such as Kaunas, Telšiai, and Šiauliai counties is expected to trigger a social transformation in various ways. In the short term, the shift to hydrogen fuel, electrified heat systems, carbon-neutral cement production, and renewables introduces a demand for new technical competencies and workforce retraining. While this transition may temporarily displace certain jobs—particularly in fossil-fuel dependent industries—it simultaneously opens pathways for high-skilled employment in engineering, maintenance, and digital monitoring systems. This realignment of labour profiles contributes to the upskilling of the regional workforce and may reduce long-term unemployment, particularly in areas previously dependent on carbon-intensive industries.

⁸² Source: International Energy Agency. *The Future of Heat Pumps*. World Energy Outlook Special Report. November 2022.

⁸³ Source: The Climate Drive. Forest Solutions Group and McKinsey Sustainability. *Switch to industrial electric boilers*.

⁸⁴ A study from the Steel Manufacturers Association claims approximately 75% lower carbon intensity using EAFs over traditional furnaces. Source – Steel Manufacturers Association. CRU International Limited. *Steelmaking Emission Report 2022*.

From a community perspective, the initial stages of decarbonization could cause friction, especially in sectors resistant to operational overhauls or within communities sceptical of new technologies. However, public acceptance tends to increase with awareness campaigns and tangible improvements in air quality, noise reduction, and overall living conditions. For example, the electrification of industrial heat sources and the reduction of cement-related emissions can significantly decrease urban particulate pollution—directly benefiting public health in densely populated industrial hubs like Kaunas. Reduced healthcare costs and improved quality of life are outcomes with widespread social dividends.

In the medium to long term, as these technologies scale and normalize, broader societal benefits are likely to emerge. Cleaner industrial operations will contribute to healthier ecosystems and increased attractiveness of these counties as places to live and work, potentially reversing demographic decline through youth retention and urban revitalization. Furthermore, the integration of renewable energy production within industrial zones, such as rooftop solar PV or wind cooperatives, can stimulate local ownership models and energy democracy, encouraging community participation in energy governance and enhancing social cohesion.

The educational sector also stands to benefit. As demand for skills in sustainability, green engineering, and environmental monitoring grows, regional educational institutions may adapt their curricula, accordingly, fostering stronger ties between industry and academia. This synergy supports long-term resilience by embedding environmental literacy and innovation into the region's socioeconomic fabric. Moreover, the emergence of green industrial clusters can stimulate local entrepreneurship and diversify the industrial base, reducing regional exposure to global fossil fuel volatility and enabling a more inclusive economic model.

Ultimately, while the social impacts of CO₂-reducing technologies are context-dependent, their strategic implementation in Lithuania holds significant promise for social renewal. If managed inclusively, this industrial decarbonization could serve not only as a climate mitigation strategy but also as a catalyst for a more equitable, educated, and resilient society.

Economic Aspects

The economic implications of deploying CO₂ reduction technologies in the Lithuanian industrial sectors are significant. In the short term, the transition to these innovative technologies will demand substantial capital investment from both public and private sectors. This includes upfront costs for infrastructure upgrades, R&D, and workforce reskilling. For SMEs and energy-intensive sectors, this may initially strain operating margins or require subsidies and policy support to remain competitive during the transitional phase.

However, these investments act as economic stimuli. They create demand in the construction, engineering, and technology supply chains, generating new jobs and boosting local GDP. Particularly in Kaunas, with its larger industrial base, these activities are likely to attract foreign direct investment (FDI) and EU green funding, reinforcing the region's position as a hub for advanced manufacturing and green innovation. Additionally, the electrification of boilers and heat pumps can reduce energy dependency and operational costs over time, especially as energy prices stabilize under increased renewable penetration.

In the medium term, industries that adopt low-carbon technologies early gain a competitive advantage in export markets increasingly governed by carbon border taxes and ESG criteria. Carbon-neutral cement, for example, can position producers in Šiauliai to access higher-margin, eco-certified markets in Western Europe. The decarbonization of production processes will also improve the resilience of

industrial supply chains against future regulatory risks, carbon pricing, and environmental liabilities, which is increasingly relevant as global climate regulations tighten.

Long-term economic benefits are tied to regional diversification and productivity gains. As industries decouple growth from emissions, there is potential for structural economic modernization. Green innovation clusters, especially around hydrogen and waste valorisation technologies, can emerge as new economic engines. Telšiai, with its agricultural-industrial mix, could particularly benefit from biogas and circular waste systems that convert agricultural by-products into industrial energy, creating closed-loop local economies and reducing import dependency.

In sum, the economic impact of CO₂ reduction technologies in these Lithuanian counties is not just a matter of compliance or sustainability, it is a forward-looking growth strategy. When coordinated with supportive policy frameworks and investment in skills and infrastructure, this transition can transform the regional industrial economy from a legacy cost centre into a resilient, high-value, low-carbon growth engine.

Environmental Aspects

The environmental impact of adopting innovative CO₂ reduction technologies across industrial sectors in Lithuania is the most profound. In the short term, the shift away from fossil-fuel-based operations leads to a direct and measurable reduction in greenhouse gas (GHG) emissions. The immediate effect includes improved local air quality and a decline in particulate matter, nitrogen oxides (NO_x), and sulphur dioxide (SO₂), which are typically associated with combustion processes in heavy industry.

Electrification of heat generation—through heat pumps and electric boilers—further mitigates emissions from traditional fuel sources like coal and natural gas, while reducing thermal pollution in nearby ecosystems. As these counties move toward cleaner electricity mixes, the environmental performance of electrified systems improves in conjunction. Additionally, carbon-neutral cement technologies significantly reduce the embedded carbon footprint of construction and infrastructure development, which is vital for sustainable urban growth across the region.

In the medium term, broader adoption of renewable energy sources within industrial operations enables systemic decarbonization and lowers the region's reliance on imported fuels. This transition enhances energy sovereignty and mitigates exposure to geopolitical supply shocks, while simultaneously reducing the environmental impact associated with resource extraction and transport.

Long-term environmental gains are anchored in the regenerative potential of these technologies. As CO₂ reduction becomes embedded into industrial processes, it enables ecosystem restoration, particularly in areas previously affected by pollution-intensive activities. Industrial decarbonization will also facilitate compliance with EU environmental directives, including the Circular Economy Action Plan and the European Green Deal.

Overall, the environmental impact of these technologies extends well beyond emission reductions. They create a systemic transformation toward cleaner production, resource efficiency, and ecological balance. This represents not just a climate imperative, but an opportunity to realign industrial development with the principles of long-term environmental sustainability and regional ecological stewardship.

4.3. Relevance and readiness assessment for each industry

Lithuania's climate action strategy centers on achieving net greenhouse gas (GHG) neutrality by 2050, with intermediate targets of a 70 % emissions reduction by 2030 and 85 % by 2040, compared to 1990 levels. Between 2005 and 2023, Lithuania reduced net emissions by 31.5 %, slightly outpacing the EU average, with ETS-covered sectors cutting emissions by over 57 %. The land-use, land-use change, and forestry (LULUCF) sector currently absorbs about one-third of national GHGs, underscoring its importance as a carbon sink.

Governance is anchored by the 2021 National Climate Change Management Agenda (NCCMA) and a 2024 updated National Energy and Climate Plan (NECP), both of which were developed through extensive stakeholder engagement and benefit from OECD and European Commission technical advice to enhance policy coherence and attract private investment. The NECP complements Lithuania's energy independence strategy and "Lithuania 2050" framework, embedding climate adaptation measures and targeting a 100 % renewable electricity mix by 2030.

Sectoral progress has been uneven: the energy industries reduced emissions by 57% since 2005, while industry cut emissions by 36% in the same period. However, transport emissions grew 46% since 2005 and now account for 33% of total GHGs, prompting measures under the 2021 Alternative Fuels Law to expand electric vehicle infrastructure and biofuel blending. Small energy (buildings) must slash emissions by 26% by 2030, with a long-term goal of 60 % lower primary energy use by 2050; an EIB-backed €625 million building renovation initiative was launched in late 2024.

Agriculture, responsible for 21% of emissions in 2023, faces a 2030 reduction target of 11% through optimized fertilizer use and improved manure management. The NECP also targets LULUCF enhancements—expanding forest cover to at least 35% of land area and restoring 8,000 ha of carbon-rich ecosystems—to secure an additional 6.5 Mt CO₂e of sinks by 2030.

Financing flows from the Recovery and Resilience Plan (37.4 % allocated to climate objectives), the Just Transition Fund (€273 million to introduce green hydrogen and innovative technologies in the regions with many highly greenhouse-gas-intensive industrial plants, such as Kaunas, Siauliai and Telšiai counties) and the Modernization Fund (including €36 million for renewable hydrogen, which have not been allocated, as there were no applications from Lithuanian producers in the Hydrogen auction) bolster decarbonization efforts across sectors. Recent policy developments—such as the 2024 intergovernmental agreement on small modular reactors with the US and the March 2025 €1 billion modernization pact with Orlen Lietuva—demonstrate Lithuania's commitment to aligning energy security with low-carbon ambitions. Despite strong progress, the 2024 Country Report notes persisting challenges in energy poverty, renovation rates, and GHG reductions in transport and agriculture, indicating that sustained policy momentum and private investment will be crucial to meet Lithuania's mid- and long-term climate goals⁸⁵.

⁸⁵ Think Tank European Parliament. *Lithuania's climate action strategy*. Briefing. Roadmap to EU climate neutrality- Scrutiny of Member States. May 14th, 2025. [https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI\(2025\)772859](https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2025)772859)

4.4. Transition strategy into innovative technologies

Lithuania's transition strategy toward innovative technologies is centered on embedding “eco-innovation” and clean production across key industrial sectors through targeted Policies & Measures (PaMs) outlined in the 2025 PaMs and Projections report⁸⁶. In the **short term (2021–2025)**, the focus is on kick-starting modernization of existing facilities. Measures P5-E (“Replacing polluting technologies”) and P6-E (“Promoting technological eco-innovation”) provide co-financing for companies—especially SMEs—to replace outdated equipment with greener alternatives, invest in low-GWP refrigerants, and adopt cleaner production methods. Concurrently, P4-E (“RES use in industry”) mandates that non-ETS industrial enterprises conduct energy audits and install renewable energy systems for on-site power (e.g., solar PV), enabling immediate CO₂ reductions and familiarizing businesses with new technologies.

By **mid-term (2024–2030)**, Lithuania plans to scale up these successes via broader “innovation hubs” and digitalization. Measure P15-E (“Innovative green products and services”) establishes financial instruments and knowledge exchanges to foster circular-economy clusters, where companies co-invest in high-TRL R&D (levels 6–9) for green technologies like advanced biochemicals or low-carbon materials. P11-E (“Promoting industrial digitization”) supports technological audits and deployment of Industry 4.0 tools—digital twins, IoT sensors, and AI-driven process controls—so firms can optimize resource use and minimize waste. Simultaneously, P12-E (“Improving energy efficiency in enterprises”) offers incentives for energy audits and subsequent investments in modern equipment (variable-speed drives, heat-recovery systems) that reduce energy intensity. These measures collectively aim to lower IPPU (Industrial Processes and Product Use) sector emissions by integrating innovative solutions directly into production lines.

Importantly, the **carbon capture and utilization/ storage (CCU/CCS)** pathway gains traction starting in 2024. Measure AEI25-P (“Implementation of CCS/CCUS technologies”) calls for deploying CO₂ capture at hard-to-abate industrial facilities, giving special priority to biogenic carbon, building a CO₂ transport network (open to all emitters), and creating market rules for e-methane or e-methanol derived from captured CO₂. Over 2025–2030, Lithuania will develop voluntary CO₂ certification and support mechanisms to incentivize synthetic fuel production, effectively linking industrial emitters to future storage sites (domestic or regional). Finally, a CO₂ monitoring system will be created, to assess the effectiveness of carbon capture, and differentiating the origin of the carbon dioxide.

By the **end of the decade (2030)**, a critical mass of “first-mover” projects—green hydrogen electrolyzers (e.g., for ammonia), CCU pilot units (e.g., converting CO₂ to methanol), and digitized energy-efficient plants—will inform a broader rollout. Financial incentives under P2-E (“Improving energy efficiency”) and P3-E (“Incentives for investment and innovation”) will be refined to reward deep-decarbonization investments (e.g., corporate tax relief on R&D and accelerated deductions for green CAPEX). As more companies adopt these technologies, industry clusters (chemical, cement, metal) will share infrastructure—electrolyzer capacity, CO₂ pipelines—to achieve economies of scale and lower per-tonne abatement costs.

⁸⁶ The Ministry of Environment of the Republic of Lithuania and the Lithuanian Environmental Protection Agency. *Policies & Measures and Projections of Greenhouse Gas Emissions in Lithuania. Report pursuant to Articles 18 and 39 of Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action and pursuant to Articles 36, 37 and 38 of Implementing regulation (EU) 2020/1208*. VILNIUS, 2023. https://aaa.lrv.lt/public/canonical/1743763154/3410/PaMs%20and%20Projections%202025_FINAL.pdf

4.5. Cost-benefit analysis of innovative technologies

The economic and operational impact of adopting innovative technologies varies significantly depending on the specific solution implemented. Each technology, whether hydrogen integration, waste reduction, electrification, or digital optimization, comes with its own cost structure, maturity level, and potential benefits across environmental, social, and financial dimensions.

Hydrogen cost-benefit analysis

A major challenge currently holding back the widespread adoption of green hydrogen solutions in industrial applications is its high production cost compared to other sources such as fossil fuels or even “grey hydrogen”. The cost of producing hydrogen depends highly on the technology which is used. In general terms, the hydrogen production cost from unabated natural gas, worldwide, is estimated to range between US\$0.8 and US\$5.7/kg of H₂. Although hydrogen produced from natural gas is, generally cheaper than hydrogen produced with electrolysis, both natural gas and electricity prices are very volatile⁸⁷. This cost disparity makes it difficult for green hydrogen to economically compete with established fuels and feedstocks in many industrial processes. In general terms, hydrogen production with electrolysis is much more expensive than using natural gas. However, significant reductions in the production costs of green hydrogen are anticipated in the coming years. These costs decreases are expected to be driven by technological advancements in electrolysis, economies of scale in electrolyser manufacturing, and the projected decline in the cost of renewable electricity, which is the primary energy input for green hydrogen production. Some projections suggest that the levelized cost of hydrogen (LCOH) from electrolysis could fall to US\$1-2/kg by 2035⁸⁸.

In the European Union, the levelized cost of hydrogen depends highly on the technology which is used to produce it. There are four main technologies which are considered to produce hydrogen:

- Steam Methane reforming (SMR): Hydrogen is produced using methane (CH₄), using a high-temperature steam (700°C- 1,000°C). Methane reacts with steam, at a 3-25 bar pressure. A catalyst is needed to produce hydrogen, carbon monoxide, and also some carbon dioxide is needed. The reaction is endothermic, so some heat needs to be supplied to the process to make the reaction happen.

In the “water-gas shift reaction”, carbon monoxide and water steam react to produce carbon dioxide and hydrogen. Finally, in the “pressure-swing adsorption”, carbon dioxide and other impurities are removed from the gas stream, leaving pure hydrogen.

Chemical reactions are as follows:

- Steam-methane reforming reaction:



- Water-gas shift reaction:



- SMR with carbon capture: It is the same process described above, but including carbon capture to reduce carbon dioxide emissions.

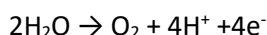
⁸⁷ Source: International Energy Agency. *Global Hydrogen Review 2024 – Hydrogen Production*. October 2024.

⁸⁸ Source: Global Efficiency Intelligence, TransitionAsia, Solutions for Our Climate (SFOC). *Green Steel Economics. Comparing Economics of Green H2- DRI and Traditional Steelmaking Around the World*. July 2024.

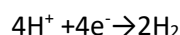
- Grid-connected electrolysis: Electrolysers can be used to produce carbon-free hydrogen, by splitting water into hydrogen and oxygen. Electricity is needed to produce the reaction of decomposition of water. It can be obtained from the power grid. However, this is not the ideal solution, since today, this electricity is not totally decarbonized, and besides, has a very high cost.

Electrolysis reaction in the cathode and the anode are as follows:

- Oxidation reaction in the anode:



- Reduction reaction in the cathode:



- Water electrolysis with a direct connection to a renewable energy source: The chemical process is similar to grid-connected electrolysis, but electricity is generated by a renewable energy power plant, which is directly connected to the electrolyser. This allows for obtaining lower electricity prices, and to make sure that emissions are not produced from electrolysis.

Based on these four technologies, the average levelized cost of hydrogen in the European Union in 2024 is as shown in the following table:

Levelized production cost of hydrogen in the European Union (€/kg H ₂)	Steam Methane Reforming (SMR)	SMR with carbon capture	Grid-connected electrolysis	Water electrolysis with a direct connection to a renewable energy source
CAPEX	0.26	0.43	2.76	3.85
CO ₂ costs	0.49	0.87		
Natural gas costs	2.49	2.69		
Wholesale electricity price			2.62	
Taxes			0.73	0.00
Grid fees			1.12	
Electricity costs				2.62
Other OPEX	0.09	0.13	0.19	0.23
Total	3.33	4.12	7.42	6.71

Table 6: Estimation of the levelized production cost of hydrogen in the European Union, in 2024 ⁸⁹

As can be seen from the table before, the lowest levelized production cost of hydrogen can be obtained with steam methane reforming. Besides, as many steam methane reforming plants are already operational, in some cases, it is not necessary to incur into additional CAPEX, so the LCOH can be as low as €3.1/kg H₂.

If a carbon capture facility is added to the steam methane reforming plant, the LCOH increases to €4.12/kg H₂.

⁸⁹ Source: European Hydrogen Observatory. Clean Hydrogen Partnership. *Hydrogen Landscape- Production, Trade and Cost- Cost of Hydrogen Production*. <https://observatory.clean-hydrogen.europa.eu/index.php/hydrogen-landscape/production-trade-and-cost/cost-hydrogen-production>

For hydrogen produced using electricity from the grid, costs in the European Union vary from €4.1/kg H₂ to €16.1/kg H₂, with an average of €7.4/kg of H₂. Variations in the LCOH depend on the wholesale electricity prices, taxes and grid fees in each country.

Finally, for hydrogen which is produced using a direct connection to a renewable energy plant, costs vary from €4.3/kg H₂ to €10.50/kg H₂, with an average of €6.7/kg H₂. The figure can vary depending on the total CAPEX, as well as the number of operational hours of the renewable energy plant, which are not the same depending on the technology and the location.

If the same assessment is carried out specifically for the case of Lithuania, in 2024, the following results are obtained:

Levelized production cost of hydrogen in the European Union (€/kg H ₂)	Steam Methane Reforming (SMR)	SMR with carbon capture	Grid-connected electrolysis	Water electrolysis with a direct connection to a renewable energy source
CAPEX	0.26	0.43	2.76	3.35
CO ₂ costs	0.49	0.87		
Natural gas costs	1.83	1.97		
Wholesale electricity price			2.05	
Taxes			0.02	
Grid fees			1.70	0
Electricity costs			2.05	2.75
Other OPEX	0.09	0.13	0.19	0.23
Total	2.68	3.40	6.72	6.32

Table 7: Estimation of the levelized production cost of hydrogen in Lithuania, in 2024 ⁸⁹

As can be seen, the levelized production cost of hydrogen in Lithuania is the lower than the average for the European Union for all the alternatives.

In Lithuania, taxes associated with the connection to the grid have been increased in 2024. For this reason, the difference between obtaining electricity from the grid or from a renewable energy plant is higher than in the European Union: €1.70/kg H₂, compared to €1.12/kg H₂ in the average European Union.

In any case, as can be seen, steam methane reforming is also the cheapest technology to produce hydrogen in Lithuania, as in the rest of the European Union.

A good view on the cost of producing hydrogen can be obtained from the Innovation Fund Auctions for the production of RFNBO (Renewable fuel of non-biological origin) hydrogen. These auctions have been designed by the European Hydrogen Bank to support innovative technologies to produce hydrogen, offering funding to projects. It can be useful to obtain a good understanding of the clearing price of hydrogen.

It should be noted that the bid prices obtained in the auction do not represent the total cost of producing hydrogen, but only the support which would be needed by producers. Hydrogen producers also have signed hydrogen sales contracts with clients. Therefore, the sale price for hydrogen agreed with offtakers, and the bid price, should be able to cover the investment cost and the operation and maintenance costs.

The first hydrogen auction was developed between November 2023 and February 2024, and grants were signed in October 7th 2024. Submitted bids for the projects which were selected ranged from €0.37 to €0.48/kg of RFNBO (renewable fuel of non-biological origin) hydrogen. However, most bids offered a price between €0.50 and €1.50/kg of RFNBO.

The following figure shows the results of the first Pilot Auction for Renewable Hydrogen:

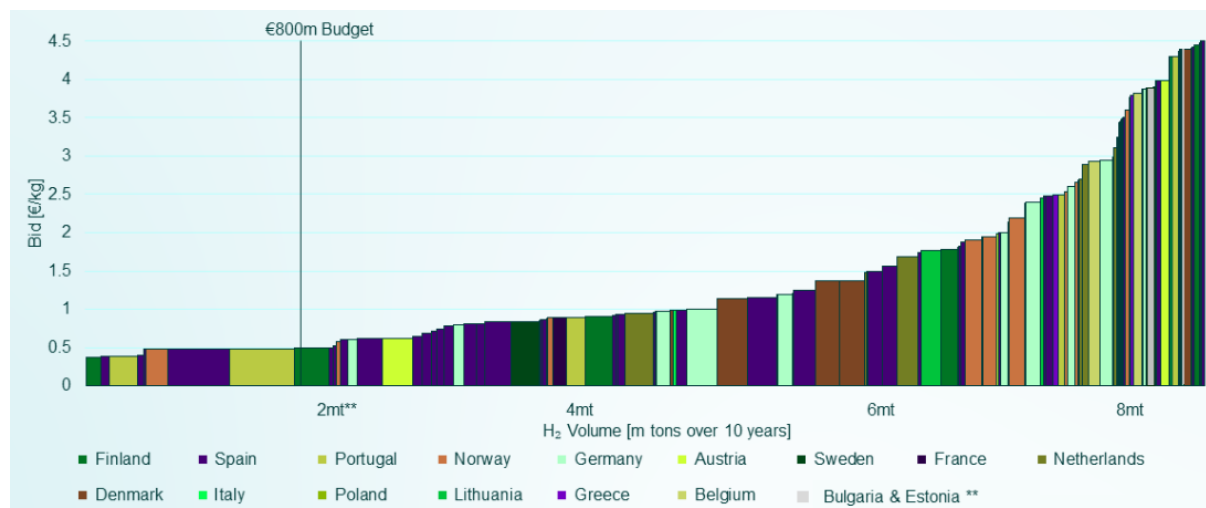


Figure 20: Results of the first hydrogen auction⁹⁰

A second hydrogen auction was called on December 3rd, 2024, and was closed on February 20th, 2025. In this case, twelve projects were selected, with a bid price ranging from €0.20 to €0,60 per kilogramme of renewable hydrogen produced. There were also three maritime projects which will receive support between €0.45 and €1.88 per kilogramme of hydrogen produced.

It is remarkable that, in this case, projects participating in the bid were larger, and asked for lower bids. Indeed, most projects presented bids below €1.00 per kilogramme of hydrogen produced.

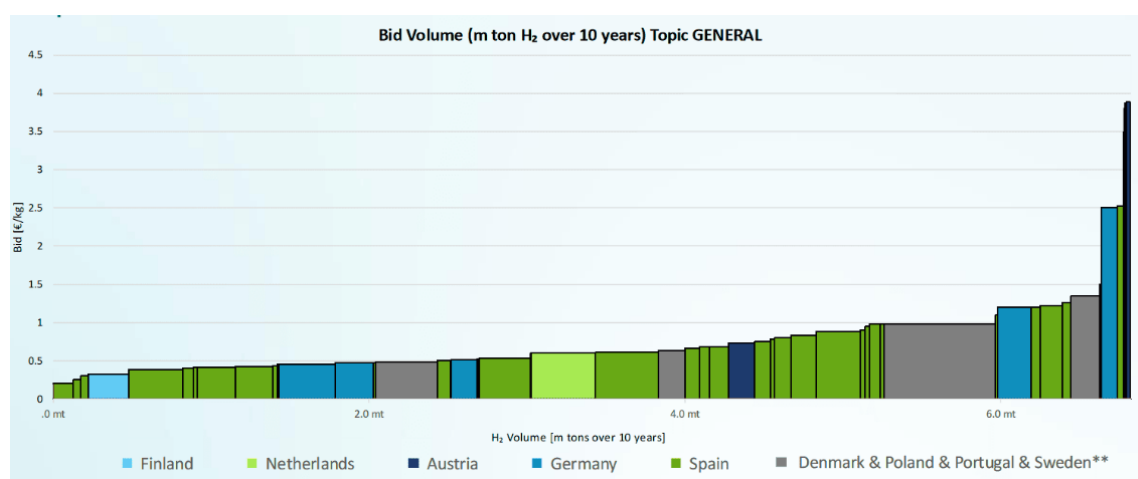


Figure 21: Results of the second hydrogen auction⁹¹

Beyond production costs, the widespread use of hydrogen requires significant investment in infrastructure for its production, storage, and transportation. This includes the development of large-

⁹⁰ Source: European Commission. *Results of the Pilot Auction for Renewable Hydrogen*.

⁹¹ Source: European Commission. *Results of the Pilot Auction for Renewable Hydrogen*.

scale electrolysis facilities, hydrogen storage solutions (both gaseous and liquid), and transportation networks such as pipelines and specialized ships. These infrastructure requirements represent a substantial financial undertaking. The cost of hydrogen transportation depends on the distance and mode. Pipeline transport is generally the most economical for large volumes over shorter distances, with costs for new pipelines being higher than repurposing existing natural gas pipelines. Below 500 km, prices for transporting can be below 0.1 dollars per kilogram. Trucking compressed gaseous hydrogen can cost between 0.1 and 2 dollars per kilogram, while liquid hydrogen can cost up to 15 dollars per kilogram.⁹² Despite these costs, the potential benefits of green hydrogen in terms of CO₂ emission reductions are numerous. For some industries like steel and certain chemical processes where direct electrification might face technical or economic limitations, green hydrogen offers emission reductions.

Hydrogen storage costs are influenced by the method and duration of said storage. Line packing in 36-to-48-inch pipelines over 100 km allows daily storage of 150–300 tonnes of hydrogen at a levelized cost below US\$0.05/kg, though pressure cycling may shorten pipeline lifespan. Salt cavern storage for 500 tonnes incurs a capital cost of around US\$18 million, with levelized costs ranging from US\$1.20/kg for long-term (120-day) use to US\$0.15/kg for shorter, 15-day cycles. Pressurized storage at refuelling stations, using 1,000 kg tanks, yields a levelized cost of US\$0.16/kg, plus US\$0.40/kg for compression. Liquid hydrogen storage in cryogenic tanks, despite higher capital costs, offers levelized costs of US\$0.055–US\$0.091/kg for one-week durations, with liquefaction adding approximately US\$1.20/kg. These numbers show the variability of costs and the need to find storage technology that can ensure a cost-effective deployment.⁹³

From an industrial standpoint, the primary economic benefit of hydrogen adoption is the avoidance of carbon-related costs. As regulatory frameworks tighten and carbon pricing mechanisms expand across the world, hydrogen offers a viable decarbonization pathway that can shield companies from escalating emission penalties, carbon taxes, or the cost of emission allowances under cap-and-trade schemes such as the one currently active in the European Union. In some sectors, especially those exposed to EU CBAM (Carbon Border Adjustment Mechanism) or similar policies, this cost avoidance can materially impact competitiveness. Additionally, for green hydrogen, there is an opportunity to price at a premium as customers who are conscious about sustainability reward low carbon products. While cost parity with conventional fuels remains a difficult challenge, technological advancements and these indirect economic benefits are slowly shifting the balance in favour of hydrogen, helping forward-looking industrial players.

Electrification cost-benefit analysis

The economic considerations of industrial electrification involve analysing both the initial capital investment and the ongoing operational expenses. The upfront costs for electric equipment, such as industrial-scale electric boilers, furnaces, and heat pumps, can vary significantly depending on the size and specific application.

While the installation of electric boilers might be simpler and potentially less expensive than gas boilers due to the absence of vent pipes and ventilation requirements, the ongoing costs for large industrial

⁹² Source: SOPHANNA, Sovechea. *An in-depth comparison between the different methods of hydrogen transportation*. Divi Gas. March 11th, 2024.

⁹³ Source: BURKE, Andrew; OGDEN, Joan, FULTON, Lewis (Institute of Transportation Studies, UC Davis); CERNIAUSKAS, Simone. *Hydrogen Storage and Transport. Technologies and Costs*. Institute of Transportation Studies, UC Davis. February 27th, 2024.

electric heating equipment can be substantial compared to traditional boilers given the price of electricity is currently higher than the price of gas. Nevertheless, electric boilers usually require less maintenance and therefore can extend their lifetime significantly.

Although the capital expenditure for industrial heat pumps is relatively high, their superior energy efficiency can lead to significantly lower operational costs over time, particularly in processes that allow for low-temperature heat integration. The coefficient of performance of modern industrial heat pumps often exceeds 3.0⁹⁴, meaning they can deliver three units of heat for every unit of electricity consumed, translating into lower energy bills when electricity prices are stable or declining. Additionally, heat pumps typically incur lower maintenance costs due to fewer moving parts and reduced wear compared to combustion-based systems.

Similarly, electric arc furnaces entail substantial upfront capital investment, particularly when designed for large-scale or continuous operation. However, their ability to operate flexibly and with high thermal efficiency can result in competitive operating costs – especially in regions with access to affordable or off-peak electricity rates. Electric arc furnaces allow for precise energy input control, reducing thermal losses and enabling cost-effective production.

Beyond the positive environmental impact gained from industrial electrification, economic benefits can also be gained. Electrified systems often enable greater process control, integration with digital energy management and responsiveness to market signals such as grid balancing incentives. This flexibility can create opportunities to reduce energy expenditure by aligning with cheaper renewable generation. On top of this, as carbon pricing mechanisms and emissions regulations become more stringent, electrified processes offer an advantage against future compliance costs.

Artificial intelligence and digitalisation costs-benefit analysis

The benefits of AI and digitalization can outweigh the initial costs of implementation in terms of operational efficiency. For example, AI-powered predictive maintenance can reduce unplanned downtime by identifying equipment failures before they occur, allowing for more proactive maintenance schedules. This results in both reduced maintenance costs and less production downtime, an example of implementation is the jet production of General Electric which saw a reduction of 10% in maintenance costs.⁹⁵

Beyond predictive maintenance, AI and digital tools are being used to optimize production processes and energy consumption in industrial energy systems to forecast energy loads, shift noncritical operations and optimize the use of renewable and battery storage systems. The result is a lower energy bill and assisting companies to meet sustainability goals for renewable energy use. A successful study case is Toyota's AI-driven energy management which achieved a 20% energy cost reduction and 15% lower CO₂ emissions⁹⁶.

⁹⁴ Source: STRASSER, Juliette. *Understanding Coefficient of Performance: From industry standard to cutting-edge technology*. Skyven technologies. December 15th, 2023.

⁹⁵ Source: Pingax - Enhancing Operational Efficiency with Predictive Maintenance: A Comprehensive Case Study

⁹⁶ Source: FILIPSSON, Friedrik. Redress compliance - *AI Case Study: Toyota – AI for Energy Management*. March 6th, 2025.

Greenhouse gas emissions reduction cost benefit analysis

The reduction of industrial emissions offers a mix of cost savings and compliance benefits. The primary cost of emission reduction stems from cleaner technologies and emission monitoring systems.

One of the most immediate benefits of emission reductions through waste reduction is the avoidance of carbon taxes and penalties. Under mechanisms like the EU Emissions Trading System (EU ETS), companies must either reduce emissions or purchase carbon allowances. With carbon prices reaching as high as €90 per tonne.

Beyond carbon pricing, improving energy efficiency through emissions-reducing measures typically results in lower energy costs. Optimizing existing combustion systems or switching to renewables does not only cut emission but also reduces energy consumption, over time these improvements can lead to significant savings.

Additionally, emission reduction contributes to enhance market positioning. Many investors and consumers prioritize companies with sustainability credentials, thus attracting investment from ESG-focused investors can lower capital cost and permit access green financing opportunities.

Renewable technologies for electricity generation cost benefit analysis

The cost benefit analysis for renewable electricity focuses on the initial cost and long-term savings potential of different renewable technologies commonly utilized for electricity generation.

Solar PV systems are among the most widely deployed renewable technologies, with significant growth driven by declining costs and technological advancements as LCOE for utility scale PV projects is projected to decline to US\$25/MWh in 2026⁹⁷. The initial capital investment for solar PV is high, due to the cost of panels, inverters, installation, and grid connections. However, the operational and maintenance costs are relatively low, requiring minimal maintenance apart from periodic cleaning of the panels. Solar PV offers substantial energy production, especially in sunny regions. It is also highly scalable and can be deployed in both utility-scale projects and residential applications. The environmental benefits are significant, as PV systems generate electricity without direct emissions.

According to IRENA⁹⁸, at the end of 2024, the global weighted levelized cost of electricity (LCOE) for utility-scale solar PV plants was around US\$43/MWh, with a reduction of 90% between 2010 and 2024. The total installed costs was around US\$691/MW.

Considering only European countries, utility-scale solar PV installed costs ranged from US\$524 to US\$1,312/MW, with an average of US\$779/MW. As for operation and maintenance costs, the median value for Europe is US\$7.9/kW.year.

Concentrated solar power has higher capital costs compared to solar PV, ranging between US\$3,000 and US\$11,000 per kW⁹⁹. According to IRENA, investment cost is around US\$3,677 per kW in 2024. This

⁹⁷ Source: Power engineering. Factor This. Clarion Events, Inc. *EIA: Levelized cost of onshore wind, solar PV dropping below gas-fired and conventional generation by 2026*. February 23rd, 2021.

⁹⁸ Source: IRENA (2025). *Renewable power generation costs in 2024*. International Renewable Energy Agency, Abu Dhabi.

⁹⁹ Source: KHAN, Muhammad Imran; GUTIÉRREZ-ÁLVAREZ, R.; ASFAND, Faisal; BICER, Yusuf; SGOURIDIS, Sgouris; AL-GHAMDI, Sami G.; JOUHARA, Hussam; ASIF, M.; KURNIAWAN, Tonni Agustiono; ABID, Muhammad; PESYRIDIS, Apostolos; FAROOQ, Muhammad. *The economics of concentrating solar power (CSP): Assessing cost*

cost was lower than in 2023, when it was US\$6,746/kW, and that of 2022, which was US\$4,537/kW. However, costs vary greatly depending on the project. Besides, as there is only a limited number of new installed plants every year, these figures are not very representative.

Operational and maintenance costs are moderate, with the need for periodic cleaning and maintenance of the mirrors and other equipment. This technology can also require significant amounts of water for cooling in certain configurations, adding to the operational costs. The main benefit of CSP is its flexibility to provide dispatchable power by storing energy in thermal form, enabling power generation even when the sun isn't shining. Operation and maintenance costs for concentrated solar power range from US\$0.02/kWh to US\$0.04/kWh, what is high compared to solar PV and onshore wind farms.

Onshore wind power offers relatively low costs and high scalability as one of the most successful renewable technologies. The capital investment for onshore wind farms is projected to be approximately 31US\$/MWh by 2026. While the initial investment is considerable, the operational and maintenance costs are low. Wind turbines require periodic maintenance and occasional repairs, but their operational lifespan is typically between 25 and 30 years.

According to IRENA, the total investment cost for an onshore wind plant in 2024 was around US\$1,041/kW, globally, with a reduction of 55% compared to 2010. However, in Europe, the cost is higher, with US\$1,659/kW. The country with the minimum costs was China, with US\$856/kW. This is related to the cost of the main piece of equipment of the wind plant, the wind turbine. Chinese manufacturers currently offer the lowest prices, compared to European manufacturers.

As for operation and maintenance costs for onshore wind energy, they ranged from US\$20/kW.year in Brazil to US\$93/kW in Japan. European countries show values between US\$20/kW.year and US\$50/kW.year.

Offshore wind offers the potential for higher energy yields, but require from higher initial capital costs due to the complexity of offshore infrastructure, marine logistics and grid connections.

The investment cost in an offshore wind plant depends highly on the depth of the seabed and the distance from the offshore wind farm to the coast. In 2024, the average total installed costs were around US\$2,852/kW. Costs in Europe are slightly higher, with an average of US\$3,389/kW. Regarding operation and maintenance costs, in 2024, they ranged between US\$76/kW.year and US\$121/kW.year.

Hydropower is a well-established renewable technology with substantial upfront costs for dam construction and infrastructure, particularly in large-scale projects. However, once operational, hydropower plants have low operating costs and provide a stable, reliable power supply. Hydropower systems have lifespans often over 50 years and relatively low maintenance costs, resulting in a favourable cost structure in the long run.

For hydropower, the average global investment cost in 2024 was US\$2,267/kW. In general terms, investment costs are rising, from the approximately US\$1,500/kW that was common until 2014. However, the total investment cost depends on the size of the dam and the reservoir, and the previous works carried out. For example, if there is already an existing dam built, and the project only involves adding hydropower capacity to the dam, the cost can be as low as US\$ 450/kW.

Operation and maintenance costs are expressed in percentage of the investment cost. According to IRENA, the average operation and maintenance cost for a hydropower plant is between 1% and 4% of the total installed costs.

Biomass energy has capital investments that vary depending on the technology used, but it generally requires infrastructure for fuel sourcing and processing. Ongoing operational costs can be significant, especially due to the need for a consistent fuel supply and transportation. The benefits of biomass are primarily in its ability to produce electricity, heat or biofuels. Biomass also reduces waste by utilizing organic material that would otherwise decompose and release methane.

According to IRENA, total investment costs for bioenergy projects vary depending on the type of project, the feedstock and the technology. The availability of low-cost, predictable and sustainably sourced feedstocks is key to keep operation and maintenance costs low. At a worldwide level, the average total investment costs are around US\$3,242/kW, although a range between US\$2,000 and US\$3,000 can be offered.

The European Union has higher investment costs, with an average around US\$4,000/kW for all technologies (higher for renewable municipal waste and wood waste, and lower for landfill gas and other vegetal and agricultural waste).

As for operation and maintenance costs, fixed O&M costs, which include labour, insurance, scheduled maintenance, replacement of plant components, feedstock handling equipment, and other expenses, can make between 2% and 6% of the total installed costs per year.

Variable O&M costs depend on the bioenergy costs, and is around US\$0.004/kWh.

Marine energy is still in the early stages of development compared to other renewable technologies, which translates into high capital investments due to the complexity of installing underwater turbines or wave energy converters. Operational and maintenance costs are also high due to the marine environment which presents unique challenges. However, marine energy offers significant benefits in terms of energy predictability and reliability as tidal movements are consistent and predictable.

It is not possible to offer realistic investment cost or operation and maintenance costs for marine energy projects, as these technologies are still not commercially viable. There is a broad range of designs and prototypes, and besides the installed capacity worldwide of this technology has not grown in the last 10 years. IRENA¹⁰⁰ considered an LCOE for tidal energy between US\$0.20/kWh and US\$0.45/kWh, and for wave energy, an LCOE even higher, between US\$0.30/kWh and US\$0.55/kWh. In 2022, OceanSET considered an average LCOE of €0.2/kWh for tidal energy, and €0.27/kWh for wave energy¹⁰¹.

Total investment costs for wave energy are around €6,400/kW for wave energy, and €3,400/kW for tidal energy. On the other hand, operation and maintenance costs for wave energy are around €500/kW.year for wave energy, and €500/kW.year for tidal energy.

¹⁰⁰ Source: IRENA (2021). *Offshore renewables: An action agenda for deployment*, International Renewable Energy Agency. Abu Dhabi. ISBN 978-92-9260-349-6

¹⁰¹ Source: European Commission. Joint Research Centre. TAPOGLOU, E., MC GOVERN, L., GEORGAKAKI, A., MOUNTRAKI, A., LETOUT, S., INCE, E., GEA BERMUDEZ, J., SCHMITZ, A. AND GRABOWSKA, M, *Clean Energy Technology Observatory: Ocean Energy in the European Union - 2024 Status Report on Technology Development, Trends, Value Chains and Markets.*, Publications Office of the European Union, Luxembourg, 2024, <https://data.europa.eu/doi/10.2760/1244922, JRC139325>

Renewable technologies for heat cost benefit analysis

The main point of the cost benefit analysis for renewable technologies for heat generation focuses on the initial investment required and the potential for long-term savings in heating systems.

Solar thermal systems have high initial capital costs for the installation of solar collectors, storage tanks and related infrastructure. However, their operational and maintenance costs are low, and they can provide significant energy savings over time. The efficiency of solar thermal systems depends largely on geographic location and sunlight availability, but they are particularly beneficial in sunny regions.

The total investment cost for a solar thermal system is around €1,000/kW, being higher for evacuated tube collectors than for flat plate collectors, for systems with a size of 10 kW. This cost can be reduced to around €800/kW for systems with 100 kW. Operation and maintenance costs can be estimated around €20/kW.year and €30/kW.year¹⁰². Geothermal heating systems are another cost-effective option, offering a reliable and consistent source of heat by tapping into the Earth's natural heat through underground pipes. While the initial capital investment for geothermal systems can be substantial for the drilling and installation of ground loops, operational and maintenance costs are low. Geothermal systems have a long lifespan exceeding 25 years, providing stable heating during the whole year, making them a great choice for regions with cold climates.

The total investment cost of geothermal heating systems ranges between €2,000/kW and €4,000/MW, although they depend highly on the system size and the depth which has to be reached with the wells.

Biomass heating technologies offers a cost-effective alternative to conventional heating systems. The capital investment for biomass heating systems can vary depending on the scale and type of technology used. However, the point of focus is the ongoing operational costs for biomass systems related to the cost of fuel and maintenance for each material, such as wood, dedicated energy crops or agricultural residues. Transport cost for the fuel is normally key, as this technology only make sense when the biomass used is waste. Residue-based biomass systems offer environmental benefits for the waste management of organic residue that would otherwise release methane when decomposing.

Bioplastics cost benefit analysis

The cost benefit analysis of bioplastics focuses on production costs compared to the long-term environmental benefits and the potential for waste reduction.

The initial capital investment for bioplastic production is generally higher than that of petroleum-based plastics due to cost associated to raw material sourcing, production processes and R&D. However, bioplastics can offer long-term cost savings as they typically have a lower carbon footprint and reduced environmental impact compared to conventional plastics. Over time, the demand for bioplastics is expected to rise as consumers and businesses increasingly prioritize sustainability, driving down production costs through economies of scale.

The operational costs of bioplastics are tied to the costs of feedstocks which fluctuate based on agricultural conditions and market demand. However, advances in production processes and the development more cost-effective raw materials could help reduce these costs. Bioplastic processes can offer advantages in energy efficiency in some processes compared to traditional plastic production methods.

¹⁰² Source: Estimates from Deloitte.

5. Carbon capture from technological processes

5.1. Possibilities for the use of carbon capture in industry

Overview of carbon capture in industrial decarbonization

Carbon capture is based on a range of techniques that utilize physical and chemical separation processes to extract CO₂ from industrial streams. In practical applications, a number of large-scale facilities have adopted carbon capture technologies as pilot projects to develop these technologies for broader industrial adoption as a way of achieving rapid reductions in CO₂ emissions.

Many projects integrate carbon capture with enhanced oil recovery, where CO₂ is injected into oil fields to improve the extraction process, to offset the costs of implementing carbon capture into industrial processes. The integration process often creates opportunities not only for emissions reduction but also for innovation in resource recovery. Captured carbon that would be released into the atmosphere can serve as a raw material in chemical processes, establishing a synergistic relationship between different industrial processes and supporting the sustainable transformation of entire industrial ecosystems. However, according to the Delegated Act on renewable fuels of non-biological origin (RFNBOs)¹⁰³, captured carbon dioxide from industrial sources can only be used to produce synthetic fuels until 2041.

Despite the benefits of carbon capture, the required capital investments required to retrofit carbon capture into existing plants limits the adoption of the technology. Integrating carbon capture technology into existing industrial systems involves complex design challenges as these processes demand the adaptation of the carbon capture to maintain operational efficiency, increasing the complexity and scalability of these solutions.

Current status of carbon capture in industrial decarbonization

A key trend in current industrial decarbonization efforts is the scaling up of carbon capture projects under supportive policy frameworks that include carbon pricing, tax credits and regulatory incentives. Governments and private investors actively support pilot projects that test the feasibility of innovative capture methods and integrated systems. These initiatives reduce the capital and operational costs associated with the capture process, such as those related to solvent regeneration, compression and storage infrastructure. In regions where policy incentives are robust, companies are more readily exploring expansive projects that promise long-term emissions reductions and a smoother transition toward net-zero targets¹⁰⁴.

Efforts for carbon capture integration have focussed on energy and emission intensive industries in the industrial sector:

- High purity CO₂ sources: Some industrial processes produce CO₂ in high-purity streams, which makes capture more efficient and cost-effective. Examples include hydrogen production through steam methane reforming, ammonia production, and fermentation processes in

¹⁰³ Source: European Commission. Commission Delegated Regulation (EU) 2023/1184 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin.

¹⁰⁴ Source: US Government Accountability Office. *Technology Assessment: Decarbonization. Status, Challenges, and Policy Options for Carbon Capture, Utilization, and Storage*. GAO-22-105274. September 29th, 2022.

bioethanol facilities. Capturing CO₂ from these sources is often less energy-intensive, enabling easier compression and storage.

- Biomass conversion: Biomass-based processes such as biofuel production and waste-to-energy facilities, offer a pathway for negative emissions through bioenergy with carbon storage. By capturing CO₂ from biomass combustion or fermentation, industries can offset emissions and even remove CO₂ from the atmosphere, supporting net-zero and carbon-negative goals.
- Cement: Cement production is responsible for substantial CO₂ emissions, primarily due to the calcination of limestone (60% of emissions), and secondly from kiln heat generation (40%)

Emissions in the calcination process cannot be reduced unless the production is also reduced, as they are produced in the process, as a result of the decomposition of limestone into clinker and CO₂.

Carbon capture in cement plants involves innovative techniques such as oxyfuel combustion, post-combustion capture using solvents and emerging direct mineralization approaches that convert CO₂ into stable carbonates.

Chemical loop-based technology is an alternative to the use of solvents, with an efficiency of 85%, with is twice the efficiency of the use of solvents¹⁰⁵.

- Iron and steel: Steel manufacturing is an energy-intensive process that generates CO₂ both from fossil fuel combustion and chemical reactions in blast furnaces. There are two main technologies used to produce iron and steel: the integrated steel mill and the mini steel mill. In the integrated steel mill, steel is produced by reducing iron ore in the blast furnace, and then the final product is produced in a basic oxygen furnace. These mills can produce a variety of steel products, such as steel plates, coils, channels and reinforcement bars.

On the other hand, mini steel mills can produce secondary steel using recycled scrap steel, pig iron, and sponge iron, but not the iron ore. For this reason, these mills are smaller, and they have lower greenhouse gas emissions. The main piece of equipment in mini mills is the electric arc furnace (EAF), which is used to melt scrap and transform it into steel.

In both cases, carbon dioxide emissions are produced. There are three main options to reduce these emissions: improve the energy efficiency of furnaces and other processes, use of carbon capture, and circular economy with increased steel recycling.

Carbon capture solutions include gas separation from blast furnace flue gases, direct reduction techniques using hydrogen, and circular approaches where captured CO₂ is converted into valuable chemical feedstocks. Several pilot projects are exploring these methods to facilitate decarbonization in steel production.

Blast furnaces are the largest source of emissions in integrated steel mills, with around 65% emissions¹⁰⁵. An option to reduce these emissions is Top Gas Recycling Blast Furnace (TGR-BF), a technology which uses carbon capture and disposal. In this technique, a solvent system based on methyl diethanolamide (MDEA) and piperazine (Pz) is used to extract CO₂ from the mixture of other gases.

¹⁰⁵ Source: LEESON, D.; MAC DOWELL, N.; SHAH, N.; PETIT, C.; FENNELL, P.S. *A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources*. Int. J. Greenh. Gas Control, 61 (2017), pp. 71-84, 10.1016/j.ijggc.2017.03.020

Another option is the use of post-combustion capture with the use of ethanolamide (MEA), and the "Calcium-looping lime production" (CaL-LP). This technology avoids the use of conventional limestone calcination, uses heat recovery, and direct CO₂ capture. It reaches an overall CO₂ reduction efficiency of 53.31%¹⁰⁶.

Although the use of carbon capture technologies in steel production can reduce greenhouse gas emissions, it can lead to an increase in other environmental damages, such as the acidification, eutrophication, ozone depletion, aquatic depletion and human toxicity¹⁰⁷.

- Chemicals: These sectors are relevant in terms of greenhouse gas emissions, so the use of post-combustion carbon capture and storage is very relevant, especially in steam crackers and steam reformers. It is estimated that the process can produce a pure CO₂ gas, with a carbon capture efficiency of 85%¹⁰⁸.
- Refineries and petrochemicals: Oil refineries are complex industrial hubs where CO₂ emissions originate from multiple units, including hydrogen production, fluid catalytic crackers, and steam generation systems. Capture technologies are tailored to different refinery streams, with post-combustion absorption, membrane separation, and cryogenic capture being deployed to address emissions hotspots. However, as there is a high variety of processes and configurations, it is not easy to evaluate options to use carbon capture in this sector. Besides, as commented before, carbon emissions are produced in many units and sources, what makes very expensive and difficult to apply carbon capture technologies¹⁰⁵. The most feasible technology would be post-combustion using amines, with an efficiency factor of 65%.
- Thermal power plants: Carbon capture technologies can be applied to existing natural gas and coal power plants to reduce their emissions, or can be used with bioenergy power plants to capture their biogenic emissions.

For example, the chemical loop-based carbon capture technology can be used in coal-fired thermal power plants, reducing efficiency only by 5%-8%, compared to the efficiency reduction of amine-based post combustion (between 9.5% and 12.5%), or oxy-fuel combustion technologies (between 8% and 12%)¹⁰⁹.

The use of oxyfuel combustion can be also used in thermal power plants¹¹⁰. In this case, the fuel is burnt with large amounts of oxygen, using oxygen obtained in an air separation unit

¹⁰⁶ Source: TIAN, S.; JUANG, J.; ZHANG, Z; MANOVIC, V. *Inherent potential of steelmaking to contribute to decarbonisation targets via industrial carbon capture and storage*. Nat. Commun. 9 (2018), pp. 1-8. 10.1038/s41467-018-06886-8.

¹⁰⁷ Source: CHISALITA, D. A.; PETRESCU, L.; COBDEN, P.; VAN DIJK, H. A. J.; CORMOS, A. M.; CORMOS, C. C. *Assessing the environmental impact of an integrated steel mill with post-combustion CO₂ capture and storage using the LCA methodology*. J. Clean. Prod., 211 (2019), pp. 1015-1025. <https://doi.org/10.1016/j.jclepro.2018.11.256>

¹⁰⁸ Source: GRIFFIN, P. W.; HAMMOND, G. P.; NORMAN, J. B. *Industrial energy use and carbon emissions reduction in the chemicals sector: a UK perspective*. Appl. Energy, 227 (2018), pp. 587-602. <https://doi.org/10.1016/j.apenergy.2017.08.010>

¹⁰⁹ Source: HANAK, D. P.; ERANS, M.; NABAVI, S. A.; JEREMIAS, M.; ROMEO, L. M.; MANOVIC, V. *Technical and economic feasibility evaluation of calcium looping with no CO₂ recirculation*. Chem. Eng. J., 335 (2018), pp. 763-773, 10.1016/j.cej.2017.11.022

¹¹⁰ Source: CABRAL, R. P.; MAC DOWELL, N. *A novel methodological approach for achieving £/MWh cost reduction of CO₂ capture and storage (CCS) processes*. Appl. Energy, 205 (2017), pp. 529-539, 10.1016/j.apenergy.2017.08.003

(ASU), improving combustion efficiency. This can be used both in coal and natural gas combined cycle power plants.

- **Pulp and paper:** In this industrial sector, there are two processes which are responsible for most of the greenhouse gas emissions: the mechanical process and the Kraft process, which transforms wood into wood pulp.

Specifically, in the Kraft process, the large source of greenhouse gas emissions is the recovery boiler. In this device, the lye or black liquor is burnt, and biogenic CO₂ is released. Gasification of the lye can improve the efficiency of the mills, and help to introduce carbon capture technologies in these plants. Carbon capture is usually based on post-combustion using amine¹⁰⁵.

5.2. Carbon capture technologies based on source and use

5.2.1. Capture from the atmosphere

There are a few carbon capture approaches for reducing CO₂ emissions by capturing carbon dioxide directly from the atmosphere from industrial processes, preventing its release into the atmosphere, and transporting it to geological formations for storage. This strategy is particularly important in sectors where emissions are hard to abate. Several approaches have been developed to achieve this:

- **Enhanced weathering¹¹¹:** A geoengineering technique that accelerates the natural process of rock weathering to absorb atmospheric CO₂. This approach involves spreading finely ground silicate or carbonate minerals over land or ocean surfaces, enhancing their reactivity with CO₂ to form stable carbonate compounds, which sequester carbon over long timescales.
- **Ocean carbon removal¹¹²:** This approach focuses on stimulating the growth of marine organisms and algae that naturally absorb CO₂ and effectively sequester carbon when they die and are deposited in the ocean floor. Some methods used are seaweed farming, artificial upwelling or iron fertilization. All these approaches are still in a very early phase and their scalability is still in question.
- **Direct Air Capture¹¹³ (DAC):** Direct Air Capture is a technology designed to remove carbon dioxide directly from the atmosphere by using large fans to pass ambient air through chemical sorbents or solid materials that selectively absorb CO₂. Once captured, the CO₂ is either permanently stored in geological formations or utilized in industrial processes such as synthetic fuel production or beverage carbonation. DAC offers a scalable solution for offsetting emissions from dispersed sources and achieving net-negative emissions when combined with permanent storage.

¹¹¹ Source: JAGOUTZ, Oliver; KROL, Aaron. *Enhanced Rock Weathering*. MIT Climate Portal. November 9th, 2023.

¹¹² Source: World Resources Institute – Ocean-based Carbon Removal.

¹¹³ Source: U.S. Department of Energy. *DOE Explains... Direct Air Capture*.

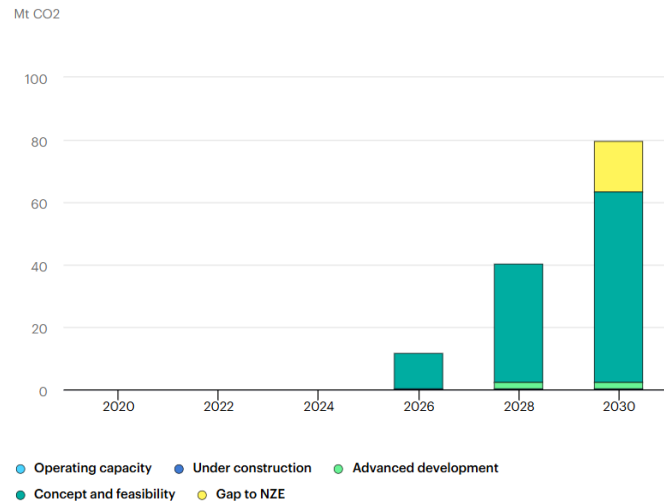


Figure 22: Planned projects for CO₂ capture by direct air capture¹¹⁴

5.2.2. Carbon capture for utilization

Carbon capture and utilization involves capturing CO₂ emissions and repurposing them into valuable products, offering an alternative to underground storage. CCU technologies are gaining traction across various industries, supporting circular carbon economies and reducing reliance on fossil-based raw materials. Key applications of CCU include:

- **Synthetic Fuels Production:** Conversion of captured CO₂ into synthetic fuels, such as methanol or aviation fuels, through chemical processes like hydrogenation or Fischer-Tropsch synthesis.

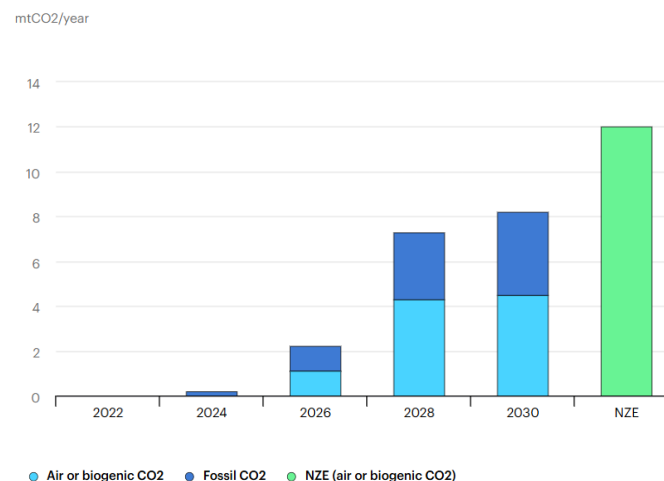


Figure 23: Planned commercial CO₂ use in synthetic fuel production by CO₂¹¹⁵

- **Chemical Production:** Utilization of CO₂ as a feedstock for producing chemicals such as urea, polymers, or carbonates.

¹¹⁴ Source: International Energy Agency. *Direct Air Capture*.

¹¹⁵ Source: International Energy Agency. *CO₂ Capture and Utilization*.

- **Construction Materials Manufacturing:** Incorporation of captured CO₂ into concrete production, where the gas reacts with minerals to form carbonates, enhancing the material's strength and durability while sequestering carbon.

5.3. Carbon capture technologies based on the technological processes

In Chapter 2, various innovative technologies for reducing CO₂ emissions were presented, including a brief mention of carbon capture technologies. This section provides a more in-depth analysis of carbon capture technologies and their potential application in the industrial sector, highlighting their role in mitigating emissions and supporting decarbonization efforts.

- **Post-combustion capture**

Post combustion carbon involves extracting the CO₂ from flue gases produced by the combustion of fossil fuels before these can be released into the atmosphere through various methods:

- **Absorption:** this method is the most commonly used for post combustion CO₂ capture, where the CO₂ present in flue gases is absorbed using liquid solvents like amines. The solvent can later be heated to release the captive CO₂ and be reused.
- **Adsorption:** this process uses solid materials such as activated carbon to adsorb CO₂ from flue gases
- **Membrane separation:** CO₂ can selectively be separated from other gases based on differences in permeability using selective membranes
- **Calcium looping:** this emerging technology uses calcium oxide (CaO) to absorb CO₂ to form calcium carbonate (CaCO₃), the calcium carbonate can then be heated to release CO₂ and regenerate carbon oxide.
- **Cryogenic Carbon Capture (CCC):** This is also a relatively new technology that uses cryogenic cooling to capture and remove CO₂ from gas streams.

- **Pre-combustion capture**

Pre-combustion capture aims to remove CO₂ from fossil fuels before combustion occurs, and it is typically applied in integrated gasification combined cycle power plants and hydrogen production facilities. The process involves three main steps: first, the gasification process where fossil fuels react with oxygen and steam at high temperatures to convert them into syngas, a mixture of hydrogen, carbon monoxide and CO₂; second, the gas mixture experiences a water-gas shift reaction where the carbon monoxide in the syngas is made to react with steam to produce additional CO₂, increasing the CO₂ concentration to facilitate its removal; and third, the CO₂-rich gas mixture is treated using absorption methods to separate the CO₂ from hydrogen, allowing both gases to be used as inputs for other processes.

- **Oxyfuel combustion**

Oxyfuel combustion attempts to burn the fossil fuels in oxygen instead of air. This helps the capture of CO₂ because the resulting flue gas consists mainly of CO₂ and water vapour. The water can then be condensed through cooling, resulting in almost pure CO₂ which can be transported and stored. This

method is very effective in capturing CO₂ as most of it will be captured, nevertheless, the initial oxygen burning is very energy intensive.¹¹⁶

5.4. Social, economic, and environmental impact from the implementation of carbon capture technologies

The introduction of carbon capture technologies across key Lithuanian industries is a critical turning point in the country's decarbonisation pathway. As industrial facilities in regions including Kaunas, Klaipėda, Šiauliai, and Panevėžys adopt capture units to isolate CO₂ from emissions streams, a range of social, economic and environmental dynamics is set into motion. These developments, while technologically driven, are equally transformative on a human and community level, reshaping labour markets, public attitudes, and regional development.

Social

In the short term, carbon capture implementation will necessitate a shift in technical capabilities within industrial workforces. The design, installation, and operation of capture systems require specialized skills in chemical engineering, automation, and environmental monitoring. This transition will drive demand for both vocational retraining and academic upskilling, particularly in sectors where carbon-intensive processes are currently dominant. Workers previously focused on conventional combustion, boiler maintenance, or emissions compliance will need to adapt to new roles involving gas separation technologies, sensor calibration, and data analytics. While some roles may be phased out, new employment opportunities will emerge around system maintenance, diagnostics, and integration with plant control systems, providing a net gain in high-skilled job profiles over time.

From a societal perspective, public perception of carbon capture tends to be influenced by familiarity and visibility. Unlike more intuitive green technologies such as solar panels or wind turbines, carbon capture operates largely out of sight which can make its benefits less immediately tangible to local communities. Early-stage adoption may therefore face scepticism, particularly if residents are unaware of the health and environmental advantages. Awareness campaigns highlighting reduced emissions of not only CO₂ but also co-pollutants can help bridge this gap. For example, installing carbon capture at cement kilns or combustion plants can lower the overall emissions profile of the site, improving air quality in surrounding areas and reducing respiratory health burdens, especially in dense industrial zones like Kaunas or Klaipėda.

In the medium to long term, carbon capture can serve as a strategic enabler of sustainable industrial continuity. By decoupling economic output from emissions, these technologies allow industries to maintain production while aligning with national and EU-level climate goals. This continuity is especially valuable for regional economies that would otherwise face plant closures or downsizing due to regulatory constraints. In towns such as Akmenė or Telšiai the modernization of emissions management systems can preserve employment bases and bolster economic resilience.

Moreover, carbon capture can stimulate innovation ecosystems by catalysing demand for ancillary services such as sensor manufacturing, control software development, and environmental analytics. Lithuanian universities and research institutions may respond by expanding curricula in climate engineering, process control, and clean manufacturing, fostering deeper industry-academia collaboration. Over time, this creates a positive feedback loop: a more skilled workforce attracts investment, and greater investment incentivizes continued educational adaptation. This alignment

¹¹⁶ Source: British Geological Survey. *Understanding Carbon Capture and Storage*.

reinforces long-term social cohesion by embedding climate action within the national development narrative.

Ultimately, while the social implications of carbon capture depend on local context and implementation strategy, its integration into Lithuanian industry presents a strong opportunity for positive transformation. If supported through inclusive labour policies, transparent community engagement, and forward-looking educational frameworks, the adoption of capture technologies can not only reduce emissions but also revitalize regional economies, enhance public health, and secure Lithuania's position in the future green industrial landscape.

Economic

Deploying carbon capture at heavy industry sites requires substantial upfront capital. Retrofit projects in the cement and chemical sectors can cost on the order of tens of euros per ton of CO₂ capacity. In chapter 3.5., the cost of carbon capture is discussed in detail for a variety of technologies and processes, but in general terms, it can be quantified ranging between US\$30 and US\$150/tonne of CO₂. Installing capture units and associated equipment will demand major plant modifications and large investments. For large corporations to be able to comply with these needs often requires co-financing by government sources. Despite the cost, this CAPEX buys the only scalable means to cut emissions in carbon-intensive processes, which long term will help keep the operation as it will comply with regulation.

Capturing carbon dioxide also increases ongoing production costs. Capture systems consume substantial energy and require maintenance, raising the operating costs of cement kilns, fertilizer plants, etc. For example, adding capture to a natural gas-based ammonia process is estimated to increase the cost of production by roughly 20-40%¹¹⁷. In practice this means higher fuel and power bills for operating the capture unit and separating CO₂. Industries must account for these extra costs in pricing and budgeting, which can temporarily reduce profit margins or require efficiency improvements elsewhere. In general, however, these operational expenses are competitive compared to other decarbonization routes.

Given the high initial costs, public and private funding support is critical. EU instruments like the innovation fund and the recovery and resilience facility offer grants and loans for large-scale CCUS demonstration projects. Lithuania and its industries can tap these to subsidize early deployment. For instance, policy analyses recommend expanding innovation funding specifically for pilot CCUS projects to share costs and build expertise.

In the medium term, carbon capture can improve the competitiveness of Lithuanian industries under tightening climate policies. By internalizing emission reductions now, firms hedge against future capture emission costs. For example, cement producers that install capture units face moderate costs increases (around 10%), whereas competitors relying on alternatives with most likely incur larger costs (35-70%). Market position for companies that adopt carbon capture may also improve as customers tend to prize low-carbon products; low carbon branding will be available for facilities with capture technologies. Moreover, the upcoming EU Carbon Border Adjustment (CBAM) will impose fees on imported carbon-intensive goods, allowing retrofitted facilities to pay less CBAM charges and compete with those paying larger sums. In Lithuania's context, adopting capture technology aligns with the National Climate Change Management Agenda which prepares firms for stricter EU climate rules.

¹¹⁷ Source: International Energy Agency. BAYLIN-STERN, Adam; BERGHOUT, Niels. *Is carbon capture too expensive?* February 17th, 2021.

In the long run, carbon capture fosters modernization of industry. Integrating CCUS requires upgrading processes, installing high-tech equipment, digital monitoring, etc. Over time, this shifts industrial structures toward more efficient, technologically advanced production. Carbon capture investment can serve as a catalyst for broader industrial renewal in line with technological trends.

Environmental

In the near future, carbon capture deployment in Lithuania will focus on pilot installations and feasibility projects within its most carbon-intensive sectors. Cement manufacturing, for example, is inherently CO₂-intensive, so the Akmenė cement plant is a logical early candidate. Likewise, fertilizer production is a large source of industrial CO₂ in Lithuania. Initial capture projects in these facilities will thus begin to remove CO₂ at point sources, even though their capacity will be limited. The Baltic CCS cement project has already been recognized by the European Commission as a Project of Common Interest, highlighting that even these early efforts are aligned with EU energy and climate goals. Overall national CO₂ reductions will be modest at first, but each captured ton immediately reduces the carbon footprint of heavy industry and builds technical expertise for broader deployment.

Local air quality effects in the short term are expected to be neutral to slightly positive. Modern carbon capture systems primarily target CO₂ and are typically coupled with advanced gas-cleaning equipment. Experience from early projects elsewhere shows that integrating CO₂ capture with these controls tends to reduce emissions of particulates and sulphur oxides. Similarly, modelling studies of cement plants indicate that capture systems can cut soot (PM) and SO₂ by nearly 90–99% from the largest point. In practice, Lithuania's initial capture installations will include these pollution controls from the start, so residents near industrial sites can expect at least maintain current air quality or see slight improvements.

By the medium term (through the 2030s), Lithuania can expect a significant expansion of capture capacity across hard-to-abate industries, yielding meaningful environmental benefits. Cement factories and ammonia plants will likely commission larger-scale capture units designed to handle most of their flue emissions. When operated at high efficiency (on the order of 90–95% CO₂ removal), such units can eliminate the vast majority of process CO₂ emissions in those facilities. For example, capturing the CO₂ from a cement kiln stack could remove nearly all of that plant's direct emissions; similarly, carbon capture in an ammonia steam-reformer can cut one of Lithuania's largest industrial CO₂ sources. In aggregate, these installations could sequester several million tonnes of CO₂ per year by mid-decade, meaning a substantial drop in national industrial emissions. This decline will make a noticeable dent in Lithuania's overall greenhouse gas inventory and help the country meet its 2030 EU targets.

In the long term (approaching mid-century), full-scale implementation of carbon capture could virtually eliminate CO₂ emissions from Lithuania's hardest-to-abate industries. If most cement, fertilizer, chemical, and energy facilities are equipped with capture technology, then stack emissions of CO₂ would be reduced by upwards of 90% in each sector. Concretely, near complete decarbonization of cement production and ammonia plants would leave only minor residual emissions, and the vast majority of industrial CO₂ would never reach the atmosphere. At the same time, local air quality would reach a markedly higher standard: studies indicate that with capture fully deployed, harmful emissions like particulate matter and SO₂ from these plants would be nearly eradicated. The surrounding environment – forests, rivers and farmland – would benefit from cleaner air, while reduced CO₂ outputs would slow climate change, mitigating long-term risks to biodiversity and agriculture.

By the 2050 timeframe, the cumulative effect of widespread carbon capture is to position Lithuania's industry squarely in compliance with EU climate and environmental goals. The European Green Deal and Climate Law mandate climate neutrality by 2050, and international scientific assessments identify

carbon capture as a precondition for decarbonizing sectors that cannot fully electrify. In fact, industry leaders in Lithuania have acknowledged that carbon capture is critical to the sustainability of heavy industry. With full capture infrastructure in place, Lithuanian cement makers, chemical producers and power generators can continue operations while emitting essentially zero CO₂.

5.5. Cost-benefit analysis of carbon capture technologies

Cost of capture for energy generation

The current cost of carbon capture in energy generation presents a complex challenge that significantly impacts the feasibility of deploying this technology at scale. Within the energy sector carbon capture is primarily applied to fossil fuel-based power plants burning coal or natural gas, where emissions are high.

One of the main cost drivers for carbon capture in power generation is the so-called “energy penalty”, the extra energy needed to run the capture process. These systems include mechanisms for separating CO₂ from flue gas, compressing it for transport, and maintaining stable operational conditions. While electricity is required to power compressors and pumps, a significant amount of heat is also needed, particularly for solvent regeneration in post-combustion capture systems. The source of this heat, whether it is extracted steam from the power cycle, a separate heat generator, or electric heating, can significantly affect the system's efficiency and overall CO₂ reduction potential. The local grid infrastructure can be limited in setups where heat is generated electrically, especially in areas with capacity constraints or high renewable penetration. As a result, the availability and carbon intensity of electricity and heat must be carefully considered when assessing the viability of carbon capture projects. Indeed, the cost of capture depends mainly on the volume, concentration and pressure of the CO₂ stream.

The following table shows a comparison between the levelized costs of energy and the costs of carbon avoidance between oxy-fuel-combustion, pre-combustion and post-combustion according to different sources. Levelized cost of energy is a metric that calculates the average cost of electricity generation over the lifetime of a power plant, while cost of carbon avoidance refers to the price for preventing that one ton of carbon dioxide emissions enters the atmosphere.

Parameters	Oxy-fuel combustion	Pre-combustion	Post-combustion	References
Levelized Cost of Energy (US\$/MWh)	79.93	89.92	115.23	[¹²⁷]
	80–120	60–100	80–120	[¹¹⁸ , ¹¹⁹ , ¹²⁰ , https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.2089 ¹²¹]
	140.45	150.33	40.34	[¹²⁷]

¹¹⁸ Source: International Energy Agency. *IEA Energy and Carbon Tracker 2024*.
¹¹⁹ Source: European Environment Agency. *Greenhouse Gas Emission Intensity of Electricity Generation in Europe*. October 31st, 2024.
¹²⁰ Source: European Commission. *EU Emissions Trading System (EU ETS)*.
¹²¹ Source: Greenhouse Gas Protocol. *IPCC Emission Factor Database*. Intergovernmental Panel on Climate Change.

Parameters	Oxy-fuel combustion	Pre-combustion	Post-combustion	References
Cost of Carbon Avoidance (US\$/tC O ₂)	130–150	120–140	30–50	[https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.2089] ^{122, 123, 124, 125, 126]}

Table 8: Comparison of current cost simulations with literature data ¹²⁷

Table 8 shows that different capture methods come with distinct cost implications. Oxy-fuel combustion demonstrates a relatively lower levelized cost of energy of US\$79.93 per MWh compared to post-combustion methods, which can reach as high as US\$115.23 per MWh. Despite its higher LCOE, post-combustion capture is widely studied due to its low cost of carbon avoidance and adaptability to existing power plants.

The conclusion of the analysis indicates that for existing coal and gas power plants, post-combustion carbon capture is the most economically viable option for retrofitting, primarily due to its compatibility with existing infrastructure and lower costs of carbon avoidance. This technology allows power producers to integrate carbon capture systems with minimal disruption to current operations, making it a practical solution for reducing emissions from the current power plants.

On the other hand, for newly built fossil fuel-based power plants oxy-fuel combustion presents the lowest levelized cost of electricity among the carbon capture technologies evaluated. This is largely attributed to its higher efficiency in capturing a concentrated stream of CO₂, which reduces the complexity and cost of downstream separation processes. Moreover, oxy-fuel systems can be optimized for performance and emissions when integrated from the design phase, making them particularly attractive for new installations.

Cost of carbon capture for industrial sectors

The costs associated with implementing carbon capture in industrial processes varies widely across different industries due to the nature of their emissions. Industries with highly concentrated CO₂ streams may benefit from lower capture cost compared to others with lower CO₂ concentration in flue gases.

¹²² Source: Cambridge University. *Sea Level Change*. Climate Change 2021: The Physical Science Basis; Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change

¹²³ Source: International Energy Agency. *Cost of Abatement and Emissions Avoided as a Result of Selected Sustainable Recovery Plan Measures, by category*. December 2nd, 2020.

¹²⁴ Source: ROUSSANALY, Simon. *Calculating CO₂ Avoidance Costs of Carbon Capture and Storage from Industry*. Carbon Management. Volume 10, 2019. Issue 1. Pages 105-112. February 6th, 2019.

¹²⁵ Source: United States Environmental Protection Agency (EPA). *Greenhouse Gas Equivalencies Calculator*. Version of November 2024.

¹²⁶ Source: BARLOW, Hugh; SHAHI, Shahrzad S M. *State of the Art: CCS Technologies 2024. Technical Report*. Global CCS Institute.

¹²⁷ Source: OBI, Donald; ONYEKURU, Samuel; ORGA, Anslem. *Minimizing Carbon Capture Costs in Power Plants: A Novel Dimensional Analysis Framework for Techno-Economic Evaluation of Oxyfuel Combustion, Pre-combustion, and Post-combustion Capture Systems*. SCI. Energy Science & Engineering. Volume 13, Issue 4. April 2025. Pages 1749-1770. February 9th, 2025. <https://doi.org/10.1002/ese3.2089>

Source	% CO ₂ in Flue Gas	CO ₂ emissions (kgCO ₂ /MWh)	Capture technology	Capture cost (US\$/ton CO ₂)	Reference	Region
Power Plant (Coal)	2%–15%	850–1,200	Post-combustion	50–100	[128]	Global
Power Plant (Gas)	4%–5%	350–600	Post-combustion	30–70	[129]	United States
Steel	5%–20%	1500–3,000	Oxyfuel combustion	40–90	[130]	China
Cement	20%– 30%	600–1,200	Post-combustion	30–60	[131]	Global
Petrochemicals	10%– 30%	100–500	Pre-combustion	20–50	[132]	Middle East
Waste Incineration	5%– 15%	400–1,000	Post-combustion	30–60	[133]	European Union
Biomass Boilers	5%– 15%	200–500	Post-combustion	20–40	[134]	Europe
Biogas	40%– 60%	150–300	Chemical scrubbing	10–30	[135]	Southeast Asia

Table 9: Cost comparison of carbon capture in industrial sectors¹²⁷

¹²⁸ Source: Intergovernmental Panel on Climate Change. MASSON-DELMOTTE, V., P. ZHAI, A. PIRANI, S.L. CONNORS, C. PÉAN, S. BERGER, N. CAUD, Y. CHEN, L. GOLDFARB, M.I. GOMIS, M. HUANG, K. LEITZELL, E. LONNOY, J.B.R. MATTHEWS, T.K. MAYCOCK, T. WATERFIELD, O. YELEKÇİ, R. YU, AND B. ZHOU. *Climate Change 2021: The Physical Science Basis; Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi: 10.1017/9781009157896.

¹²⁹ Source: U.S. Environmental Protection Agency. *Air Pollution and Health*.

¹³⁰ Source: RAHO, Brenda; COLANGELO, Gianpiero; MILANESE, Marco; DE RISI, Arturo. *A Critical Analysis of the Oxy-Combustion Process: From Mathematical Models to Combustion Product Analysis*. *Energies* 2022, 15(18), 6514; <https://doi.org/10.3390/en15186514>.

¹³¹ Source: BAHMAN, Nahed; AL-KHALIFA, Mohamed; AL BAHARNA, Safeya; ABDULMOHSEN, Zainab; KHAN, Ezzat. *Review of Carbon Capture and Storage Technologies in Selected Industries: Potentials and Challenges. Reviews in Environmental Science and Bio/Technology*. Volume 22, pages 451-470 (2023). March 1st, 2023. <https://doi.org/10.1007/s11157-023-09649-0>.

¹³² Source: HANSEN, James; SATO, Makiko; HEARTY, Paul; RUEDY, Reto; KELLEY, Maxwell; MASSON-DELMOTTE, Valerie; RUSSELL, Gary; TSEOIUDIS, George; CAO, Junji; RIGNOT, Eric; VELICOGNA, Isabella; TORMEY, Blair; DONOVAN, Bailey; KANDIANO, Evgeniya; VON SCHUCKMANN, Karina; KHARECHA, Pushker; LEGRANDE, Allegra N.; BAUER, Michael; LO, Kwok-Wai. *Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming could be dangerous*. European Geosciences Union. Volume 16, Issue 6. *ACP*, 16, 3761-3812, 2016. <https://doi.org/10.5194/acp-16-3761-2016>

¹³³ Source: European Commission - *Energy Policy: Delivering Secure, Sustainable and Affordable Energy for European Citizens and Businesses*.

¹³⁴ Source: Intergovernmental Panel on Climate Change. SHUKLA, P. R.; SKEA, J.; CALVO BUENDIA, E.; MASSON-DELMOTTE, v.; PÖRTNER, H.O.; ROBERTS, D.C.; ZHAI, P.; SLADE, R.; CONNORS, S.; VAN DIEMEN, R.; FERRAT, M.; HAUGHEY, E.; LUZ, S.; NEOGI, S.; PATHAK, M.; PETZOLD, J.; PORTUGAL PEREIRA, J.; VYAS, P.; HUNTLEY, E.; KISSICK, K.; BELKACEMI, M.; MALLEY, J.. *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. 2019. <https://doi.org/10.1017/9781009157988.001>

¹³⁵ Source: OLABI, A.G.; OBAIDEEN, Khaled; ELSAID, Khaled; WILBERFORCE, Tabbi; SAYED, Enas Taha; MAGHRABIE, Hussein M.; ABDELKAREEM, Mohammad Ali. *Assessment of the Pre-Combustion Carbon Capture Contribution into Sustainable Development Goals SDGs Using Novel Indicators*. *Renewable and Sustainable Energy Reviews*. Volume 153, January 2022, 111710. <https://doi.org/10.1016/j.rser.2021.111710>.

For power plants, the cost of post-combustion capture ranges from US\$50 to US\$100 per ton of CO₂, where CO₂ concentration in flue gas is between 2% and 15%. For gas-fired power plants, a study in the United States suggests the cost is slightly lower, ranging from US\$30 to US\$70 per ton of CO₂, with a CO₂ concentration of 4%–5%.

In heavy industries, the costs also differ. For steel production in China, utilizing oxyfuel combustion, the capture cost is estimated between US\$40 and US\$90 per ton of CO₂, with CO₂ concentrations ranging from 5% to 20%. The cement industry globally sees post-combustion capture costs between US\$30 and US\$60 per ton of CO₂, with higher CO₂ concentration in flue gas (20%–30%).

The petrochemical sector in the Middle East, employing pre-combustion capture, reports lower costs, ranging from US\$20 to US\$50 per ton of CO₂, despite a CO₂ concentration of 10%–30%. Similarly, waste incineration in the European Union using post-combustion capture has costs between US\$30 and US\$60 per ton of CO₂, with a CO₂ concentration of 5%–15%.

For biomass-based energy, post-combustion capture in Europe shows costs ranging from US\$20 to US\$40 per ton of CO₂, with a CO₂ concentration of 5%–15%. The lowest costs reported are for biogas in Southeast Asia, where chemical scrubbing is used at a cost of US\$10–US\$30 per ton of CO₂, with a high CO₂ concentration in the biogas (40%–60%).

Other relevant examples of costs of carbon capture are published by the International Energy Agency, and can be found in the following list¹³⁶:

- Direct air capture: Cost ranging between US\$134 and US\$342/tonne, but can reach even US\$800/tonne.
- Chemical looping combustion (CLC): Cost above US\$59.20/tonne¹³⁷.
- Compression of CO₂ only: Cost ranging between US\$13 and US\$25/tonne.
- Bioenergy with carbon capture storage (BECCS): Cost ranging between €40 and €75/tonne¹³⁸.
- Hydrogen (steam methane reforming, SMR): Cost ranging between US\$50 and US\$80/tonne.
- Ethylene oxide: Cost ranging between US\$25 and US\$35/tonne.
- Bioethanol: Cost ranging between US\$25 and US\$35/tonne.
- Ammonia and fertilizer production: Cost ranging between US\$25 and US\$35/tonne.
- Coal to chemicals: Cost ranging between US\$15 and US\$25/tonne.
- Natural gas processing: Cost ranging between US\$5 and US\$275/tonne.
- Refineries: Cost ranging between €40 and €110/tonne.
- Pulp and paper: Cost ranging between €45 and €90/tonne¹³⁸.

¹³⁶ Source: BAYLIN-STERN, Adam; BERGHOUT, Niels. *Is carbon capture too expensive?* International Energy Agency. February 17th, 2021.

¹³⁷ Source: OH, D. H.; LEE, C. H.; LEE, J.C. *Performance and cost analysis of natural gas combined cycle plants with chemical looping combustion*. ACS Omega, 6 (2021), pp. 21043-21058

¹³⁸ Source: European Commission, Joint Research Centre, MARTINEZ CASTILLA, G., TUMARA, D., MOUNTRAKI, A., LETOUT, S., JAXA-ROZEN, M., SCHMITZ, A., INCE, E. AND GEORGAKAKI, A., Clean Energy Technology Observatory:

These figures highlight the diverse economic landscape of carbon capture across industrial sectors, emphasizing the need for tailored approaches and technological advancements to reduce costs and facilitate widespread adoption.

Although CO₂ capture volumes are technically significant, the market for CO₂ utilization is limited. Current estimates suggest that only a small fraction (up to around 230 Mt of CO₂, worldwide¹³⁹) of the captured CO₂ can be viably incorporated into industrial products or materials. As a result, CCU should be seen as a complementary pathway, with permanent geological storage (CCS) playing a much larger role in climate mitigation strategies.

Benefits from carbon capture

There are two main ways to get economic benefits from the carbon capture:

- Method 1: Sell the carbon captured for its utilization in different industrial sectors, where carbon dioxide can be used as raw material.
- Method 2: Receive credits for its capture (US) // Stop paying for carbon credits (Europe). This benefit will depend on the cost of carbon allowances in the EU ETS, or in alternative carbon markets.

5.6. The potential and qualitative assessment of the CO₂ to be captured

Lithuania's industrial sector remains one of the country's chief sources of CO₂ emissions, predominantly through energy-intensive processes in chemicals, cement, and related manufacturing. As CO₂ could be split in fossil and biogenic nature, "biogenic-first" will be investigated in this chapter.

Lithuania's potential in building valuable biogenic CO₂ value chain is heavily rooted in its rapidly expanding biogenic emissions from bioenergy, biogas, and waste-to-energy facilities. Because biogenic CO₂ is considered carbon-neutral or even carbon-negative when captured and permanently stored or utilized, it represents a foundational pillar for Lithuania's transition toward a circular carbon economy. According to the Amber Grid analysis, biogas production sites alone—driven by growing biomethane and biofuel output—could yield nearly 0.2 million tonnes of CO₂ annually by 2030 if capture systems were retrofitted to existing facilities¹⁴⁰. As biogas generation is projected to rise from roughly 1.4 TWh in 2030 to over 3.4 TWh by 2040, biogenic CO₂ capture at these sites could more than double, reaching about 0.45 million tonnes per year within that decade.

Beyond biogas, dedicated biofuel combustion plants also present significant capture opportunities. Although current biofuel usage remains modest, Amber Grid's qualitative assessment identifies several mid-sized biomass power plants—especially those using wood chips and agricultural residues—as prime candidates for CO₂ capture upgrades. These facilities typically emit CO₂ streams with high purity and relatively low impurity loads, making post-combustion capture technically straightforward. Importantly, because these plants already interface with district heat networks, capturing their biogenic CO₂ can leverage existing thermal integration, thereby minimizing additional energy penalties.

Carbon Capture, Utilisation and Storage in the European Union - 2024 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2024, <https://data.europa.eu/doi/10.2760/0287566, JRC139285>.

¹³⁹ Source: International Energy Agency. *CO₂ Capture and Utilisation*. <https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/co2-capture-and-utilisation>

¹⁴⁰ Source: Amber Grid. *Biogenis kilmės anglies dioksido (CO₂) perspektyvos Lietuvoje. Analizės apibendrinti rezultatai viešam skelbimui*. <https://ambergrid.lt/doclib/ans2vreks4ca8rvdm7vy3k928azzmsrr>

The study emphasizes that retrofitting two to three of the largest biofuel units could, on its own, remove over 100,000 tonnes of CO₂ per year, serving as an early demonstration of scalable biogenic capture in Lithuania. In biofuel combustion plants, it is possible to capture around 2.3 million tonnes of CO₂ per year between 2030 and 2040 in the major facilities, and 1.4 million tonnes of CO₂ per year, of which approximately 420 thousand tonnes of biogenic CO₂ per year.

Waste-to-energy (WtE) facilities further enhance Lithuania's capture landscape. Amber Grid highlights four major incineration plants—Vilnius Cogeneration Plant (VKJ), Kaunas Cogeneration Plant (KKJ), Gren Klaipėda, and Akmenės Cementas's hybrid cement-waste furnace—as particularly promising. Although these are “hybrid” sites where biogenic and fossil CO₂ are co-emitted, they offer centralized flue gas streams amenable to capture. For instance, VKJ's total emissions exceed half a million tonnes annually, of which roughly 445,000 tonnes derive from biogenic sources. Capturing this biogenic fraction at VKJ alone could sequester nearly 90 % of its renewable CO₂ output, provided that technological and economic conditions align for post-2025 implementation. Similarly, KKJ and Gren Klaipėda each harbor biogenic shares of roughly 40,000 to 120,000 tonnes per year within broader emissions totals, highlighting the scale at which biogenic capture could begin in a clustered manner.

Cement production, traditionally a hard-to-abate sector, contributes substantially to Lithuania's industrial emissions. However, the Akmenės Cementas site—unique for coupling clinker production with waste incineration—already delivers about 120,000 tonnes of biogenic CO₂ annually. While the bulk of its 800,000 tonnes of total CO₂ is fossil-derived, capturing the biogenic portion offers immediate benefits without competing with fossil CO₂ reduction efforts. Moreover, embedding capture technology at this cement plant dovetails with broader decarbonization pathways in the construction materials sector, as it can feed captured CO₂ into local utilization chains (e.g., carbonate curing of precast concrete).

Qualitatively, the Amber Grid analysis underscores that Lithuania's biogenic CO₂ potential is both substantial and cost-effective relative to capturing fossil emissions. Because biogenic streams are already concentrated and do not require upstream flue gas separation from high volumes of nitrogen, capture units can operate at higher efficiency and lower incremental energy cost. Furthermore, by prioritizing biogenic sources, Lithuania can establish early value chains for CO₂ transport, storage, and utilization—thereby de-risking infrastructure investments needed for later fossil capture deployments. From a strategic viewpoint, this “biogenic-first” approach aligns with EU mandates to maximize negative emission options and helps Lithuania meet near-term climate targets without adversely impacting industrial competitiveness.

Looking forward, Amber Grid projects that total biogenic CO₂ capture potential—combining biogas, biofuel, and WtE sources—could exceed 0.2 million tonnes per year by 2030 and approach 3.5 million tonnes by 2040 if capture is rolled out to all major facilities. When integrated with the fossil capture potential from ETS-covered sites like chemical and cement producers, Lithuania's combined annual capture ceiling could reach roughly 3.5 million tonnes by the mid-2040s. Critically, realizing this potential hinge on synchronous development of CO₂ transport infrastructure—whether via shared pipelines or coordinated trucking networks—and the availability of local or regional utilization and storage options. Nonetheless, even at conservative uptake rates (e.g., equipping only the top five biogenic emitters by 2030), Lithuania can achieve capture of over 0.5 million tonnes per year by that date, carving a clear decarbonization pathway that leverages its renewable energy strengths and industrial geography. Amber Grid considers biogenic carbon dioxide from biogas and biofuel production as the easiest to capture, due to its high concentration. In contrast, CO₂ capture in hybrid plants would require flue gas treatment technologies, which involve significantly higher investment costs.

Along with the detailed assessment from Amber Grid, the Lithuanian National Energy and Climate Plan of the Republic of Lithuania also offers some estimates of the amount of carbon dioxide which can be captured in the future.

According to this Plan, it is estimated that, by 2050, the carbon dioxide emissions of the largest companies which participate in the EU-ETS will reach around 1 million tonnes of fossil CO₂ and 0.6 million tonnes of biogenic CO₂ by 2050. The potential of fossil CO₂ which can be captured will reach 2.4 million tonnes by 2040, and 1.0 million tonnes by 2050.

The following table shows the estimated potential for carbon capture in Lithuania, in million tonnes/year:

	By 2030	By 2040	By 2050
Fossil CO₂ capture forecast¹⁴¹	0	2.4	1.0
Biogenic CO₂ capture forecast¹⁴²	0.2	3.5	2.4-3.5

Table 10: Potential for carbon capture in Lithuania, in million tonnes/year¹⁴³

¹⁴¹ Source: Based on the CO₂ companies with the largest share of emissions in the Lithuanian ETS.

¹⁴² Source: Based on biomethane production, waste incineration, biofuel production and/or use

¹⁴³ Source: Ministry of Energy of the Republic of Lithuania. *Integrated National Energy and Climate Plan of the Republic of Lithuania*. October 3rd, 2022.

6. Carbon utilization

6.1. Possibilities for direct and indirect carbon utilization

Direct and indirect carbon utilization represent two broad strategies to utilize captured CO₂ in industrial processes to compensate the costs of capture.

Direct carbon utilization

In direct carbon utilization, captured CO₂ is used as an input for other chemical processes. This direct approach is often more energetically efficient in cases where the captured CO₂ has a high purity, and the end product can accommodate the characteristics of gaseous CO₂. Some of the processes that utilize CO₂ include:

- **Material synthesis:** Incorporating CO₂ into construction materials such as concrete. The mineralization of CO₂ into carbonate minerals allows for the production of additives that enhance building materials, effectively trapping the captured carbon in the chemical structure of said materials.
- **Enhanced oil recovery:** CO₂ gas can be injected into oil reservoirs to facilitate the extraction of remaining oil and gas deposits. This approach ties the value of the captured CO₂ with petrol prices which can fluctuate, making it difficult for long term planning.
- **Chemical processes:** Certain chemical reactions use CO₂ as a reactant for chemical and polymer synthesis.

Indirect carbon utilization

Indirect carbon utilization involves converting captured CO₂ into other compounds before using it as an input in industrial processes. Although this is a more energy intensive process, it facilitates the integration into existing industrial value chains. The processes to upgrade CO₂ into more versatile compounds include:

- **Catalytic conversion to fuel:** Captured CO₂ can be reduced via catalytic processes to produce synthetic gas, which can then be treated to obtain methanol and other chemicals that can be utilised as a replacement for traditional fuels.
- **Electrochemical Processes:** Emerging technologies use electricity to drive reactions that convert CO₂ into chemicals like formic acid or even more complex hydrocarbons, when paired with renewable energy sources these methods can ensure CO₂ are reduced.
- **Biological Conversion:** Microalgae or other microorganisms can be cultured in bioreactors that use captured CO₂ as their carbon source. The biomass generated through these biological processes can later be processed into biofuels or animal feeds.

6.2. Carbon utilization technologies

Captured CO₂ can serve as a versatile building block in the synthesis of a wide range of chemicals, effectively closing the carbon loop and reducing reliance on fossil feedstocks^{144,145}.

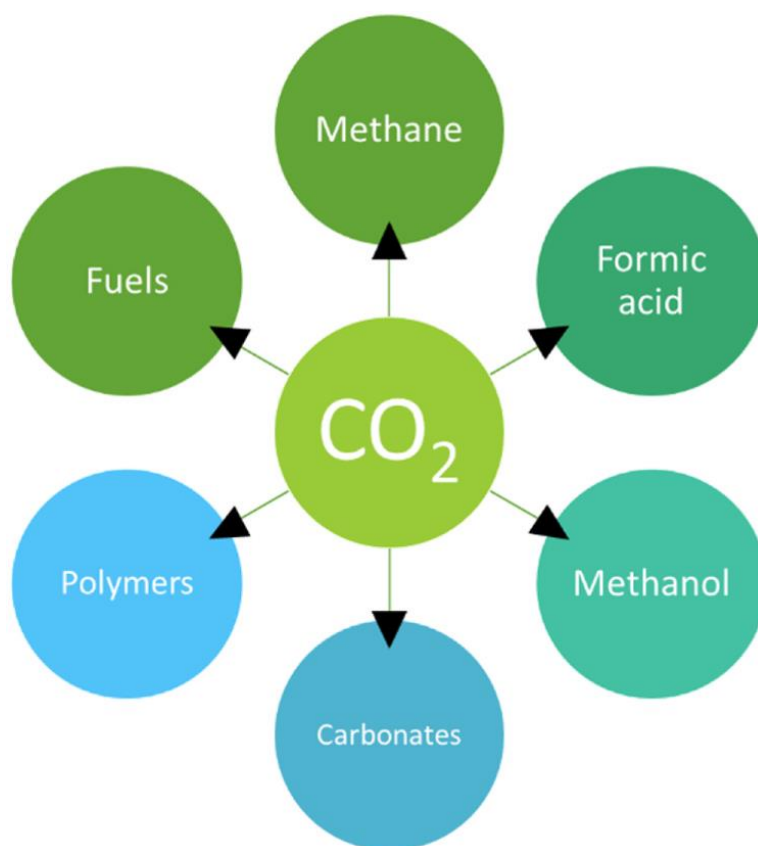


Figure 24 Value-added products obtained from CO₂ conversion¹⁴⁶

One of the most mature pathways is thermocatalytic hydrogenation: CO₂ reacts with renewable hydrogen to yield methanol ($\text{CO}_2 + 3 \text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$), which not only functions as a low-carbon fuel but also as a precursor for formaldehyde, acetic acid and a host of polymers, plastics, solvents and surfactants in the chemical industry. When this route is combined with a secondary dehydration step, dimethyl ether (DME) is formed, a non-toxic solvent and propellant that can substitute chlorofluorocarbons in aerosol applications and serve as a diesel substitute.

Beyond fuels, hydrogenation of CO₂ to formic acid ($\text{CO}_2 + \text{H}_2 \rightarrow \text{HCOOH}$) affords a high-value chemical used both as a hydrogen carrier and as a preservative, and it can be further transformed into formate

¹⁴⁴ Source: GHIAT, Ikhlas; BANU, Aliya; BICER, Yusuf; AMHAMED, Abdulkarem I.; AL-ANSARI, Tareq. *Circularity within carbon capture networks: A review of capture and utilization technologies*. Journal of CO₂ Utilization. Volume 95, May 2025, 103075. <https://doi.org/10.1016/j.jcou.2025.103075>.

¹⁴⁵ Source: ELAOUZY, Youssef; ZAABOUT, Abdelghafhour. *Carbon capture, utilisation and storage in buildings: Analysis of performance, social acceptance, policy measures, and the role of artificial intelligence*. Building and Environment. Volume 275, May 1st, 2025, 112817. <https://doi.org/10.1016/j.buildenv.2025.112817>

¹⁴⁶ Source: Based on GHIAT, Ikhlas; BANU, Aliya; BICER, Yusuf; AMHAMED, Abdulkarem I.; AL-ANSARI, Tareq. *Circularity within carbon capture networks: A review of capture and utilization technologies*. Journal of CO₂ Utilization. Volume 95, May 2025, 103075. <https://doi.org/10.1016/j.jcou.2025.103075>

esters for solvents and detergents. Reaction of CO₂ with ammonia yields urea ($\text{CO}_2 + 2 \text{NH}_3 \rightarrow \text{CO}(\text{NH}_2)_2 + \text{H}_2\text{O}$), the cornerstone of resin production, adhesives and certain pharmaceutical formulations.

CO₂ can also be incorporated into cyclic carbonates—such as propylene carbonate ($\text{CO}_2 + \text{C}_3\text{H}_8\text{O}_2 \rightarrow \text{C}_4\text{H}_6\text{O}_3 + \text{H}_2\text{O}$)—which are valuable aprotic solvents for lithium-ion batteries, paints, coatings and as intermediates in the manufacture of polycarbonate plastics and polyurethane foams. These cyclic carbonates react further with diols or diamines to yield polycarbonates or polyurethanes, thereby creating high-performance polymers from captured carbon.

Electrochemical CO₂ reduction (ECR) represents another promising route, operating at ambient temperature and pressure to generate formate, carbon monoxide, ethylene and other building blocks directly from CO₂ and water-derived electrons. When powered by renewable electricity, ECR can produce monomers for polyolefins and specialty polymers with a minimal carbon footprint.

In the consumer goods sector, supercritical CO₂ extraction—leveraging CO₂ low critical temperature and tunable solvent properties—has already been adopted at scale to isolate fragrances, oils and active ingredients in cosmetics and pharmaceuticals, replacing traditional organic solvents and improving product purity. Supercritical CO₂ is also employed in the textile industry for dyeing, significantly reducing water usage and eliminating toxic solvent residues.

Finally, mineral-based utilization of CO₂ produces inorganic carbonates—such as calcium carbonate ($\text{CO}_2 + \text{Ca}(\text{OH})_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}$) and sodium bicarbonate ($\text{CO}_2 + \text{NaOH} \rightarrow \text{NaHCO}_3$)—which serve as fillers and pigments in paints, plastics, paper and detergents, and as mild abrasives or pH-adjusters in personal care products. By integrating these CO₂-derived materials into commercial formulations, manufacturers can both enhance product performance and sequester carbon in long-lived goods.

Through a combination of thermocatalysis, electrochemistry, and supercritical and mineralization pathways, captured CO₂ can thus be upcycled into an array of solvents, polymers, plastics, paints, detergents, cosmetics and pharmaceuticals—advancing circular carbon strategies and providing sustainable alternatives to conventional petrochemical processes.

Summarizing, the deployment of carbon capture and utilisation (CCU) technologies carries profound social, economic, and environmental implications that must be evaluated in concert to ensure truly sustainable outcomes. Socially, CCU can enhance local air quality and public health when integrated at or near emission sources. For example, incorporating CO₂ capture and conversion units into buildings not only reduces indoor CO₂ concentrations—improving cognitive performance and occupant well-being—but also demonstrates visible climate action to communities, bolstering social acceptance for broader CCUS deployment. Nonetheless, successful adoption hinges on transparent stakeholder engagement: residents, workers, and local regulators must be informed about system safety, lifecycle impacts, and potential disruptions (e.g., noise, maintenance activities) to build trust and avoid “not-in-my-backyard” opposition¹⁴⁷.

Economically, CCU offers new revenue streams by transforming a waste gas into marketable commodities—methanol, formic acid, urea, polycarbonates, cyclic carbonates and specialty polymers—thereby offsetting capture and conversion costs. Techno-economic assessments demonstrate that, with maturing hydrogenation and electrochemical routes, the unit cost of CO₂-derived methanol could fall below traditional syngas-based processes when coupled with renewable

¹⁴⁷ Source: EL FARSAOUI, Maryem; URATANI, Joao M.; ABU ZAHRA, Mohammad; GRIFFITHS, Steve. 2025. *Establishing leadership in bringing carbon capture, utilisation and storage to scale*. Energy Research & Social Science. Volume 121, March 2025, 103960. <https://doi.org/10.1016/j.erss.2025.103960>

energy incentives and carbon credits. Likewise, in cementitious applications, CO₂ curing of concrete has shown potential for 4–6 % cement reduction and a 10 % strength gain, translating to material savings and lower embodied emissions—enhancements readily monetized by producers seeking low-carbon product premiums. Yet, today's first-of-a-kind plants still face capital intensity and scale-up risks; thus, supportive policy frameworks (e.g., tax credits, carbon pricing) and public–private partnerships are critical to de-risk investments and accelerate learning-curve cost reductions¹⁴⁸.

Environmentally, CCU can contribute materially to GHG mitigation by displacing fossil-derived feedstocks and sequestering carbon in long-lived materials. When powered by low-carbon electricity and green hydrogen, CO₂ hydrogenation to methanol or formic acid can achieve net-negative footprints, provided upstream emissions are minimized. Mineralisation pathways—forming calcium or magnesium carbonates for use as fillers, aggregates, or paper coatings—lock CO₂ into stable solids, offering durability and zero-leakage profiles. Additionally, supercritical CO₂ extraction replaces volatile organic solvents in food, cosmetics, and pharmaceutical manufacture, reducing hazardous emissions, improving product purity, and lowering wastewater generation.

However, environmental benefits must be weighed against energy inputs: high-temperature solvent regeneration, compression, or electrolysis can incur significant electricity or heat demands. Life-cycle assessments thus emphasize coupling CCU processes with waste heat recovery, renewable grids, and circular water use to prevent unintended trade-offs, such as increased particulate emissions from power generation or freshwater depletion in desalination synergies. By aligning CCU deployment with broader decarbonization and circular-economy strategies—integrating CO₂ capture into industrial symbiosis clusters, utilizing by-product streams, and valorising residual heat—stakeholders can maximize social co-benefits, economic viability, and environmental integrity.

6.3. Social, Economic and environmental aspects of carbon utilization in industry

As Lithuania advances its decarbonization agenda, the utilization of captured carbon creates potential social, economic, and environmental benefits. The following analysis outlines these impacts in the Lithuanian context.

Social

Many environmental groups regard carbon capture projects as unproven and expensive. Nevertheless, Lithuanian utilization of captured carbon can have broad social implications. In the short term, deploying CCU infrastructure requires a skilled workforce, stimulating demand for engineers, technicians and researchers trained in carbon capture and utilization. This upskilling can lead to higher-value jobs and closer ties between industry and academia. Communities near CCU facilities may see new economic activity, while public engagement around climate innovation can raise awareness of decarbonization goals. Clear communication and inclusive stakeholder involvement will be crucial to build public trust and social license for carbon utilization projects.

Carbon utilization is expected to find a niche in sectors like heavy industry and plant retrofits. Social dynamics will thus evolve as CCU becomes integrated: for example, new rural or regional jobs could emerge if capture plants are co-located with agriculture or forestry operations. The growth of a domestic CCU sector could spawn clusters of specialized firms and research centres, enhancing

¹⁴⁸ Source: DANIELI, Sarah; ANDRADE NETO, José S.; GRÜNHÄUSER SOARES, Erick; FARIA OLIVEIRA; Thainá; BRITO, Bruna L.F.; KIRCHHEIM, Ana Paula. 2025. *Shaping a sustainable path: Exploring opportunities and challenges in carbon capture and utilization in cement and concrete industry*. CEMENT. Volume 19, March 2025, 100135. <https://doi.org/10.1016/j.cement.2025.100135>

Lithuania's expertise in clean technologies. Over time, workers' career paths may shift from traditional fossil-based roles to advanced manufacturing and sustainable fuels. These changes can reinforce a shared commitment to Lithuania's climate targets.

Economic

Lithuania will likely need to mobilize substantial public and private investment to develop carbon utilization infrastructure. In the short term, such investments will be necessary to offset the high capital and operating costs of new capture and conversion facilities. Early CCU projects may rely on mechanisms like carbon-credit auction schemes or state subsidies to be financially viable. These initial expenditures will stimulate the economy through construction, manufacturing, and services related to the CCU supply chain. Importantly, by capturing CO₂ at emitting plants, industries can reduce their needs to purchase emissions allowances, which improves their operating costs under the EU Emissions Trading System. In any case, it is important to consider that carbon utilization technologies do not reduce the carbon emissions themselves, but they use carbon dioxide as a product. While they are useful to reach decarbonization goals, as they reduce the needs for reducing emissions in origin, the objective should be minimizing emissions as much as possible, more than using carbon dioxide. It is also relevant as not all emissions will be avoidable, so greenhouse gas emission reduction projects should focus not only on the absolute emissions, but also on the net emissions (this is, gross emissions minus the captured, used and stored carbon dioxide). Carbon products are very useful, for example, in petrochemical industry, to produce plastic products. For this reason, carbon utilization technologies are considered as sustainable.

For the longer term, Lithuania's competitiveness hinges on integrating CCU into a broader strategy of market reform and technological innovation. Over time, a robust CCU industry could create new domestic value chains: for example, producing carbon-derived materials, fuels or chemicals for local use or export. Export opportunities may arise if Lithuania can supply low-carbon products (such as synthetic fuels or chemical feedstocks) to European markets that demand reduced-carbon content. Simultaneously, using captured CO₂ as a raw material can shrink dependence on imported fossil feedstocks, improving energy security. If well-executed, CCU deployment could diversify Lithuania's economy, turning a costly waste stream into a commercial asset. However, achieving these economic benefits will require sustained policy support and innovation, since CCU technologies are still emerging. Aligning CCU with market signals (for example, by reflecting carbon costs in pricing or border adjustments) will be key to making low-carbon products competitive.

Globally, around 80% of captured CO₂ is currently used for enhanced oil recovery, highlighting the fossil fuel orientation of existing CCUS projects. Lithuania's CCU strategy would instead emphasize value-added applications such as low-carbon fuels, chemicals, and construction materials. For instance, producing synthetic methane or methanol from captured CO₂ and renewable hydrogen could reduce fuel imports and create exportable green fuels. In the long run, a mature CCU sector could contribute significantly to GDP by creating advanced manufacturing jobs and by reducing national spending on energy imports.

Environmental

Lithuania is commended for its ambitious 2050 climate-neutrality targets, a context that drives interest in carbon utilization. In the short term, CCU can directly lower point-source emissions by diverting CO₂ into useful products. However, its current global scale is very small. In addition, most of today's captured CO₂ is used to extract more oil, which complicates its net climate benefit. For Lithuania to achieve real greenhouse-gas reductions, CCU must focus on pathways that securely lock away carbon

or displace new emissions – for example, converting CO₂ into long-lived materials or carbon-neutral fuels rather than products that re-release CO₂ immediately. This can be combined with carbon storage.

Recent analyses suggest that only about 1% of captured CO₂ is currently used to make products such as fuels, plastics or building materials¹⁴⁹. When CO₂ is embedded in long-lived construction materials (for example, by curing concrete with CO₂), the carbon can remain sequestered for decades, yielding a permanent environmental benefit. In contrast, CO₂ converted into fuels or short-lived chemicals will eventually return to the atmosphere. A key environmental advantage of CCU is that it substitutes recycled CO₂ for virgin fossil carbon, potentially shrinking the lifecycle footprint of industrial products. To realize these benefits, capture and conversion processes must be powered by renewable energy; if fossil fuels power the CCU chain, the carbon savings may be offset. Careful life-cycle management is therefore essential.

CCU processes themselves consume significant energy and resources. Plants equipped for capture and utilization typically incur an energy penalty, meaning they must burn additional fuel if not supplied by clean power. This extra energy use can increase local air emissions unless sourced from renewables or excess heat. In practical terms, Lithuania will need to integrate CCU plants with its expanding wind, solar, or biomass energy systems to ensure a net gain. If managed well, the environmental co-benefits of CCU can outweigh the added energy inputs. In the long run, scaling up CCU could help turn CO₂ into a circular resource, aligning with Lithuania's sustainability objectives and strengthening ecosystem and public health by mitigating climate change.

6.4. Cost-benefit analysis of carbon utilization technologies

Costs analysis of carbon utilization technologies

The economic outlook for carbon utilization varies significantly depending on the specific technology being used. The costs associated with each method are influenced by a multitude of factors, including the maturity of the technology, the scale of the operation, energy requirements, etc. For this reason, it is not easy to offer a good figure, as extreme variations can happen even considering that the carbon dioxide is used for the same objective. For instance, to produce methanol, the carbon utilization cost can vary from €300 to €2,500/tonne of CO₂, depending on the assumptions¹⁵⁰.

The most common use for captured carbon at the moment is in enhanced oil recovery. The costs usually considered for this method are the cost of the carbon dioxide itself and the cost of pumping this carbon dioxide into the ground (injection cost). On top of this, the need to retrofit the oil fields for CO₂ also introduces a high capital investment.

In the realm of building materials, utilizing captured CO₂ faces considerable cost hurdles. CO₂ based construction aggregates and CO₂ cured concrete are currently significantly more expensive than

¹⁴⁹ Source: MARTIN-ROBERTS, Emma; SCOTT, Vivian; FLUDE, Stephanie; JOHNSON, Gareth; STUART HASZELDINE, R.; GILFILLAN, Stuart. *Carbon Capture and storage at the end of the lost decade*. One Earth. Volume 4, Issue 11, November 19th, 2021, pages 1569- 1584. <https://doi.org/10.1016/j.oneear.2021.10.002>.

¹⁵⁰ Source: European Commission, Joint Research Centre, MARTINEZ CASTILLA, G., TUMARA, D., MOUNTRAKI, A., LETOUT, S., JAXA-ROZEN, M., SCHMITZ, A., INCE, E. AND GEORGAKAKI, A., Clean Energy Technology Observatory: *Carbon Capture, Utilisation and Storage in the European Union - 2024 Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg, 2024, <https://data.europa.eu/doi/10.2760/0287566, JRC139285>.

conventional alternatives. In the case of construction aggregates OGCI reports¹⁵¹ it to be two to four times more expensive than other aggregates. They also estimate one and a half to two times more costly cured concrete over standard concrete. Nevertheless, some studies are suggesting that price parity with conventional concrete can be achieved by leveraging additional sources of revenue such as waste disposal fees¹⁵².

Integrating carbon utilization into the production of chemicals like ammonia and methanol also adds to the cost. CCUS-equipped plants using natural gas are estimated to have production costs 20-40% higher than unabated facilities¹⁵³.

Other industries, such as steel manufacturing and cement production, also face significant challenges when it comes to the economic feasibility of carbon utilization. In the steel industry using CO₂ as a reducing agent in the production of iron and steel offers the potential for decarbonization, but capturing CO₂ emissions in steel plants can cost between €28 and €45 per tonne, depending on the capture rate and technology used¹⁵⁴. In cement production the high cost of retrofitting existing plants and the need for reliable CO₂ storage systems make these technologies expensive at present, cost of clinker is shown to increase with 49–92% when CO₂ capture is retrofitted to the cement plant. For chilled ammonia and calcium looping technologies the cost of clinker is in the range of 105–110 €/tonne of clinker, while oxyfuel technology has the lowest cost of clinker, 93 €/tonne of clinker¹⁵⁵.

Economic benefits of carbon utilization

Despite the significant cost challenges, carbon utilization technologies can yield tangible economic benefits that may offset some of the initial capital and operational expenditures.

For instance, CO₂-enhanced oil recovery (CO₂-EOR) remains economically attractive in regions with high oil prices and mature reservoirs. By injecting CO₂ into depleted oil fields, operators can increase extraction efficiency—recovering up to 15% more oil than with conventional methods. This translates into additional revenue streams, particularly when CO₂ is acquired at low cost or subsidized.

In the construction materials sector, the potential to monetize captured CO₂ through the production of marketable materials represents a dual benefit: avoiding carbon emissions and generating new products. The economic case strengthens further if carbon credits, subsidies, or waste disposal fees are included as additional revenue mechanisms. Lifecycle analyses also indicate long-term savings in embodied carbon, which may become financially relevant in markets with carbon pricing or embodied carbon regulations.

In the chemical industry, while cost increases of 20–40% are currently observed for CCUS-equipped ammonia and methanol plants, integration with renewable hydrogen or waste CO₂ streams could

¹⁵¹ Source: Oil and Gas Climate Initiative and Boston Consulting Group. *White paper. Carbon capture and utilization as a decarbonization lever*. April 2024.

¹⁵² Source: POPE, Eve. *Building a Net-Negative Future: CO₂-derived concrete*. IDTechEx. February 21st, 2024.

¹⁵³ Source: International Energy Agency. BAYLIN-STERN, Adam; BERGHOUT, Niels. *Is carbon capture too expensive?* February 27th, 2021.

¹⁵⁴ Source IEAGHG. NORMAN, Friedrik; SKAGESTAD, Ragnild; BIERMAN, Maximilian; WOLF, Jens; MATHISEN, Anette; LARSSON, Mikael. *IEAGHG Technical Review 2019-TR02 November 2019. CO₂stCap (Cutting Cost of CO₂ Capture in Process Industry)*. IEAGHG.

¹⁵⁵ Source: GARDARSDOTTIR, Stefania Osk; DE LENA, Edoardo; ROMANO, Matteo; ROUSSANALY, Simon; VOLDSUND, Mari; PÉREZ-CALVO, José Francisco; BERSTAD, David; FU, Chao; ANANTHARAMAN, Rahul; SUTTER, Daniel; GAZZANI, Matteo; MAZZOTTI, Marco; CINTI, Giovanni. *Comparison of Technologies for CO₂ Capture from Cement Production—Part 2: Cost Analysis*. *Energies* 2019, 12(3), 542; <https://doi.org/10.3390/en12030542>.

reduce marginal costs over time. Furthermore, the development of premium “low-carbon” chemical products, priced higher due to sustainability attributes, may create niche market advantages.

Lastly, in hard-to-abate sectors such as steel and cement, long-term economic viability will depend on policy support mechanisms such as carbon pricing, tax credits, and green procurement mandates. For example, a robust carbon price of €100 per tonne would significantly narrow the cost gap between traditional and low-carbon clinker production. Additionally, early movers in these sectors may benefit from first-mover advantages and improved ESG performance, enhancing their competitiveness and access to capital as banks prioritize green projects for their portfolio.

7. Carbon storage

7.1. Possibilities for carbon storage

Overview of Carbon Storage in Industrial Decarbonization

Carbon Storage refers to the long-term containment of carbon dioxide that has been captured from industrial processes or directly from the atmosphere. This containment can be achieved through a variety of pathways, each with distinct technical, economic and geographic considerations. As industrial decarbonization strategies mature, carbon storage is becoming a critical part in the transition to net-zero, particularly for industries where electrification or the use of green energies is not possible.

Geological storage remains the most mature and widely implemented form of carbon storage. This method involves the injection of compressed carbon dioxide into deep underground rock formations such as depleted oil and gas reservoirs, deep saline aquifers, and other underground seams. These formations provide the capacity and integrity required to contain CO₂ for centuries or longer, they are subject to strict rules on monitoring protocols to ensure the carbon does not end up back in the atmosphere.

In parallel, emerging storage technologies are being developed to expand the scope of carbon storage systems. Mineral carbonation involves the reaction of carbon dioxide with naturally occurring magnesium or calcium-rich rocks to form stable carbonates. These carbonates can then be disposed in silicate mines or reused in construction. The approach offers minimal risk with permanent storage, however, the costs and the energy required for the whole process now is a big challenge. Technological advancements have the potential of reducing these costs, making mineral carbonation a very attractive alternative.¹⁵⁶

Ocean-based carbon storage, although still in early research stages, presents another potential pathway. This includes deep-ocean injection of CO₂. While theoretically the storage potential is vast, significant environmental and regulatory concerns are being raised.

Despite its central role in carbon management, the deployment of storage infrastructure remains constrained by high upfront capital costs and complex permitting procedures. Transport infrastructure, especially pipelines and shipping terminals for CO₂, is a key enabler for linking capture sites with suitable storage reservoirs.

Status of Carbon Storage in Industrial Decarbonization

Policy frameworks and partnerships between the public and private sectors are accelerating the deployment of carbon storage projects. Government incentives, such as financial support for geological storage (described into detail in chapter 7)), and other funding, are supporting the commercial-scale development for storage. In most countries, national mapping of subsurface storage is being done to better plan and enable investment decisions.

¹⁵⁶ Source: MILLER, Bruce G. *10- CO₂ Capture and Storage*. Clean Coal Engineering Technology. Science Direct. 2011, pages 483-511. <https://doi.org/10.1016/B978-1-85617-710-8.00010-8>

Storage development is being prioritized in regions with suitable geology and existing industrial clusters. Key areas of focus are:¹⁵⁷

- **Depleted Hydrocarbon Reservoirs:** These formations offer proven structural integrity and, in many cases, existing infrastructure from oil and gas operations. They are often the first targets for carbon storage initiatives due to reduced development costs and known performance characteristics.
- **Saline Aquifers:** Deep saline formations are widely distributed and offer large storage capacities. While they require more upfront characterization and monitoring, they represent the bulk of global storage potential. Large-scale demonstrations projects, while they have experienced some difficulties, are proving the viability of saline storage at industrial scale.
- **Mineralization Sites:** Pilot projects are exploring both natural and industrial settings where CO₂ can react with minerals to form carbonates. This includes the CarbFix¹⁵⁸ project in Iceland, which injects CO₂ into basalt formations, and efforts to process alkaline industrial residues into carbonate materials.
- **Bioenergy with Carbon Storage (BECCS):** When coupled with geological storage, biomass-based energy generation can achieve negative emissions. CO₂ captured from fermentation or combustion of biomass is injected into storage formations, creating a net removal of carbon from the atmosphere.

Carbon storage remains indispensable for achieving industrial decarbonization at scale. It complements other mitigation strategies by providing a permanent sink for residual and process-related emissions. As regulatory clarity improves and storage networks expand, industrial players are increasingly viewing access to long term storage solutions as a strategic asset in the carbon constrained economy.

7.2. Social, economic and environmental impact of the use of carbon storage

Social

Carbon storage facilities often have mixed public reception. Many environmental advocates question their long-term viability and capacity to effectively monitor CO₂ leakage. However, the demand for skilled professionals for the construction and operation of these facilities can contribute to the economic revitalization of local communities with new jobs and ancillary business growth. Over time, carbon storage can reshape labour markets by creating opportunities for workers to transition into low carbon sectors.

Carbon storage projects can foster partnerships between industry, government and educational institutions, encouraging research and development initiatives and providing pathways for youth and displaced workers to access training and reskilling programs. This can support social mobility and reduce resistance to climate initiatives.

¹⁵⁷ Source: DURAI SWAMI, Raymond. A. *Global Carbon Capture and Storage Efforts: Challenges and Opportunities*. January 2025. Journal of Geological Society of India. 101 (2): 143-148. (<https://doi.org/10.17491/jgsi/2025/174076>)

¹⁵⁸ Source: SNÆBJÖRNSDÓTTIR, Sandra Ó.; SIGFÚSSON; Bergur; MARIENI, Chiara et al. *Carbon dioxide storage through mineral carbonation*. January 20th, 2020. Nature Reviews Earth & Environment, 20p20, vol. 1, no 2, p. 90-102.

The presence of carbon storage projects often necessitates strong community engagement and transparent communication strategies to build public trust and address concerns related to safety, environmental risks, and potential impacts on land use.

Economic

The impact of carbon storage infrastructure can have significant effects. The construction of these facilities requires considerable initial investments which can stimulate local economies in the short term through construction contracts. In the medium to long term, effective carbon storage can reduce carbon compliance costs for domestic industries and improve competitiveness in carbon intensive sectors like cement, steel and energy generation. Furthermore, establishing carbon storage hubs can enable the growth of specialized sectors in geological surveying and monitoring services.

In regions dependent on fossil fuel industries, carbon storage may be seen as a transitional technology, helping to preserve economic stability while broader structural changes toward renewable energy take place. However, careful management is needed to avoid entrenching dependency on fossil fuels or delaying necessary shifts in energy systems.

Environmental impact

In the broader environmental context, carbon storage is not a standalone solution but part of a portfolio of climate actions to buy time while cleaner technologies scale up and energy systems decarbonize fully. Carbon storage can complement renewable energy expansion by enabling carbon-intensive processes to continue temporarily by reducing industrial point emissions, thereby facilitating a smoother energy transition.

The environmental effectiveness depends on secure and long-term containment of stored CO₂ in deep geological formations or saline aquifers. Robust monitoring and verification protocols are essential to detect potential leaks and maintain ecosystem safety. There are risks related to carbon storage, such as induced seismicity (small-scale earthquakes triggered by injection activities) and contamination of underground water sources, which are unlikely to occur. However, these risks necessitate stringent site selection criteria and continuous geological assessments to mitigate potential adverse impacts¹⁵⁹.

7.3. Strategy for the transition to carbon capture and storage

Lithuania's successful transition to Carbon Capture and Storage (CCS) requires a holistic strategic approach, encompassing regulatory enhancements, focused research and development activities, essential infrastructure investments, and the integration of advanced green technologies. Initially, it is critical to align the national legislative and regulatory framework with EU directives, creating a favourable environment for CCS deployment. Clear and robust legal standards must be established for geological CO₂ storage, addressing critical aspects such as environmental safety, long-term liability, and thorough monitoring protocols.

Enhanced collaboration between academia, research institutions, and industry will be vital to developing technologies and methodologies to ensure safe and effective CO₂ storage. Areas of particular importance include comprehensive geological assessments, innovative storage solutions, and reliable monitoring techniques.

¹⁵⁹ Source: VILARRASA, Víctor and CARRERA, Jesús. *Geologic carbon storage is unlikely to trigger large earthquakes and reactivate faults through which CO₂ could leak*, Proc. Natl. Acad. Sci. U.S.A. April 20th, 2015. 112 (19) 5938-5943. <https://doi.org/10.1073/pnas.1413284112> (2015).

Considering Lithuania's strategic location and existing energy infrastructure, the development of pipelines for CO₂ transportation is crucial. This infrastructure should efficiently support both domestic CO₂ storage initiatives and international CO₂ export to for example, established North Sea storage facilities. This strategy not only optimizes economic outcomes but also enhances Lithuania's participation in broader European CO₂ storage initiatives and partnerships. However, as is discussed in the next chapter, although carbon dioxide transport by pipelines is the most economical way, it is only feasible for great amounts of gas. For this reason, barges and ships can be considered as a first step, to begin developing carbon storage facilities, to transport small carbon dioxide amounts, until the needed pipeline infrastructure is developed.

Additionally, to storage approaches, Lithuania must proactively develop CO₂ utilisation technologies as part of the broader CCS framework. By converting captured biogenic CO₂ into marketable products such as synthetic fuels, chemical precursors, and construction materials, Lithuania can promote circular economy principles. Facilitating industrial partnerships and providing incentives for adopting these innovative technologies at a commercial scale will help ensure their practical viability and market competitiveness.

Direct electrification of industrial processes, supported by the expansion of renewable energy infrastructure, such as solar photovoltaic and wind power installations, will substantially decrease carbon emissions. Additionally, incorporating hydrogen solutions for industrial applications and energy storage will further complement these renewable strategies and reinforce Lithuania's decarbonisation efforts.

Lastly, the establishment of specialized educational initiatives and dedicated training programs is essential for developing local expertise in CCUS and other emerging green technologies. Creating focused academic and vocational training platforms will ensure a steady supply of qualified professionals to support Lithuania's ambitious transition towards industrial decarbonisation and achieving its climate neutrality objectives.

7.4. Cost-benefit analysis of carbon transport and storage

Many climate models tend to simplify the costs of moving and storing CO₂ using a flat estimate of US\$10 per tonne, for example, the IPCC Fifth Assessment Report¹⁶⁰. But these costs can vary significantly depending on the project and location, ranging from US\$4 up to US\$45 per tonne¹⁶¹. This wide range shows that the US\$10 figure might work in some areas but is inaccurate in others. As a result, early carbon capture and storage projects are likely to happen first in places where it is cheaper to build pipelines and store CO₂. These low-cost areas will get a head start for the development of this technology, while regions with higher costs will face more hurdles, needing stronger government support or breakthroughs in technology to compete¹⁶¹.

Carbon transport costs

The cost of transporting CO₂ plays a major role in determining the feasibility of CCUS projects, with pipelines generally offering the lowest costs for large, steady flows over short to medium distances.

¹⁶⁰ Source: Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2014: Mitigation of Climate Change*. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

¹⁶¹ Source: SMITH, Erin; MORRIS, Jennifer; KHESHGI, Haroon; TELETZKE, Gary; HERZOG, Howard; PALTSEV, Sergey. *The cost of CO₂ transport and storage in global integrated assessment modelling*. International Journal of Greenhouse Gas Control. Volume 109, July 2021, 103367. <https://doi.org/10.1016/j.ijggc.2021.103367>

CO₂ pipelines are considered as a mature technology and have been extensively used for enhanced oil recovery in oil fields. The cost of CO₂ transport can be calculated based on the cost of natural gas pipelines. Indeed, natural gas and CO₂ transport cost by pipeline depend mostly on distance and pipe length. However, generally, CO₂ pipelines are more expensive, as this gas is transported at higher pressure, and the pipeline has to be thicker than natural gas ones. For this reason, the use of existing natural gas pipelines to transport CO₂ is only feasible for small amounts of CO₂, at a low pressure, and short distances.

Pipeline transport benefits strongly from economies of scale to reduce per-tonne of CO₂ cost as volume increases. However, the initial capital investment required is extremely high, making pipelines more suitable for mature CCS networks with centralized infrastructure.

According to different studies, the cost of CO₂ transport by pipeline ranges from US\$50,000 to US\$100,000, for a 100-mile onshore pipeline in the USA.

The cost also depends on the pressure, as shown in the following graph:

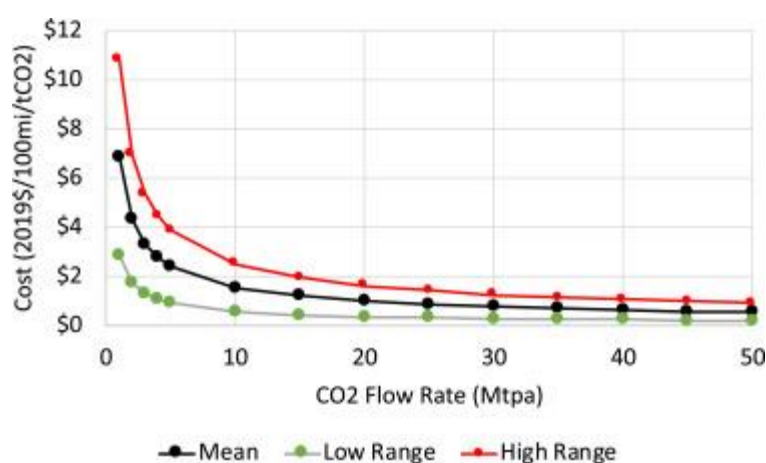


Figure 25. Cost of CO₂ transport by pipeline, in US\$₂₀₁₉/100 miles and tonne CO₂¹⁶¹.

As can be seen, the cost is lower as the pressure grows. At very low pressure, transport cost by pipeline can reach a maximum of US\$₂₀₁₉ 11/100 miles and tonne CO₂. However, the minimum cost is before US\$₂₀₁₉ 1/100 miles and tonne CO₂.

A similar assessment, focused on the European market, was carried out by the Zero Emissions Platform. In this case, a standard pressure of 200 bar is considered inlet and 60 bar outlet. The cost of transporting CO₂ by an onshore pipeline is reduced as the capacity of the pipeline increases, as shown in the following figure, which compares the transport costs by pipeline of a carbon dioxide flow of 2.5 tonnes of CO₂ per year, 10 Mt of CO₂ per year and 20 Mt of CO₂ per year:

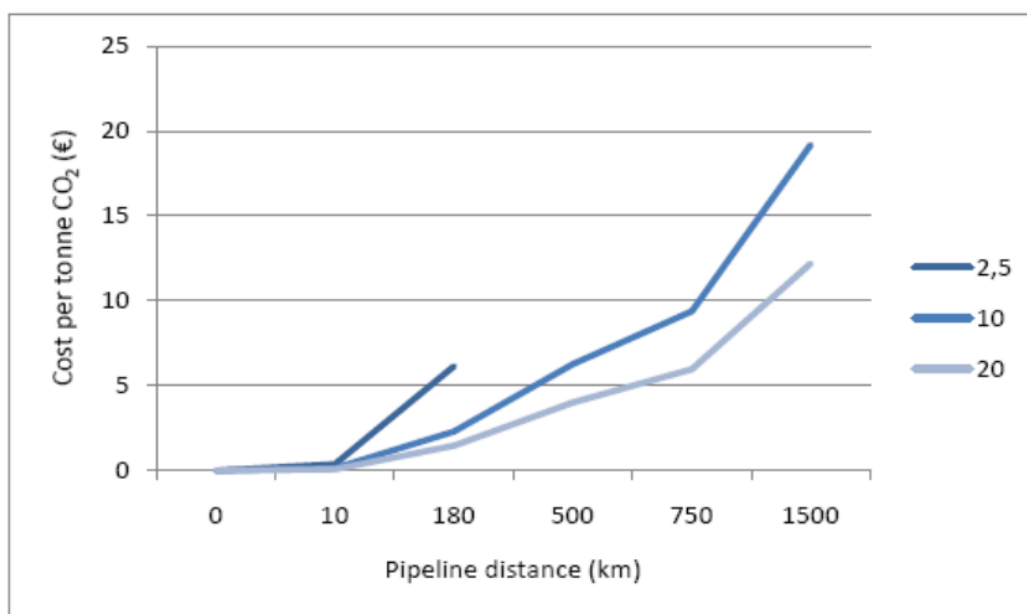


Figure 26. Cost of CO₂ transport by onshore pipeline, depending on the pipeline distance¹⁶²

For offshore routes or smaller volumes, costs are notably higher. They depend on distance, pressure and amount of CO₂ transported. However, costs can be reduced by using economies of scale and sharing infrastructure. Offshore pipelines can cost 50% to 100% more than onshore pipelines¹⁶³, although the use of pipeline networks can reduce costs up to 75%¹⁶⁴.

In the European market, the transport cost per tonne of CO₂ in offshore routes decreases with the pipeline capacity. When the distance is higher, there are relevant economies of scale derived from using pipelines with larger capacities. For example, the following figure shows the difference between a pipeline with a capacity of 2.5 Mt of CO₂ per year, 10 Mt of CO₂ per year and 20 Mt of CO₂ per year.

¹⁶² Source: ZEP. European Technology Platform for Zero Emission Fossil Fuel Plants. *CO₂ Transport Cost*. 2011.

¹⁶³ Source: CO2Europe. *Towards a Transport Infrastructure for Large-Scale CCS in Europe: WP3.3 Report – Legal, Financial, and Organizational Aspects of CO₂ Pipeline Infrastructure*, May 2011. European Commission. 7th Framework Programme.

¹⁶⁴ Source: ZAPANTIS, Alex; TOWNSEND, Alex; RASSOOL, Dominic. *Policy Priorities to Incentivise Large Scale Deployment of CCS*. 2019. Global CCS Institute.

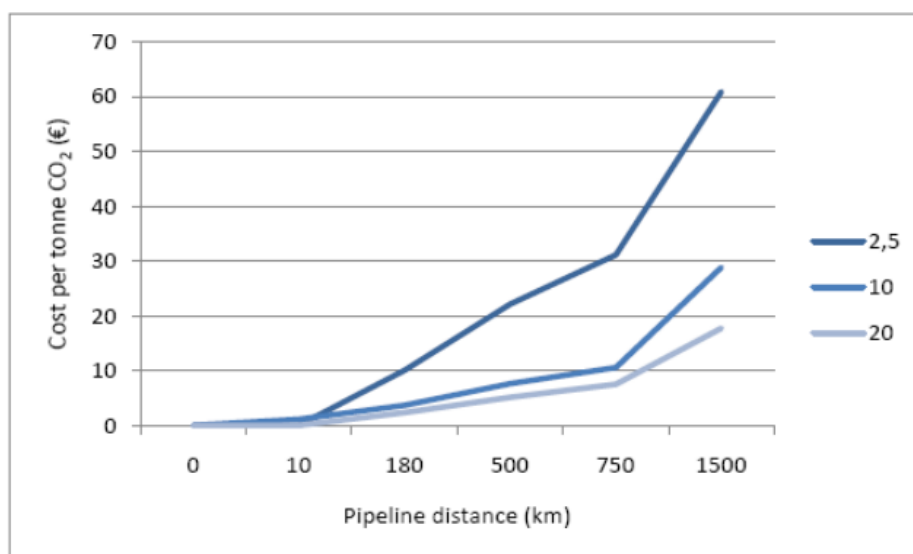


Figure 27. Cost of CO₂ transport by offshore pipeline, depending on the pipeline distance¹⁶⁵

The economic break-even point where pipelines become more cost-effective than alternatives like trucking lies at around 0.5 to 0.6 million tonnes of CO₂ per year, reinforcing that pipelines are not the best solution for early-stage or small-scale deployments.¹⁶⁶

For smaller volumes or regions without pipeline infrastructure, alternative transport modes become essential. Barges and ships offer reasonable costs over both short and long distances, with relatively stable pricing regardless of length. Rail can outperform trucking for long hauls, while trucking remains the most flexible and cost-effective option for short distances and dispersed sources. However, these modes are more sensitive to energy prices and labour costs, and they require additional expenses for CO₂ liquefaction. As a result, effective CCS deployment will depend on a transport system that integrates different options to match project size, geography, and development phase. Strategic planning, infrastructure flexibility, and early investments in transloading hubs and storage will be critical to scale up CCS in a cost-efficient way.

Shipping is not very employed to transport CO₂, but as commented, is considered for very short or very long distances and smaller amounts of CO₂. Transport costs by shipping rely mostly on liquefaction costs, while the cost of increasing the distance is not so relevant. Transport costs by pipeline, instead are very influenced by distance.

The following figure shows the estimation of the transport costs by ship, for a standard carbon dioxide transported volume of 2.5 Mt per year.

¹⁶⁵ Source: ZEP. European Technology Platform for Zero Emission Fossil Fuel Plants. *CO₂ Transport Cost*. 2011.

¹⁶⁶ Source: Roads2Removal. Options for Carbon Dioxide Removal in the United States. Chapter 5: CO₂ and Biomass Transport. 2025. Livermore Lab Foundation. https://roads2removal.org/wp-content/uploads/05_RtR_CO2-Biomass-Transport.pdf

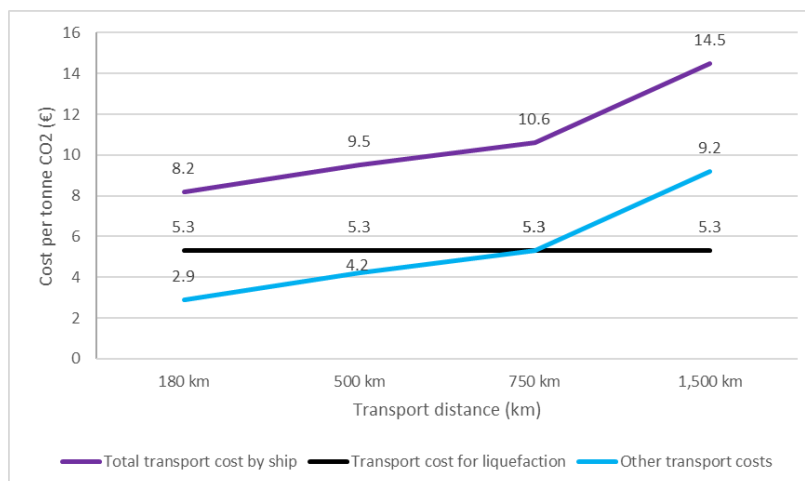


Figure 28. Cost of CO₂ transport by boat, depending on the distance, for a network of 2.5 Mt per year¹⁶⁷

As can be seen from the figure shown before, the transport cost by boat does not depend very largely on distance. Instead, there is an initial unavoidable cost, liquefaction, which reaches around 5.3 € per tonne of CO₂. The cost of transporting 1 tonne of CO₂ along 1,500 km is only 77% higher than the cost of transporting this amount along 180 km.

If these figures are compared to transport by onshore and offshore pipeline, offshore pipelines are not competitive for these amounts of transported carbon dioxide. However, onshore pipelines can be competitive for very short distances. The choice between onshore and offshore pipelines depends on the way to transport the carbon dioxide from the origin to the carbon storage formation. In principle, the length of offshore pipelines should be minimized, except if there are other aspects to be considered, such as the need to avoid protected natural areas.

If a larger amount of transported carbon dioxide, for example 20 Mt per year is considered, and the three alternative means of transport are compared, the following conclusions can be obtained from this figure:

¹⁶⁷ Source: European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP). *The Costs of CO₂ Capture, Transport and Storage. Post-demonstration CCS in the EU*. July 2011. <https://www.globalccsinstitute.com/archive/hub/publications/17011/costs-co2-capture-transport-and-storage.pdf>

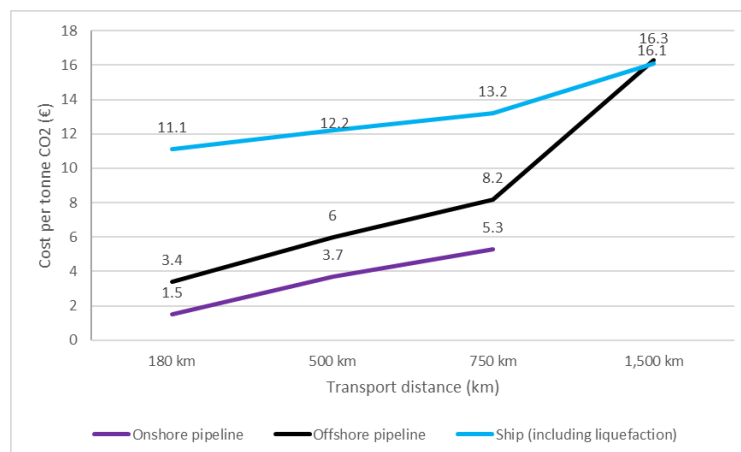


Figure 29. Cost of CO₂ transport by boat, onshore pipeline and offshore pipeline depending on the distance, for a network of 20 Mt per year¹⁶⁸

As can be seen from this figure, once the carbon capture and storage technologies are commercially developed, pipelines can benefit from economies of scale, compared to the results of 2.5 Mt per year. However, this effect is not applicable to shipping.

Shipping becomes more profitable when distances grow. For example, for a distance longer than 1,500 km, onshore pipelines are not applicable, and offshore pipelines become more expensive than shipping.

To offer some approximate figures for transport by pipeline and boat, it is possible to take a range between €5 and €25/tonne of CO₂ for pipelines, and €10-50/tonne of CO₂ for boat, however, as has been discussed before, there are many factors which should be considered.

As for railway, the transport costs ranges from €10/tonne of CO₂ to €60/tonne of CO₂. Transport cost by truck, on the other hand, can vary from €15/tonne of CO₂ to €42/tonne of CO₂, approximately. These two options can compete with onshore pipeline, if the amounts of CO₂ to be transported are low¹⁶⁹. As a conclusion, in the first steps of development of carbon capture and storage, the combination of shipping and pipelines can be appropriate for modest volumes of transported CO₂. However, for short and medium distances, and for large volumes of CO₂, pipelines are most cost-effective.

Storage costs

Most of the CO₂ storage potential is located in onshore and offshore saline aquifers. Generally, as happens with pipeline cost, the cost of CO₂ offshore storage is higher than CO₂ onshore storage. To store carbon dioxide in a saline aquifer, it is necessary to drill different wells, such as exploration, injection and monitoring. Drilling these wells make most of the overall storage costs.

¹⁶⁸ Source: European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP). *The Costs of CO₂ Capture, Transport and Storage. Post-demonstration CCS in the EU*. July 2011. <https://www.globalccsinstitute.com/archive/hub/publications/17011/costs-co2-capture-transport-and-storage.pdf>

¹⁶⁹ Source: European Commission, Joint Research Centre, MARTINEZ CASTILLA, G., TUMARA, D., MOUNTRAKI, A., LETOUT, S., JAXA-ROZEN, M., SCHMITZ, A., INCE, E. AND GEORGAKAKI, A., *Clean Energy Technology Observatory: Carbon Capture, Utilisation and Storage in the European Union - 2024 Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg, 2024, <https://data.europa.eu/doi/10.2760/0287566, JRC139285>.

It has been said that using depleted oil and natural gas fields to store CO₂ is cheaper than using saline aquifers, as the geology of oil and natural gas fields is much better studied. However, these savings can be balanced with failures in old infrastructure, or damages to the field derived from the extraction of oil and natural gas, and leakages through existing wells.

There are several factors that determine the cost for storage:

- Size of the project: The economies of scale of larger projects tend to lower the cost per tonne because they can spread fixed costs over more CO₂, particularly when pipelines and big storage sites are used. The use of CO₂ hubs, this is, industrial centres which make use of the same CO₂ transport and storage infrastructure, can reduce these costs.
- Monitoring requirements: Long-term safety and oversight of stored CO₂ adds to the fixed operation cost of storage sites, some geographies may require additional monitoring measures to prevent CO₂ leaks.
- Number of injection and monitoring wells which are needed.
- Geology of the storage site: The characteristics of underground rock, permeability, thickness of the reservoir or aquifer, porosity, lateral continuity, storage depth and complexity for injecting CO₂ influence the final storage cost. They also affect the total amount of CO₂ which can be stored, and the CO₂ pressure buildup. For example, storage costs are lower for a reservoir which is permeable, porous and thick.
- Upfront investment in infrastructure: Building the transport systems, especially pipelines, requires a lot of capital up front, which plays a major role in overall cost.
- Location of the project: Labor, drilling, capital and other costs vary regionally.
- Regulation: Different regulatory framework can impact the long-term liability of CO₂ storage, and the duration of the carbon storage monitoring period.

The primary determinants for the costs of CO₂ storage are the location and specific type of storage site, as well as reservoir capacity and quality. Larger reservoirs are inherently cheaper on a per-tonne basis than smaller ones due to economies of scale in development and operation. High injectivity, which refers to the rate at which CO₂ can be injected into the reservoir, leads to lower costs compared to sites with poor injectivity, as it reduces the number of wells required and operational energy. Sensitivity analysis consistently indicates that field capacity has the largest or second largest effect on costs across all storage cases.

Cost Ranges Across Storage Types

The broad, observed cost range for CO₂ storage varies significantly from €1 to €20/tonne of CO₂, with an average of €10/tonne of CO₂. This wide range is further refined when considering specific geological formations and locations:^{170, 171}

¹⁷⁰ Source: Global CCS Institute. European Technology Platform for Zero Emission Fossil Fuel Power Plants. Zero Emissions Platform and IEAGHG. *The Costs of CO₂ Capture, Transport and Storage. Post-demonstration CCS in the EU. Zero Emissions Platform*.

¹⁷¹ Source: European Commission, Joint Research Centre, MARTINEZ CASTILLA, G., TUMARA, D., MOUNTRAKI, A., LETOUT, S., JAXA-ROZEN, M., SCHMITZ, A., INCE, E. AND GEORGAKAKI, A., Clean Energy Technology Observatory: *Carbon Capture, Utilisation and Storage in the European Union - 2024 Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg, 2024, <https://data.europa.eu/doi/10.2760/0287566, JRC139285>.

- Depleted oil and gas fields (DOGF):
 - Onshore DOGF: €1-7/tonne if existing infrastructure is re-used, and €1-10/tonne if there is not any existing infrastructure which can be used.
 - Offshore DOGF: €2-9/tonne if existing infrastructure can be re-used, and €3-14/tonne if there is not any existing infrastructure which can be used.
- Deep saline aquifers (SA):
 - Onshore SA: €2-12/tonne.
 - Offshore SA: €6-20/tonne.

In the United States, the average storage costs range between €5 and €15/tonne of CO₂, both in saline aquifers and depleted oil and gas fields¹⁷².

A clear trend emerges: onshore storage is consistently cheaper than offshore options and Depleted Oil and Gas Fields are generally cheaper than Saline Aquifers due to reduced drilling and infrastructure costs. Notably, Offshore Saline Aquifers typically exhibit the highest costs and the widest cost range among all storage types, despite often offering the largest potential capacities. Monitoring costs are also identified as a key source of cost variability, reflecting the need to account for potential liabilities associated with ensuring the permanent containment and safety of stored CO₂. Monitoring costs, for a commercial scale project with a capacity of 1 Mtpa, can reach between US\$1 million and US\$4 million per year¹⁷³.

7.5. Results from the stakeholder interviews

Structured interviews with important industrial stakeholders in Kaunas, Akmenė, and Šiauliai Counties revealed several consistent insights regarding CO₂ capture and utilization. It is important to mention that about 80 requests were submitted to fill up questionnaires, however only 4 answers were received back. Important and very detailed answers from glass, fertilizers and power plants were received. First, while technical feasibility is generally acknowledged—high-purity process streams and relatively concentrated flue gases lend themselves to established capture technologies—economic viability remains the dominant concern. Stakeholders noted that even when capturing nearly pure CO₂ (as in chemical synthesis processes), the combined capital and operating costs for separation, compression, and transport often outweigh perceived benefits under current energy and carbon-pricing conditions. For lower-concentration streams (such as those from boiler exhausts), the energy penalty for capture further erodes the business case, making early adoption unlikely without substantial financial support.

A second recurring theme was the preference to prioritize biogenic CO₂ sources. Facilities burning biomass or processing wood residues produce carbon-neutral emissions that can be captured at relatively low energy cost, since biogenic CO₂ streams do not carry ETS liabilities and can be counted toward negative-emission goals. By retrofitting capture units onto these biomass-fed boilers or biomass-derived fuel plants, companies could develop operational know-how and establish initial transport and utilization networks. Many interviewees believed that demonstrating successful biogenic capture would de-risk subsequent investments in fossil CO₂ capture, while also providing feedstock for

¹⁷² Source: SMITH, E.; MORRIS, J.; KHESHGI, H.; TELETZKE, G.; HERZOG, H. and PALTSEV, S. *The cost of CO₂ transport and storage in global integrated assessment modeling*. Int. J. Greenh. Gas Control, vol. 109, p. 103367, 2021, doi: 10.1016/j.ijggc.2021.103367.

¹⁷³ Source: IEAGHG. *Monitoring and Modelling of CO₂ Storage: The Potential for Improving the Cost-Benefit Ratio of Reducing Risk* IEAGHG Technical Report. 2020. Available: www.ieaghg.org.

value-added products—such as synthetic fuels or carbonate-based building materials—thereby creating early revenue streams.

Third, regulatory and infrastructure uncertainties were cited as major deterrents. Current legislation prohibits domestic geological CO₂ storage, leaving stakeholders unsure about long-term options for captured volumes. Without clarity on permitting, liability, and ownership of storage sites, companies are reluctant to commit to pilot projects. Likewise, the lack of shared transport infrastructure—pipelines or centralized compression hubs—forces each plant to consider stand-alone solutions, which dramatically increases per-tonne costs. Consensus emerged that a regional, clustered approach to transport—linking several high-emitting facilities to a common capture corridor—would lower barriers and create scale advantages.

Interviewees suggested several priority actions to move CCUS forward. They emphasized the need for targeted financial instruments—low-interest loans or cost-sharing grants for first-of-a-kind capture installations—to bridge the gap between technical readiness and commercial deployment. For ongoing costs, per-tonne capture subsidies or guaranteed offtake contracts (for example, purchasing captured CO₂ for synthetic fuel or chemical synthesis) would improve predictability and investor confidence. Many also recommended structured partnerships with research institutions to conduct site-specific techno-economic studies, quantify actual capture volumes, and optimize heat integration in capture processes. These studies would clarify trade-offs, highlight integration synergies, and support more accurate long-term planning.

Finally, stakeholders called for urgent regulatory reform—namely, lifting the ban on experimental geological storage, creating a transparent national CO₂ registry to track capture and distinguish biogenic versus fossil emissions, and streamlining permitting for pilot CCU/CCS projects. Parallel to legal changes, early investments in feasibility assessments of domestic storage sites (such as deep saline aquifers) would signal government commitment and catalyse private interest. By aligning financial incentives, clarifying legal frameworks, and planning shared transport infrastructure, Lithuania can build momentum—starting with biogenic capture pilots and progressing toward integrated, large-scale capture at fossil-fuel-based chemical, cement, and energy-generation facilities—thereby charting a pragmatic path to meet mid-century decarbonization targets.

As a result of these conditions, two carbon inland storage scenarios are suitable for Lithuanian conditions, which require different assessment strategies. The first group of potential storage sites consists of saline aquifers. The second type includes anticline-type structures, including oil fields. Anticline-type structures are the safest, (the presence of impermeable materials sealing the potential storage CO₂ formation makes anticlines safer than other structures) but their potential is limited compared to saline aquifers. As the experience of long-term research in Lithuania shows, higher closed elevations are only common in the Cambrian saline aquifer.

However, according to Šliaupa et al.¹⁷⁵, offshore options of CCS for Lithuania are limited, and their storage potential has low estimates. Nevertheless, storage in the Baltic Sea has been studied (structure D11) and very close to Lithuania there is structure D6 (Latvia) which could storage CO₂ derived from Lithuanian industry. Only one Lithuanian offshore structure is considered here due to its size and potential storage. The other ones are much smaller with very low capacity and no storage possibilities.

8.1.1. Geological formations fit for CO₂ storage

Geological formations capable of storing CO₂ are characterized mainly by their porosity, thickness, rock type, depth, permeability, and sealing capacity among others. These formations include saline aquifers, depleted oil and gas fields, and unconventional resources such as basalts and coal seams.

Saline Aquifers

These formations account for 98% of global theoretical storage capacity. Their widespread availability makes them critical for large-scale deployment and long-term storage, although the lack of detailed assessments and that they remain underexplored, hinders immediate development¹⁷⁶.

According to the conditions of temperature and pressure, there are two promising saline aquifers in the territory of Lithuania: Cambrian and Pärnu-Kemeri (Lower Devonian and Lower-Middle Devonian) (Figure 31). Other aqueous layers common in the Lithuanian basins show lower temperature and pressure than those required to have CO₂ in supercritical conditions; therefore, CO₂ burial is not possible in them.

¹⁷⁶ Source: IEAGHG. 2009. *Development of Storage Coefficients for CO₂ Storage in Deep Saline Formations*. 2009. IEA Greenhouse Gas R&D Programme. Report No. 2009/13.

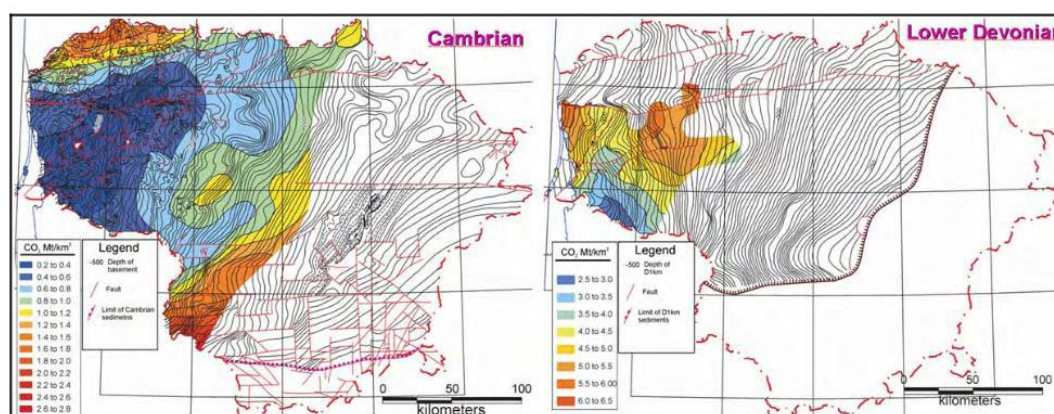


Figure 31: Regional storage capacity of Cambrian (left) and Lower Devonian (right) saline aquifers, onshore Lithuania¹⁷⁷.

It has to be considered that a number of parameters were evaluated when studying the CO₂ disposal potential of Lithuanian depths. Temperature measurement data of 160 deep wells were used to determine the temperature regime and the hydrostatic pressure information was reviewed. The reservoir porosity database consists of over 10,000 porosity and permeability measurements¹⁷⁸, and the Devonian reservoir database contains several hundred measurements. The water mineralisation database consists of: Cambrian reservoir - 170 wells, Lower Devonian and Pärnu- Kemeru reservoir - 75 wells, Upninkai-Šventoji – 1,300 wells. As mentioned above, other saline aquifers were not analysed because they are in unfavourable thermobaric conditions. Assessing the potential of local traps in the Cambrian reservoir, 72 structures on land and 30 structures in the Baltic Sea were inventoried.

According to the thermobaric characteristics, the **Cambrian saline aquifer** shows the most favourable conditions (Tables 6-8). The deep saline Cambrian aquifer matches the basic requirements to a reservoir for CO₂ sequestration^{179, 180, 181, 182}. It represents the basal part of the sedimentary cover and is the most tectonized (though to a minor degree) layer in the region (Stirpeika, 1997). Accordingly, a number of structural traps have been identified. The reservoir is well studied owing to petroleum prospects in West Lithuania. The reservoir is sealed by 400–800 m thick carbonaceous-shaly cap rocks;

¹⁷⁷ Source: European Commission. Sixth Framework Programme. Storage Capacity. Project no.: SES6-518319. EU GeoCapacity project- Assessing European Capacity for Geological Storage of Carbon Dioxide. D16. WP2 Report. Storage Capacity. January 2009.

¹⁷⁸ Source: ŠLIAUPA, S., LOJKA, R., TASÁRYOVÁ, Z., KOLEJKA, V., HLADÍK, V., KOTULOVÁ, J., KUCHARIČ L., FEJDI, V., WÓJCICKI, A., TARKOWSKI, R., ULIASZ-MISIAK, B., ŠLIAUPIENĖ, R., NULLE I., POMERANCEVA, R., IVANOVA, O., SHOGENOVA, A., SHOGENOV, K. *CO₂ storage potential of sedimentary basins of Slovakia, the Czech Republic, Poland and the Baltic States*. 2013. Geological Quarterly. Vol. 57(2), 219–232, doi: 10.7306/gq.1088

¹⁷⁹Source: SHOGENOVA A ., ŠLIAUPA S., SHOGENOV K., VAHER R., ŠLIAUPIENĖ R. *Geological Storage of CO₂ – Prospects in the Baltic States*. 2007. 69th EAGE Conference and Exhibition, Incorporating SPE EUROPEC, London, Extended Abstracts, EAGE 2007.

¹⁸⁰ Source: Source: SHOGENOVA A ., ŠLIAUPA S., SHOGENOV K., ŠLIAUPIENĖ R., VAHER R., ZABELE A . *Carbon Dioxide Geological Storage Potential of the Baltic Sedimentary Basin*. 2008. 3rd Saint Petersburg International Conference and Exhibition, April 7th- 10th, 2008, European Association of Geoscientists and Engineers, Extended Abstract and Exhibitors Catalogue, 1–5: 132.

¹⁸¹ Source: SHOGENOVA, A., ŠLIAUPA, S., SHOGENOV, K., ŠLIAUPIENĖ, R., POMERANCEVA, R., VAHER, R., UIBU, M., KUUSIK, R. *Possibilities for geological storage and mineral trapping of industrial CO₂ emissions in the Baltic region*. 2009. Energy Procedia. Vol. 1, 2753-2760.

¹⁸² Source: ŠLIAUPA, S., SHOGENOVA, A ., SHOGENOV K., ŠLIAUPIENĖ R., ZABELE A ., VAHER R. *Industrial carbon dioxide emissions and potential geological sinks in the Baltic States*. 2008. Oil Shale Vol. 25(4), 465–484.

this is important for a safe storage of CO₂. The depth of the Cambrian sediments ranges from 0.3 km in Southeast Lithuania to more than 2 km in West Lithuania (Figure 30). The prospective area, in terms of P-T conditions, encompasses the western part of Lithuania and extends to West Latvia, Kaliningrad District and offshore (Figure 32).

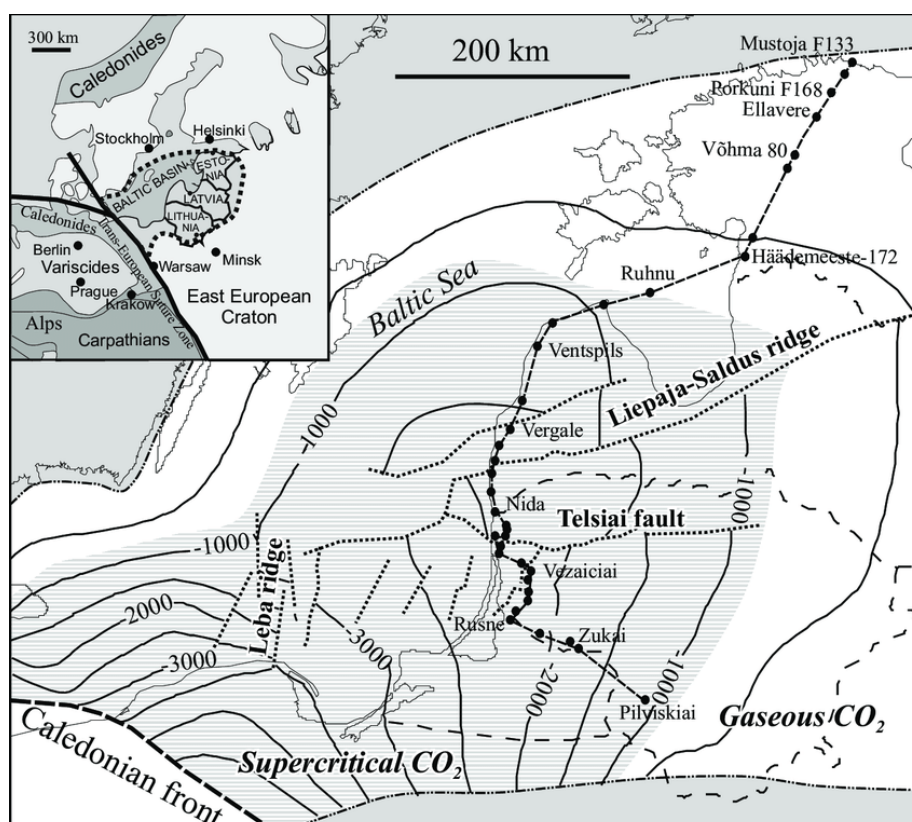


Figure 32: Structure map of the Baltic Basin¹⁸². The contour lines indicate the depth of the top of the Cambrian saline aquifer. The dotted lines denote major faults. The pressure-temperature fields of gaseous (white) and supercritical (hatched) state of CO₂ are shown.¹⁷⁴

The reservoir is composed of quartz sandstones with rare shale and siltstone layers. The thickness of the reservoir is about 40–60 m. The formation water is of Na–Cl type and salinity is in the range 100–200 g/l within the prospective area.

The reservoir properties are decreasing westward mainly due to an increase in quartz cementation. The average porosity is about 22% in Central Lithuania and less than 10% in West Lithuania.

The critical isotherm of 32°C is in central Lithuania, whereas in the west part temperature reaches 70–85°C¹⁸³. This high-temperature area roughly coincides with the pressure range higher than 7.8 MPa, and in western Lithuania it reaches up to 20 MPa (Figure 33). Thus, the entire western side of Lithuania is promising in this aspect as CO₂ has to be in supercritical state. In the eastern part of Lithuania, CO₂ would be in the gas phase, and it will only reach liquid state (between the 32°C isotherm and the 7.8 MPa isobar) in a small area (Figure 32). The Cambrian reservoir consists primarily of the Middle Cambrian Deimena Sandstone Formation, which is present both in western and central Lithuania. In addition, suitable Lower Cambrian sandstone units are also found in central areas, contributing to the

¹⁸³ Source: ŠLIAUPIENĖ, R., ŠLIAUPA, S. *Prospects for CO₂ Geological Storage in Deep Saline Aquifers of Lithuania and Adjacent Territories*. 2012. Geologija. Vol. 53, 121–133.

overall reservoir potential. The thickness varies from 20-30 to 60-70 m. Cambrian sandstone is characterised by decreasing porosity (19.5% to 24.5%¹⁸⁴) and permeability to the west, which is associated with greater depths of deposition. In general terms, in the Lithuanian context, the open porosity varies from an average of 25% to 16% at a depth range of 400-1,800 m, however, the Deimena Formation Middle Cambrian sandstones range 9.5-33.5% porosity (maximum-minimum)¹⁸⁵.

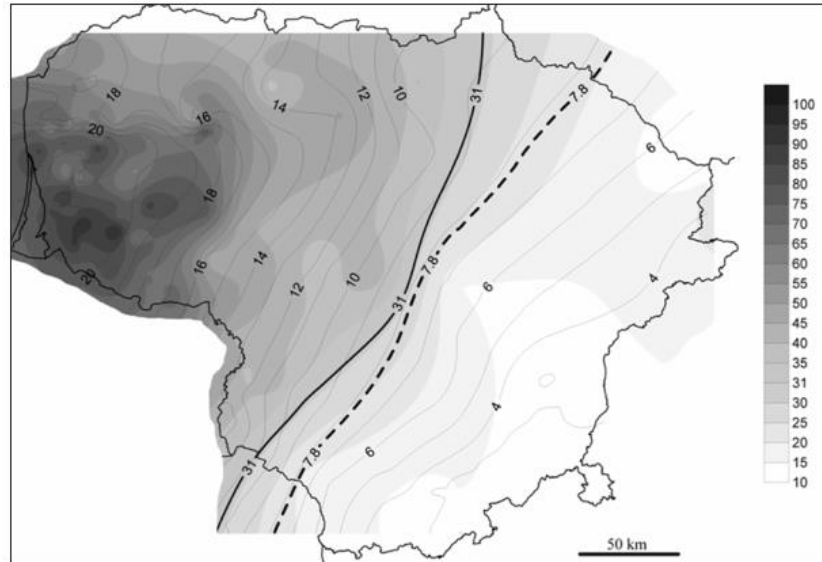


Figure 33: Hydrostatic pressure (contour lines, MPa) and temperature (grey colour scale, °C) of Cambrian saline aquifer¹⁸³

The storage potential of 76 uplifts defined in the Cambrian layer (saline aquifer) was assessed ¹⁸³ (Figure 34).

In a saline aquifer, the pore volume available for CO₂ storage (the effective storage capacity) depends on the geometric volume of the structural or stratigraphic trap down to the spill point, as well as on its porosity, sweep efficiency and the irreducible water saturation and is calculated using the following equation¹⁸⁶:

$$M_{CO_2} = A \times h \times \phi \times \rho_{CO_2} \times S_{eff} \times S_{Wirr} \text{ [eq. 1]}$$

where:

- M_{CO_2} : Effective storage capacity
- A: Area of trap.

¹⁸⁴ Source: MALIK, S., MAKASKAS, P., SHARMA, R., PAL, M. *Evaluating Petrophysical Properties Using Digital Rock Physics Analysis: A CO₂ Storage Feasibility Study of Lithuanian Reservoirs*. 2024. Applied Sciences. Vol. 14(23), 10826. <https://doi.org/10.3390/app142310826>

¹⁸⁵ Source: SHOGENOV, K; SHOGENOVA, A; VIZIKA-KAVVADIAS, O. *Potential structures for CO₂ geological storage in the Baltic Sea: case study offshore Latvia*. Bulletin of the Geological Society of Finland. 2013. doi:10.17741/bgsf/85.1.005

¹⁸⁶ Source: Task Force on CO₂ Storage Capacity Estimation for the Technical Group (TG) of the Carbon Sequestration Leadership Forum (CSLF). *Phase II Final Report from the Task Force for Review and Identification of Standards for CO₂ Storage Capacity Estimation*. June 15th, 2007. <http://www.cslforum.org/publi cations/docu ment/PhaseIIReport - StorageCapacityMeasurementTaskForce.pdf>

- h : Average thickness of trap multiplied by the net-to-gross ratio.
- ϕ : Average saline aquifer porosity.
- ρ_{CO_2} : CO_2 density at saline aquifer conditions.
- S_{eff} : Sweep efficiency (fraction of porewater that can be replaced by injected CO_2).
- S_{Wirr} : Irreducible water saturation.

The storage capacity of hydrocarbon fields has been estimated as suming 1:1 volumetric replacement ratio between hydrocarbons and CO_2 :

$$M_{CO_2} = \rho_{CO_2} \times URp \times B \text{ [eq. 2]}$$

where:

- M_{CO_2} : Hydrocarbon field effective storage capacity.
- ρ_{CO_2} : CO_2 density at reservoir conditions (best estimate).
- URp : the volume of proven ultimate recoverable oil or gas.
- B : the oil or gas formation volume factor.

However, many of these structures are small-scale and not suitable for storing CO_2 . Only two structures consisting of saline aquifers onshore (Syderiai and Vaškai) and one offshore (D11) are large enough to be considered prospective for CO_2 storage.

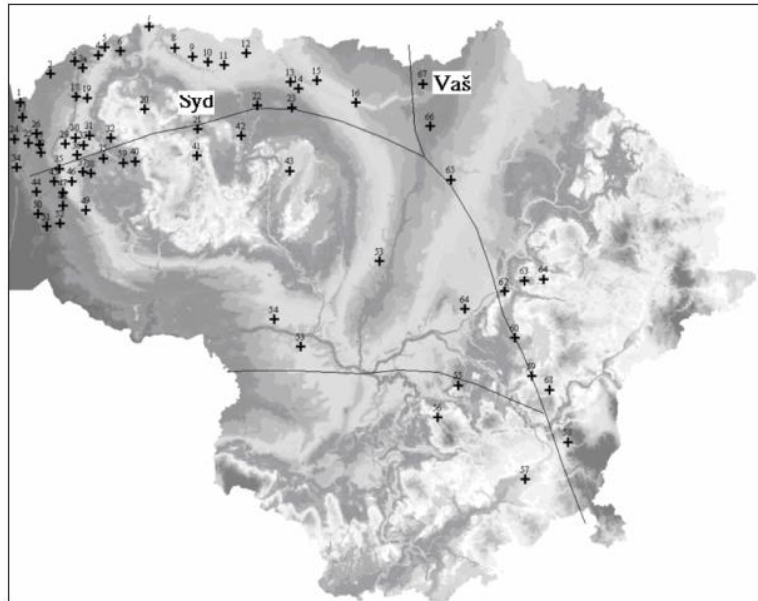


Figure 34: Local uplifts (crosses) of the Cambrian saline aquifer assessed for CO_2 storage in Lithuania (surface shown as a background). Syderiai (Syd) and Vaškai (Vaš) structures, which were selected as potential CO_2 reservoirs, are marked.

Major gas pipelines are shown¹⁸³

The onshore structures (Figure 35) with the capacity of 0.1–0.2 Mt of CO_2 comprise 13% of the assessed uplifts (Figure 34); structures of 0.2–0.4 Mt capacity comprise 14%, 0.4–0.7 Mt 24%, 0.7–1 Mt 13%, 1–2 Mt 20% and 2–5 Mt 12%¹⁸³. The total storage capacity is 102 Mt of CO_2 .

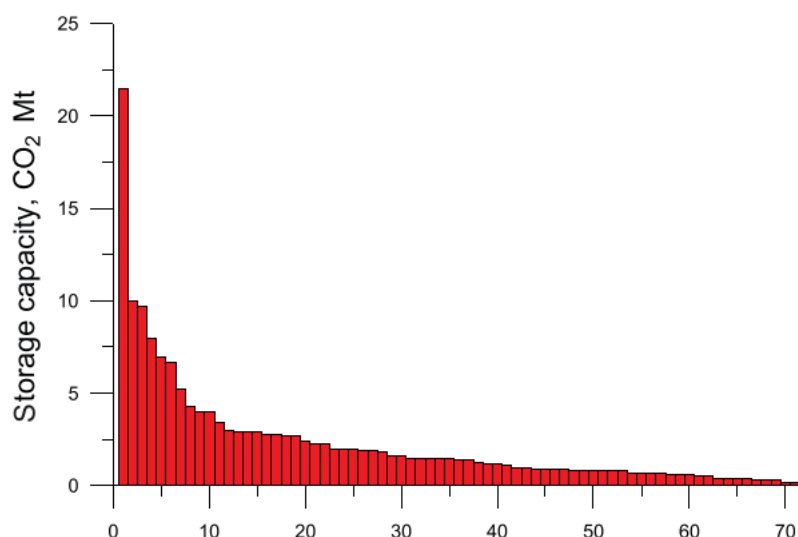


Figure 35: Storage capacity of Cambrian structures of Lithuanian onshore (76 structures)¹⁸⁷

The **Pärnu–Kemerī saline aquifer** (Middle–Lower Devonian) is distributed in Central and West Lithuania. The depths exceeding 800 m and a temperature higher than 31°C have been reported from only westernmost Lithuania and the adjacent Baltic Sea (Figure 37). The saline aquifer is composed of quartz and feldspar-quartz fine-grained sandstones with siltstone and shaly layers composing 30–40% of the succession. The average porosity of sandstones is 26%, and the permeability is in the range 0.5–4 mD. The total thickness varies from 100 m in the east to 160 m in the west of Lithuania and in the adjacent offshore. The saline aquifer is covered by 80–120 m thick marlstones with subordinate dolomites and strongly cemented sandstones attributed to the Narva Formation of the Middle Devonian. It is a basin-scale aquitard which separates the Pärnu–Kemerī saline aquifer from the overlying Šventoji–Upninkai saline aquifer extensively used for drinking water supply. The salinity of the Pärnu–Kemerī formation water in West Lithuania is 40–90 g/l.

Despite the high quality of the reservoir, the Pärnu–Kemerī saline aquifer is not considered as prospective for CO₂ storage as hydrodynamic traps (structures) are required to store CO₂. Based on seismic and drilling data, only small-scale uplifts were identified; their amplitude did not exceed 15 m. Typical examples of Lower Devonian structures are shown in Figure 36.

The temperature and pressure exceed 32°C and 7.8 MPa. The maximum temperature on the ridge reaches up to 45°C, the pressure - 9 MPa, in some places (e.g. near Syderiai, along the lowered Telšiai fracture wing) it exceeds 10 MPa. CO₂ will be in a supercritical state here, while in central and eastern Lithuania it will be in a gaseous consistency (Figure 37). In the transition zone, CO₂ is in the liquid phase. The thickness of the saline aquifer reaches up to 190 metres in the northern part of western Lithuania (Paluknė-1 borehole). The Gargždai series below is characterised by poor reservoir properties, low-permeability siltstones predominate, abundant layers of clay and sandstone form a small part of the section. The saline aquifer of Pernu-Kemerī has good reservoir properties, the section is dominated by weakly cemented sandstone, the porosity of which is usually 25-30%. The permeability of sandstone is 0.5-4 mD - these are very good reservoir properties. Sandstone makes up 62- 67% of the saline aquifer section.

¹⁸⁷ Source: ŠLIAUPIENĖ, R., ŠLIAUPA, S. *Prospects for CO₂ Geological Storage in Deep Saline Aquifers of Lithuania and Adjacent Territories*. 2012. *Geologija*. Vol. 53, 121–133

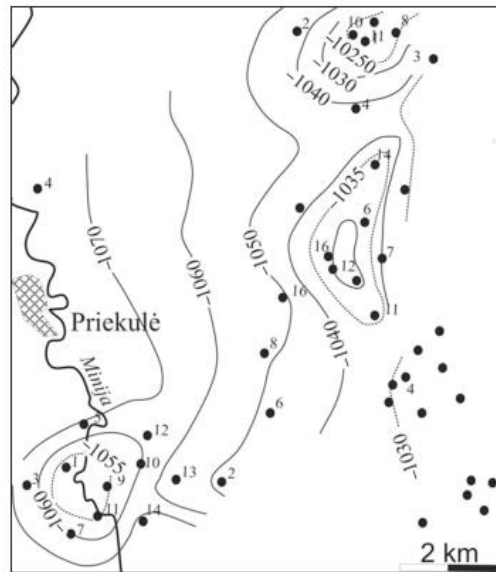


Figure 36: Structural map of Lower Devonian reservoir top. Several uplifts are defined in Gargždai area, West Lithuania.

The amplitude of local uplifts is 8–16 m¹⁸³.

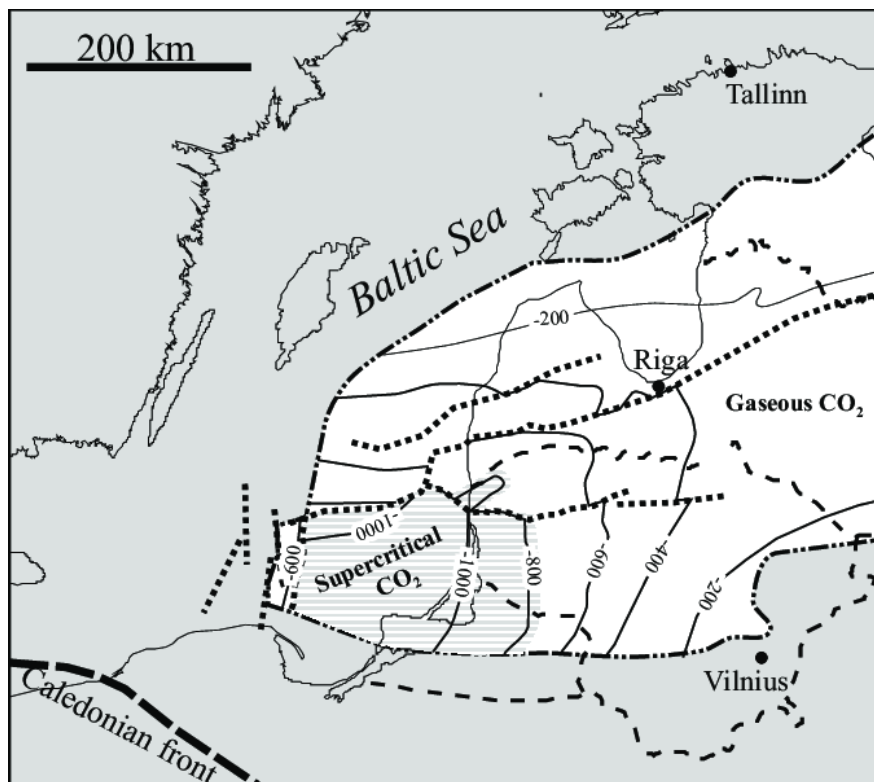


Figure 37: Depths of the top of the Lower-Middle (Pärnu-Kemer) saline aquifer¹⁸⁸, shown by contour lines. The dotted lines show major faults. The pressure temperature fields of gaseous (white) and supercritical (hatched) state of CO₂ are indicated.

¹⁸⁸ Source: ŠLIAUPA, S. *Potential of Geological Formations for CO₂ sequestration in Lithuania*. 2008.

Although the Middle Cambrian and the Lower-Middle Devonian saline aquifer systems are both appropriate for CO₂ storage due to the geological properties of media, the Lower-Middle Devonian saline aquifer system reaches the depths necessary for retaining CO₂ in its supercritical state only in Western Lithuania, and no prospective structural traps can be found within this system. At the same time, the depth of the Syderiai Cambrian saline aquifer system meets the depth requirements in Western Lithuania (especially good in Western and Central Latvia, Northern Poland), and the Baltic Sea¹⁸⁹. Thus, the Cambrian saline aquifer system undeniably has the highest CO₂ storage potential in comparison with other structures (Table 11). The geological conditions that meet the requirements for CO₂ storage is found in western Lithuania and the Baltic Sea. Even if it is possible to store CO₂ in the Lithuanian structural traps, they are too few and have a low overall storage capacity. The middle Cambrian reservoir within the Baltic sedimentary basin is known to have oil fields in the deeper parts of the basin—in Western Lithuania, Latvia, and the Baltic Sea^{190, 191}.

In brief, the largest structures in the territory of Lithuania are Syderiai and Vaškai, belonging to the Cambrian saline aquifer. Another large structure stands out in the Baltic Sea near the coast (5 km). The CO₂ storage potential of these structures is shown in Table 11 and will be described below.

Saline aquifer	X coordinates (WGS-84)	Y coordinates (WGS-84)	Formation	Age	Top depth (m)	Lithology	Capacity (Mt CO ₂)
Syderiai	22.43	55.92	Deimena	Middle Cambrian	1,458	Sandstone	21.5 (1) 56.7 (2) 54-232 (3)
Vaškai	24.25	56.07	Gégé-Deimena	Lower-Middle Cambrian	896	Sandstone	8.7 (1) 25-106 (3)
D11 (Baltic Sea)	20.9	56.02	Deimena	Middle Cambrian	1,700	Sandstone	11.3 (1) 17-69 (3)

Table 11: Characteristics of the main geological saline aquifers fit for storage in Lithuania (1)¹⁹², (2)¹⁹³, (3)¹⁹⁴

¹⁸⁹ Source: SHOGENOVA, A., ŠLIAUPA, S., SHOGENOV, K., ŠLIAUPIENĖ, R., POMERANCEVA, R., VAHER, R., UIBU, M., KUUSIK, R. *Possibilities for geological storage and mineral trapping of industrial CO₂ emissions in the Baltic region*. 2009. Energy Procedia. Vol. 1, 2753-2760.

¹⁹⁰ Source: Source: KRUMBEIN, W.C., MONK, G.D. *Permeability as a Function of the Size Parameters of Unconsolidated Sand*. 1943. Trans. AIME 1943, 151, 153–163.

¹⁹¹ Source: ALIYEV, E., SAIDIAN, M., PRASAD, M., RUSSELL, B. *Rock Typing of Tight Gas Sands: A Case Study in Lance and Mesaverde Formations from Jonah Field*. 2016. J. Nat. Gas Sci. Eng. 33, 1260–1270.

¹⁹² Source: ŠLIAUPIENĖ, R., ŠLIAUPA, S. *Prospects for CO₂ Geological Storage in Deep Saline Aquifers of Lithuania and Adjacent Territories*. 2012. Geologija. Vol. 53, 121–133.

¹⁹³ Source: LIUGAS, J., ŠLIAUPIENĖ, R., GRENDAITĖ, M., MICHELEVIČIUS, D., ŠLIAUPA, S. *CO₂ geological storage prospects of Lithuania – update*. 2023. Baltic Carbon Forum 2023 in Riga, Latvia, October 12-13.

¹⁹⁴ Source: MALIK, S., MAKASKAS, P., KARALIUTE, V., PAL, M., SHARMA, R. *Assessing the geological storage potential of CO₂ in Baltic Basin: A case study of Lithuanian hydrocarbon and deep saline reservoirs*. 2024. International Journal of Greenhouse Gas Control. Vol 133 <https://doi.org/10.1016/j.ijggc.2024.104097>

Syderiai saline aquifer

The Syderiai saline aquifer in Telšiai region (Figure 38), occurring at the depth of about 1,450 metres which contains a large formation suitable for gas storage. Of note, the Syderiai saline aquifer is situated in a favourable geographic position as it is located 40–50 km away of the Mažeikiai refinery and Akmenė Cementas, two largest CO₂ emitters in Lithuania (Figure 38).

The Syderiai saline aquifer has been investigated in detail by seismics and deep wells (e.g., Syderiai-1, Syderiai-2 and Syderiai-3) as the prospective structure for oil exploration in the 1980s was drilled in the centre of the structure. It is bounded by the large-scale Telšiai fault in the south (Figure 38) while in the east, the structure is bordered by a small-scale fault trending NE–SW.. It is 12 km long and 8 km wide (Figure 38). Based on seismic studies, the Cambrian top occurs at a depth of 1,458 m (Figure 38 and Figure 39) and the thickness of the reservoir is 57 m. The formation of the Syderiai saline aquifer was related to the tectonic compression induced by a collision of the Baltica and the Laurentia continents in the latest Silurian – earliest Devonian¹⁹⁵. It led to the formation of a number of faults and associated uplifts in the Baltic basin.

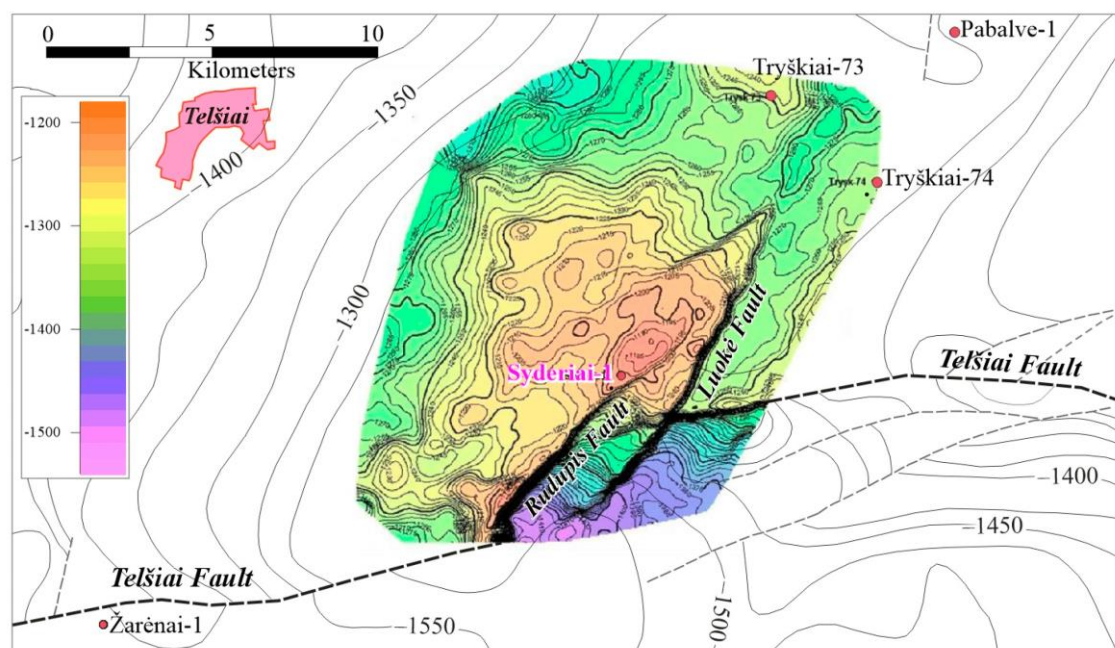


Figure 38: Depth (contour lines) of the top of the Cambrian key seismic reflector (b.s.l., m; depth–1,190 m in well Syderiai-1). The 3D seismic data cube is highlighted (depth colour scale). The Syderiai 3D seismic data cube were studied to specify the deformation of the Telšiai fault and the branching small-scale tectonic features; the adjacent wells are shown¹⁹⁶.

¹⁹⁵ Source: ŠLIAUPA, S., POPRAWA, P., LAZAUSKIENE, J., STEPHENSON, R.A., 1997. *The Palaeozoic subsidence history of the Baltic Syneclise in Poland and Lithuania*. 1997. Geophys. J. Vol. 19, 137 – 139.

¹⁹⁶ Source: ŠLIAUPA, Saulius; MICHELIVICIUS, Dainius; ŠLUAUPENĖ, Rasa; LIUGAS, Jonas. *Assessment of the Potential for CO₂ Storage and Utilization in the Fractured and Porous Reservoir of the Cambrian Sandstones in West Lithuania's Baltic Basin*. October 30th, 2024. Minerals 2024, 14(11), 1112, <https://doi.org/10.3390/min14111112>

The prospective reservoir belongs to the Deimena series (Middle Cambrian), which consist of 57 m thick sandstones deposited in an aeolian environment (sandy dunes) with an average porosity of 16% and the net-to-gross being as high as 0.75. Sandstones are well sorted, fine-grained, cemented by late diagenetic quartz. Quartz comprises about 97–98% of rock volume with a scarce potassium feldspar, pyrite, clay and mixture. A clay layer about 10 m thick divides the collector into two parts. Thus, two compartments are defined in the section (Figure 41). Sandstone 1 and Sandstone 2 are attributed respectively to the Ablinga and the Pajūris formations separated by a 10 m thick shaly basal part of the Ablinga Formation. Neutron Gamma Ray (NGR) logging data were used to calculate the porosity distribution. The average porosity of sandstones is 16%. The reservoir properties are increasing downward in the Ablinga Formation (Sandstone 1) from about 10% at the top to 24% at the base (Figure 41); this is related to a decrease in quartz content. In this regard, the average porosity of the upper sandstone is 18% (27 m thick), and the lower Pajūris Formation (Sandstone 2) is 16% (12 m thick). The permeability correlates with porosity. It ranges from 4 mD in shaly sandstone to 850 mD in massive sandstone. The correlation is described by the equation $\text{Permeability} = 0.3 * \text{Porosity} + 0.97$. The average permeability of Middle Cambrian sandstones is 400 mD. Sandstones are rather anisotropic. The ratio of the vertical to horizontal permeability is 0.56.

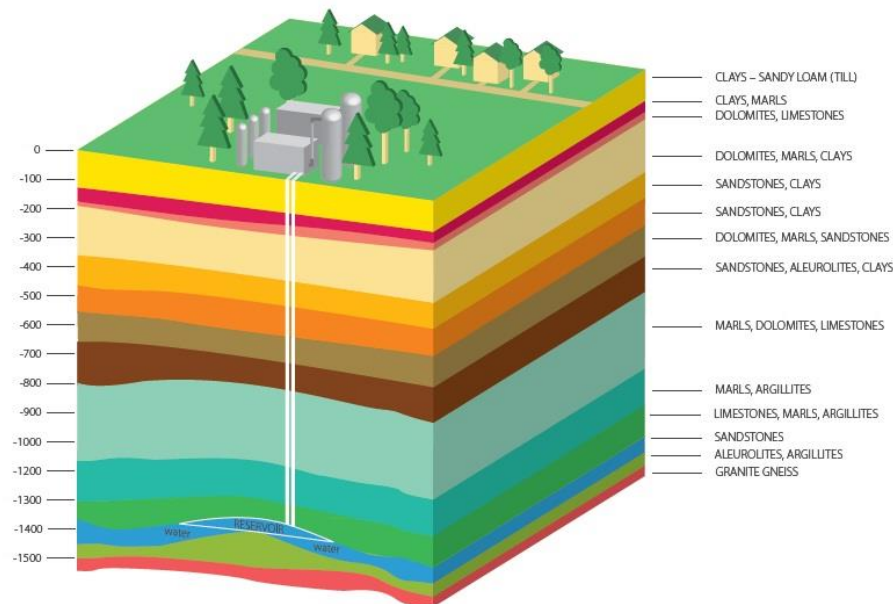


Figure 39: Geological structure of the Syderiai saline aquifer.

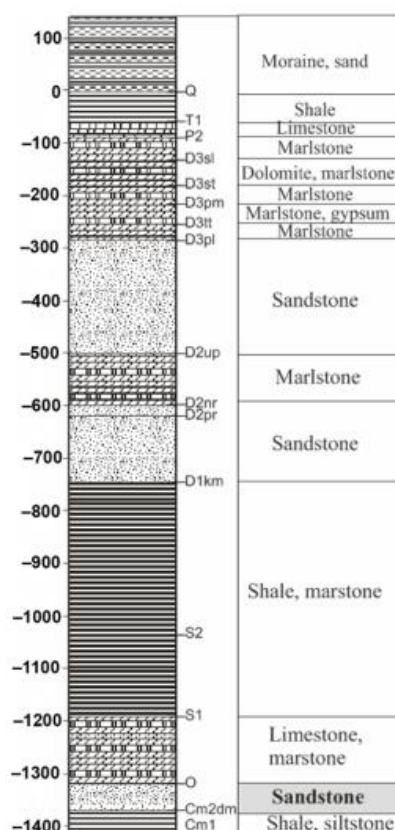


Figure 40: Lithological sequence of Syderiai. The sandstones of the Cambrian saline aquifer are marked in grey

The density of supercritical CO₂ is an important parameter in assessing the storage capacity of a particular structure. The density depends basically on temperature, pressure and pore water salinity¹⁹⁷. The temperature of the layer is 50°C and the water mineralisation - 122.4 g/l (sodium-chloride type water). The density of CO₂ was estimated using the MIDCARB calculator (<http://www.kgs.ku.edu/Midcarb/>). In these conditions, CO₂ density is 710 kg/m³.

¹⁹⁷ Source: DUAN ZH., HU J., LI D., MAO SH. *Densities of the CO₂-H₂O and CO₂-H₂O-NaCl systems up to 647 K and 100 MPa*. 2008. Energy & Fuels Vol. 22, 1666-1674.

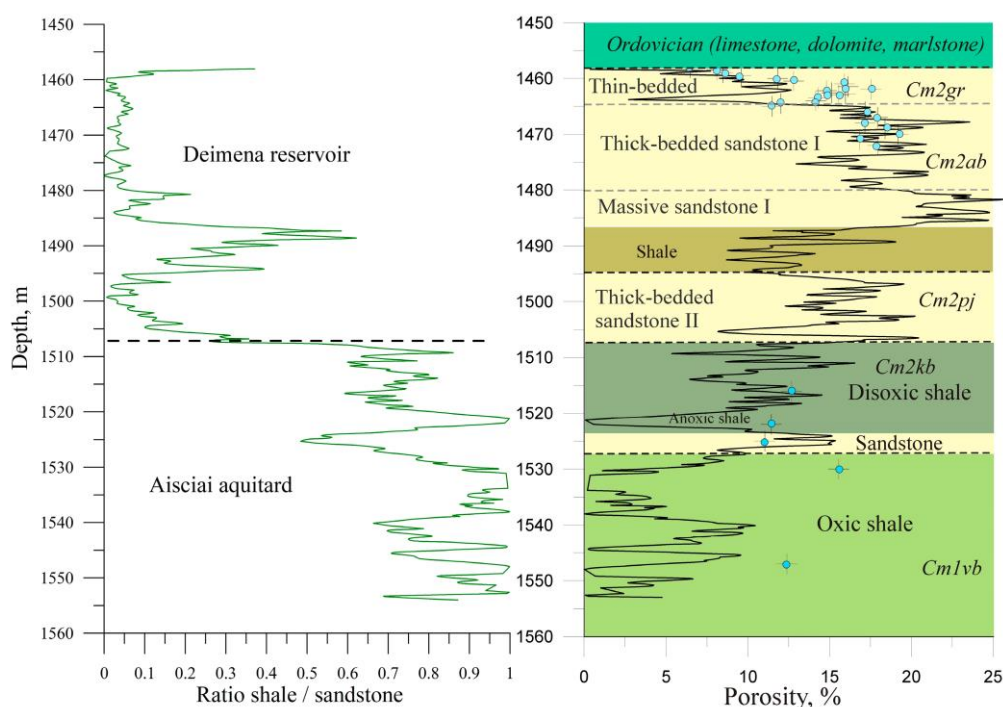


Figure 41: Lithological section of Cambrian succession showing the calculated ratios of sandstones and shales, based on a well gamma-ray wirelog, and the porosity defined in drill core samples (blue points) and interpreted by well logs (curve). Cambrian units are overlain by lowermost Ordovician carbonate cap rocks^{198, 199}.

The saline aquifer is sealed by a ca. 560 m thick shaly package of Ordovician age (Figure 39 and Figure 40) which is a safety good seal for CO₂ storage in the sandstones. Above the sealing package, there are several large-scale saline aquifers, but they are not used for water supply due to the high salinity. Potable water is supplied from the Upper Permian carbonaceous aquifer and younger aquifers at a depth less than 90 m (Figure 40).

Taking into consideration the volumetrics, reservoir properties and CO₂ density, the storage capacity of the Syderiai saline aquifer is assessed to be as large as 21.5 Mt of CO₂, using the equations [1] and [2] (Table 11). However, recently Liugas et al. (2023) estimated the CO₂ storage capacity of the Syderiai saline aquifer in 56.7 Mt (area 62 km²) owing to the high reservoir properties (average porosity 17% and permeability 400 mD) with a thickness of 50 m thick and 1,458-1,508 m deep²⁰⁰. In addition, the potential storage of this site was estimated between 54 to 232 Mt²⁰¹. These values were obtained using micro X-ray computed tomography (MXCT) and multi-resolution scanning at 8 µm and 22 µm, thus

¹⁹⁸ Source: ŠLIAUPIENĖ, R., ŠLIAUPA, S. *Prospects for CO₂ Geological Storage in Deep Saline Aquifers of Lithuania and Adjacent Territories*. 2012. *Geologija*. Vol. 53, 121–133.

¹⁹⁹ Source: ŠLIAUPA, Saulius; MICHELIVIČIUS, Dainius; ŠLIAUPENĖ, Rasa; LIUGAS, Jonas. *Assessment of the Potential for CO₂ Storage and Utilization in the Fractured and Porous Reservoir of the Cambrian Sandstones in West Lithuania's Baltic Basin*. October 30th, 2024. *Minerals* 2024, 14(11), 1112, <https://doi.org/10.3390/min14111112>

²⁰⁰ LIUGAS, J., ŠLIAUPIENĖ, R., GRENDAITĖ, M., MICHELEVIČIUS, D., ŠLIAUPA, S. *CO₂ geological storage prospects of Lithuania – update*. 2023. Baltic Carbon Forum 2023 in Riga, Latvia, October 12-13

²⁰¹ Source: MALIK, S., MAKASKAS, P., SHARMA, R., PAL, M. *Evaluating Petrophysical Properties Using Digital Rock Physics Analysis: A CO₂ Storage Feasibility Study of Lithuanian Reservoirs*. 2024. *Appl. Sci.* Vol. 14, 10826. <https://doi.org/10.3390/app142310826>

digital rock volumes (DRVs) from core samples were created to determine porosity and permeability; the method, validated against analogous samples, identified a representative element volume (REV) within subvolumes, showing a homogeneous distribution of petrophysical properties in the Lithuanian samples. The results show that DRVs can accurately reflect pore-scale properties, achieving 90–95% agreement with lab measurements, and offer a rapid, efficient means for analysing storage potentials. Syderiai saline aquifer is close to the gas pipeline, which increases the potential of this structure. However, it should be emphasised that this structure is one of the most promising for the development of an underground gas storage facility in Lithuania.

Vaškai

The structure in Vaškai is located in Pasvalys district, 10 km northwest of Pasvalys City (see Figure 32). Between 1992 and 1999, 168 km of seismic lines were carried out and 5 wells were drilled to evaluate the suitability of the Vaškai saline aquifer for underground gas storage. However, the structure was abandoned due to uncertain tightness of the bounding faults as the Vaškai saline aquifer is limited by two faults trending West–East. The length of the structure is 12 km. The Telšiai fault zone is of complex geometry and is 500 m to 1,000 m wide; the Cambrian reservoir is 250 m away (Figure 42). The area of the Vaškai saline aquifer is 11 × 3.2 km.

No significant geothermal studies have been carried out here, one can only guess from the general regional situation that the temperature of the chamber is about 30°C (taking into account the typical geothermal gradient), so it may be a bit too low to maintain a supercritical state in the reservoir. The carbon dioxide will be in the liquid phase, which is heavier than the pore water, so it will migrate downwards, erupting from the structure.

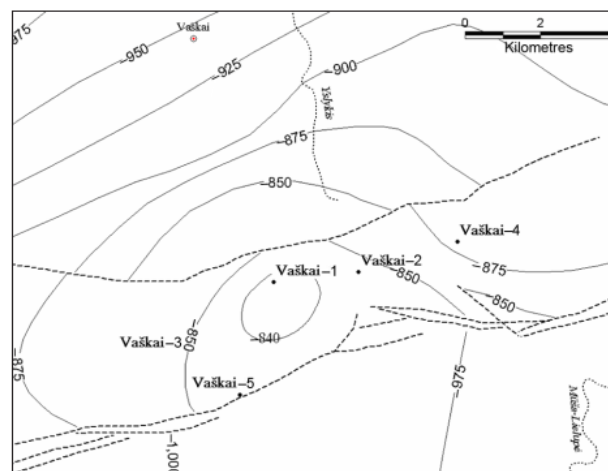


Figure 42: Structural map of top of the Vaškai saline aquifer. Contour lines indicate Cambrian top depths (896 m), hatched lines show faults, dotted lines mark rivers; deep wells are indicated²⁰²,

The closure amplitude is 36 m. It is, however, not clear whether the closure is controlled by faults on the either side of the uplift or the Cambrian layer is flexed at the faults.

The saline aquifer is composed of Lower–Middle Cambrian sandstones with subordinate shales and siltstones. Sandstones are fine-grained, silty, cemented by dolomite and quartz, their content being 2–

²⁰² Source: ŠLIAUPIENĖ, R.; ŠLIAUPA, S. *Prospects for CO₂ geological storage in deep saline aquifers of Lithuania and adjacent territories*. 2011. Geologija, Vol. 53. No 3(75), pp.121-133

4%; quartz grains comprise about 94%, clay admixture averages to 2%, and the pyrite content is about 2%.

The top of the Cambrian reservoir occurs at the depth of 896–932 m. It is overlain by 360 m thick Ordovician–Silurian shales and carbonates (Figure 43). They provide a reliable seal for storing CO₂. The tightness of the Ordovician caprock was proven by a drill stem test, logs in the wells and threshold pressure measurements on cores. The Cambrian reservoir overlies the crystalline basement.

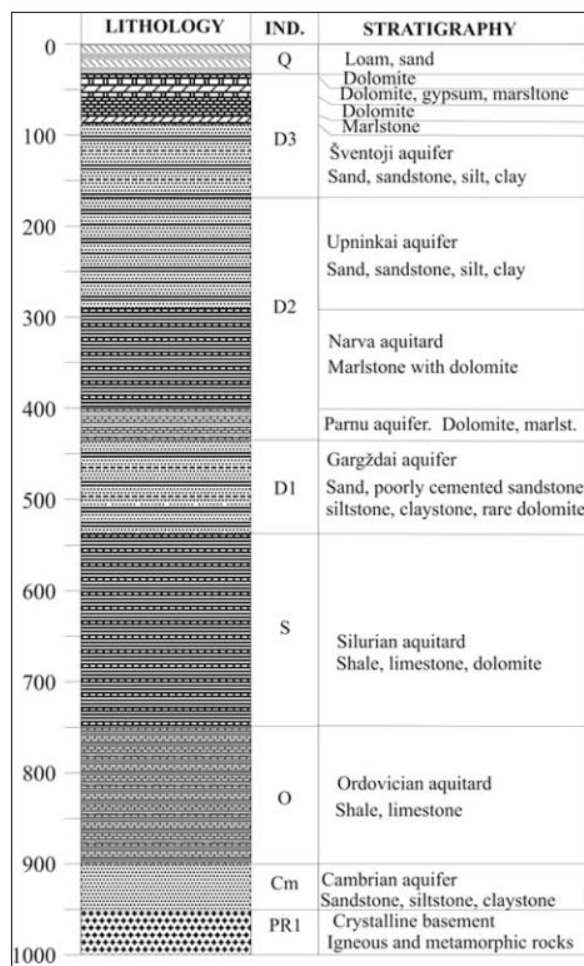


Figure 43: Stratigraphic section of Vaškai area²⁰³¹⁹⁸.

There are three compartments defined in the Cambrian saline aquifer (Figure 44). The upper compartment (Sandstone 1) represents the basal part of the Deimena Regional Stage. It is separated from the Lower Cambrian by Kybartai Formation shales 8 m thick with rare sandstones. The middle and the lower compartments (Sandstone 1 and Sandstone 2) represent the upper and the lower parts of the Virbalis Formation (Lower Cambrian). They are separated by 10 m thick shales with sandstone interlayers. The lower part of the Cambrian succession is comprised by siltstones and shales of the Gėgė Formation.

²⁰³ Source: ŠLIAUPIENĖ, R.; ŠLIAUPA, S. *Prospects for CO₂ geological storage in deep saline aquifers of Lithuania and adjacent territories*. 2011. Geologija, Vol. 53. No 3(75), pp.121-133

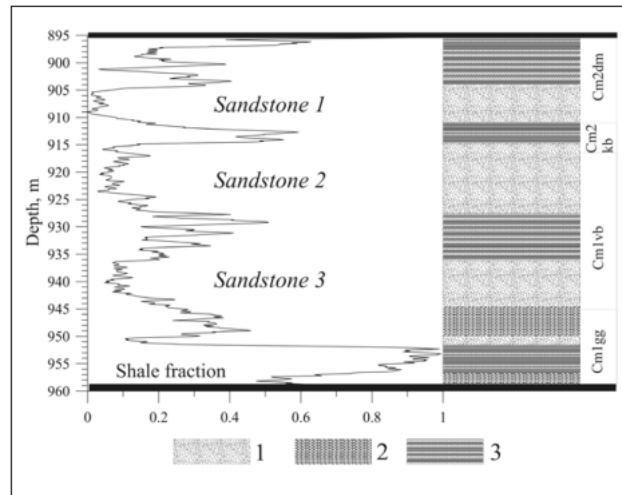


Figure 44: Lithological section of Cambrian succession, Vaškai-1 well^{204, 198}.

The porosity of Cambrian sandstones is 17–26.5% obtained from samples taken from wells for laboratory analysis. Furthermore, the porosity distribution was also calculated using sonic logging data. The average porosity of sandstones is 23%, the net-to-gross ratio is 0.5, and the permeability ranges from 90 to 1,628 mD (Figure 41). However, the average permeability is rather low (280 mD) mainly because of the presence of some clay admixture in sandstones. The vertical permeability of sandstones is half as low.

The hydrostatic pressure is 90 bar. The temperature was not measured in this area. Based on regional estimates, the temperature of Cambrian water is 33 °C. The pore water salinity is as high as 127 g/l, similarly to that in the Syderiai saline aquifer. The water is of Na–Cl type. In these conditions, the density of CO₂ was evaluated to be 580 kg/m³, which is lower than in the Syderiai area due to pressure difference.

Based on the above data, the storage capacity of the Vaškai saline aquifer was assessed to be 8.7 Mt of CO₂, although recently, Malik et al. (2024) estimated the potential storage of this site between 25 to 106 Mt. This estimation was obtained by utilizing 3D mechanistic models across varying scenarios—low, mid, and high—it was aimed to address property uncertainties in the deep saline aquifers; the resulting 3D numerical simulations conducted through the CO2SOL modelling option within T-navigator revealed a substantial CO₂ storage potential. Moreover, the simulations highlight the significant influence of high-permeability faults in CO₂ leakage, particularly when they are interconnected. Despite these challenges, the thorough examination of CO₂ storage risks, including caprock integrity, shows promising outcomes. The minimal deformation observed in the models suggests that safe injection methods can be employed without jeopardizing caprock stability. This supports the viability of long-term CO₂ containment in Lithuanian reservoirs, supported by the presence of Silurian shale for extended sequestration.

The advantage of this structure is that it is close to gas pipelines and the simple geometric shape of the structure. Weaknesses of the Vaškai saline aquifer - 1) underground gas storage facilities are planned in the perspective, 2) unclear fracture closure; 3) there is a lack of temperature measurement data that would allow one to substantiate the supercritical state of CO₂ in the Cambrian saline aquifer.

²⁰⁴ Source: ŠLIAUPIENĖ, R.; ŠLIAUPA, S. *Prospects for CO₂ geological storage in deep saline aquifers of Lithuania and adjacent territories*. 2011. Geologija, Vol. 53. No 3(75), pp.121-133.

D11 Baltic Sea structure

The aforementioned two structures of the Cambrian promising salty aquifer extend into the Baltic Sea (Figure 45). Geological and geophysical surveys have also been carried out in the past, mainly related to oil exploration. Seismic surveying data identified 52 structures into the Baltic Sea for which the CO₂ storage potential was calculated although only one of them (D11) seemed to have potential for CO₂ storage.

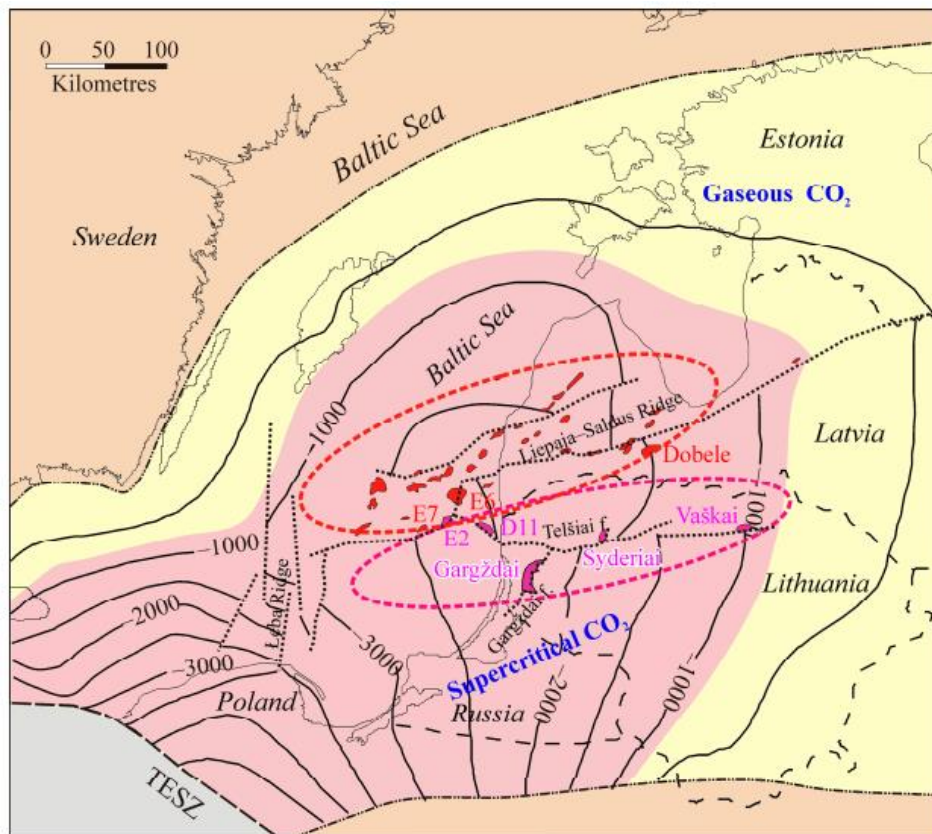


Figure 45: Distribution and depths (contour lines) of top of Cambrian succession in Baltic basin. Two zones of gaseous (yellow) and supercritical (pink) CO₂ phases are distinguished on the map. Major faults are shown (dotted lines). Prospective Cambrian structures for CO₂ storage in Latvia (red) are marked (structures mentioned in the text are marked). Four structures in Lithuania are highlighted in pink. The Trans-European Suture Zone (TESZ) is shown bordering the Baltic basin in the west²⁰⁵.

The storage potential was preliminarily assessed for the offshore territories of Lithuania and Latvia (the eastern Baltic Sea)²⁰⁶. A dense 2 x 2 km network of the industrial seismic profiles covers the offshore territory. One well (D5-1) was drilled through the sedimentary cover to the crystalline basement, the

²⁰⁵ Source: ŠLIAUPA, Saulius; MICHELIVICIUS, Dainius; ŠLUAUPENĖ, Rasa; LIUGAS, Jonas. *Assessment of the Potential for CO₂ Storage and Utilization in the Fractured and Porous Reservoir of the Cambrian Sandstones in West Lithuania's Baltic Basin*. October 30th, 2024. Minerals 2024, 14(11), 1112, <https://doi.org/10.3390/min14111112>

²⁰⁶ Source: ŠLIAUPIENĖ, R; ŠLIAUPA, S. *Prospects of CO₂ geological storage in deep saline aquifers of Lithuania and adjacent territories*. Geologija 53(3). 2011. DOI:10.6001/geologija.v53i3.1893

drill cores were collected from the upper part of the Middle Cambrian succession. Several wells penetrated the whole sedimentary cover in the Latvian economic zone (E7-1 and E6-1 wells) although here we center in Lithuanian structures, especially in D11.

In the Lithuanian economic zone, the amplitudes of the structures reach 20–40 m, the area of the largest structures being 5–20 km². In the Lithuanian economic zone, only one rather large structure D11 has been identified, which is located 5 km west of the Lithuanian shoreline. The amplitude of the D11 saline aquifer is 35 m, and the area is 80 km². The storage capacity was evaluated to be 11.3 Mt CO₂²⁰⁷, and 17–69 Mt CO₂²⁰⁸. Other structures range from 100,000 tonnes to 7.8 Mt. in this regard, based on the 52 structures assessed offshore, it was estimated that the storage offshore potential is 35 Mt of CO₂^{209,210} (Figure 46). No promising structures were found in the Devonian strata, as on land, so the prospects for this saline aquifer are virtually nil.

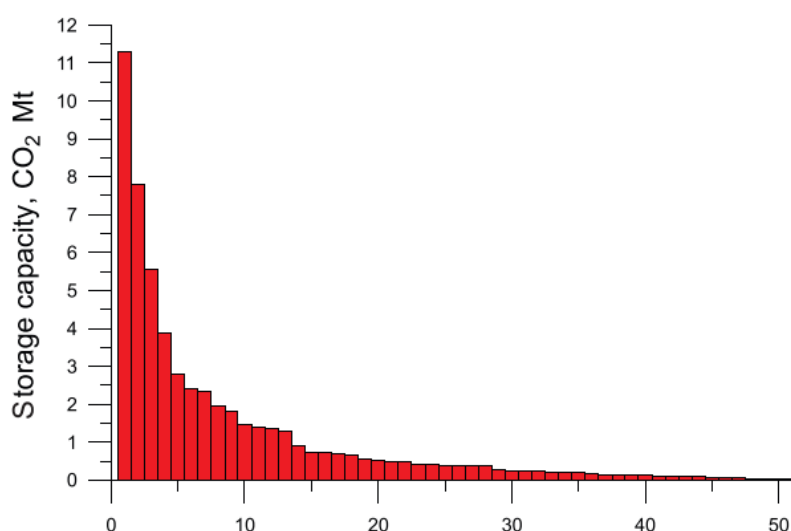


Figure 46: Storage capacity of 52 Cambrian structures of Lithuanian offshore^{211,198}.

Of note, fifteen prospective structures were defined in the Cambrian reservoir in the economic zone of Latvia which will be commented below. The total offshore storage capacity is preliminarily estimated to be 300–400 Mt (Latvia and Lithuania). Similarly, a large storage potential is suggested in the western part of the Baltic Sea in the Swedish offshore economic zone (Bergman, Juhojuntti, 2010).

²⁰⁷ Source: ŠLIAUPIENĖ, R., ŠLIAUPA, S. *Prospects for CO₂ Geological Storage in Deep Saline Aquifers of Lithuania and Adjacent Territories*. 2012. Geologija. Vol. 53, 121–133.

²⁰⁸ Source: MALIK, S., MAKASKAS, P., KARALIUTE, V., PAL, M., SHARMA, R. *Assessing the geological storage potential of CO₂ in Baltic Basin: A case study of Lithuanian hydrocarbon and deep saline reservoirs*. 2024. International Journal of Greenhouse Gas Control. Vol 133 <https://doi.org/10.1016/j.ijggc.2024.104097>

²⁰⁹ Source: ŠLIAUPA, S. *Potential of Geological Formations for CO₂ sequestration in Lithuania*. 2008.

²¹⁰ Source: ŠLIAUPIENĖ, R.; ŠLIAUPA, S. *Prospects for CO₂ geological storage in deep saline aquifers of Lithuania and adjacent territories*. 2011. Geologija, Vol. 53. No 3(75), pp.121-133

²¹¹ Source: ŠLIAUPIENĖ, R.; ŠLIAUPA, S. *Prospects for CO₂ geological storage in deep saline aquifers of Lithuania and adjacent territories*. 2011. Geologija, Vol. 53. No 3(75), pp.121-133

8.1.2. Oil fields

Oil/gas field offer significant advantages, including existing infrastructure and well-characterized reservoirs. Therefore, they involve lower costs for initial projects. However, regulatory and technical challenges, such as well integrity and potential interactions with remaining hydrocarbons limit their use.

The Gargždai zone of uplifts is located 110 km to the southwest (Figure 30). The study of the Gargždai uplifts was carried out over more than 50 years. More than fifty wells were drilled, which led to the discovery of six oil fields and the creation of a database comprising 2,724 samples compiled from industrial reports²¹². An option is the utilization of CO₂ for enhanced oil recovery (EOR).

Depleted hydrocarbon reservoirs make excellent targets for CO₂ storage. Primary reason is that depleted hydrocarbon reservoirs typically have a very high residual oil saturation, sometimes in range of 25–60%. If the depleted hydrocarbon reservoir is at right temperature and pressures, which are favourable for CO₂ storage then the thermodynamic phase exchange allows for CO₂ to be dissolved in residual oil (remaining oil) in the reservoir. Experiments (CO₂ injection tests) conducted for CO₂ interaction with Gargždai zone of uplifts demonstrates very good potential for CO₂ storage^{213, 214}. If the reservoir is not produced for enhanced oil recovery the trapped CO₂ will remain in the reservoir without being released for millions of years. The process has been well documented in several published literature^{215, 216, 217, 218, 219, 220}. Only aspects which could impact the long-term trapping in such hydrocarbon reservoirs is leakage due to presence of any fault or fractures, or due to slow migration

²¹² Source: ŠLIAUPA, S; MICHELEVICIUS, D; ŠLIAUPIENĖ, R; LIUGAS, J. *Assessment of the Potential for CO₂ Storage and Utilization in the Fractured and Porous Reservoir of the Cambrian Sandstones in West Lithuania's Baltic Basin*. 2024. Minerals. Vol. 14(11), 1112. <https://doi.org/10.3390/min1411112>

²¹³ Source: HASELTON, T.M. *Exploiting the ROZ in Lithuania*. 2013. Paper Presented At 19th Annual CO₂ Flooding Conference, Midlands, Texas, USA. Available online at: <https://www.co2conference.net/wp-content/uploads/2013/12/15-Haselton-Exploiting-the-ROZ-in-Lithuania-new-new.pdf> (Accessed: July 2025).

²¹⁴ Source: HASELTON, T.M. *Minijos Nafta Clean Energy Project*. 2019. Paper presented at the Baltic Carbon Forum 2019, Tallin, Estonia. Available online at: <https://bcforum.net/presentations2019/02-04-Baltic-Carbon-Forum-2019-Nafta.pdf> (Accessed: July 2025).

²¹⁵ Source: ANDRAE, H., COMBARET, N., DVORKIN, J., GLATT, E., HAN, J., KABEL, M., KEEHM, Y., KRZIKALLA, F., LEE, M., MADONNA, C., MARSH, M., MUKERJI, T., SAENGER, E.H., SAIN, R., SAXENA, N., RICKER, S., WIEGMANN, A., ZHAN, X.. *Digital rock physics benchmarks—Part I: imaging and segmentation*. 2013. Comput. Geosci. 26–33.

²¹⁶ Source: HASAN, M.M.F., FIRST, E.L., BOUKOUVALA, F., FLOUDAS, C.A. *A multi-scale framework for CO₂ capture, utilization, and sequestration: CCUS and CCU*. 2015. Comput. Chem. Eng. 81, 2–21. <https://doi.org/10.1016/j.compchemeng.2015.04.034>.

²¹⁷ Source: TAPIA, J.F.D., LEE, J.-Y., OOI, R.E.H., FOO, D.C.Y., TAN, R.R. *A review of optimization and decision-making models for the planning of CO₂ capture, utilization and storage (CCUS) systems*. 2018. Sustain. Prod. Consump. 13, 1–15. <https://doi.org/10.1016/j.spc.2017.10.001>.

²¹⁸ Source: SHARMA, R., MALIK, S., SHETTAR, A.S. *Sensitivity of digital rock method for pore-space estimation to heterogeneity in carbonate formations*. 2021. SPE Journal 2914–2927. <https://doi.org/10.2118/205006-PA>.

²¹⁹ Source: GUPTA, S., LI, L. *The potential of machine learning for enhancing CO₂ sequestration, storage, transportation, and utilization-based processes: a Brief Perspective*. 2022. JOM 74, 414–428. <https://doi.org/10.1007/s11837-021-05079-x>.

²²⁰ Source: YAO, P., YU, Z., ZHANG, Y., XU, T. *Application of machine learning in carbon capture and storage: an in-depth insight from the perspective of geoscience*. 2022. Fuel Vol. 333, 126296. <https://doi.org/10.1016/j.fuel.2022.126296>.

towards caprock and breaching of caprock due to geochemical reactions, or due to any other pressure sink, which would need evaluation using reservoir simulation, and it's not possible to evaluate such phenomenon using analytical methods.

The Gargždai zone of uplifts is the largest tectonic one in Lithuania with 233 km², which is comprised by some uplifts. The first discovery of oil was recorded in the well Šiupariai in 1968 (Figure 47). More than 50 wells were drilled at this elevation, leading to the discovery of six oil fields (Vilkyciai, Pociai, Degliai, Pietu, Siupariai, Uoksai, Agluonenai) in the 1970s that are aligned along the Gargždai fault zone and are complicated by the occurrence of smaller-scale faults. The northernmost Vežaičiai oil field is only partially connected to the major elevation to the south, and this connection occurs exclusively within the Gargždai Fault Zone. This southern structure includes the Šiūpariai, South Šiūpariai, Diegliai, Pociai, and Vilkyciai oil fields²²¹(see Figure 47). The Ablinga oil field is a small, isolated anticline associated with the northern termination of the Gargždai zone of uplifts (see Figure 47). In comparison, the Syderiai saline aquifer, one of Lithuania's major identified CO₂ storage sites, covers approximately 62 km² and is estimated to store ~21.5 Mt CO₂, thanks to high-quality reservoir properties. Meanwhile, the Vaškai saline aquifer spans roughly 20 km² with a storage capacity of ~8.7 Mt CO₂²²².

The intricate pattern of the local uplifts in the Gargždai zone of uplifts and the adjacent structures was defined using 3D seismic data. Different seismic blocks were unified into a common structural model²²³ (Figure 48: Structural map of the Gargždai region.

and Figure 49). The depth of the Cambrian reservoir varied from –1,935 m (Vilkyciai oil field) to –1,977 m (Vežaičiai oil field) and reached as low as –1,996 m in the Ablinga oil field. The bottom of the Gargždai zone of uplifts is located at a –2,015 m depth²²⁴. It is notable that the oil fields in the underlying residual oil zones (ROZs, subsurface intervals containing immobile or low-saturation oil that remains after natural water flushing or secondary migration) were found to be only partially saturated due to the partial release and south-facing leakage of hydrocarbons into the rapidly uplifted Mazury–Belarus High (Anteclise) during the Late Carboniferous–Early Permian²²⁵.

The seismic stratigraphic interpretation argues that the Gargždai zone of uplifts was established in the earliest Devonian. Accordingly, the Telšiai and Gargždai faults were formed during the very short tectonic phase initiated by the collision of the Baltic and Laurentia continents²²⁶. Furthermore, no

²²¹ Source: GRENDAITĖ, M., MICHELEVICIUS, D., RADZEVICIUS, S. *Insights into the Structural Geology and Sedimentary Succession of the Baltic Basin, Western Lithuania*. 2023. Marine and Petroleum Geology. Vol. 147, 106009.

²²² Source: ŠLIAUPIENĖ, R.; ŠLIAUPA, S. *Prospects for CO₂ Geological Storage in Deep Saline Aquifers of Lithuania and Adjacent Territories*. 2005. Geologija. Vol. 53, 121–133.

²²³ Source: GRENDAITĖ, M., MICHELEVICIUS, D., RADZEVICIUS, S. *Insights into the Structural Geology and Sedimentary Succession of the Baltic Basin, Western Lithuania*. 2023. Marine and Petroleum Geology. Vol. 147, 106009.

²²⁴ Source: ŠLIAUPA, S; MICHELEVICIUS, D; ŠLIAUPIENĖ, R; LIUGAS, J. *Assessment of the Potential for CO₂ Storage and Utilization in the Fractured and Porous Reservoir of the Cambrian Sandstones in West Lithuania's Baltic Basin*. 2024. Minerals. Vol. 14(11), 1112. <https://doi.org/10.3390/min14111112>

²²⁵ Source: ŠLIAUPA, S; MICHELEVICIUS, D; ŠLIAUPIENĖ, R; LIUGAS, J. *Assessment of the Potential for CO₂ Storage and Utilization in the Fractured and Porous Reservoir of the Cambrian Sandstones in West Lithuania's Baltic Basin*. 2024. Minerals. Vol. 14(11), 1112. <https://doi.org/10.3390/min14111112>

²²⁶ Source: POPRAWA, P., ŠLIAUPA, S., STEPHENSON, R., LAZAUSKIEN, J. *Late Vendian–Early Palaeozoic Tectonic Evolution of the Baltic Basin: Regional Tectonic Implications from Subsidence Analysis*. 1999. Tectonophysics Vol. 314, 219–239.

discernible deformation along the Caledonian faults was documented in the seismic profiles crossing the Gargždai Fault Zone. Only weak activity was recorded, comprising few-meter-long amplitude deformations, along the secondary faults during the Upper Palaeozoic and Mesozoic eras²²⁷.

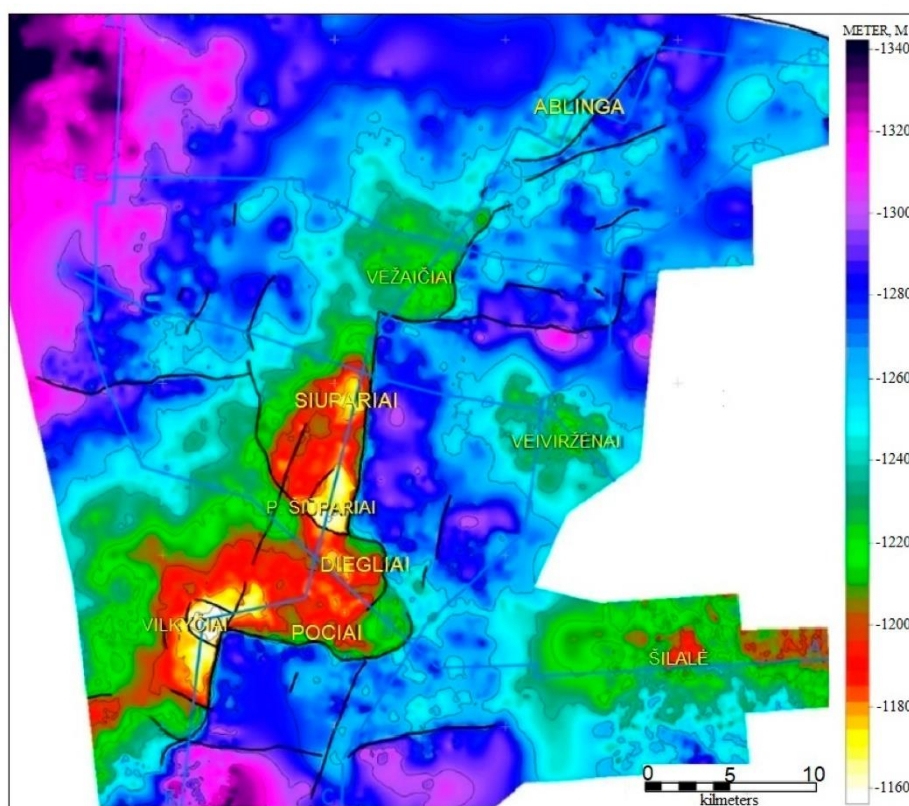


Figure 47: Depth map showing the base of the Silurian succession.

²²⁷ Source: GRENDAITĖ, M., MICHELEVICIUS, D., RADZEVICIUS, S. *Insights into the Structural Geology and Sedimentary Succession of the Baltic Basin, Western Lithuania*. 2023. Marine and Petroleum Geology. Vol. 147, 106009.

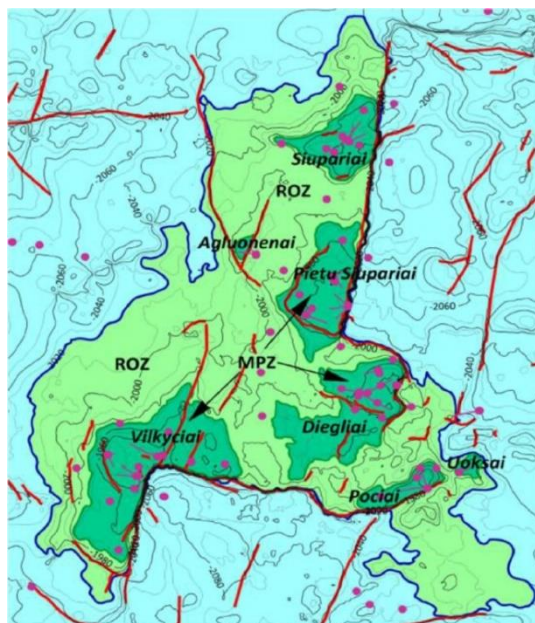


Figure 48: Structural map of the Gargždai region²²⁸.

By contrast to the reservoir studied in the Syderiai, the Deimena Regional Stage (RSt.) in the Gargždai zone of uplifts showed more complicated reservoir architecture. The persistent quartz cementation considerably reduces the reservoir quality in the deepest part of the basin²²⁹. Furthermore, the inhibiting role of quartz cementation should be considered in the context of the oil fields²³⁰ which were formed as long ago as the Middle Devonian²³¹.

²²⁸ Source: [https://doi.org/10.3390/MALIK, S., MAKASKAS, P., KARALIUTE, V., PAL, M., SHARMA, R. Assessing the geological storage potential of CO₂ in Baltic Basin: A case study of Lithuanian hydrocarbon and deep saline reservoirs. International Journal of Greenhouse Gas Control. Vol. 133 \(104097\) https://doi.org/10.1016/j.ijggc.2024.104097](https://doi.org/10.3390/MALIK, S., MAKASKAS, P., KARALIUTE, V., PAL, M., SHARMA, R. Assessing the geological storage potential of CO₂ in Baltic Basin: A case study of Lithuanian hydrocarbon and deep saline reservoirs. International Journal of Greenhouse Gas Control. Vol. 133 (104097) https://doi.org/10.1016/j.ijggc.2024.104097)

²²⁹ Source: MOLENAAR, N., CYZIENE, J., ŠLIAUPA, S. *Quartz Cementation Mechanisms and Porosity Variation in Baltic Cambrian Sandstones*. 2007. *Sedimentary Geology*. Vol., 195, 135–159.

²³⁰ Source: MOLENAAR, N., CYZIENE, J., ŠLIAUPA, S., CRAVEN, J. *Lack of Inhibiting Effect of Oil Emplacement on Quartz Cementation: Evidence from Cambrian Reservoir Sandstones, Paleozoic Baltic Basin*. 2008. *Geological Society of America Bulletin*. Vol. 120, 1280–1295.

²³¹ Source: ŠLIAUPA, S., HOTH, P. *Geological Evolution and Resources of the Baltic Sea Area from the Precambrian to the Quaternary*. 2011. In *The Baltic Sea Basin*; Harff, J., Björck, S., Hoth, P., Eds.; Central and Eastern European Development Studies (CEEDES); Springer: Berlin/Heidelberg, Germany, pp. 13–51.

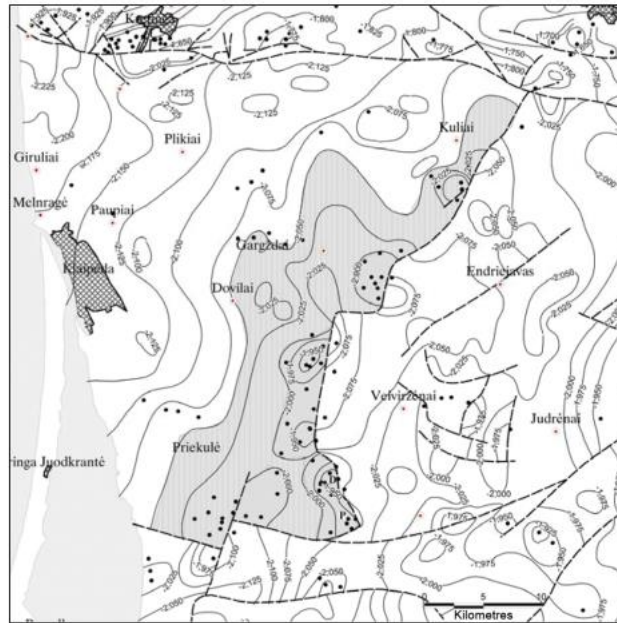


Figure 49: Structural map of the top of the Cambrian saline aquifer. Shaded area indicates the area of Gargždai zone of uplifts. Faults are shown as hatched lines. P and D mark Pocių and Diegliai oil fields, respectively²³². The zone is encompassed by the depth contour line of 2050 m and the prospective storage area is limited by the depth contour line of 2015 m.

With respect to Diegliai oil field, five reservoir compartments were defined in the vertical section of the reservoir (Figure 50). In terms of the stratigraphic nomenclature for Lithuania, the Deimena RSt. is subdivided into stratigraphic units attributed to, respectively, the Giruliai, Ablinga, and Pajūris Fms. The Ablinga and Giruliai Fms. represent the common upward-deepening sedimentation trend (Figure 47), similar to that at the Syderiai site. The thickness of the Ordovician cap rock ranges from 58 m to 91 m and the thickness of the Silurian shales varies from 670 m to 710 m, which are thicker layers than those found in the Gargždai zone of uplifts. The lithological composition of the cap rock is similar in both sites.

The authigenic quartz cementation reduces the reservoir quality in west Lithuania. The average porosity, horizontal permeability, anisotropy of permeability, and rock density of different formations are presented (Table 12). The average porosity is as low as 4.74% and the permeability is 9.33 mD in the Giruliai Fm.; the sandstones of the Ablinga Fm. have a slightly higher porosity of 6.10% and a lower permeability of 6.88 mD²³³.

²³²Source: ŠLIAUPIENĖ, R; ŠLIAUPA, S. *Prospects for CO₂ geological storage in deep saline aquifers of Lithuania and adjacent territories*. Geologija 53(3). 2011. DOI:10.6001/geologija.v53i3.1893

²³³ ŠLIAUPA, S; MICHELEVIČIUS, D; ŠLIAUPIENĖ, R; LIUGAS, J. *Assessment of the Potential for CO₂ Storage and Utilization in the Fractured and Porous Reservoir of the Cambrian Sandstones in West Lithuania's Baltic Basin*. 2024. Minerals 14(11):1112. DOI: 10.3390/min14111112

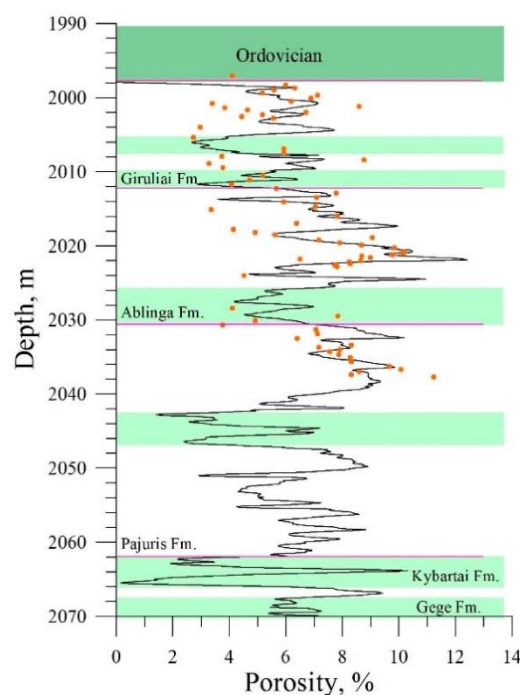


Figure 50: Measured (pink dots) and log-interpreted (curve) porosity of Deimena RSt. in reference well Diegliai-3. Five reservoir sandstone units alternate with shales that are a few meters thick (green). Number of samples (N) = 57²³⁴

	Porosity (%)	Maximum permeability (mD)	Anisotropy permeability (mD)	Density (kg/m ³)
Gituliai Fm.	4.74	9.33	0.74	2,530
Ablinga Fm.	6.1	6.88	0.88	2,490
Pajuris Fm. (I)	5.33	12.33	1	2,480
Pajuris Fm. (II)	6.35	10.3	1	2,470
Vargale Rst.	12.2	0.3	No data	2,400

Table 12: Reservoir properties of Cambrian sandstones in the Gargždai zone of uplifts.

The permeability–porosity relationship in sandstones is subjected to various processes^{235, 236} and has been tested in sedimentary rocks in relation to petroleum and reservoir characterization²³⁷. The effects of grain size, packing, compaction, and solution/dissolution processes related to the development of primary and secondary porosity can lead to a wide variation in permeability.

²³⁴ ŠLIAUPA, S; MICHELEVIČIUS, D; ŠLIAUPIENĖ, R; LIUGAS, J. *Assessment of the Potential for CO₂ Storage and Utilization in the Fractured and Porous Reservoir of the Cambrian Sandstones in West Lithuania's Baltic Basin*. 2024. Minerals 14(11):1112. DOI: 10.3390/min14111112

²³⁵ Source: BERG, R.R. *Method for Determining Permeability from Reservoir Rock Properties*. 1970. Gulf Coast Assoc. Geol. Soc. Trans. Vol. 20, 303–317.

²³⁶ Source: BERNABÉ, Y., MOK, U., EVANS, B. *Permeability-Porosity Relationships in Rocks Subjected to Various Evolution Processes*. 2003. Pure Appl. Geophys. Vol. 160, 937–960.

²³⁷ Source: MA, S., MORROW, N.R. *Relationships between Porosity and Permeability for Porous Rocks*. 1996. In Proceedings of the International Symposium of the Society of Core Analysts, Montpellier, France, 8–10 September 1996, pp. 8–10.

The authigenic quartz cementation is one the most important parameters that controls the porosity–permeability relationship²³⁸, while secondary porosity is only selectively distributed in scarce areas²³⁹; this is likely related to the hydrocarbon generation phase, which was associated with the partial corrosion of quartz grains and the precipitation of carbonate cement. There is no discernible grain mineral composition effect on the petrophysical parameters of sandstones. The increase in aluminium and associated bulk elements was related to fine clay lamina (including sub-millimetre-scale stylolites) incorporated into the studied samples. The amount of carbonate cement is as low as <0.8%. Therefore, the mineral composition of the sandstones exerts only a negligible effect on the reservoir quality^{240 241}.

The mean grain size of sandstones varies from very fine sand to medium sand which are related to the porosity and permeability. The average grain size is 0.16 mm in west Lithuania. The best-sorted sandstones are in the diameter range of 0.16–0.18 mm and classified as very-well-sorted sand (sorting value: 1.24)²⁴².

The porosity of the sandstones of the Pajuris Fm. is compatible with the porosity values found in the upper part of the reservoir (5.33% in the Upper Giruliai and 6.35% in the Lower Giruliai sandstones). The increased permeability of the sandstones in the lower part of the reservoir is primarily related to more extensive fracturing of the sandstones (12.33 and 10.30 mD) (Table 12).

Thick-bedded storm deposits and thin-bedded inner shelf deposits alternate in marine basin sediments. Similarly, the permeability of most of the sandstones was restricted to 0.1–1 mD, which correlated with the low porosity of the sandstones, while an increased permeability of 10–200 mD was recorded for some few-meter-thick layers. Similar to the Syderiai area, the stability of the reservoir properties of the lithofacies is suggested, which may be indicated by two petrophysical clusters in the Deimena sandstones.

The highest density of sandstones is reported in the Giruliai Fm. (2530 kg/m³), which showed a minor decreasing trend in density (from 2,490 to 2,470 kg/m³) in the Ablinga and Pajuris Fms. This is likely related to the variable quartz cementation, which is the main parameter controlling reservoir quality. It has been extensively studied in the west Lithuanian oil fields^{243, 244}. Generally, the most quartz-cemented ones had the highest-density sandstones, while there are others which have a low-density trend, implying the admixture of a clay fraction in the sandstones (possibly from drilling mud).

²³⁸ Source: MOLENAAR, N., CYZIENE, J., ŠLIAUPA, S. *Quartz Cementation Mechanisms and Porosity Variation in Baltic Cambrian Sandstones*. 2007. *Sedimentary Geology*. Vol., 195, 135–159.

²³⁹ Source: KILDA, L., FRIIS, H. *The Key Factors Controlling Reservoir Quality of the Middle Cambrian Deimena Group Sandstone in West Lithuania*. 2022. *Bull. Geol. Soc. Den.* Vol. 49, 25–39.

²⁴⁰ Source: KRUMBEIN, W.C., MONK, G.D. *Permeability as a Function of the Size Parameters of Unconsolidated Sand*. 1943. *Trans. AIME* 1943, 151, 153–163.

²⁴¹ Source: ALIYEV, E., SAIDIAN, M., PRASAD, M., RUSSELL, B. *Rock Typing of Tight Gas Sands: A Case Study in Lance and Mesaverde Formations from Jonah Field*. 2016. *J. Nat. Gas Sci. Eng.* 33, 1260–1270.

²⁴² Source: BLOTT, S.J., PYE, K. *GRADISTAT: A Grain Size Distribution and Statistics Package for the Analysis of Unconsolidated Sediments*. 2001. *Earth Surf. Process. Landf.* Vol. 26, 1237–1248.

²⁴³ Source: CYŽIENE, J., MOLENAAR, N., ŠLIAUPA, S. *Clay-Induced Pressure Solution as a Si Source for Quartz Cement in Sandstones of the Cambrian Deimena Group*. 2006. *Geologija* Vol. 53, 8–21.

²⁴⁴ Source: MOLENAAR, N., CYZIENE, J., ŠLIAUPA, S., CRAVEN, J. *Lack of Inhibiting Effect of Oil Emplacement on Quartz Cementation: Evidence from Cambrian Reservoir Sandstones, Paleozoic Baltic Basin*. 2008. *Geological Society of America Bulletin*. Vol. 120, 1280–1295.

The high anisotropy of vertical vs. horizontal permeability should be stressed as an important feature of the Gargždai zone of uplifts, similar to that of the Syderiai reservoir, as discussed above (with an anisotropy ratio of 0.70). The ratio of vertical vs. horizontal permeability is 0.74 in the Giruliai Fm. and 0.88 in the Ablinga Fm. Abundant stylolites, nucleated along the bedding surface and spaced at 2–4 cm, contributing significantly to the anisotropy of the reservoir structure²⁴⁵. The isotropic structure of the lower reservoir (Table 12) can reasonably account for grain size and sorting, which strongly affects permeability in the Pajuris Fm²⁴⁶. No dedicated study was carried out on the grain size sorting of Cambrian sandstones in west Lithuania.

The temperature of an aquifer is a paramount parameter for CO₂ geological storage. The Gargždai region is located within a geothermal anomaly in west Lithuania. Temperature logging was carried out in four wells, which were drilled to depths of approximately 2,100 m. The bottomhole temperature varied from 80°C (Diegliai-2) to 88°C (Vilkyciai-5); the thermal gradient varied, respectively, from 3.7°C/100 m to 4.1°C/100 m²⁴⁷.

The chemical composition of the Deimena saline aquifer water was analysed using 29 wells. The average mineralization of the brine was 170 g/L. The chemical composition of the saline aquifer was classified as Na–Cl. Despite the limited study area, the concentration of analysed chemical elements showed a rather wide variation, as the following: Cl = 83,600–112,700 mg/L; SO₄ = 109–952 mg/L; HCO₃ = 21–220 mg/L; Na = 26,593–32,913 mg/L; and K = 611–1,368 mg/L. No systematic lateral variations in water composition were observed, as only the concentrations of sulphate, bicarbonate, and potassium were considered. The iron concentration was 60 mg/l and the silica content was 31 mg/l in well Vilkyciai-5²⁴⁸.

In brief, the Gargždai zone of uplifts can be seen as one single continuous structure as observed through continuity of the sands across the field (Figure 51). However, it should be noted that the structural closure of the formation is not fully demonstrated in the figure, and further structural mapping together with hydrodynamic studies would be required to confirm the presence of a fully enclosed trap suitable for long-term CO₂ storage. The Gargždai zone of uplifts, which includes mature and declining oil fields, covers approximately 233 km². The estimated CO₂ storage volume under partial depletion conditions was around 31.3 Mt²⁴⁹. Of note, one of the key limiting parameters is the relatively low average porosity (7 %) and the fractured reservoir type, with an estimated permeability of about 10 mD, a net thickness of ~70 m, and a depth of ~2,200 m. Recent ROZ (Residual Oil Zone) assessments suggest that this area could offer high potential for combined CO₂-EOR and storage operations, making

²⁴⁵ Source: LAPINSKAS, P. *Structure and Petroliferosity of the Silurian in Lithuania*. 2000. Institute of Geology: Vilnius, Lithuania, 203p.

²⁴⁶ Source: ZABA, J., POPRAWA, P. *Deformation History of the Koszalin-Chojnice Zone (Pomeranian Segment of TESZ, NW Poland) Constraints from Structural Analysis of Palaeozoic and Mesozoic Successions in Polskie Łąki PIG 1 and Toruń 1 Boreholes*. 1997. Prace-Panstw. Inst. Geol. Vol. 186, 225–252.

²⁴⁷ ŠLIAUPA, S; MICHELEVICIUS, D; ŠLIAUPIENĖ, R; LIUGAS, J. Assessment of the Potential for CO₂ Storage and Utilization in the Fractured and Porous Reservoir of the Cambrian Sandstones in West Lithuania's Baltic Basin. 2024. Minerals, 14(11). <https://doi.org/10.3390/min14111112>

²⁴⁸ ŠLIAUPA, S; MICHELEVICIUS, D; ŠLIAUPIENĖ, R; LIUGAS, J. Assessment of the Potential for CO₂ Storage and Utilization in the Fractured and Porous Reservoir of the Cambrian Sandstones in West Lithuania's Baltic Basin. 2024. Minerals, 14(11). <https://doi.org/10.3390/min14111112>

²⁴⁹ Source: ŠLIAUPA, Saulius; MICHELEVIČIUS, Dainius; ŠLIAUPIENĖ, Rasa; LIUGAS, Jonas. *Assessment of the Potential for CO₂ Storage and Utilization in the Fractured and Porous Reservoir of the Cambrian Sandstones in West Lithuania's Baltic Basin*. October 30th, 2024. Minerals 2024, 14(11), 1112, <https://doi.org/10.3390/min14111112>

it one of the few prospective zones of this kind in the Baltic region and recent numerical modelling of the Gargždai zone of uplifts has projected a possible CO₂ storage capacity ranging from 64 to 267 Mt, depending on the degree of depletion and injection strategy.²⁵⁰

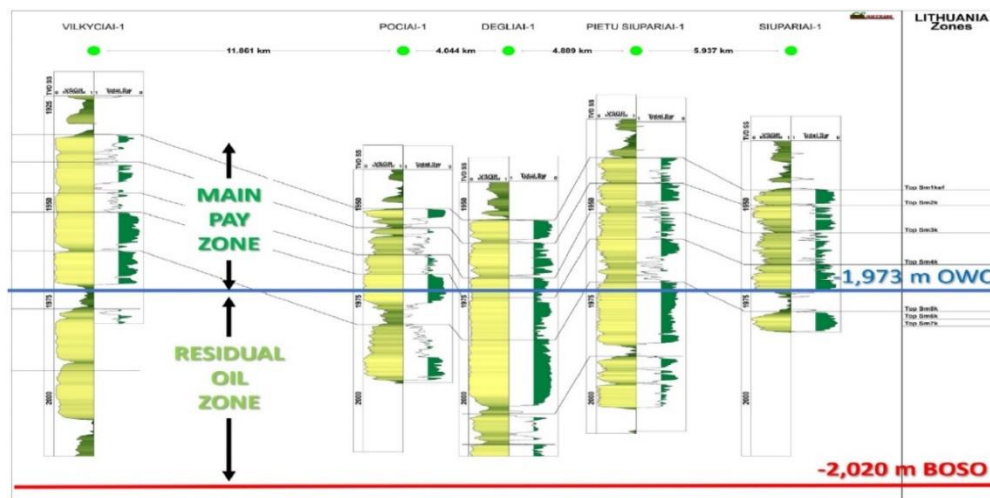


Figure 51: Gargždai zone of uplifts made of sandstones (Malik et al., 2024)

In addition, the Telšiai fault in Lithuania has been identified as a potential site for CO₂ storage due to its favourable characteristics compartmentalising some oil bearing structures. In this regard, the Telšiai fault zone, along with its branching faults, is associated with the Syderiai saline aquifer (commented above), an elongated dome, which exhibits good reservoir properties for CO₂ storage. This fault is also associated to Vaškai and D11 structures which were commented above. The Telšiai fault zone is located in the southern region of the Syderiai saline aquifer in western Lithuania.

This structure was originally considered to be a prospective site for natural underground gas storage. The main target of the seismic study was to prove the tectonic tightness of the faults, which is of paramount importance for the safe storage of gas. Furthermore, the analysis of wells Pabalvė-1, Tryškiai-73, Tryškiai-74, and Žarėnai-1 provided information on the Cambrian reservoir's properties close to the Syderiai site. The amplitude of the Telšiai fault measures 250 m, making it the largest tectonic structure defined within the sedimentary cover in Lithuanian territory.

This tectonic structure was classified as a right lateral strike-slip fault induced by NW–SE propagation of transgressional forces²⁵¹. The well Syderiai-1, which has been used as the reference well in the Syderiai area as it was drilled in the crestal part of the largest uplift, located on the hanging wall of the Telšiai fault, penetrated the top of the Cambrian at a depth of 1458 m (–1320 m b.s.l.) and the thickness of the reservoir is 50 m²⁵².

²⁵⁰ Source: MALIK, S., MAKASKAS, P., KARALIUTE, V., PAL, M., SHARMA, R. *Assessing the geological storage potential of CO₂ in Baltic basin: A case study of Lithuanian hydrocarbon and deep saline reservoirs*. 2024. Int. J. Greenh. Gas Control. Vol. 133, 104097.

²⁵¹ Source: BOROWIEC, K.; ANOLIK, P.; ZARĘBSKA, B.; SOWIŃSKI, A. *B8 Crude Oil Field Development-Concept and Basic Design Assumptions*. In Proceedings of the International Conference “Baltic-Petrol’2010”, Gdańsk, Poland, 28

²⁵² Source: ŠLIAUPA, Saulius; MICHELEVIČIUS, Dainius; ŠLIAUPIENĖ, Rasa; LIUGAS, Jonas. *Assessment of the Potential for CO₂ Storage and Utilization in the Fractured and Porous Reservoir of the Cambrian Sandstones in West Lithuania’s Baltic Basin*. October 30th, 2024. Minerals 2024, 14(11), 1112, <https://doi.org/10.3390/min14111112>

The structure contains Cambrian sandstones with good porosity (14-18%) and permeability (400 mD) in the Deimena series²⁵³. Cambrian sandstones are overlain by the Letse Fm. (Lower Ordovician), measuring 1.0 m thick, and are composed of dolostones, marlstones and limestones, representing the basal section of the cap rocks^{254, 255}. The total thickness of the Ordovician succession measures 128.3 m. The ratio of limestones and marlstones with some interlayers of organic-rich shale was assessed at 58%. The Silurian thickness of the overlying shales is 430 m and contains only scarce limestone interlayers; therefore, it is considered essentially a high-quality cap rock. Still, no specific petrophysical measurements were available. The storage potential of the two largest oil fields in West Lithuania reaches 2 Mt CO₂²⁵⁶. The storage capacities of other minor oil fields are shown in Table 13 and Table 14²⁵⁷.

Conclusions

Of note, the geological information provided here about the capacities estimated for potential storage sites in Lithuania has been provided based on the results of research projects published in scientific journals. Therefore, in the future, additional geological data can be obtained (e.g., from the Reports stored in the archives of the Lithuanian Geological Survey under the Ministry of Environment or other research organisations of Lithuania), and could be used to carry out additional estimations of CO₂ capacities applying different recent methodologies. The modelling results show that all three deep saline aquifers (Syderiai, Vaškai and D11) present combined theoretical capacity of CO₂ storage ranging from 41.5 to 407 Mt^{258,259, 260} and for the Gargždai zone of uplifts, the numerical modelling results shows

²⁵³ Source: ŠLIAUPA, Saulius; MICHELEVIČIUS, Dainius; ŠLIAUPIENĖ, Rasa; LIUGAS, Jonas. *Assessment of the Potential for CO₂ Storage and Utilization in the Fractured and Porous Reservoir of the Cambrian Sandstones in West Lithuania's Baltic Basin*. October 30th, 2024. Minerals 2024, 14(11), 1112, <https://doi.org/10.3390/min14111112>

²⁵⁴ Source: LAŠKOVAS, J. *The Sedimentation Environments of the Ordovician Basin in the South-Western Margin of the East European Platform and Lithogenesis of Deposits*; Institute of Geology: Vilnius, Lithuania, 2000; 314p.

²⁵⁵ Source: NIELSEN, A.T.; SCHOVSBO, N. Cambrian to Basal Ordovician Lithostratigraphy in Southern Scandinavia. *Bull. Geol. Soc. Den.* 2006, 53, 47–92.

²⁵⁶ Source: SHOGENOVA, Alla; ŠLIAUPA, Saulius; VAHER, Rein; SHOGENOV, Kazbulat; POMERANCEVA, RAISA. *The Baltic Basin: Structure, properties of reservoir rocks, and capacity for geological storage of CO₂*. Estonian Journal of Earth Sciences, 2009, 58, 4, 259-267. December 2009. DOI: 10.3176/earth.2009.4.04.

²⁵⁷ Source: ŠLIAUPA, S. *Potential of Geological Formations for CO₂ sequestration in Lithuania*. 2008.

²⁵⁸ Source: ŠLIAUPIENĖ, R., ŠLIAUPA, S. *Prospects for CO₂ Geological Storage in Deep Saline Aquifers of Lithuania and Adjacent Territories*. 2012. Geologija. Vol. 53, 121–133.

²⁵⁹ Source: MALIK, S., MAKASKAS, P., KARALIUTE, V., PAL, M., SHARMA, R. *Assessing the geological storage potential of CO₂ in Baltic Basin: A case study of Lithuanian hydrocarbon and deep saline reservoirs*. 2024.

International Journal of Greenhouse Gas Control. Vol 133 <https://doi.org/10.1016/j.ijggc.2024.104097>

²⁶⁰ Source: LIUGAS, J., ŠLIAUPIENĖ, R., GRENDAITĖ, M., MICHELEVIČIUS, D., ŠLIAUPA, S. *CO₂ geological storage prospects of Lithuania – update*. 2023. Baltic Carbon Forum 2023 in Riga, Latvia, October 12-13.

that storage volume ranges from 31.3 to 267 Mt^{261, 262,263,264}. The storage capacity estimation for the Telšiai fault area is ca. 2 Mt CO₂²⁶⁵ and those for other minor structures are shown in Table 13 and Table 14²⁶⁶. These results show that it seems possible to store large CO₂ within the boundary of Lithuanian territory. It is also important to mention that further work may be required to develop a full CCS injection project in Lithuania and to narrow down the range of storage capacity estimates for saline aquifers and the Gargždai zone of uplifts, which will require additional data collection and integration of data into geological and simulation models.

Saline aquifer	Area (km ²)	Top depth (m)	Thickness (m)	Porosity	CO ₂ density (t/m ³)	Permeability (mD)	Storage efficiency factor	Capacity (Mt CO ₂)
Syderiai	26.0	1,458	57	0.16	710	400	0.3	21.5 (1) 56.7 (2) 54-232 (3)
Vaškai	12.3	896	57	0.23	580	280	0.3	8.7 (1) 25-106 (3)
D11	25.0	1,700	65	0.10	750	300	0.3	11.3 (1) 17-69 (3)

Table 13: Estimation of CO₂ storage capacity in saline aquifers (closed structures) (1)²⁶⁷, (2)²⁶⁸, (3)²⁶⁹

²⁶¹ Source: ŠLIAUPIENĖ, R., ŠLIAUPA, S. *Prospects for CO₂ Geological Storage in Deep Saline Aquifers of Lithuania and Adjacent Territories*. 2012. Geologija. Vol. 53, 121–133.

²⁶² Source: LIUGAS, J., ŠLIAUPIENĖ, R., GRENDAITĖ, M., MICHELEVIČIUS, D., ŠLIAUPA, S. *CO₂ geological storage prospects of Lithuania – update*. 2023. Baltic Carbon Forum 2023 in Riga, Latvia, October 12-13.

²⁶³ Source: MALIK, S., MAKASKAS, P., KARALIUTE, V., PAL, M., SHARMA, R. *Assessing the geological storage potential of CO₂ in Baltic basin: A case study of Lithuanian hydrocarbon and deep saline reservoirs*. 2024. Int. J. Greenh. Gas Control. Vol. 133, 104097.

²⁶⁵ Source: SHOGENOVA, Alla; ŠLIAUPA, Saulius;VAHER, Rein; SHOGENOV, Kazbulat; POMERANCEVA, RAISA. *The Baltic Basin: Structure, properties of reservoir rocks, and capacity for geological storage of CO₂*. Estonian Journal of Earth Sciences, 2009, 58, 4, 259-267. December 2009. DOI: 10.3176/earth.2009.4.04.

²⁶⁶ Source: ŠLIAUPA, S. *Potential of Geological Formations for CO₂ sequestration in Lithuania*. 2008.

²⁶⁷ Source: ŠLIAUPIENĖ, R., ŠLIAUPA, S. *Prospects for CO₂ Geological Storage in Deep Saline Aquifers of Lithuania and Adjacent Territories*. 2012. Geologija. Vol. 53, 121–133.

²⁶⁸ Source: LIUGAS, J., ŠLIAUPIENĖ, R., GRENDAITĖ, M., MICHELEVIČIUS, D., ŠLIAUPA, S. *CO₂ geological storage prospects of Lithuania – update*. 2023. Baltic Carbon Forum 2023 in Riga, Latvia, October 12-13.

²⁶⁹ Source: MALIK, S., MAKASKAS, P., KARALIUTE, V., PAL, M., SHARMA, R. *Assessing the geological storage potential of CO₂ in Baltic Basin: A case study of Lithuanian hydrocarbon and deep saline reservoirs*. 2024. International Journal of Greenhouse Gas Control. Vol 133 <https://doi.org/10.1016/j.ijggc.2024.104097>

Average properties for the Gargždai zone of uplifts as one single reservoir entity are shown in Table 14:

Zone	Area (km ²)	Top depth (m)	Thickness (m)	Porosity	CO ₂ density (t/m ³)	Permeability (mD)	Storage efficiency factor	Capacity (Mt CO ₂)
Gargždai	233.0	1,973	50	0.07	610	10	0.3	31.3 (4) 64-267 (5)

Table 14: Estimation of CO₂ storage capacity in Gargždai zone of uplifts (4)²⁷⁰, (5)²⁷¹.

²⁷⁰ Source: ŠLIAUPA, Saulius; MICHELEVIČIUS, Dainius; ŠLIAUPIENĖ, Rasa; LIUGAS, Jonas. *Assessment of the Potential for CO₂ Storage and Utilization in the Fractured and Porous Reservoir of the Cambrian Sandstones in West Lithuania's Baltic Basin*. October 30th, 2024. Minerals 2024, 14(11), 1112, <https://doi.org/10.3390/min14111112>

²⁷¹ Source: MALIK, S., MAKASKAS, P., KARALIUTE, V., PAL, M., SHARMA, R. *Assessing the geological storage potential of CO₂ in Baltic Basin: A case study of Lithuanian hydrocarbon and deep saline reservoirs*. 2024. International Journal of Greenhouse Gas Control. Vol 133 <https://doi.org/10.1016/j.ijggc.2024.104097>

8.1.3. Potential CO₂ storage sites in the Baltic countries

The most prospective CO₂ storage reservoir in the Baltic States is related to Deimena Fm. which consists of sandstones of the Cambrian Wulian Stage and constitutes the Lithuanian saline aquifers of Syderiai and Vaškai and D11 with an estimated storage capacity between 41.5 and 407 Mt CO₂.

Potential CO₂ storage structures do not only appear in Lithuania, but in other Baltic countries (Figure 52). The CO₂ storage capacity of the largest structures has been re-estimated and static structural geological models were constructed for four west Latvian onshore structures (Dobele, South-Kandava, Blidene, and North Blidene; Figure 52) and offshore structure E6^{207, 208}. The largest storage capacity onshore is available in the Latvian North-Blidene and Dobele structures and the largest storage site offshore is E6 structure²⁷² (Table 15).

The geological formations within Lithuania and Latvia that are suitable for fossil CO₂ storage, can be found also in Estonia. In contrast, in this country they are located too shallow (beyond the limit of the supercritical state of CO₂) and contains potable groundwater (Figure 52) and therefore, they are not favourable for CO₂ storage^{273, 274}.

²⁷² Source: SHOGENOVA, Alla; SHOGENOV, Kazbulat; ŠLIAUPA, Saulius, ŠLIAUPIENNÉ, Rasa. *The Role of CCUS Clusters and Hubs in Reaching Carbon Neutrality: Case Study from the Baltic Sea Region*. 2023. Chemical Engineering Transactions. Vol. 105, 2023. The Italian Association of Chemical Engineering. DOI: 10.3303/CET23105029

²⁷³ Source: KRŪMIŅŠ, J.; KĻAVIŅŠ, M.; DĒLIŅA, A., DAMKEVICS, R., SEGLIŅŠ, V.. *Potential of the Middle Cambrian Aquifer for Carbon Dioxide Storage in the Baltic States*. *Energies* 2021, 14, 3681. <https://doi.org/10.3390/en14123681>

²⁷⁴ Source: SHOGENOVA, Alla; ŠLIAUPA, Saulius; VAHER, Rein; SHOGENOV, Kazbulat; POMERANCEVA, RAISA. *The Baltic Basin: Structure, properties of reservoir rocks, and capacity for geological storage of CO₂*. *Estonian Journal of Earth Sciences*, 2009, 58, 4, 259-267. December 2009. DOI: 10.3176/earth.2009.4.04

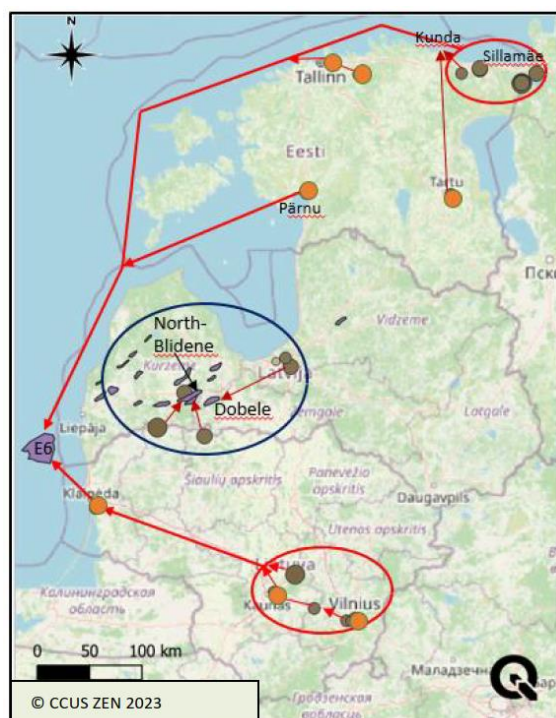


Figure 52: Estonian-Latvian-Lithuanian CCUS (Carbon Capture, Usage and Storage) clusters. Large fossil CO₂ emissions reported in EU ETS are shown by brown circles. Bio-CO₂ emissions and waste to energy plants (not reported in EU ETS) are shown in orange points. The onshore cluster is shown by the large blue oval, while the offshore CCUS cluster is shown by red circles and arrows (updated after the CCUS ZEN project Q-GIS database)

The North Blidene and Blidene structures located in western Latvia were recently applied in the Estonian-Latvian onshore CCUS scenario²⁷⁵. Their optimistic and conservative CO₂ storage capacity was estimated (Table 15). The North Blidene is an anticlinal uplift cut by west-east striking fault.

The Blidene uplift is located in the down-dip block confined by the paralleling fault to the south and verging SW-NE of, the amplitude of down-thrust fault is about 400 m. The estimated area of the Dobeles structure considering closing contour of 1,075 m is 70 km² and amplitude is up to 110 m. The tectonic structure is located on the hanging-wall of the west-east oriented fault. These three structures are confined to the common Saldus-Inčukalna elevated fault zone. The Dobeles uplift was drilled by 17 deep wells penetrating the Cambrian Deimena Formation and 5 wells were drilled in the hanging wall of the controlling fault. The Cambrian reservoir is represented by quartz sandstones interbedded by thin

²⁷⁵ Source: SHOGENOVA, A., SHOGENOV, K., UIBU, M., KUUSIK, R., SIMMER, K., CANONICO, F. *Techno-economic modelling of the Baltic CCUS onshore scenario for the cement industry supported by CLEANER project*. 2021. 15th International Conference on Greenhouse Gas Control Technologies, GHGT-15, 15-18 March 2021, Abu Dhabi, UAE, Elsevier, SSRN, 1–13, DOI: 10.2139/ssrn.3817710.

layers of sandy siltstone and mudstones. Deimena Formation sandstones were defined at 965–1,013 m depth in the Db91 well, and 1,346–1,390 m depth^{276, 277}.

The E6 offshore structure was discovered by seismic exploration and drilled in 1984 by well E6-1 (1,068 m depth) located 37 km from the coast of Latvia. The structure coincides with the zone of Liepaja-Saldus uplifts and was estimated as prospective for oil exploration in the 10.5 m thick Upper Ordovician Saldus Formation reservoir²⁷⁶. The structure is an anticline bounded on three sides by faults (Figure 53). The E6 structure consists of two different compartments (E6-A and E6-B) divided by the inner fault. The total area of the structure is 600 km² considering the closing contour of the reservoir top located at a depth of 1350 m (BSL). The area of the larger E6-A part is 553 km²²⁷⁶. Prospective for CO₂ storage Cambrian Deimena Formation reservoir in the E6 structure was assessed as the largest storage site in the region. The Deimena Formation consists of quartz oil-stained sandstones with subordinate shale layers deposited in a shallow marine basin. The major Deimena reservoir overlies the shales of the Kybartai Regional stage (40 m thick). The Cambrian reservoir is sealed by large thick Silurian-Ordovician shale cap rock of 268 m thick in well E6-1. Offshore E6 structure has a smaller depth compared to onshore structures. Both onshore and offshore structures have good reservoir properties, while the temperature is higher offshore (36°C) compared to 18–23°C onshore. Because the lower temperature is more suitable for CO₂ storage, the density of CO₂ stored will be higher onshore than in offshore structure²⁷⁷ (Table 15). All structures discussed in the paper were drilled by one (E6) to 23 (Dobele) wells that can be rated as an optimistic scenario, rather than Conservative scenario, considering of seismic exploration, drill cores, logging, hydrogeological, geothermal and other data available.

²⁷⁶ Source: SHOGENOV, K., SHOGENOVA, A., VIZIKA-KAVVADIAS, O. *Potential structures for CO₂ geological storage in the Baltic Sea: case study offshore Latvia*. 2013. Bulletin of the Geological Society of Finland. Vol. 85(1), 65–81.

²⁷⁷ Source: JANSONS, L., ZELTINS, N. *Technical Studies on Development of the Dobele Underground Natural Gas Storage Facility, 2015*. Proceedings of REHVA Annual Conference 2015 “Advanced HVAC and Natural Gas Technologies” Riga, Latvia, May 6 – 9, 2015. 162-166, doi:10.7250/rehvaconf.2015.023.

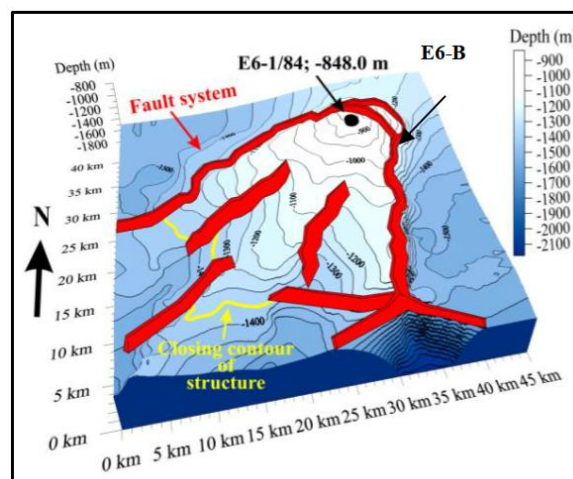


Figure 53: Structural model of E6 storage site offshore Latvia^{278,279}.

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

Table 15: Parameters of CO₂ storage sites selected for Latvia²⁸⁰

Two large CCUS clusters could be composed of Estonian, Latvian and Lithuanian large emission sources and the most prospective storage sites in Latvia (Table 16). A CCUS cluster refers to a regional concentration of CO₂ emitters, CO₂ transport infrastructure, and storage or utilization sites that are connected through an integrated value chain.

²⁷⁸ Source: SHOGENOV, K., SHOGENOVA, A., VIZIKA-KAVVADIAS, O. *Potential structures for CO₂ geological storage in the Baltic Sea: case study offshore Latvia*. 2013. Bulletin of the Geological Society of Finland. Vol. 85(1), 65–81.

²⁷⁹ Source: SHOGENOV, K., SHOGENOVA, A., VIZIKA-KAVVADIAS, O. *Petrophysical properties and capacity of prospective for CO₂ geological storage Baltic offshore and onshore structures*. 2013. Energy Procedia, 5036–5045, DOI: 10.1016/j.egypro.2013.06.417.

²⁸⁰ Source: SHOGENOVA, Alla; SHOGENOV, Kazbulat; ŠLIAUPA, Saulius, ŠLIAUPIENNÉ, Rasa. *The Role of CCUS Clusters and Hubs in Reaching Carbon Neutrality: Case Study from the Baltic Sea Region*. 2023. Chemical Engineering Transactions. Vol. 105, 2023. The Italian Association of Chemical Engineering. DOI: 10.3303/CET23105029

The Baltic offshore cluster includes all large Estonian and Lithuanian fossil and bio-emission sources – one of which Klaipėda WtE Plant and other sources located in central and south-eastern Lithuania. The CO₂ could be transported from proximal emitters by pipelines, while the E6 structure may be linked by pipelines and ships, located as far as 80 km from Klaipėda Port. Estonian north-east cluster, composed of seven emission sources (four plants produced only fossil emissions and three power co-generation plants using both oil shales and biomass for energy production) will use CO₂ pipeline or truck/train transport to Sillamäe and Kunda ports and then ship CO₂ to the E6 storage site in Latvia (615 km by ship from Sillamäe). This cluster will be able to capture and store annually 11.1 t CO₂, including 9 Mt of fossil and 2.1 Mt of bio-CO₂.

The Baltic onshore cluster includes four of the largest Latvian CO₂ emitters and two Lithuanian plants located close to the Latvian-Lithuanian border (Orlen refinery and Akmenes cement plant, owned by Schwenk).

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

Table 16: CCUS full value chain clusters

This cluster may store annually 3.1 Mt CO₂ from three plants (Latvian and Lithuanian Schwenk-owned cement plants and Orlen Refinery) in the onshore North Blidene and Blidene structures. Latvian two Latvenergo PP and one Rigas Siltums TP located in the Riga region could transport about 0.95 Mt CO₂ in the Dobele storage site in western Latvia using up to 150 km CO₂ pipelines.

The alternative CO₂ use option for Estonia is the application of CO₂ for mineral carbonation of Estonian burned oil shale (BOS) ²⁸¹. Another option for geothermal energy recovery in the E6 structure for the local energy needs of the drilling rig. The Baltic countries are looking forward to producing hydrogen. It can be stored in the smaller E6-B compartment of the E6 structure offshore and/or in the Blidene structure onshore (Figure 53).

A total amount of 15.23 Mt of fossil and bio- CO₂ emissions could be captured, transported, used and stored, while only 13.7 Mt of fossil CO₂ gas was produced in 2021. The negative balance is calculated about 1.53 Mt CO₂.

In brief:

- The two largest onshore and one offshore storage sites in Latvia have the capacity to store all large Estonian, Latvian, and Lithuanian fossil and bio-CO₂ emissions.
- A total 15.1 Mt of fossil and bio- CO₂ could be captured, transported, used and stored, while only 13.7 Mt of fossil CO₂ produced annually. The negative balance is about 1.4 Mt CO₂.

²⁸¹ Source: SHOGENOVA, A., SHOGENOV, K., UIBU, M., KUUSIK, R., SIMMER, K., CANONICO, F. *Techno-economic modelling of the Baltic CCUS onshore scenario for the cement industry supported by CLEANER project*. 2021. 15th International Conference on Greenhouse Gas Control Technologies, GHGT-15, 15-18 March 2021, Abu Dhabi, UAE, Elsevier, SSRN, 1–13, DOI: 10.2139/ssrn.3817710.

- Additional revenues will come from geothermal energy recovery in Latvia for local heating and cooling needs, CO₂ mineral carbonation of BOS in Estonia and hydrogen production and storage in the Baltic CCUS clusters.
- The average optimistic storage capacity of the studied structures will be enough for more than 50 years, while conservative for 14.5 years. The CCUS cluster scenario represents the substantial volume to store the emitted CO₂ for the long transitional period

Conclusions

Thus, the geological Lithuanian structures seem fitting for CCS, although further work may be required, which will require additional data collection and integration into geological and simulation models. In addition, geological structures of neighbouring countries might be also taken into account.

These mentioned additional data required are: acquisition and reinterpretation of seismic data, drilling of new exploratory wells, coring and laboratory testing of reservoir and caprock samples, geophysical logging, pressure and hydrodynamic testing, geochemical characterization of formation fluids, and the integration of all collected data into three-dimensional geological and reservoir simulation models.

This recommended further work should be done in accordance with the current Lithuanian regulatory framework. According to the Decision of the Government of the Republic of Lithuania of 5 October 2011, No. 1166, and in particular Annex 1 of this Decision²⁷⁷, a series of direct and indirect geological investigations are permitted and required in order to confirm the suitability of a geological formation for CO₂ storage.

All these investigations (except for the injection of CO₂ itself) are authorised under the Lithuanian legal acts regulating subsurface, petroleum and related geological activities, and can therefore be undertaken to refine the estimates of storage capacity and to more accurately assess the suitability of saline aquifers and uplift zones as potential CO₂ storage sites in Lithuania. Incorporating these investigations in future work would significantly reduce the current uncertainty associated with geological models and capacity ranges.

In the context of the EU's climate change and energy policy set out in Directive 2009/31/EC on the implementation of geological storage of carbon dioxide, Lithuania should continue to assess the conditions and prospects for CO₂ capture, transport and geological storage, focussing on the supercritical site and alternative geological storage technologies and opportunities.

The European Innovation Fund will provide more than € 10 billion in support in five strategic areas between 2020 and 2030, two of which are directly related to CO₂ storage.

It has to be emphasized that the geological data and information provided in this Study about the capacities estimated for potential structures in Lithuania has been provided based on the results of the studies published in scientific journals without an interpretation of the publicly available initial archival geological data. Therefore, in the future these numerous geological data could be obtained (e.g. from the Reports stored in the archives of Lithuanian Geological Survey under the Ministry of Environment or other research organisations of Lithuania) and used for the estimations of CO₂ capacities applying different recent methodologies.

8.1.4. Best practices of CO₂ Geological Storage

Geological Storage - Guidelines

It refers to the process of injecting captured CO₂ into deep underground formations, including depleted oil and gas fields, saline aquifers, and other deep geological structures, where it remains securely stored for long geological periods^{282, 283}.

Best practices for geological storage involve:

1. **Careful site selection and characterization** to identify appropriate storage locations with the capacity and structural integrity to securely store CO₂. This process includes Geological surveys, seismic imaging, and well logging to evaluate subsurface conditions, locate potential storage formations, and assess containment mechanisms.
2. **Understanding reservoir properties:** porosity, permeability, and caprock integrity, is critical for estimating storage capacity and predicting CO₂ behaviour over time.
3. **Numerical modelling tools:** Like reservoir simulation, are used to model CO₂ injection and migration, assess storage performance, and optimize injection techniques^{284 285}.
4. **Ongoing monitoring and verification:** For storage sites, monitoring and verification are vital to ensuring the safety and stability of the stored CO₂. Monitoring methods include seismic, pressure, and geochemical monitoring to detect leaks, track CO₂ migration, and assess storage efficiency.

²⁸² Source: ALBERTZ, Markus; STEWART, Simon; GOTETI, Rajesh. *Perspectives on geologic carbon storage*. Frontiers in Energy Research 10, 1071735. 2023.

²⁸³ Source: DIGITEMIE, Wags; EKEMEZIE, Ifeanyi. *A comprehensive review of Building Energy Management Systems (BEMS) for Improved Efficiency*. World Journal of Advanced Research and Reviews 21(03), 829–841. 2024. <https://doi.org/10.30574/wjarr.2024.21.3.0746>.

²⁸⁴ Source: KHAN, Sikandar; KHULIEF, Yehia; JUANES, Ruben; BASHMAL, Salem; USMAN, Muhammed; AL-SHUHAIL, Abdullatif. *Geomechanical Modeling of CO₂ Sequestration: A Review Focused on CO₂ Injection and Monitoring*. Journal of Environmental Chemical Engineering, 112847. 2024.

²⁸⁵ Source: SOLOMON, Nko Okina; SIMPA, Peter; ADENEKAN, Olubunmi Adeolu; OBASI, Scholar Chinenye. *Circular economy principles and their integration into global supply chain strategies*. Finance & Accounting Research Journal, 6(5), 747-762. 2024. <https://doi.org/10.51594/farj.v6i5.1133>

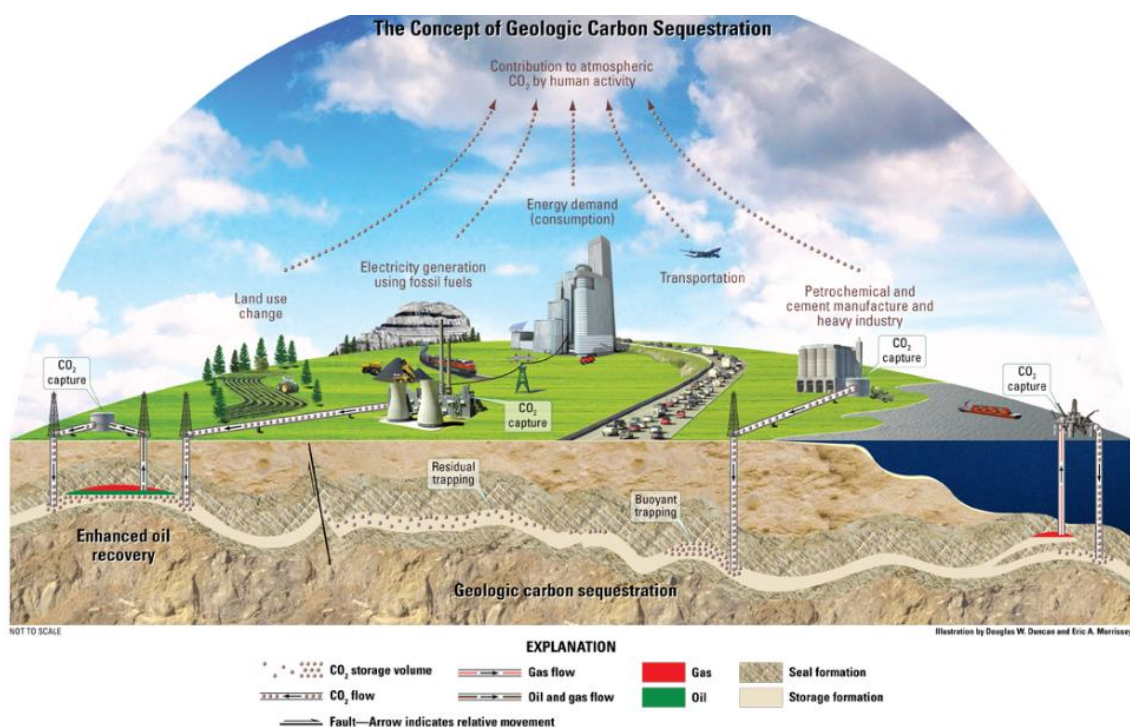


Figure 54: Scheme of the geologic carbon storage ²⁸⁶.

Site-selection criteria

Geological storage sites should typically possess (1) sufficient capacity and injectivity, (2) a reliable sealing caprock or confining layer, and (3) a stable geological setting to ensure the storage site's integrity is maintained.

According to Bradshaw et al.²⁸⁷ criteria for evaluating basin suitability include: basin characteristics (such as tectonic activity, sediment composition, geothermal conditions, and hydrodynamic regimes); basin resources; the maturity of local industry and available infrastructure; and societal factors like development level, economic conditions, environmental considerations, public awareness, and attitudes. These and other criteria can be found for interest of the reader who wants to deepen on in the European Commission Guidance²⁸⁸

The suitability of sedimentary basins for CO₂ storage is influenced by their location on the continental plate. Basins situated in mid-continental regions or near the edges of stable continental plates are ideal for long-term CO₂ storage due to their structural stability. Basins with **poor** CO₂ storage potential typically exhibit characteristics such as:

²⁸⁶ Source: United States Geological Survey. *The Concept of Geologic Carbon Sequestration*. 2011. Web reference accessed in July 2025: <https://www.usgs.gov/media/images/concept-geologic-carbon-sequestration>

²⁸⁷ Source: BRADSHAW, John; BRADSHAW, Barry; ALLINSON, G.; RIGG, A.J.; NGUYEN, V. *The potential for geological sequestration of CO₂ in Australia: preliminary findings and implications for new gas field development*. Australian Petroleum Production and Exploration Association Journal, 42(1), 24–46. 2002.

²⁸⁸ Source: EUROPEAN COMMISSION, 2024. *Guidance Document 1: CO₂ Storage Life-Cycle and Risk Management Framework*. European Climate, Infrastructure and Environment Executive Agency (CINEA). Available at: https://climate.ec.europa.eu/document/download/951d14ea-ce0f-4753-92dd-35ba88920888_en?filename=ccs-implementation_gd1_en_0.pdf

1. Being thin ($\leq 1,000$ m).
2. Having inadequate reservoir and seal relationships.
3. Extensive faulting and fracturing.
4. Location within fold belts.
5. Strongly discordant stratigraphic sequences.
6. Significant diagenetic alteration.
7. Overpressured reservoirs.

On the other hand, with respect to **optimal** areas for CO₂ storage, the British Natural Environment Research Council²⁸⁹ stated the following guidelines:

Parameters	Positive indicators	Cautionary indicators
Total storage capacity	Total capacity of reservoir estimated to be much larger than the total amount produced from the CO ₂ source.	Total capacity of reservoir estimated to be similar or less than the total amount produced from the CO ₂ source.
Depth	1000- 2500 m	< 800 m or > 2,500 m
Thickness (net)	>> 50 m	< 20 m
Porosity	> 20%	< 10%
Permeability	> 300 mD	10- 100 mD
Salinity	> 100 g/l	< 30 g/l
Seal properties		
Lateral continuity	Un-faulted	Laterally variable faults
Thickness	> 100 m	< 20 m
Capillary entry pressure	Much greater than buoyancy force of maximum produced CO ₂ column height	Similar to buoyancy force of maximum produced CO ₂ column height

Table 17: Screening criterion for the CO₂ storage²⁸⁹.

An alternative version and more specific criteria were proposed ²⁹⁰, especially when selecting global depleted gas reservoirs.

²⁸⁹ Source: CHADWICK, Andy; ARTS, Rob; BERNSTONE, Christian; MAY, Franz; THIBEAU, Sylvain; ZWEIGEL, Peter. *Book Best practice for the storage of CO₂ in saline aquifers: Observations and guidelines from the SACS and CO2STORE projects*. British Geological Survey, Nottingham, 14: 267. 2008.

²⁹⁰ Source: RAZA, Arshad; REZAEI, Reza; GHOLAMI, Raoof; CHUA, Han Bing; NAGARAJAN, Ramasamy; HAMID, Mohamed Ali. *A screening criterion for selection of suitable CO₂ storage sites*. Journal of Natural Gas Science and Engineering 28, pp. 317-327. 2016. <https://doi.org/10.1016/j.jngse.2015.11.053>

Parameters	Positive indicators	Cautionary indicators	Indication of aspect
CO ₂ source and total storage capacity	Total capacity of reservoir estimated to be much larger than the total amount produced from the CO ₂ source.	Total capacity of reservoir estimated to be similar or less than the total amount produced from the CO ₂ source.	Storage capacity.
Depth	> 800 m.	800 m > depth > 2,000 m	Storage capacity.
CO ₂ density	High.	Low	Storage capacity.
Porosity	> 20%.	< 10%	Storage capacity.
Thickness (net)	>> 50 m.	< 20 m	Capillary trapping.
Permeability (near-wellbore)	> 100 mD.	10 - 100 mD	Storage capacity.
Well type	Horizontal well with or without hydraulic fracture/vertical well with hydraulic fracture.	Vertical well without hydraulic fracture	Injectivity.
Type of minerals	Ca-, Mg-, or Fe- rich framework minerals such as feldspars, clays, micas, and Fe-oxides.	Fast reacting carbonate minerals.	Injectivity.
Residual gas/water saturation	Less.	High.	Injectivity / mineral trapping.
Pore throat size distribution	Less heterogeneous.	Highly heterogeneous.	Injectivity.
Salinity	Low.	High.	Injectivity and trapping.
Temperature	Low temperature gradient.	High temperature gradient.	Solubility trapping.
Pressure	Under pressure.	Overpressure.	Solubility trapping.
Gravity number	Less.	High.	Solubility trapping.
Rock type	Quartz rich sandstones and carbonates.	Highly stress sensitive carbonates.	Capillary trapping.
Rock wettability	Strong water wet.	Less water wet or oil-wet.	Capillary trapping.
Interfacial tension	High.	Low.	Capillary trapping.
Reservoir type	Reservoir without compaction/aquifer support.	Reservoir with compaction/ aquifer support.	Capillary trapping.
Hydraulic integrity	Have not experienced any injection in past. Less faults and fractures.	Have experienced any injection in past. More faults and fractures.	Containment.
Well location and condition	Good completion condition and away from faults & fractures.	Poor completion and near to faults & fractures.	Injectivity
Seal capacity- CO ₂ column height	Capillary entry pressure much greater than buoyancy force of maximum produced CO ₂ column high.	Capillary entry pressure similar to buoyancy force of maximum produced CO ₂ column height.	Containment.
Seal geometry- Lateral continuity	Un-faulted.	Laterally variable faults.	Containment.
Seal geometry- Thickness	> 100 m.	< 20 m.	Containment.
Hydraulic integrity: seal	Presence of mineral and stress characterization data of seal.	Absence of mineral and stress characterization data of seal.	Containment.
Distance between CO ₂ emission sources and target medium	< 300 km.	> 300 km.	Transportation cost.

Table 18: A new screening criterion for the selection of global depleted gas reservoirs.²⁹¹

Moreover, some key aspects must be considered:

- Definition of Storage Efficiency: The efficiency of CO₂ storage is determined by the amount of CO₂ stored per unit volume, which increases with higher CO₂ density.
- Impact of CO₂ Density on Safety: Higher CO₂ density enhances storage safety by reducing buoyancy forces that drive upward migration.

Density Changes with Depth:

- CO₂ density increases significantly while in the gaseous phase.
- Density levels off or slightly increases upon transitioning to the dense phase.
- At greater depths, density may decrease depending on the temperature gradient.

²⁹¹ Source: RAZA, Arshad; REZAEI, Reza; GHOLAMI, Raoof; CHUA, Han Bing; NAGARAJAN, Ramasamy; HAMID, Mohamed Ali. *A screening criterion for selection of suitable CO₂ storage sites*. Journal of Natural Gas Science and Engineering 28, pp. 317-327. 2016. <https://doi.org/10.1016/j.jngse.2015.11.053>

Favourable Basin Characteristics:

- "Cold" sedimentary basins with low temperature gradients are more suitable for CO₂ storage, as CO₂ reaches higher density at shallower depths (700–1,000 m).
- "Warm" sedimentary basins with high temperature gradients require greater depths (1,000–1,500 m) for dense-fluid conditions.

Influence of Depth on Site Selection: The depth of the storage formation affects site selection due to increased drilling and compression costs associated with deeper formations.

Adequate porosity, thickness, and permeability are critical for CO₂ storage, though porosity decreases with depth due to compaction. A secure seal, such as shale, salt, or anhydrite layers, is necessary to prevent CO₂ leakage. Faulted and fractured basins, especially in seismic zones, require careful assessment to ensure faults are sealed and injection won't cause reactivation.

In the next paragraphs, it is described the most typical geological formations and solutions for CO₂ storage.

The presence of fossil fuels and the exploration maturity of a basin are important factors in selecting CO₂ storage sites. Basins with limited hydrocarbon exploration may pose uncertainties due to insufficient geological data and the risk of contaminating undiscovered hydrocarbon resources ²⁹².

Mature sedimentary basins are ideal candidates for CO₂ storage because they:

- Their characteristics are well understood.
- Hydrocarbon reserves and/or coal deposits have been identified and extracted.
- Certain petroleum reservoirs may be depleted, close to depletion, or abandoned due to being economically unviable.
- The necessary infrastructure for CO₂ transport and injection might already exist.

Note that, in many instances, locating wells can be challenging, and the integrity of the caprock may need to be verified through pressure and tracer monitoring.

Deep saline aquifers

Deep saline aquifers and hydrocarbon reservoir rocks, whether depleted or active, are regarded as key potential mediums for CO₂ storage. Both options have significant storage capacities and are widely available globally ²⁹³. The volume of CO₂ that these formations can store may account for the majority of the total underground CO₂ storage capacity.

²⁹² Source: XIA, C; WILKINSON, M. *The geological risks of exploring for a CO₂ storage reservoir*. International Journal of Greenhouse Gas Control. Vol. 63, pp. 272-280. 2017. <https://doi.org/10.1016/j.ijggc.2017.05.016>

²⁹³ Source: ALI, Muhammad; AFTAB, Adnan; ARAIN, Zain-UI-Abidin; AL-YASERI, Ahmed; ROSHAN, Hamid; SAEEDI, Ali; IGLAUER, Stefan; SARMADIVALEH, Mohammad. *Influence of Organic Acid Concentration on Wettability Alteration of Cap-Rock: Implications for CO₂ Trapping/Storage*. ACS Applied Materials & Interfaces 12 (35). 2020. <https://pubs.acs.org/doi/10.1021/acsami.0c10491>.

Carbonate rocks

Another geological formation is commonly composed of sandstone or carbonate rocks. Compared to sandstone, which has lower permeability, carbonate rocks are highly permeable and allow for more efficient CO₂ injection. The caprock, usually made of shale, acts as a seal to trap buoyant CO₂ and prevent capillary leakage^{294 295}.

Basalts

Basaltic rocks have recently shown significant potential for CO₂ storage in mineralized form through a method pioneered by CarbFix²⁹⁶. This approach involves injecting CO₂ and water into basalt formations, triggering a rapid chemical reaction that converts CO₂ into solid carbonate minerals. A key advantage of this method is that it does not require the CO₂ to be concentrated during injection, and it can store up to 100 kilograms of CO₂ per cubic meter of basalt.

Organic rich shales

Organic-rich shales are another suitable option for the permanent immobilization of CO₂. These sedimentary rocks are characterized by their low porosity and impermeability, yet they can store significant amounts of CO₂. In such formations, CO₂ is securely trapped in an adsorbed state within the dispersed organic material, such as kerogen²⁹⁷.

Coal seam reservoirs are also considered promising candidates for CO₂ storage, particularly in deep, unmineable seams, where they can be utilized for enhanced coal bed methane recovery. In these reservoirs, CO₂ can exist in three forms: as free gas within the pore matrix, dissolved in liquid within the pores, or adsorbed onto the coal surface.

However, not all porous geological media are suitable for the permanent storage of CO₂. Some formations may lack the necessary conditions, such as an effective caprock seal, appropriate trapping mechanisms, or a stable storage environment. In such cases, physical trapping of gas may dominate, potentially leading to the formation of a free gas cap, which does not provide a reliable long-term storage solution.

Trapping mechanisms

In carbon geo-storage sites, a primary concern is the potential leakage of CO₂ into the environment, which can occur through artificial pathways such as wells or natural features like fractures and faults. This risk arises from the buoyant nature of CO₂, which causes it to migrate upward under most storage

²⁹⁴ Source: DURAND, Bernard. *Carbon dioxide capture and storage*. 2005.

²⁹⁵ Source: ARIF, Muhammad; ABU-KHAMSIN, Sidqi A.; IGLAUER, Stefan. *Wettability of rock/CO₂/brine and rock/oil/CO₂-enriched-brine systems: Critical parametric analysis and future outlook*. *Advances in Colloid and Interface Science* 266, pp. 91-113. 2019. <https://doi.org/10.1016/j.cis.2019.03.009>

²⁹⁶ Source: GÍSLASON, Sigurdur R.; SIGURDARDÓTTIR, Hólmfríður; ARADÓTTIR, Edda Sif; OELKERS, Eric H. *A brief history of CarbFix: Challenges and victories of the project's pilot phase*. *Energy Procedia* 146, pp. 103-114. <https://doi.org/10.1016/j.egypro.2018.07.014>

²⁹⁷ Source: SU, Erlei; LIANG, Yunpei; ZOU, Quanle; NIU, Fanfan; LI, Lei. *Analysis of Effects of CO₂ Injection on Coalbed Permeability: Implications for Coal Seam CO₂ Sequestration*. *Energy & Fuels* 33 (7). 2019. <https://doi.org/10.1021/acs.energyfuels.9b01190>

conditions²⁹⁸. To address this, CO₂ is typically injected in its supercritical phase, as geological formations with nano- to micropore structures are better suited for this state. The supercritical phase of CO₂ is advantageous because it allows the fluid to adapt its properties depending on the surrounding physicochemical conditions.

Main trapping mechanisms include:

- **Structural or hydrodynamic trapping** occurs in sandstone, carbonate, and caprock formations, where the CO₂ is physically trapped beneath impermeable layers.
- **Residual (or capillary) trapping** takes place in sandstone and carbonate formations, where CO₂ is immobilized within pore spaces due to capillary forces²⁹⁹.
- **Mineral and dissolution trapping** happens in carbonate, sandstone, and basaltic formations, where CO₂ reacts chemically with minerals to form stable compounds or dissolves into formation fluids³⁰⁰.
- **Adsorption and diffusion** trapping is prominent in organic-rich shales, clay interlayers, and coal seams, where CO₂ adheres to surfaces or diffuses into fine pores within the material³⁰¹.

8.2. Risk assessment of the geological storage of carbon in Lithuania

According to Malik et al.³⁰², the porosity and permeability values of the two Lithuanian saline aquifers (Syderiai and Vaškai) closely align with the laboratory values. This consistency across sub-volumes implies that the rock sample exhibits relative uniformity in terms of its porosity and permeability characteristics shown in Section 8.1.1. The results highlight that the distribution of the petrophysical properties of the Lithuanian saline aquifers is uniform, reducing the uncertainties associated with the storage capacity estimation. An analysis of parameters at the pore scale helps to understand the processes occurring in the porous media³⁰³. This also facilitates uniform CO₂ distribution and storage throughout the reservoir, maximizing storage efficiency. So, formations with well-sealed caprock layers can enhance the long-term security of CO₂ storage by minimizing the risk of leakage or migration through preferential pathways.

²⁹⁸ Source: IGLAUER, Stefan; PENTLAND, C. H.; BUSCH, A. *CO₂ wettability of seal and reservoir rocks and the implications for carbon geo-sequestration*. Water Resources Research 51 (1), pp. 729-774. 2015. <https://doi.org/10.1002/2014WR015553>

²⁹⁹ Source: PENTLAND, Christopher H.; EL-MAGHRABY, Rehab; IGLAUER, Stefan; BLUNT, Martin J. *Measurements of the capillary trapping of super-critical carbon dioxide in Berea sandstone*. Geophysical Research Letters 38 (6). 2011. <https://doi.org/10.1029/2011GL046683>

³⁰⁰ Source: AGARTAN, Elif; TREVISAN, Luca; CIHAN, Abdullah; BIRKHOLZER, Jens; ZHOU, Quanlin; ILLANGASEKARE, Tissa H. *Experimental study on effects of geologic heterogeneity in enhancing dissolution trapping of supercritical CO₂*. Water Resources Research 51 (3). <https://doi.org/10.1002/2014WR015778>

³⁰¹ Source: SHOJAI KAVEH, N.; WOLF, K-H.; ASHRAFIZADEH, S.N.; RUDOLPH, E.S.J. *Effect of coal petrology and pressure on wetting properties of wet coal for CO₂ and flue gas storage*. International Journal of Greenhouse Gas Control 11. 2011. <https://doi.org/10.1016/j.ijggc.2012.09.009>

³⁰² Source: MALIK, S., MAKASKAS, P., SHARMA, R., PAL, M. *Evaluating Petrophysical Properties Using Digital Rock Physics Analysis: A CO₂ Storage Feasibility Study of Lithuanian Reservoirs*. 2024. Appl. Sci. Vol. 14, 10826. <https://doi.org/10.3390/app142310826>

³⁰³ Source: ZABA, J., POPRAWA, P. *Deformation History of the Koszalin-Chojnice Zone (Pomeranian Segment of TESZ, NW Poland) Constraints from Structural Analysis of Palaeozoic and Mesozoic Successions in Polskie Łąki PIG 1 and Toruń 1 Boreholes*. 1997. Prace-Panstw. Inst. Geol. Vol. 186, 225–252

However, there are risks and challenges associated with the long-term storage of CO₂, including the risk of leakage through existing faults or existing wells drilled into and around the structure which were commented in sections 8.1.1 and 8.1.2, the creation of cracks and fractures due to changes in mechanical properties during injection, and the impacts of the injection and storage process on the integrity of the caprock.^{304, 305}

The most common risk is the one associated with leakage of CO₂ due to heterogeneity, such as the presence of high permeability layers, or faults and fractures^{306, 307}. To quantify its impact, a hypothetical case with the presence of high permeability fault/fracture cells in the models and simulated it to see its impact was created³⁰⁸. The major leakage impact is seen only in case when there are highly conductive vertically and horizontally connected faults in the model. It has been inspected for Syderiai mid-case model, where CO₂ is injected in the saline aquifers with the help of five vertical injection wells in a quarter-five-spot pattern. Two scenarios were addressed - one where the fault/fracture conductivity is 10 times the surrounding matrix block and second, where the fault/fracture conductivity is 100 times the surrounding matrix block. Simulation results show that in second scenario, the injected gas very quickly reaches to the surface and hardly any storage actually takes place and lot of leakage through fault/fractures is evident³⁰⁹.

Apart from leakage, another risk associated with CO₂ storage is risk of Caprock integrity^{310, 311, 312, 313}. In this regard, the Syderiai saline aquifer is a ca. 75 m height structure related to the largest Telšiai strike-slip fault. The main risk of storage site is the small-scale fault trending NE-SW. The most positive

³⁰⁴ Source: PAL, M., MALIK, S., KARALIUTE, V., MAKASKAS, P., SHARMA, R. *Assessing the feasibility of carbon capture and storage potential in Lithuanian geological formations: A simulation-based assessment*. In Proceedings of the 84th European Association of Geoscientists & Engineers (EAGE) Annual Conference & Exhibition, Vienna, Austria, 5–8 June 2023. Vol. 1, pp. 1–5.

³⁰⁵ Source: MALIK, S., MAKASKAS, P., KARALIUTE, V., PAL, M., SHARMA, R. *Assessing the geological storage potential of CO₂ in Baltic basin: A case study of Lithuanian hydrocarbon and deep saline reservoirs*. 2024. Int. J. Greenh. Gas Control. Vol. 133, 104097.

³⁰⁶ Source: ORLIC, B., SCHROOT, B. *The mechanical impact of CO₂ injection*. 2005. In: 67th EAGE Conference & Exhibition (pp. cp-1). European Association of Geoscientists & Engineers.

³⁰⁷ Source: MIU, L., NAZARE, D., CĂTUTU, M., DUDĂU, R., POSTOIU, C., BĂLAN, M. *Assessment of current state, past experiences and potential for CCS deployment in the CEE region-Romania*. 2021. CCS4CEE report.

³⁰⁸ Source: MALIK, S., MAKASKAS, P., KARALIUTE, V., PAL, M., SHARMA, R. *Assessing the geological storage potential of CO₂ in Baltic basin: A case study of Lithuanian hydrocarbon and deep saline reservoirs*. 2024. Int. J. Greenh. Gas Control. Vol. 133, 104097

³⁰⁹ Source: MALIK, S., MAKASKAS, P., KARALIUTE, V., PAL, M., SHARMA, R. *Assessing the geological storage potential of CO₂ in Baltic basin: A case study of Lithuanian hydrocarbon and deep saline reservoirs*. 2024. Int. J. Greenh. Gas Control. Vol. 133, 104097

³¹⁰ Source: HAWKES, C.D., MCLELLAN, P.J., ZIMMER, U., BACHU, S. *Geomechanical factors affecting geological storage of CO₂ in depleted oil and gas reservoirs: risks and mechanisms*. 2004. In: ARMA North America Rock Mechanics Symposium. ARMA, pp. ARMA–AR04.

³¹¹ Source: HOFSTEE, C., SEEBERGER, F., ORLIC, B., MULDER, F., VAN BERGEN, F., BISSCHOP, R. *The feasibility of effective and safe carbon dioxide storage in the De Lier gas field*. 2008. First Break 26.

³¹² Source: ORLIC, B., SCHROOT, B. *The mechanical impact of CO₂ injection*. 2005. In: 67th EAGE Conference & Exhibition (pp. cp-1). European Association of Geoscientists & Engineers.

³¹³ Source: DANGI, S.L., MALIK, S., MAKASKAS, P., KARALIUTE, V., SHARMA, R., PAL, M. *Assessment of CO₂ leakage using mechanistic modelling approach for CO₂ injection in deep saline aquifer of Lithuanian basin in presence of fault and fractures*. 2023. Baltic Carbon Forum

parameter is that the saline aquifer is sealed by thick (500-900 m) shale package of Ordovician-Silurian age that ensures effective retention for CO₂ escape to the overlying saline aquifers³¹⁴. The tightness of the Ordovician seal rocks was studied within the frames of the evaluation of the UGS prospects of the Cambrian reservoir in Lithuania. These studies proved high quality of the sealing shales.

Vaškai saline aquifer is overlain by 360 m thick Ordovician–Silurian shales and carbonates and they provide a reliable seal for storing CO₂. The tightness of the Ordovician caprock was proven by a drill stem test, logs in the wells and threshold pressure measurements on cores³¹⁵.

In D11 saline aquifer, the Cambrian sandstones are sealed by the Lower Ordovician shales with subordinate limestones (bulk porosity of carbonates is 2-5%) together with 100 m thick Ordovician and 750-1150 m thick Silurian shale package, which represents a reliable seal of the Cambrian reservoir. However, the Lower Palaeozoic succession is affected by faulting. Faults show different geometry. Accordingly, the tightness can be different²⁹⁸.

The Gagždai oil zone is related to the Garždai reverse fault of 150 m amplitude. Fault remains not active since Upper Devonian and no significant risks are defined²⁹⁸.

Thus, the Lithuanian Cambrian reservoirs have a Silurian shale, which ensures that injected CO₂ remains in the subsurface for a long period of time. The impact of CO₂ injection and storage has been investigated by looking at the vertical and horizontal displacement of the model after 30 years of injection. This sensitivity analysis is carried out by invoking the Geo-mechanical modelling option in T-navigator, which allows the prediction of reservoir deformation as well as prediction of possible fracture direction. The modelling is carried out again for Syderiai mid-case model. The results show that negligible deformation of order 10⁻⁹ m takes place. Likewise, no deformation is seen in other models, indicating that safe CO₂ injection can be carried out without resulting in any damage to caprock.

Although a simplified modelling approach has been used to investigate the risk associated with CO₂ storage, the assessment of risks for CO₂ storage is highly dependent on the chosen site and specific operational parameters of the CO₂ storage project. In general, the depth of the potential storage structures together with the thickness of the caprocks, and the material of the seals are important characteristics to enhance the long-term security of CO₂ storage in Lithuania. In addition, the general homogeneity of the potential storage formations minimize the risk of leakage. However, the presence of faults and wells and may have a negative impact in the injection and storage process on the integrity of the caprock. While the simplified modelling done can be illustrative, more rigorous modelling and detailed site-specific risk assessment would need to be done to thoroughly understand potential risk.

The analysis of potential CO₂ storage structures in Lithuania highlights several key risks, including limited geological data in underexplored formations, variable porosity and permeability—especially in western regions affected by compaction and cementation—and the presence of faults and fractures that may compromise caprock integrity. In some areas, a lack of structural closure further reduces trapping efficiency. These factors underline the need for detailed site-specific investigations before deployment.

³¹⁴ Source: ŠLIAUPA, Saulius; MICHELEVIČIUS, Dainius; ŠLIAUPIENĖ, Rasa; LIUGAS, Jonas. *Assessment of the Potential for CO₂ Storage and Utilization in the Fractured and Porous Reservoir of the Cambrian Sandstones in West Lithuania's Baltic Basin*. October 30th, 2024. Minerals 2024, 14(11), 1112, <https://doi.org/10.3390/min14111112>

³¹⁵ Source: ŠLIAUPIENĖ, R.; ŠLIAUPA, S. *Prospects for CO₂ geological storage in deep saline aquifers of Lithuania and adjacent territories*. 2011. Geologija, Vol. 53. No 3(75), pp.121-133

Here, the assessment of CO₂ Storage Readiness Levels (SRL) of Lithuanian sites are provided based on the analysis of geological and infrastructural peculiarities of the particular potential storage sites. The European Commission industrial carbon management strategy Communication requires that “each potential storage site will be labelled according to its ‘storage readiness level (SRL)’ and matched with public data to speed up the work to identify and assess the storage capacities”.

SRLs are presented to communicate CO₂ storage site technical appraisal, Carbon Capture and Storage (CCS) project planning and permitting activities that have been completed, and what remains to be achieved for a CO₂ storage site to become operational³¹⁶. The SRL schema is based on learning gained from the experience of the UK, Norway and The Netherlands from the 1990s and is applied to more than 700 sites. SRLs are a qualitative appraisal, not a quantitative measure, since each site will have its own specific characteristics, including aspects, such as, history of investigation, ownership, availability of CO₂, national policy and regulation.

Although the structures are different in origin, in all cases the stage of geological studies and knowledge about the structures are similar. Based on the scientific studies and the degree of information about the structures presented in this document (Section 8.1), the three deep saline aquifers (Syderiai, Vaškai and D11) and the Gargždai zone of uplifts are considered as ranked as between SRL2 and SRL 3 from the 9 CO₂ Storage Readiness Levels defined.

SRL 2 represents a site identified as theoretical capacity³¹⁷. At SRL 2 there has been systematic mapping of the storage potential of an area, region, country or jurisdiction’s potential storage resource. A consistent and referenced methodology will have been followed and applied to calculate theoretical CO₂ storage capacity based on accepted criteria for storage sites. The assessment is a desk-based study and requires sufficient data to enable the calculation of storage capacity, such as geological maps, published data, national databases and existing publicly available seismic survey and well data. The results of large-scale mapping at SRL 2 may be presented as storage atlases of country-wide or regional storage potential. Theoretical capacity appraisals may rely on average values for storage site properties and physical characteristics. Alternatively, the assessment is based on minimum, maximum and most likely values for parameters such as storage formation porosity, permeability and thickness. In some cases, Monte Carlo simulations will then be performed to ensure statistical representation of the required parameters. The theoretical potential for CO₂ storage by area, region or country may include individual storage sites; the degree of assessment at each site will depend upon the available data. At SRL 2 a high-level identification of possible geological risks to containment of stored CO₂ may have been undertaken.

SRL 3 represents the screening study to identify an individual storage site and an initial storage project concept. At SRL 3 a screening study will have been completed, achieved after a ranking exercise based on a 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. A CO₂ storage site may have been identified, either individually or as a group of sites, as having high potential for storage. All

³¹⁶ Source: AKHURST, M., KIRK, K., NEELE, F., GRIMSTAD, A.A., BENTHAM, M., BERGMO, P. *Storage Readiness Levels: communicating the maturity of site technical understanding, permitting and planning needed for storage operations using CO₂*. 2021. International Journal of Greenhouse Gas Control 110. <https://doi.org/10.1016/j.ijggc.2021.103402>

³¹⁷ Source: AKHURST, M., KIRK, K., NEELE, F., GRIMSTAD, A.A., BENTHAM, M., BERGMO, P. *Storage Readiness Levels: communicating the maturity of site technical understanding, permitting and planning needed for storage operations using CO₂*. 2021. International Journal of Greenhouse Gas Control 110. <https://doi.org/10.1016/j.ijggc.2021.103402>

relevant existing data and readily accessible data are compiled and interpreted at SRL 3 although only publicly available data is likely to have been used. The site or group of sites will have been considered within the context of the initial concept for a storage project. Equally, the envisaged project might comprise a site for a specific industry project, a concept for storage or a component within a national portfolio of storage provision. The SRL 3 screening study will have identified all major risks to storage. Data required to increase understanding and address 'data gaps' to mitigate or reduce risks to containment, will also have been identified. A hydrocarbon field that is well known from hydrocarbon licensing and production but has not been assessed in terms of risks to containment of CO₂, as a prospective storage site, would be at SRL 3.

In brief, Lithuanian structures seem to be favourable for CCS, but further work is required, which include more additional data collection and integration into geological and simulation models.

8.3. Technical requirements and conditions for CO₂ injection and leakage monitoring

This chapter will describe the process to drill the wells which will be used to inject the CO₂, and the further monitoring of the wells to avoid any leakages^{318, 319}.

Wells connect the surface, and the structures placed above the earth, such as platforms, pipelines, or compressors, with the geological storage formation. Each well should have barriers to isolate the different geological layers it goes through, to avoid fluid contamination due to mud or water leakages, as well as gas leakages. It is so necessary that the reservoir formation is sealed by an impermeable layer, and to correctly install the casing and the cementation which separates the injection tubing and the geological formations.

The well drilling operation as described below, is relevant specifically for CO₂ storage in porous media, such as deep saline aquifers or oil and gas fields. It is like other similar wells used for natural gas or oil fields. The most important parts of a drilling platform include:

- The derrick or drill mast, a large and vertical structure which is located in the surface and supports the drilling line.
- The top drive, a mechanical device located on the derrick, which is used to rotate the drill string and to put weight on the drill bit.
- The drill pipes are an assembly of pipes, which connect the surface equipment to the drill bit. They are used to raise and lower the drilling bit, and to transport the drilling mud into the well.
- The drilling line is a cable or rope, which is used to raise and lower the drilling pipe and other equipment in the hole.
- The rotary table, a large mechanical device which makes the drilling pipes rotate. At the end of the drilling pipes, the drill bit also rotates and perforates the rock.

³¹⁸ Source: ZHOU, Y.; HATZIGNATIOU, D. G.; HELAND, J. O. *On the estimation of CO₂ capillary entry pressure: Implications on geological CO₂ storage*. 2017. International Journal of Greenhouse Gas Control, Vol. 63, pp. 26–36. <https://doi.org/10.1016/j.ijggc.2017.04.013>

³¹⁹ Source: IEAGHG. *Well Engineering and Injection Regularity in CO₂ Storage Wells*. IEA Greenhouse Gas R&D Programme, Report 2018/08, pp. 1–122. 2018.

- The kelly bar is a square or hexagonal-section pipe, which connects the drill pipe and the swivel, and transfers the rotation to the drilling pipes.
- The swivel connects the kelly bar and the drilling pipes. It makes the drilling pipe rotate, while the drilling line is still.
- Drill bits are the tools which are placed at the bottom of the drill string, and directly cut the rock to create the borehole. They are the most important part of the drilling platform and determine the depth and the hardness of the rock which can be drilled. There are two main types of drill bits: roller cone bits, where the cutting pieces rotate independently of the drilling pipes, and fixed cutting bits, which have not a rotating part.

The most important roller cone bits are tricones, which consist of three cone-shaped rollers, which are connected to a head which is fixed to the drilling pipes. The rollers are made of a metal and have teeth. Teeth can be made of steel (milled teeth), or of tungsten carbide (tungsten carbide teeth). Milled teeth are cheaper and good for soft to medium-hard formations, while tungsten carbide teeth are more expensive, but can drill harder rocks.

Fixed cutting bits can be classified according to the materials and their use. For example, there are PDC bits (polycrystalline diamond compact bits), which have synthetic diamond bits or composite cutter bits. They are extensively used due to their high speed, long life, and high penetration rates. On the other hand, natural diamond bits, although are more expensive, have higher penetration rates and have an exceptionally long life. They have natural diamonds stuck into their surface or matrix.

To drill a borehole, the drilling bit (normally, a tricone), is put at the end of the drill pipe. The drill pipe is lifted with the derrick and connected to the kelly bar. The kelly bar is attached at the top of the drilling pipes and transfers the torque from a rotary drive tool (the top drive or the rotary table) to the drill pipe. The top drive puts weight on the drill bit, which drills the rock combining while it rotates.

When the drill bit breaks the rock, it generates heat. For this reason, it is necessary to pump mud through the drilling pipes, which goes out by the drilling bit. Drilling mud has different roles. Firstly, it cools and lubricates the drill bit, extending its lifespan. On the other hand, it removes the rock cuttings which are created by the drill bit and lifts them to the surface. This makes sure that the drill bit continues breaking new rock. Drilling mud also controls the hydrostatic pressure of the rock which is around the borehole, preventing the collapse of the borehole, or the influx of unwanted fluids. Drilling muds also seal the permeable layers, avoiding their contamination and damage. Drilling muds can be water-based muds, or oil-based muds, and include other additives, such as polymers.

Once the well has been drilled, it is necessary to complete it. Completion includes the final operations to be able to inject carbon dioxide into the geological formation. A final tube is set in the well, called casing. The casing is cemented to put it in place. Cement is poured to fill the annulus, or the space between the well and the casing. Cement is used to isolate the casing from the formation, avoiding the contamination of the different layers, as well as corrosion. Therefore, having good cement interfaces between the geological layers and the casing is needed to avoid any fluid migration.

Recommended actions to properly put the cement in place are to design the most appropriate cement composition, to blend it well in surface, to test and clean tubes, displace and pump the cement, and use practices such as pipe rotation and centralization.

It is necessary to drill the reservoir section, with drilling fluids, to make sure that the carbon dioxide can be injected into the layers. Alternatively, a perforating gun is used to make some holes through the casing and the cement. Besides, tubing is needed to inject the carbon dioxide.

It is particularly important to correctly select appropriate materials for the casing which is used in the well. The injection of carbon dioxide can potentially lead to a chemical reaction with water, which would produce carbonic acid, and make the fluid corrosive. Normally, the carbon dioxide flux is dehydrated and injected in a supercritical state to avoid this. However, if the injectant contains oxygen, hydrogen sulphide, and/or hydrocarbons, the dew point of the stream can be affected. If water is present, materials can corrode.

To avoid corrosion, it is necessary to have a complete knowledge about³²⁰:

- The chemical composition, and the phases of the injectant.
- The reservoir fluid, rock chemistry and composition.
- Pressure and temperature profile over the expected life of the well.
- Expected service life.
- Service requirements post abandonment.
- Expected injection rate or velocity of injectant.

According to the composition of the injected fluid, dehydration can be needed, and a special metal composition can be required. The composition of the fluid can impact the phase behaviour.

The reservoir fluid can corrode the wellbore. Besides, if there is some formation dissolution, the well can collapse in the zone where injection takes place. Casing should be designed to resist corrosion for some years after the closure of the well. A corrosion-resistant alloy (CRA) can be required depending on the geological intervals. For example, in that cases when there are potential aquifers or where internal or external casing corrosion has been identified.

Another point to be considered is the injection speed, which can affect the potential erosion of the materials by the CO₂ stream. If the erosional speed is exceeded, it is advisable to select an alloy which can resist corrosion.

Other factors which can increase casing corrosion include:

- When injector wells are shut-in, due to maintenance actions, the water can condensate, or water from the reservoir can flow back to the well. However, as this fluid will not move, corrosion will not be important.
- The stream can have enough amounts of hydrogen sulphide to create a sour environment for the materials. This can cause sulphide stress cracking on the casing.

If there are not relevant water or hydrogen sulphide amounts, then standard metallurgy can be used.

Besides, as supercritical carbon dioxide is a solvent, it can attack or solve many elastomers, plastics, rubbers, or resins. These materials should be avoided. Elastomers, for example, are used to seal components in the well. They should be chosen to be inert to the injection fluid and be of sufficient strength to withstand the differential pressure and explosive decompression. It should be also considered that many elastomer material characteristics can change with pressure and temperature, so the material choice should consider the full range of pressures and temperatures along the well.

If the reservoir is not consolidated, and sand can fall into the wellbore, sand control for injectors can be needed. The sand can fall and block the wellbore when it is shut for maintenance or upsets.

³²⁰ Source: The CO₂ Capture Project. *A Technical Basis for Carbon Dioxide Storage*. 2009. ISBN: 978-1-872691-48-

Additionally, gravel pack contents can be dehydrated and cannot be displaced from the well, or sand control resins can dissolve and dehydrate.

Until now, actions to drill the wells to inject CO₂ have been described, as well as the completion of the borehole, until putting them into operation. However, it is also necessary to closely monitor their operation during the lifetime of the CCS project, and to conduct maintenance actions.

Just after the beginning of the operation, it is necessary to check if there are relevant amounts of fluids in the wellbore. These fluids can corrode the tubes, cause bacterial growth, or cause solid precipitation. Fluids can also travel to the formation, changing their permeability. Finally, hydrates can form and reduce the permeability of the well.

In some cases, along the lifetime of the well, it is necessary to close it temporarily. In these cases, hydrates can be formed when the well comes back to operation again, just as happens when it is operated for the first time. In other cases, additional pressure can be needed to re-start injection again.

Maintenance actions are usually needed only if there is a mechanical failure and injection rates are reduced. In these cases, it is necessary to consider the following:

- The use of a brine or similar fluid for maintenance actions can result in intermixing the CO₂ and the well control fluid, leading to hydrate formation or hydrate blocks. To avoid this, it is possible to use hydrate inhibited fluids, or reducing the amount of CO₂ which is injected during maintenance actions.
- To keep injectivity as high as possible, it is necessary to minimize the negative impacts of fluid loss control procedures.
- It is necessary to make sure that any CO₂ which is circulated is kept in a sole phase.

Well stimulation is often needed when the permeability of the formation is reduced due to damages during operation. There are two main stimulation procedures: hydraulic fracturing and acidizing. Hydraulic fractures are created when fluid is pumped into the formation quicker than the formation can absorb it. Then, the pressure at the formation goes up quickly, and fractures are developed. To make sure that the fractures do not close after the fluid is removed, a proppant is added. Proppants, which include sand, resin-coated sand, or ceramics, are solid particles which are introduced in the fractures, and do not allow them to close after the liquid is removed.

In acidizing, acid is injected in the formation, solving it and creating fractures. In some cases, the acid injection is conducted at a high rate, which also involves the creation of fractures in the formation (acid fracturing). In matrix acidizing, the acid is injected at a lower rate, so it only solves the rock, and does not create fractures.

In any case, a well stimulation action must be carefully designed, to avoid any damage to the reservoir seal. Besides, the chosen acid should not affect the well casing, cement, or other materials.

Finally, the proper operation of the well must be monitored. Monitoring makes sure that the well operates as designed, with reduced risks of CO₂ movement or release to the surface. Well monitoring is important to make sure that the cement integrity is maintained, that the pressure isolation barriers work properly, that corrosion is controlled, and that CO₂ is injected at the planned rates.

Monitoring includes the use of different logs which are used in the casing to check well integrity, cement integrity logging, and mechanical integrity testing and annular pressure monitoring.

- Cased hole logging can be done with a leak detection log (LDL), tubular inspection logs, production profile logs, or neutron, neutron decay and spectral logs. Leak detection logs

identify the leak point location in the wellbore, as well as their nature. They are based on pumping fluid into the suspect part of the casing, and a downhole tool is used to detect the leak point, such as spinner/temperature logs, video logs, or ultrasonic logs.

Tubular inspection logs are introduced in the well to review the mechanical condition of the tubes, and identify leakages. They include calliper logs, to measure the inside diameter, and logs based on the magnetic flux leakage or ultrasonics.

Production profile logs can measure injectivity and the injection profile. They can be combined with spinner and temperature logs.

Neutron, neutron decay and spectral logs are used to measure the fluid content, as well as the phase behaviour of carbon dioxide, and to locate carbon dioxide and water.

- Cement integrity logging: These logs can detect defects caused by mud channels in the cement, due to an inefficient placement of the cement, gas and other fluids which can be mixed in the cement, and micro-annuli at the cement-casing and the cement-formation interfaces. However, these logs cannot detect fractures.
- Mechanical integrity testing and annular pressure monitoring: They are used to check the mechanical integrity of tubulars and other well equipment. During the drilling operations, positive or negative testing can determine that the casing is well placed. Leakages between the tubing, the cement and the formation can be detected with changes in pressures.

Wellhead seat tests can be conducted to evaluate the mechanical integrity of the sealing elements, and if they can withhold well pressure. Finally, if any equipment is removed from the well for maintenance actions, it should be checked, to identify any problem.

- Seismic surveys can also be used to monitor CO₂ movement within the reservoir.

Finally, when the CO₂ injection finishes, it is time to close the well. The formation pressure goes down once the injection has stopped, until it stabilizes. When the CCS project is finished, all wells should be closed, except for some monitoring wells.

The plug and closure of the well operation is conducted making sure that a vertical barrier is formed, preventing fluid flow or migration in the long term. The following actions are carried out:

- Remove the tubing and the packer.
- Seal the formation with a fluid to reduce permeability.
- Use cement plugs to isolate the well, and test them.
- Place a cap at the surface.
- Cover with soil and record the well location.

8.4. Assessment of the carbon capture, transport, and storage value chain

A practical assessment of Lithuania's carbon capture, transport, and storage (CCS) value chain involves evaluating each component's integration, efficiency, economic viability, and sustainability in the CCS process. Firstly, the capture segment demands attention to technological maturity, operational costs, and scalability of carbon capture technologies. Industries such as cement production, ammonia-based fertilizers, and energy generation (both electricity and heat, biomass-based) represent ideal initial targets due to their significant emissions and concentrated emission sources, simplifying capture processes and reducing costs.

Transporting captured CO₂ requires careful planning and infrastructure investment, primarily focusing on pipeline systems. Pipelines offer the most efficient and economic method of transportation, particularly for short and medium distances, high-volume transfers necessary for both domestic storage and export to, for example, North Sea facilities. Strategic planning must consider pipeline route optimization, proximity to emission sources and storage sites, and potential environmental and social impacts.

The storage component necessitates rigorous geological evaluations to identify suitable locations with sufficient capacity, stability, and containment security. Lithuania should prioritize exploring saline aquifers and depleted hydrocarbon fields, as initial studies have shown their promising storage potential. It is essential to establish robust monitoring and verification protocols to ensure long-term storage integrity and environmental safety.

Financially, a comprehensive cost-benefit analysis must underpin the entire CCS value chain. While upfront investments in infrastructure and technology are substantial, the long-term economic benefits of mitigating carbon emissions, such as compliance with EU emissions regulations, access to carbon markets, and reduced carbon taxation, will significantly offset initial costs. Public-private partnerships and EU funding schemes can substantially support these capital-intensive initiatives.

Finally, sustainability and stakeholder engagement are critical elements throughout the CCS value chain. Transparent communication, public acceptance, and community involvement will foster broader societal support. Integrating sustainable practices across capture, transport, and storage segments enhances environmental outcomes and strengthens Lithuania's positioning within the EU's broader climate and energy objectives.

8.5. Feasibility of reusing existing infrastructure for carbon capture and storage and hydrogen transport

The extensive use of carbon capture and storage will require large investments in the different operations needed to capture and store CO₂: capture, conditioning (including purification and dehydration), compression, transport by pipelines or ships, well injection, and storage. The possibility to reuse existing infrastructure is key to make sure that investments are kept as low as possible, while making sure that the carbon storage is safe.

There are diverse ways to optimize this investment, many of them based on the reutilization of existing infrastructure:

- CCS clusters or hubs: To make use of economies of scale, it is highly advisable to develop CCS systems in industrial clusters, this is, locations where many CO₂ emitters are placed, especially highly intensive industries, such as cement, fertilizers, steel, refinery, power, hydrogen production, etc. In these cases, it is possible to use a common transport infrastructure.

For example, the project Northern Lights³²¹, in Norway, has a shared CCS transport and storage infrastructure which receives CO₂ emissions from emitters around Europe, specially from the Northern countries. The CO₂ is captured, liquified and transported from the source to a CO₂ receiving terminal in the Energieparken industrial area in the municipality of Øygarden in western Norway. From there, it is liquified and transported by ship, injected and stored below the seabed of the North Sea.

³²¹ Source: Northern Lights.

Other relevant CCS clusters which are being developed include HyNet, in the United Kingdom, Porthos, in the Netherlands, East Coast Clusters (United Kingdom), Acorn (United Kingdom), V Net Zero (United Kingdom), Morecambe Bay (United Kingdom), Greensand (Denmark), Aramis (the Netherlands).

- Pipelines: Lithuania has a limited network of oil pipelines primarily used for transporting crude oil and refined products. The key infrastructure includes the Druzhba pipeline, which historically transported Russian crude oil through Lithuania to other European countries. Additionally, Lithuania operates the Klaipėda liquid energy products terminal, which allows for imports and exports of oil by sea, somewhat reducing reliance on pipeline transport. However, the current and future role of oil pipelines in Lithuania is limited compared to other countries with larger domestic oil production or transit needs³²². The reuse of existing onshore and offshore oil and gas pipelines to transport CO₂ is a very good option to reduce the costs of carbon capture and sequestration projects, and there are no major limitations.

However, it is necessary to conduct an assessment of existing pipelines to evaluate if they can be used to transport CO₂. Such assessment includes the following criteria:

- Flow assurance: The hydraulic capacity of the pipeline must be evaluated, to verify that the design pressures, or maximum operating pressures (MAOP) are higher than the operating pressures to transport CO₂.

It is necessary to evaluate the original design or maximum allowable pressures, the fluid specification and allowable impurities in the fluid, the phase of the transported CO₂, and the minimum design temperature.

The optimal transport of CO₂ needs to exceed the critical pressure for CO₂ mixture, avoiding transporting two phases: liquid and gas. If the critical pressure cannot be reached, it is always possible to transport CO₂ in gas phase, but efficiency is much lower.

As the captured carbon dioxide is never pure, but there are impurities depending on the CO₂ source and the capture technology, the thermo-physical and chemical properties of the mixture can be very different from that of the pure carbon dioxide flow. For example, the supercritical CO₂ is a very good solvent, and reacts with impurities such as NO_x and SO_x, creating corrosive products.

- Internal corrosion: Depending on the material of the pipeline, corrosion due to the combination of water and carbon dioxide to form carbonic acid can be important. Besides, depending on the composition, other chemical damages can happen, such as hydrogen sulphide, stress cracking or oxygen corrosion.

All alloys can corrode if there is water in the carbon dioxide flow, so it is advisable to keep the flow as dry as possible. If there are impurities in the flow, water solubility can change, especially when there are chemical reactions with salt, glycols and methanol. Impurities absorb water and create an aqueous corrosive phase

- Mechanical design: The use of dense carbon dioxide can lead to running ductile fractures. In these cases, a small initial fracture can run along the pipeline in both

³²² Source: PAULAUSKAS, V; PLACIENE, B; PAULAUSKAS, D; BARZDZIUKAS, R. *Quay wall stability and strength evaluation*. 2017. Mechanical Technologies. Vol. 23(2). <https://doi.org/10.5755/j01.mech.23.2.13776>

directions, causing large leaks. It is necessary to evaluate if the design toughness requirement of the pipeline is enough to transport dense carbon dioxide. To avoid running ductile fractures, the arrest pressure of the pipeline must be higher than the saturation pressure of the CO₂ composition, around 80 bar.

It is then necessary to evaluate the material which is used to manufacture the pipelines, since depending on the composition and degree of the steel, there can be limitations to the use of the pipelines to transport CO₂.

To transport hydrogen, it is necessary to consider that the higher-grade steel can become brittle and lose ductility when it transports hydrogen³²³.

There is also the option of blending hydrogen and natural gas, and transport it in the natural gas network. This has some advantages:

- Small hydrogen outputs can be used in onshore settings, if they are transported in the natural gas network.
- This can support a quick development of hydrogen supply technologies, such as electrolyzers and power to gas, if they made use of existing natural gas infrastructure.
- Many natural gas transmission pipelines can accept some amounts of hydrogen.
- Blending is very cost-efficient, as it avoids the need to build a totally new hydrogen transmission infrastructure.
- Storage and transport of hydrogen has a very low marginal cost, if it is possible to use existing natural gas infrastructure with a 2%-10% of hydrogen.
- The use of natural gas transmission infrastructures to transport hydrogen can optimize the use of electrolyzers, which would only operate when electricity prices are lower.
- The use of the natural gas transmission network would allow for more flexible locations, reducing logistic and production costs.
- It can reduce investment costs, and develop economies of scale until the dedicated hydrogen pipeline is mature.

In some cases, hydrogen can be transported with a carrier, such as LOHC (Liquid Organic Hydrogen Carrier) and ammonia. However, there are additional costs to convert the carrier into hydrogen, and to transport the carrier back to the hydrogen production plant.

- Platforms: The possibility of the reuse of platforms was evaluated by the Department for Business, Energy & Industrial Strategy³²⁴. According to this analysis, platforms can quickly break down after the end of the well closure. It is not recommended to reuse platforms, unless they are modified. Note that while offshore platforms are not present in Lithuania, the general principle remains relevant for onshore facilities.

³²³ Source: Carbon Limits AS and DNV ASE. *Re-Stream- Study on the reuse of oil and gas infrastructure for hydrogen and CCS in Europe*. October 2021.

³²⁴ Source: BEIS. 2020. Department for Business, Energy & Industrial Strategy. *Carbon Capture, Usage and Storage – A Government Response on Re-use of Oil and Gas Assets for Carbon Capture and Storage Projects*.

In some cases, the jacket structure, which is connected to the seabed, can be reused, as long as the platform itself is replaced. In any case, it is necessary to make sure that the platform can withstand the weight of the new equipment. Platforms need to be adapted to inject carbon dioxide. Modifications include the replacement of pipes, installation of filters and advanced control, monitoring and metering systems.

Limitations in weight and space can affect if there is need to install a compressor for CO₂. Of course, platforms can be used only if there are wells.

- Wells: In principle, it is feasible to use any type of well, including exploration, appraisal, production, and so on, to inject CO₂ or to monitor the behaviour of the carbon store. However, it is necessary to make sure, before their use, that the wells are in good conditions, and can be used to inject the CO₂. For example, plugged and closed wells can have leakages, and be not suitable.

Another important issue which can prevent the use of existing wells is the fact that they can be in a bad location, which does not ensure the efficient and safe flow of the CO₂, or have fractures or leakages. In any case, to reuse an existing well, it is necessary to make completion and review works, what has a cost lower than drilling new wells.

There are minimum criteria which must be fulfilled to be able to use an existing well³²⁵:

- Material compatibility: The carbon dioxide which will be injected should not affect the piping or the environment of the well. For example, carbon dioxide can react with water to form carbonic acid, which can corrode the metals, or can react with sulphur and nitrous compounds or hydrogen. It is also necessary to evaluate that the polymer sealing works well.
 - Structural integrity: All components of the borehole need to be in good mechanical conditions, including the wellhead, the casings, the tubing, the annulus or the cement. It is necessary to analyse the response to the cold start-up, induced Joule-Thomson due to well choking, thermal contractions along the well, thermal and pressure cycling, venting, well kill after completion, cement degradation, etc.
 - Well barrier elements integrity: It is necessary to make sure that the primary and secondary safety barriers work correctly, including the downhole safety valves, chokes, actuated valves, annulus valves, shoes and packers. Besides, it is necessary to evaluate the leakages of CO₂ from the reservoir to the annulus.
 - Flow assurance: As the CO₂ is injected at low temperatures and high pressures, it is necessary to evaluate the behaviour of the well under these conditions.
- Oil reservoirs: The use of oil fields, which have been closed or are near the end of their economic lifetime, are considered as very good geological stores. One reason for this is that their geological characteristics (such as pressure, permeability, rock integrity, porosity) are extensively known, and their capacity to safely store carbon dioxide has been proven, as they have stored oil before it was extracted. The total storage capacity is perfectly known, as well as the pressure build-up. Besides, many of the existing infrastructures, such as pipelines,

³²⁵ Source: LUNA-ORTIZ, Eduardo, Pace CCS Ltd. 2022. *Reusing Infrastructure for CO₂ transport: Risks and Opportunities*. Offshore Technology Conference. DOI 10.4043/31457-MS

platforms and wells can be reused. This delays the decommissioning costs of already built infrastructure, and reduces the carbon footprint of CCS projects.

A drawback of the use of oil reservoirs is that their capacity is lower than that of saline aquifers. However, as there are many natural gas reservoirs which have been already closed, their potential in the near term is high. It is also necessary to make sure that the integrity of the infrastructure is kept, especially during the period since the natural gas exploitation has come to an end, until the use of the deposit to store carbon dioxide begins. Depending on the regulation, and the extension of the period when the deposit is not used, it can be needed to make some investments in keeping the deposit in good conditions for its use³²⁶.

There have already been successful tests in depleted natural gas reservoirs to store carbon dioxide. For example, in Otway, onshore Australia, around 65,000 tonnes of CO₂ have been safely stored, at bottom-hole pressure of 178 bar and a bottom-hole temperature of 63°C³²⁷

As a conclusion, in principle, it can be possible to use existing infrastructure, especially pipelines, wells and oil reservoirs, but it is essential to carry out previous assessments to check their integrity and feasibility to be used with carbon dioxide. It should be considered that infrastructure previously used can need some repairs, or be not suitable for the different properties of carbon dioxide compared to natural gas.

³²⁶ Source: DRANKIER, D. and GAZENDAM, J. 2021. *Reuse of Offshore Oil and Gas Infrastructure: a Case Study on CCS*. ElgarEncyclopedia of Environmental Law Chapter IX. 25: 291–301

³²⁷ Source: JENKINS, C. R.; COOK, P. J. et al. 2012. *Safe Storage and Effective Monitoring of CO₂ in Depleted Gas Fields*. Proc Natl Acad Sci 109: E35–E41.

9. Promotion of CCUS and Innovative Technologies

9.1. National Lithuanian support measures for CCUS

Although Lithuania considers the use of carbon capture and storage, and the use of carbon sinks as a need to compensate hard-to-abate emissions, regulation is not encouraging these technologies. Currently, CO₂ geological storage is explicitly forbidden by the Law on Subsurface³²⁸, whether in underground geological surfaces, in the water column, in geological formations beneath the seabed.

At the same time, the Law on Geological Storage of Carbon Dioxide³²⁹, from 2011, defines the rights, duties and responsibilities to explore, transport and store CO₂. As commented, CO₂ geological storage was then forbidden in an amendment introduced in 2019 in the Law on Subsurface. Therefore, if Lithuania developed carbon capture technologies, the captured CO₂ would be exported to store it in other countries.

However, in its draft updated National Energy and Climate Plan of the Republic of Lithuania for 2021-2030 (NECP), carbon capture, use and storage are considered as necessary to be developed. One of the measures which is included in the NECP is the assessment of the CO₂ capture, use and storage chain alternatives in Lithuania. Besides, a detailed analysis of the feasibility and usefulness of projects implemented in other countries of the European Union will be carried out, to consider if they can be exported to Lithuania. These assessments will be useful to take decisions to authorize geological CO₂ storage.

The NECP considers necessary to further develop carbon capture and storage technologies in Lithuania. The use of the European Innovation Fund is suggested to support research on these topics.

Lithuania has also other policies aimed at using carbon sequestration from Land-Use, Land-Use Change and Forestry (LULUCF) sector. For example, the Common Agricultural Policy Strategic Plan offers landowners incentives to carry out activities which increase soil carbon sequestration.

The Soil Sustainable Use Action Plan 2030 has developed a plan to preserve soil health. Along with the NECP, targets for the LULUCF sector have been created, including increasing the stock of organic carbon in forests and wood products, an increase in the total woodland in Lithuania to at least 35% by 2024, developing at least 8,000 ha of permanent grassland, restoring at least 8,000 ha of carbon-rich ecosystems, ensuring sustainable use and stopping the use of new natural wetlands by 2024. As a result of these actions, sinks for at least 6.5 MtCO_{2e} are expected to be created.

There are other policies which protect peatlands, wetlands, grassland, forests, and carries out agroforestry measures, as well as the promotion of “organic construction”.

Regarding climate change, although Lithuania has not a climate law, the National Climate Change Management Agenda has set indicative objectives regarding the reduction of greenhouse gas emissions. In particular:

- By 2030, CO₂ emissions must be reduced by 70% compared to 1990, and by 30% compared to 2005.

³²⁸ Source: Lietuvos Respublikos žemės gelmių įstatymas (Žin., 1995, Nr. 63-1582; 2001, Nr. 35-1164; TAR, 2019-10-31, Nr. 2019-17357).

³²⁹ Source: ANGLIES DIOKSIDO GEOLOGINIO SAUGOJIMO ĮSTATYMAS 2011 m. birželio 28 d. Nr. XI-1550 <https://e-seimas.lrs.lt/portal/legalAct/lt/TAD/TAIS.403288/asr>

- By 2040, CO₂ emissions must be reduced by 85% compared to 1990. From this, 15% can be offset by environmentally friendly technology.
- By 2050, CO₂ emissions must be reduced by 100% compared to 1990. Out of this, 20% can be offset by environmentally friendly technology.

The Order on the Approval of the Action Plan for Sustainable Soil Use, from 2023, involved the adoption of the Soil Sustainable Use Action Plan 2030, described before.

The Lithuanian Climate Change Program collects funds from the transfer of assigned amounts and auctioned allowances, as well as voluntary contributions from natural persons and legal entities. It is managed by the Ministry of Environment, and funds projects related to the mitigation of climate change and adoption to changes derived from climate change. Some examples of projects which can be funded by the Lithuanian Climate Change Program are:

- Projects related to energy efficiency and reduction of energy consumption.
- Projects which promote the use of renewable energy sources and environmentally friendly technologies.
- Implementation of development cooperation projects in developing countries, to transfer Lithuanian technologies and experience.
- Public information and education, scientific research works, consultancy and training.
- Reforestation and forest growing, adaptation to changes caused by climate change, and implementation of measures to mitigate the climate change consequences.

9.2. The CCS Baltic Consortium project

The CCS Baltic Consortium project has as objective to reduce CO₂ emissions from two countries, Lithuania and Latvia, using carbon capture and sequestration. These countries currently do not have any CCS infrastructure, and the CCS Baltic Consortium will develop a robust and sustainable CO₂ value chain, to reduce emissions from all emitters in the Baltics. The CCS Baltic Consortium project was formed in 2022, and will be the first integrated carbon capture, transport, and storage (CCS) value chain in the region.

The CCS Baltic Consortium project involves the following value chain:

- a) Capture of CO₂ from cement plants operated by SCHWENK Latvija SIA and Akmenės Cementas AB in Lithuania and Latvia (both cement factories are owned by the German capital company SCHWENK).
- b) Liquefaction and transport of CO₂ via new onshore pipelines with the assistance of gas transmission operators AB Amber Grid (from Lithuania) and Conexus Baltic Grid AS (from Latvia) and supplemented by road or rail for lower volumes. CO₂ will be sent to Klaipėdos Sea Port. AB Amber Grid and Conexus Baltic Grid AS are the responsible parties for the analysis and construction and operation of onshore pipelines.
- c) Transport and storage of CO₂ at the multimodal LCO₂ import/export terminal operated by KN Energijos, AB, located in Klaipėda Port. Besides, this terminal can accept CO₂ transported by trucks or railway by wagons for small-medium volumes.
- d) Transport of liquid CO₂ by ships owned by Mitsui O.S.K. Lines, Ltd. and Larvik Shipping AS to a permanent storage facility located underground in the North Sea.

The following figure shows the CCS Baltic value chain:

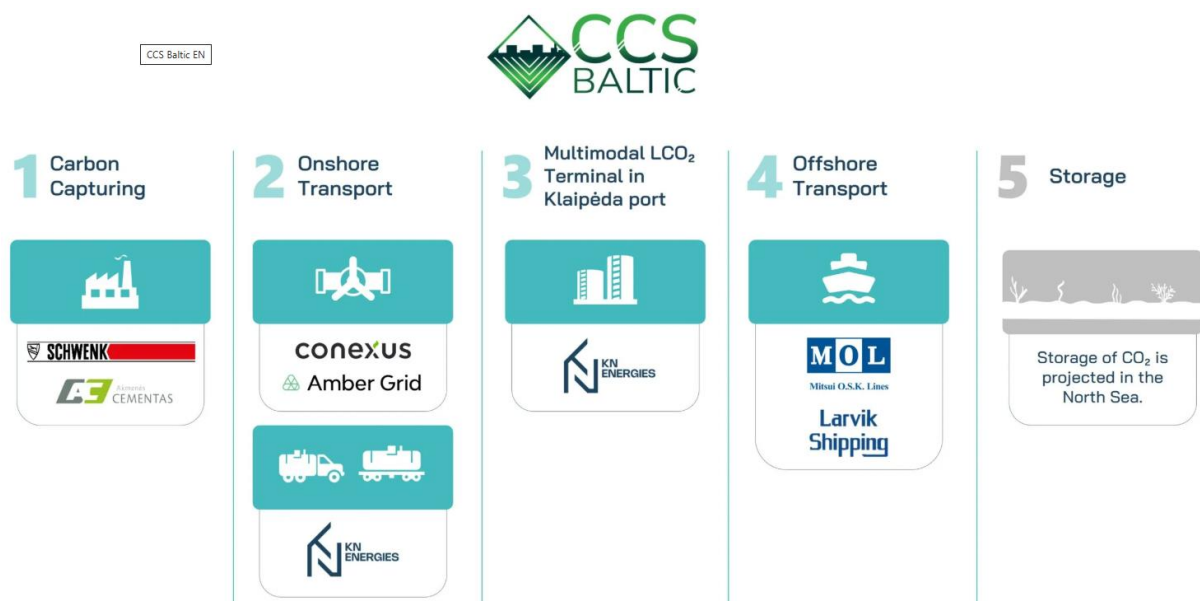


Figure 55: The CCS Baltic Consortium Project.³³⁰

The project aims to mitigate 24.9 million tonnes of CO₂ emissions over its lifetime.³³¹ The initial design capacity will be able to capture up to 2.8 million tonnes of CO₂ per year. It is also estimated that around 1.6 million tonnes of CO₂ emissions can be captured yearly in the factories of SCHWENK Latvija and Akmenės Cementas, in Latvia and Lithuania. It is important to mention that, apart from the emissions from these two factories, also other companies in the region will be able to use this infrastructure to transport and store CO₂.

The Klaipėda liquid CO₂ terminal is expected to:

- Serve as a multimodal import/export hub for CO₂ capture, sequestration and storage.
- Include buffer storage and flexible reception systems for liquid and/or dense CO₂, which will be transported to the terminal by pipeline and/or by rail tank wagons and semi-trailers.
- Feature marine vessel interfaces for international shipments to offshore permanent storage sites.

This makes this project very relevant in both the Baltic region and in Europe.

The consortium secured Project of Common Interest (PCI) status from the European Commission in November 2023 as a key cross-border infrastructure project that significantly contributes to the EU's energy policy and climate goals. Besides, the project has received €3 million (50% of the cost) in EU Connecting Europe funding in June 2025 to conduct technical, environmental and commercial studies for the CO₂ terminal in Klaipėda. The total needed investments to develop the project are expected to reach €1.1-1.2 billion.

Regarding the calendar, by 2025, many works such as the analysis, feasibility studies and applications for grants such as the Project of Common Interest have been already carried out. The Final Investment Decision will be made in 2027, and CO₂ capture and export operations will start in 2030.

³³⁰ Source: CCS Baltic Consortium. About CCS Baltic Consortium. <https://ccs-baltic.eu/about/>

³³¹ Source: CCS Baltic Consortium. *CCS Baltic – Pioneering carbon capture and storage project in the Baltics*.

This project addresses the need for CO₂ transport and sequestration infrastructure in the Baltic region, positioning it as a vital component in the EU's strategy to achieve climate neutrality by 2050 by facilitating the capture and storage of CO₂ emissions from hard-to-decarbonize industries. However, this project remains a multilateral initiative under EU frameworks with no formal bilateral pact between governments.

9.3. EU support measures

The European Commission has paid attention to carbon capture, storage, transport and use, to reduce hard-to-abate CO₂ emissions in industrial and energy production facilities, as well as to remove CO₂ from the atmosphere.

The support offered by the European Commission to this kind of projects can be divided as follows. Each one of the mechanisms is analysed in another chapter of this report, so here only a very brief description is provided.

Firstly, there are some general policies developed by the European Commission which, although do not consider specifically CCUS, impact these technologies as part of the effort to reduce GHG emissions in the European Union:

- **The European Green Deal:** It includes a package of policies that the European Commission approved in 2020, with the objective of making the European Union climate neutral in 2050. As part of the European Green Deal, each existing law and directive is being reviewed to make it align with the global objective of making the EU climate neutral in 2050.

Besides, it includes an intermediate target of reducing emissions of the European Union by 55% by 2030, compared to 1990 levels.

The European Green Deal has the following general objectives:

- To reduce emissions in a broad range of sectors, boosting natural carbon sinks, updating the emissions trading system to cap emissions, and to ensure the support to citizens and small businesses in the green transition.
- To offer clean, accessible and affordable transport and logistics to all Europeans. All new cars and vans registered in Europe must be zero-emissions by 2035, with intermediate targets of a 55% reduction of emissions from cars by 2030, and 50% reduction of emissions from vans by 2030. Carbon pricing is applied to the aviation and the maritime sectors.
- To support the green industry, with the Green Deal Industrial Plan, and the Net-Zero Industry Act. The objective is to scale up manufacturing of clean technologies in the EU, create green jobs, and to prepare the EU for the clean-energy transition. At least 40% of the EU's annual deployment needs for strategic net-zero technologies must be developed in the EU by 2030.
- To reduce greenhouse gas emissions from the energy system, by using more renewable energy, improving energy efficiency, and diversifying energy supplies. In March 2023, the EU agreed to increase the renewable capacity, to a binding target of 42.5% for 2030, with the ambition to reach 45%. Energy efficiency must be improved by 11.7% by 2030.
- To renovate buildings, with the objective of saving energy, protecting citizens against extreme heat and cold, and reducing energy poverty. The renovation rates should be doubled by the next ten years, and the Energy Performance of Buildings Directive was

reviewed. There is a new indicative national benchmark of 49% of renewable energy in the building sector. From 2027, building and transport fuels will be covered by emissions trading.

- To restore nature and protect biodiversity. In particular, natural restoration is expected to support in the carbon capture and storage, as well as to adapt to the climate change and mitigate its effects.
- To lead by example in global climate change action, and to collaborate with international partners to reduce their emissions. To do this, the EU, its Member States and the European Investment Bank provided €28.5 billion in 2022 to support third countries climate action.
- **European Climate Law:** It is the law which reflects the goals set in the European Green Deal, to make the European economy and society climate-neutral by 2050. It makes this objective legally binding for all European institutions and Member States, which are forced to take the necessary measures at EU and national level to meet this target.

The objectives of the European Climate Law are:

- To set a long-term path to reach the 2050 climate neutrality objective, using all policies in a socially fair and cost-efficient way.
- To set a more ambitious 2030 target, of reducing greenhouse gas emissions by 55% compared to 1990, to make sure that the European Union is on track since the beginning to reach the 2050 target.
- To develop a system to monitor progress and take further actions if needed.
- To provide predictability to investors and other economic actors.
- To make sure that the transition to climate neutrality is irreversible.
- To enhance EU's carbon sink using a more ambitious LULUCF regulation.
- To develop a European Scientific Advisory Board on Climate Change, to provide independent scientific advice.
- To engage with sectors to prepare sector-specific roadmaps charting the path to climate neutrality in different areas of the economy.

The European Climate Law was published in the Official Journal on July 9th, 2021, and entered into force on July 29th, 2021.

Other relevant European directives which have been published about Carbon Capture, Utilization, and Storage (CCUS) are much more specific. They will be only listed in this chapter, as they are described in much more detail in chapter 10:

- The Industrial Carbon Management Strategy: Towards an ambitious Industrial Carbon Management for the EU (COM/2024/62): This strategy considers the carbon management technologies as key to reduce emissions by 90% by 2040 and reach carbon neutrality by 2050, as well as to develop 50 million tonnes of CO₂ storage capacity by 2030, scaling up to 280 million tonnes CO₂ by 2040.
- The Geological Storage of Carbon Dioxide Directive: Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives

2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006 ELI. This Directive sets the rules to select carbon storage sites, how exploration and storage permits should be granted, and basic lines on the operation, closure and post-closure of carbon dioxide storage sites.

- The Renewable Energy Directive: Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources: This directive requires that, by 2030, at least 32% of the gross final energy consumption in the EU is based on renewable energies. The objective was increased to 42.5% with an additional clause in 2023, including that all Member States will collectively strive to increase the share of energy from renewable sources in the Union's gross final energy consumption in 2030 to 45%.

Although the directive is not specifically related to Carbon Capture, Utilization and Storage (CCUS), it considers the use and promotion of renewable fuels of non-biological origin (RFNBO). This term includes synthetic fuels which are produced from renewable energy sources, using electricity, and carbon dioxide, and include hydrogen, and the combination of hydrogen with captured carbon dioxide to create synthetic fuels, such as e-diesel, e-kerosene or e-methanol. RFNBOs are a good solution to reduce CO₂ emissions in sectors which are difficult to electrify, such as aviation or maritime transport.

- The Communication from the Commission to the European Parliament and the Council on Sustainable Carbon Cycles (COM/2021/800).

This communication is focused on developing sustainable carbon cycles in the EU economy and ecosystems. On the short term, carbon farming will be promoted to make it a sustainable business model. Besides, a new industrial value chain for the sustainable capture, recycling, transport and storage of carbon will be developed.

Carbon farming includes the use of land and terrestrial ecosystems as carbon sinks, rewarding land managers for improving their land management practices, increasing the amount of carbon dioxide which is sequestered in living biomass, dead organic matter and soils. Carbon farming credits can be awarded to those land managers who follow sustainable practices.

Regulation of the European Parliament and of the Council establishing a Union certification framework for carbon removals- COM(2022)0672 – C9-0399/2022 – 2022/0394(COD) This regulation develops a voluntary Union certification framework for carbon removals, to incentivize the uptake of high-quality carbon removals, respecting the biodiversity and the zero-pollution objectives. The Union certification framework is expected to support the development of carbon removal activities in the European Union, avoiding greenwashing.

The regulation sets some requirements to consider carbon removals as eligible for certification. Carbon removals should be quantified clearly and accurately, and should be generated by activities which lead to a net carbon removal benefit, and have a neutral impact or co-benefit on sustainability objectives.

Certification schemes should be created to verify carbon removal activities. They can be used by operators to show compliance with the Regulation.

- Net-Zero Industry Act (NZIA): It has as objective to enhance the European manufacturing capacity for net-zero technologies and their key components. The regulation tries to remove obstacles for the manufacturing of these technologies in the European countries, increasing

their competitiveness, attracting investments, and improving market access for clean tech in the EU. This act is described in detail in chapter 3.6.

The European Commission also directly supports economically industrial carbon management projects. A description of the most important programmes from the European Commission to support these projects is offered in chapter 9.6.1.

There are also different European funds to support projects related to the reduction of greenhouse gas emissions and climate transition, although they are not specifically linked to carbon capture and storage. Among them, it is useful to mention the following one:

- **Just Transition Fund:** The Just Transition Fund is offered by the European Commission to Member States, to support those zones which are expected to be the most negatively affected by the transition towards climate-neutrality.

For this reason, these funds focus on zones whose economies rely most on activities which produce more greenhouse gas emissions, for example, industrial zones with carbon intensive industries, or coal thermal power plants.

Just Transition Funds support the reconversion and diversification of activities of these zones. To do this, they support the reskilling for professionals who will be affected by the closure of industries or power plants, investments in small and medium-sized companies, creation of new companies, research and innovation, environmental rehabilitation, clean energy, job-search assistance and transformation of existing carbon-intensive installations.

In the case of Lithuania, the Just Transition Fund has allocated €273 million to the country to adopt the Territorial Just Transition Plan (TJTP). This Plan will be targeted at the most affected regions, in Kaunas, Siauliai and Telšiai counties.

The fund will promote the adoption of green hydrogen and other low-carbon technologies in production processes. Among the most relevant actions of the fund, it is possible to mention the following ones³³²:

- €100 million to create new jobs in sustainable sectors, and to diversify the economy in these regions, specially focused on small and medium-sized enterprises.
- Support to the workers of the carbon-intensive facilities, to find new jobs and get the needed skills in the green and digital economy. Around 4,500 workers will benefit from the program.
- Increase the use of energy efficiency measures and renewable energies, supporting the replacement of fossil fuel boilers for renewable heat pumps, and using renewable energies and hydrogen in production processes.
- Refurbishing and modernization of industrial sites.

Finally, there are two important platforms which include representatives from the EU institutions, EU countries, third countries, NGOs, professionals and research and education institution, to promote the development of CCUS:

- **Industrial Carbon Management Forum (ICM Forum):** It was created in 2021, named as the CCUS Forum until 2023, and meets annually. It brings together representatives from the EU

³³² Source: European Commission. *EU Cohesion Policy: €273 million for a just climate transition in Lithuania*. December 14th, 2022.

institutions, different countries and professionals from both the business and the research and education sectors. Each year, a meeting is organized for 2 days, when these professionals could to discuss on the deployment of carbon capture and storage (CCS) and carbon capture and utilisation (CCU) technologies. There are also 4 working groups which publish different papers which collect the view of their participants, coordinated by working group's co-chairs.

- **CCUS Zero Emission Network (ZEN)**³³³: The CCUS ZEN project is funded by the European Union's Horizon Europe research and innovation programme, with the Grant Agreement No 101075693. The objective of the project is to explore the potential for accelerating the deployment of CCUS in two regions which have lower maturity level for CCUS, compared to the North Sea region: The Baltic Sea region, which includes Denmark, Sweden, Finland, Germany, Estonia, Latvia, Lithuania, Poland and the Baltic Sea, and the Mediterranean Sea region, which covers France, Italy, Turkey, the Mediterranean Sea, and some locations in Greece and Spain.

The project tries to build an ecosystem of CCUS actors in Europe, making sure that they actively cooperate and share the knowledge acquired through other projects.

- **Cohesion Fund**³³⁴: The Cohesion Fund offers support to some European countries whose gross national income per capita is below 90% of the average EU-27 income per capita. The objective of the funds is to strengthen the economic, social and territorial cohesion of the EU. The funds support, specially, investments in environment and trans-European networks in transport infrastructure carried out by public and regional authorities. Some of the countries which can receive these funds is Lithuania.

The total budget of the Cohesion Funds for the period 2021-2027 amount to €48.03 billion (current prices). Around 37% of the budget should be used in to contribute to climate objectives. From them, €11.29 billion are transferred to the Connecting Europe Facility.

- **InvestEU**³³⁵: This fund supports private and public investments in four main areas, which are the most relevant priorities for the Union: Sustainable infrastructure (€9.9 billion), Research, innovation and digitisation (€6.6 billion), SMEs (€6.9 billion) and Social investment and skills (€2.8 billion). The total budget is, therefore, €26.2 billion.

Although there is a variety of projects which can be supported, among the Sustainable infrastructures, there can be some projects related to renewable energy, energy efficiency, and energy infrastructure. Carbon capture, utilization and sequestration projects can be also funded by InvestEU.

- **European Regional Development Fund (ERDF)**: With a total budget for the period 2021-2027 of €226.05 billion, these funds support the economic, social and territorial cohesion of the European Union members.

They try to correct imbalances between the countries, and invest in making a smarter, greener, more connected and more social Europe. The total budget of European Regional Development Fund, for all the European Union for the period 2021-2027, is €226.05 billion. The fund invests in innovation and research, digital transition, small and medium-sized enterprises, the environment and the net-zero economy. Besides, it tries to face the economic, environmental,

³³³ Source: CCUS Zero Emission Network (ZEN) website: <https://www.ccuszen.eu/about-project.html>

³³⁴ Source: European Commission. Cohesion Fund (CF).

³³⁵ Source: European Commission. InvestEU Fund.

and social problems in urban areas. The fund is managed by the European Commission and each Member State, sharing the responsibility to implement it. Local authorities can select the projects which are considered as more needed.

During the period 2021-2027, Lithuania has received more than €3.6 billion from ERDF funds³³⁶.

- **Recovery and Resilience Facility³³⁷:** After the COVID19 pandemics, the European Commission launched the Next Generation EU Funds (NGEU), a package to make the European economies recover from the pandemics. They were agreed on July 21st, 2020, and launched on December 14th, 2020. The total budget of Next Generation EU Funds amounts to €806.9 billion in current prices..

The Recovery and Resilience Facility has a total budget of €650 billion, with €359 billion in grants and €291 billion in loans (in current prices). Therefore, most of the budget of Next Generation EU Funds is provided through the Recovery and Resilience Facility. It funds reforms and investments in EU Member States, since February 2020 to December 31st, 2026.

Specifically, Lithuania received funds worth €3.85 billion, from which, €2.3 billion were grants, and €1.55 billion as loans. The Lithuania's National Recovery and Resilience Plan, which describes the way funds are going to be spent, considers as the main objective the Green transition, with €1,439.6 million (37.4% of the total budget).

EU Emissions Trading System

The EU Emissions Trading System, EU ETS for short, is a cornerstone of the EU's climate policy and was the world's first international emissions trading system. This market-based mechanism is designed to drive the decarbonisation of the energy and industrial sectors by placing a price on carbon emissions. At its core, the EU ETS operates on a "cap and trade" principle, setting a limit on the total amount of greenhouse gases that can be emitted by participating entities.

Lithuania actively participates in the EU ETS, with all major power generators, refineries, cement and chemical plants exceeding an annual emission threshold of CO₂ being included within its scope. In 2023, 59 stationary installations across Lithuania, encompassing both power generation and manufacturing industries, emitted about 4.8 million tonnes of CO₂ equivalent (Mt CO_{2e}).³³⁸ This figure represents roughly 25% of the country's total greenhouse gas emissions, a share that has steadily decreased since 2013. This decline in the proportion of emissions from ETS-covered sectors within Lithuania's overall emissions suggests a notable trend. It indicates that either these specific sectors are achieving decarbonization at a faster rate compared to other areas of the Lithuanian economy, or that emissions from sectors outside the EU ETS's current scope are increasing. For instance, data from 2021 and 2022 reveals that the transport sector has become a major and growing contributor to Lithuania's total greenhouse gas emissions, a sector that is not fully addressed by the initial EU ETS.

The fundamental principle of the EU ETS is a "cap and trade" system. The European Union establishes a ceiling, or cap, on the total volume of specific greenhouse gases that can be emitted by the installations and operators covered by the system. This cap is expressed in terms of emission allowances, known as EUAs, where one EUA grants the holder the right to emit one tonne of carbon

³³⁶ Source: European Commission. Pact for Skills. European Regional Development Fund (ERDF) in Lithuania.

³³⁷ Source: European Commission. The Recovery and Resilience Facility.

³³⁸ Source: European Commission. Directorate- General for Climate Action. Directorate A- Strategy, Analysis and Planning. Unit A.2- Foresight, Economic Analysis & Modelling. *Climate Action Progress Report 2024 country profile – Lithuania*. December 2024.

dioxide equivalent. Crucially, this cap is not static, it is progressively reduced over time in line with the EU's climate targets, ensuring an overall decrease in emissions. Currently, the EU aims to achieve a 62% reduction in emissions from ETS sectors by 2030 compared to 2005 levels. The annual rate at which the cap decreases, known as the reduction factor, has been increased in Phase 4 of the ETS, signalling a more ambitious approach to emissions reduction. This tightening cap indicates a growing scarcity of allowances, which is expected to drive up the price of carbon and further incentivize deeper emissions cuts and investments in cleaner technologies.

Participating companies receive a certain number of these emission allowances for free, particularly those in energy-intensive industries as per Article 10c of the ETS Directive. The rationale behind this free allocation is to mitigate the risk of "carbon leakage", where industries might relocate outside the EU to regions with less stringent climate regulations. However, this free allocation is being gradually scaled down and made conditional upon the companies demonstrating their efforts towards decarbonization. The remaining allowances that companies need to cover their emissions must be acquired through EU-wide auctions, which serve as the primary method for distributing allowances since 2013. Over 57% of the total allowances are now auctioned. Additionally, companies have the flexibility to trade these allowances among themselves on secondary markets, allowing for the efficient allocation of emission reductions where they are most cost-effective. The price of these allowances is determined by the dynamics of the EU carbon market.

Each year, companies covered by the EU ETS are required to monitor their greenhouse gas emissions, report these emissions accurately, and have their reports verified by accredited bodies. This process ensures transparency and accuracy within the emissions trading system. Following the reporting year, these companies are obligated to surrender one emission allowance for each tonne of CO₂ equivalent that they have emitted. Failure to comply with these requirements carries significant financial penalties, including substantial fines of €100 per excess tonne of emissions. All transactions and holdings of emission allowances are recorded and tracked within the Union Registry, an online database that ensures precise accounting and helps in assessing the compliance of operators.

Cost of European Emission Allowance

The price of EUAs has fluctuated significantly since the system's inception. Initially, prices were low, sometimes even near zero. However, after 2018, more stringent climate policies and changes in the market design led to a substantial increase. Factors influencing EUA prices include energy demand, weather conditions, economic activity, fuel prices, and policy changes. For example, colder weather increases energy demand, leading to higher EUA prices. Similarly, higher gas prices can encourage a switch to coal, increasing the demand for and price of EUAs.

The following graph shows that between 2008 and 2020, the price stayed in the range of 5 to 30 euros per tonne of CO₂. After 2020, EUA prices experienced a consistent upward trend, oscillating around the EUR 80 range between 2021 and 2023. Currently, EUA prices are around €67 per tonne. Forecasts suggest that prices could rise significantly by 2030, potentially reaching €149 per metric ton. This increase is expected to drive further emissions reductions but may also increase costs for consumers.

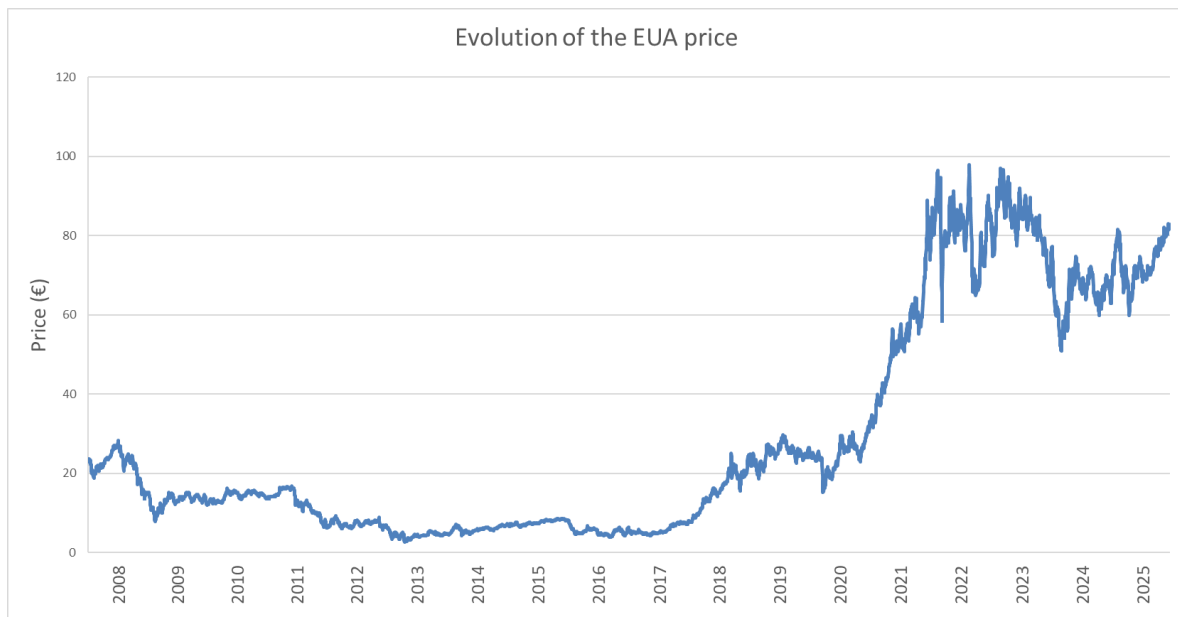


Figure 56: Evolution of the price of EUA's from 2008 until today.³³⁹

A key conclusion about the cost of the European carbon allowance is that, as prices have remained very low during the period from 2008 to 2021 (under €30/tonne of CO₂), there was not an incentive to large emitters to invest in carbon capture, utilization and storage projects. As has been discussed in chapters related to costs, the combined cost of capture are between US\$20 and US\$100/tonne of CO₂, transport costs range from US\$1.5 to US\$16 per tonne of CO₂, and storage costs vary between US\$1 and US\$20 per tonne of CO₂. Therefore, until 2022, there has not been a real incentive for large greenhouse gas emitters to invest in carbon capture, utilization and storage projects. Besides, as long as the cost of the European carbon allowances can be transferred to final users, investing in developing these projects is not seen as an urgent issue in business plans. On the other hand, Carbon Border Adjustment Mechanisms (CBAM) have been designed to avoid loss of competitiveness by European industry compared to third countries which do not apply the EU Emission Trading System.

Relevance of the EU ETS

The overarching objective of the EU ETS is to stimulate a reduction in greenhouse gas emissions across Europe in a manner that is both cost-effective and economically efficient. By establishing a price for carbon emissions, the system provides a direct financial incentive for businesses to minimize their carbon footprint and invest in technologies that lead to lower emissions. The sectors currently covered include electricity and heat generation, a wide range of industrial manufacturing activities, and aviation. Furthermore, in a move to broaden its impact, the EU ETS expanded its scope in 2024 to include emissions from maritime transport. Looking ahead, there are plans to further extend carbon pricing to sectors like buildings and road transport through a new, separate system known as ETS 2, which will become fully operational by 2027, with potential future inclusion of agriculture.

Beyond its regulatory function, the EU ETS also generates substantial revenue through the auctioning of emission allowances. These revenues are specifically earmarked for climate-related purposes within the Member States. Since 2013, the EU ETS has raised over €175 billion, with €43.6 billion generated

³³⁹ Source: SendeCO₂ – CO₂ Prices. Website: <https://www.sendeco2.com/es/precios-co2>

in 2023 alone³⁴⁰. Member States are now mandated to utilize all their EU ETS revenues, or an equivalent financial amount, to support climate action and a just green transition.

The primary Lithuanian entities participating in the EU ETS include³⁴¹ Achema, responsible for roughly 44.7% of the country's industrial emissions, Orlen Lietuva, accounting for about 33.9%, and Akmenės Cementas, contributing approximately 17.9%. These three companies collectively account for over 97% of Lithuania's total industrial emissions, highlighting their significant role within the national context of the EU ETS. Historically, these major emitters in Lithuania held surpluses of emission allowances. For example, "Achema" was significantly over-allocated prior to 2013, Orlen Lietuva anticipated its surplus to last until 2020, and Akmenės Cementas invested in modernization efforts to maintain a surplus into 2023. However, the overall trend in Lithuania indicates a decrease in verified ETS emissions, with emissions from stationary installations in 2023 being 6.2% lower than in 2022.

Voluntary carbon credit programs

Voluntary carbon credit programs contribute to combat climate change by enabling organizations to offset their greenhouse gas emissions through credible projects. The Verified Carbon Standard program and the Gold Standard Foundation are the most widely used entities that certify carbon credits, ensuring CO₂ reductions are real, measurable, additional, permanent, independently verified, and conservatively estimated.

While both programs certify high-quality carbon credits, the Gold Standard places additional emphasis on sustainable development and community benefits, making it particularly appealing for projects aiming to deliver broader socio-economic impacts for local communities, this difference may lead to CCUS project favouring cost-effective carbon credits of the VCS program.

In the Verified Carbon Standard Program each certified project issues Verified Carbon Units (VCUs), with one VCU representing the reduction or removal of one metric tonne of CO₂ equivalent., Gold Standard carbon credits, known as Verified Emission Reductions (VERs), also represent one metric ton of CO₂-equivalent emissions reduced or removed from the atmosphere.

The verification process for VCS requires the following steps:

- **Project development and pipeline listing:** Prepare a comprehensive project description detailing the project design, expected emission reduction and monitoring following an existing VCS approved methodology. For CCS the current methodology framework is VM0049, v1.0.
- **Validation and registration:** Assess through an accredited validation/verification body the compliance of the project with VCS methodologies, obtaining a validation report to confirm the adherence to VCS standards. Submit the project for registration after successful validation.
- **Monitoring and verification:** Monitor and record the actual emission reduction or removals during the project implementation, validating the reported reductions with a validation/verification body.

³⁴⁰ Source: European Commission. *EU Action- EU Emissions Trading Systems (EU ETS) – About the EU ETS*. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/about-eu-ets_en

³⁴¹ Source: sandbag. Lithuania and the EU ETS. *Arguments in favour of an enhanced Market Stability Reserve*. April 2025.

- **Issuance of verified carbon units:** Upon successful verification, submitting a request for the issuance of VCUs corresponding with the verified emission reductions.

Both VCS and Gold Standard ensure that carbon offset projects are rigorously assessed and verified, providing credibility and transparency in the voluntary carbon market. While VCS focuses on robust emission reduction methodologies, Gold Standard emphasizes additional sustainable development benefits.

Lithuanian organizations are increasingly active in voluntary carbon credit programs, focusing on regenerative agriculture and peatland restoration. Companies like HeavyFinance are leading initiatives to generate carbon credits through sustainable farming practices under the VCS standards, with credits expected to be issued by 2025. Environmental groups such as Pelkių Fondas and projects like MoorFutures are restoring wetlands and peatlands to enhance carbon sequestration and reduce emissions. Additionally, Lithuania is part of the GFarm for LIFE project, developing national systems for greenhouse gas monitoring and certification. These efforts reflect Lithuania's growing role in climate mitigation and the voluntary carbon market.

9.4. Best practices from other countries

9.4.1. Hydrogen and Innovative Technologies

Several countries have implemented innovative technologies and strategies to reduce CO₂ emissions in industrial enterprises. Below is an overview of best practices from five advanced countries, highlighting their key industrial sectors, technological processes, and implemented technologies:

Germany

Germany stands as one of the global leaders in the adoption of hydrogen and innovative technologies to reduce CO₂ emissions. The country's steel and chemical industries have been at the forefront of the transition, with major projects exploring the potential of green hydrogen³⁴². The "Hydrogen Roadmap" outlines Germany's long-term strategy to integrate hydrogen into industrial processes. One notable example is the SALCOS project, which aims to replace coal-based steel production with hydrogen-based direct reduction, significantly cutting emissions³⁴³. Additionally, Germany is leveraging digitalization through smart energy management systems, enhancing energy efficiency and reducing overall carbon footprints across industries.

As part of the German National Hydrogen Strategy Germany has allocated €740 million for lead projects for offshore hydrogen production (H2-Mare), technologies for hydrogen transport (TransHyDE) and the serial development of electrolyzers (H2-Giga). Additionally, the program H2 Global is a 10-year German scheme to support investments in green hydrogen for export to Germany. The intention is to create a double auction system through which hydrogen is purchased in non-EU countries at the lowest possible price with 10-year contracts via a competitive process.³⁴⁴

Japan

Japan has invested heavily in hydrogen fuel cells for both transport and industrial applications. Companies like Toyota have integrated hydrogen fuel cells into production lines, while Mitsubishi

³⁴² Source: McKinsey. Net-Zero Germany: *Chances and challenges on the path to climate neutrality by 2045*. October 19th, 2024.

³⁴³ Source: Saltzgitter AG. SALCOS. <https://salcos.saltzgitte-ag.com/en/index.html>

³⁴⁴ Source: Green Hydrogen Organisation. *Germany*. <https://gh2.org/countries/germany>

Chemical is exploring hydrogen for chemical synthesis processes³⁴⁵. Waste-to-energy technologies and AI-based predictive maintenance systems further support the reduction of CO₂ emissions by optimising resource use and minimising waste³⁴⁶. Japan's commitment to a hydrogen society is reflected in its Basic Hydrogen Strategy³⁴⁷, which envisions widespread adoption across industries.

Through the enactment of the “Hydrogen Society Promotion Act”, the Japanese government has allocated 3 trillion yen in subsidies (approximately US\$ 20 billion) through a Contracts for Difference (CfD) system that is designed to incentivize the adoption and uptake of Japan’s definition of ‘low-carbon’ hydrogen. The support measures are structured around two main pillars: price gap and infrastructure development support. The price gap support covers the difference between the benchmark price (what suppliers need to charge) and the reference price (what end-users would pay based on alternative fuel costs). The subsidy rate is 100% of eligible expenses, with specific caps to ensure budget control. To access the price gap support, projects must supply at least 1,000 tons of hydrogen equivalent annually and focus on hard-to-decarbonize sectors. Infrastructure development support has a higher threshold of 10,000 tons annually and requires clear regional economic benefits. These projects must demonstrate shared infrastructure potential for multiple users and have strong community support.³⁴⁸

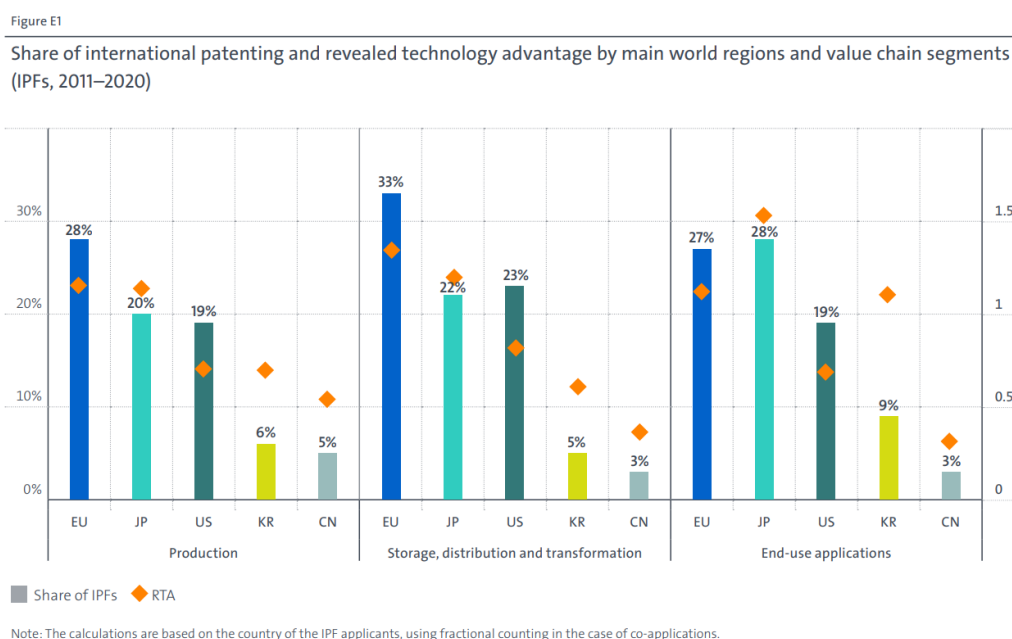


Figure 57: Europe and Japan are leading the number of patents regarding hydrogen³⁴⁹

³⁴⁵ Source: DELAVAL, Benedicte; RAPSON, Trevor; SHARMA, Raghav; HUGH-JONES, Will; MCCLURE, Erin; TEMMINGHOFF, Max; SRINIVASAN, Vivek. *Hydrogen RD&D Collaboration Opportunities: Japan*. Australia’s National Science Agency. CSIRO, Australia. 2022.

³⁴⁶ Source: Climate Adaptation Platform. *Can Japan’s Waste-to-Energy Technology Shape Global Waste Management?* November 14th, 2023.

³⁴⁷ Source: The Ministerial Council on Renewable Energy, Hydrogen and Related Issues. *Basic Hydrogen Strategy*. December 26th, 2017.

³⁴⁸ Source: Green Hydrogen Organisation. *Japan*. <https://gh2.org/countries/japan>

³⁴⁹ Source: World Economic Forum. *Which countries are leading the way with hydrogen?* March 16th, 2023.

The Netherlands

The Netherlands has adopted a multifaceted approach to CO₂ reduction, combining hydrogen, bioplastics, carbon capture and storage (CCS) and carbon capture and utilisation (CCU) technologies. The petrochemical industry, particularly in the Rotterdam port area, has been a key focus for hydrogen implementation. Projects such as the H-Vision initiative are developing large-scale hydrogen production from residual gases combined with CCS³⁵⁰. Additionally, the Dutch food processing industry is shifting towards bioplastic packaging, contributing to the reduction of plastic waste³⁵¹. The integration of electrified transport fleets and smart logistics systems further enhances the sustainability of industrial operations³⁵².

The government has subsidized the installation of electrolyzer capacity in the Netherlands with €1.43 billion. Additionally, with a modification in the ministerial decree on gas quality, the Dutch legal framework allows hydrogen injection up to 0.5% in regional gas distribution systems. To create demand for green hydrogen, the government is considering the possibility of mandatory injection of green hydrogen (physically or through certificates).³⁵³

Denmark

Denmark has emerged as a front-runner in the development of green hydrogen through its ambitious X (PtX) stPower-to-rategy, aiming to produce and utilize hydrogen and hydrogen-derived fuels from renewable electricity. The Danish government has committed more than DKK 1.25 billion (€167 million) through the Energy Technology Development and Demonstration Program (EUDP)³⁵⁴ and additional funds from the PtX tender scheme, launched in 2023 to support large-scale electrolysis projects.

Major initiatives include the Green Fuels for Denmark consortium in Copenhagen, which targets the production of green ammonia, methanol, and e-kerosene for maritime and aviation use, as well as HØST PtX Esbjerg, which combines offshore wind with a 1 GW electrolyzer facility for green ammonia production³⁵⁵. Denmark's hydrogen strategy explicitly prioritizes hard-to-abate sectors and cross-border infrastructure integration with Germany and the Netherlands. These efforts illustrate how robust public-private partnerships and early regulatory alignment can accelerate hydrogen deployment and serve as a useful reference for Lithuania's industrial decarbonization plans.

³⁵⁰ Source: The Netherlands Organization for Applied Scientific Research TNO. *H-vision: blue hydrogen to accelerate carbon-low industry*.

³⁵¹ Source: VAN DEN OEVER, Martien; MOLENVELD, Karin; VAN DER ZEE, Maarten; BOS, Harriëte. *Bio-based and biodegradable plastics. Facts and Figures. Focus on food packaging in the Netherlands*. Wagenigen Food & Biobased Research. Rapport nr. 1722. April 2017. ISBN- number: 978-94-6343-121-7. DOI: <http://dx.doi.org/10.18174/408350>.

³⁵² Source: The Netherlands Organization for Applied Scientific Research TNO. *Green Transport Delta – Electrification (GTD-E)*. <https://www.tno.nl/en/sustainable/mobility-logistics/batteries/gtde/>

³⁵³ Source: Green Hydrogen Organisation. *Netherlands*. <https://gh2.org/countries/netherlands>

³⁵⁴ Source: EUDP. About the EUDP: *The Energy Technology Development and Demonstration Programme*. 2025. Web reference accessed in July 2025: <https://eudp.dk/en/om-eudp>

³⁵⁵ Source: HØST PtX Esbjerg. *Harvesting renewable energy*. Web reference accessed in July 2025: <https://hoestptxesbjerg.dk/>

Norway³⁵⁶

Norway's efforts to decarbonise its industrial sectors are closely linked to its abundant renewable resources. The shipping industry has seen the introduction of hydrogen-powered vessels, such as the MF Hydra ferry, as part of the country's broader hydrogen strategy³⁵⁷. Norway's oil and gas sector is very significant, and so they are also exploring CCS technologies to mitigate emissions from extraction processes³⁵⁸. Other innovative technologies like the electrification in aluminium production³⁵⁹, along with a highly developed circular economy framework, places Norway at the forefront of industrial decarbonisation in Northern Europe.

The Norwegian agency Enova has granted over NOK 1.6 billion (approximately €140 million) for demonstration projects. Among those project are Yara Norge AS (NOK 283 million) for the production of ammonia and fertilizers, TiZir Titanium and Iron AS (NOK 261 million) for coal replacement with hydrogen in smelting and Horisont Energi (NOK 482 million) to produce ammonia from captured carbon from natural gas.³⁶⁰

South Korea

South Korea has rapidly advanced in the deployment of hydrogen and digitalisation technologies across its steel, chemical, and energy sectors. The country's Hydrogen Economy Roadmap sets ambitious targets for hydrogen production and usage (6.2 million fuel cell electric vehicles by 2040)³⁶¹. The use of AI-based energy management systems, along with nation-wide implementation of digitalisation, is helping optimise energy use and reduce emissions in manufacturing processes. South Korea's integrated approach highlights the role of hydrogen as a cornerstone of the country's energy transition.

On May 2024, the Korean Ministry of Trade, Industry and Energy announced the launch of a clean hydrogen power bidding market. This market facilitates the sale and purchase of electricity generated from clean hydrogen, with participation restricted to only power generators that meet Korea's domestic clean hydrogen certification standards. The total bidding volume for 2024 was set at 6,500 GWh, with contracts lasting for 15 years. Commercial operations will commence by 2028, following a three-year preparation phase and an additional year for grace.³⁶²

9.4.2. Carbon Capture

Several countries have made significant strides in implementing carbon capture technologies to mitigate CO₂ emissions from industrial enterprises. Below is an overview of best practices from five leading countries, detailing the key industrial sectors, technological processes, and implemented carbon capture technologies.

³⁵⁶ Source: Norwegian Ministry of climate and Environment. *Norway's Eighth National Communication under the Framework Convention on Climate Change*. Status report as of December 2022, resubmitted in March 2023.

³⁵⁷ Source: Renewable energy magazine. *Hydrogen-fueled ferry MF Hydra to commence operations in Norway*. March 31st, 2023.

³⁵⁸ Source: Norwegian Petroleum. *Carbon Capture and Storage*.

³⁵⁹ Source: Hydro. *Our roadmap to net-zero emissions in aluminum production*. March 25th, 2025.

³⁶⁰ Source: Ocean Hyway Cluster. (2021, December 17). *Enova grants more than 1 billion NOK to three industrial projects: Hydrogen is the climate solution in all three projects*.

³⁶¹ Source: International Energy Agency. *Korea Hydrogen Economy Roadmap 2040*.

³⁶² Source: Green Hydrogen Organisation. *South Korea*. <https://gh2.org/countries/south-korea>

United States

The United States remains at the forefront of carbon capture innovation, particularly within the energy and industrial sectors. Flagship initiatives such as the Illinois Industrial Carbon Capture and Storage (ICCS) project and the Petra Nova project exemplify the country's leadership in this domain. Petra Nova, originally designed to capture 90% of CO₂ emissions from a 240 MW slipstream of flue gas—equivalent to approximately 1.4 million metric tons annually—temporarily ceased operations in 2021 due to COVID-19-related challenges but resumed activity in 2023.³⁶³

The industrial sector, notably cement production, is increasingly deploying on-site carbon capture systems to decarbonize hard-to-abate processes. On top of this, Climeworks, a Swiss leader in direct air capture (DAC), has expanded its footprint in the U.S. through a strategic agreement with Morgan Stanley, aiming to remove 40,000 tonnes of CO₂ annually³⁶⁴.

Specific support policies for Carbon capture include the 45Q federal tax credits, providing up to US\$85 per metric ton of CO₂ as well as the investment of US\$3.5 billion for funding of regional direct air capture pilot projects.

Canada

Canada has been a pioneer in adopting carbon capture technologies across various industrial sectors, including energy and cement. The Boundary Dam Power Station was one of the first commercial-scale coal plant with integrated carbon capture. The quest project is capturing 1 million tonnes of CO₂ emissions per year from hydrogen production, nevertheless some analyses on the facility claim that the GHG emitted are higher than those being captured³⁶⁵.

Government support for carbon capture is managed through the Energy Innovation Program, administered by Natural Resources Canada, with investments of \$319 million over seven years for CCUS projects. Additionally, the federal government of Canada has approved investment tax credits for CCUS projects.³⁶⁶

United Kingdom

The UK has focused on the capture of CO₂ emitted from its electricity generation units which rely on fossil fuels. An example of the developments towards these low emission powerplants is the Net Zero Teesside Power plant, a gas-fired power station with integrated carbon capture and storage technology. The plants are designed to generate 742 MW of low carbon electricity, capturing 800,000 tonnes of CO₂ annually from its operation, which will be stored in the North Sea³⁶⁷.

³⁶³ Source: U.S. Department of Energy. *Petra Nova - W.A. Parish Project*. <https://www.energy.gov/fecm/petra-nova-wa-parish-project>

³⁶⁴ Source: Wall Street Journal. CLAIRE BROWN, H. *Climeworks Strikes 40,000-Ton Carbon Removal Deal With Morgan Stanley*. October 24th, 2024.

³⁶⁵ Source: Global Witness. *Hydrogen's Hidden Emissions*. January 20th, 2020.

³⁶⁶ Source: Natural Resources Canada. (2025, July 4). *Canada invests in carbon capture and storage in Alberta*. Government of Canada.

³⁶⁷ Source: U.K. Department for Energy Security and Net Zero. *Contracts signed for UK's first carbon capture projects in Teesside*. December 10th, 2024.

Governmental support for CCUS is focused on four main projects with £1 billion of funding to capture 10 Metric tons of CO₂ per year, in addition to a commitment of £30 billion over the next 20 years for projects that aim to store 20-30 million tons of CO₂ per year.³⁶⁸

Australia

Australia is making significant progress in implementing carbon capture technologies in its extractive industries. A remarkable project for carbon capture in Australia is the Gorgon Carbon Dioxide Injection Project, located on Barrow Island off the coast of Western Australia.

This CCS facility captures CO₂ emissions generated during natural gas processing at the Gorgon LNG plant. The captured CO₂ is then injected into the Dupuy Formation, a deep geological reservoir beneath Barrow Island, ensuring long-term storage. Once fully operational, the Gorgon project is expected to store up to 4 million tonnes of CO₂ annually. Government support for carbon capture consists of grants for pilot projects up to 25% of project cost at a maximum of US\$1.5 million³⁶⁹ as well as the inclusion of carbon capture projects in the Australian Carbon Credits System by awarding Carbon credit units which can be sold in secondary markets.³⁷⁰

Norway

Norway has positioned itself at the forefront of carbon capture and storage technology particularly within the cement production. A notable initiative is the Brevik project which develops a pioneering CO₂ capture facility at Heidelberg Materials' cement plant in Brevik, Norway. The Brevik CCS facility is designed to capture up to 400,000 metric tons of CO₂ annually. Captured CO₂ will then be transported via pipeline to the Northern Lights storage site beneath the North Sea, ensuring permanent sequestration³⁷¹.

Two Norwegian carbon capture projects have received subsidies as part of the Northern Lights infrastructure project which has received €2billion from the Norwegian government.

Denmark

Denmark is advancing carbon capture and storage (CCS) with strong government backing, including a USD 4.2 billion CCS Fund aiming to reduce CO₂ emissions by 2.3 million tonnes annually from 2030. The NECCS Fund also supports capturing CO₂ for negative emissions. Ørsted is building the country's first full-scale CCS plants at Avedøre and Asnæs, expected to capture 430,000 tonnes of CO₂ per year by 2026. In industrial decarbonisation, the ACCSION project in Aalborg is an initiative set to become one of Europe's first fully integrated onshore CCS value chains.

³⁶⁸ Source: Department for Energy Security and Net Zero, & Department for Business, Energy & Industrial Strategy. (2025, January 17). *Carbon capture, usage and storage (CCUS): Business models*. Government of the United Kingdom.

³⁶⁹ Source: Government of Western Australia. *Carbon Innovation Grants Program*. <https://www.wa.gov.au/service/community-services/grants-and-subsidies/carbon-innovation-grants-program>

³⁷⁰ Source: Clean Energy Regulator. *Carbon capture and storage method*. <https://www.cer.gov.au/schemes/australian-carbon-credit-unit-scheme/accu-scheme-methods/carbon-capture-and-storage-method>

³⁷¹ Source: Heidelberg Materials. *Opening of Northern Lights at Øygården*. September 26th, 2024.

The European Commission has approved a €1.1 billion support scheme for carbon capture projects in Denmark that permanently store at least 400 kt of CO₂ per year for the award of 20-year contracts to cover the difference between estimated total cost and expected returns.³⁷²

9.4.3. Carbon Utilization

Several countries have made significant strides in implementing carbon utilisation technologies to make use of the carbon captures in industrial processes and fossil fuel combustion. Below is an overview of best practices from five leading countries in these technologies:

United States

The United States is leading in carbon utilization technologies³⁷³, particularly in the chemicals, fuels, and agriculture sectors. For instance, algae-based CO₂ uptake is being used for biomass production, which can be further processed into biofuels or other products. Captured carbon dioxide is also being used for producing organic and inorganic chemicals. Lastly, Enhanced Oil Recovery continues to be a significant part of the use of captured CO₂.³⁷⁴

China

The Anyang plant located in Henan Province in China represents a significant advancement in carbon utilization, particularly in the production of methanol. The plant captures approximately 160,000 tons of CO₂ annually from the oven gas produced by a nearby metallurgical coke facility. This captured CO₂ is then converted into methanol using Carbon Recycling International's proprietary Emissions-to-Liquids technology. The plant produces around 110,000 tons of methanol each year, which can be used as a fuel or chemical feedstock.³⁷⁵

Canada

Canada's 2022 federal Budget outlines a proposed investment tax credit aimed at supporting CCUS initiatives from 2022 through 2030, with a 37.5% rate applicable to utilization equipment. Although the 2023 budget reiterated this commitment, the measure remains pending legislative approval.³⁷⁶ Lafarge Canada has created a Carbon Capture Utilization Demonstration Hub in which they are implementing two projects to the Richmond Cement Plant to transform CO₂ into energy dense liquid fuels and produce a lower intensity cement.³⁷⁷

Sweden

The FReSMe project in Luleå, Sweden, exemplifies the feasibility of integrating carbon capture and utilization technologies into existing steel manufacturing processes. The facility captures CO₂ emissions from the blast furnace gases of a nearby steel mill to produce up to 1 ton of methanol per day. This methanol is utilized as fuel for the operation of the Stena Germanica ferry between Gothenburg,

³⁷² Source: European Commission. (2023). *State aid: Commission approves €1.1 billion Danish scheme to support roll-out of carbon capture and storage technologies*.

³⁷³ Source: U.S. Department of Energy. *U.S. Department of Energy Announces \$16.5 Million in Funding for Carbon Utilization Projects*. Bioenergy Technologies Office. August 31st, 2022.

³⁷⁴ Source: National Energy Technology Laboratory. *About Carbon Utilization*.

³⁷⁵ Source: Carbon Recycling International. *CO₂ -to-methanol plant: commercial scale production in China*.

³⁷⁶ Source: International Energy Agency. *Carbon Capture and Utilisation (Country and Regional Highlights)*.

³⁷⁷ Source: CICE. *B.C. Invests in Innovative Technology in Cement Industry*. May 15th, 2023.

Sweden and Kiel, Germany. This project received 100% of its funding from the Horizon 2020 programme.³⁷⁸

Netherlands

While the Netherlands has primarily concentrated its efforts on developing carbon storage infrastructure, the country is also actively promoting the utilization of captured carbon dioxide. A notable example is the waste-to-energy facility in Duiven, which features a carbon capture system with an annual capacity of 50,000 tonnes of CO₂. Rather than being stored, the captured CO₂ is repurposed for use in greenhouse horticulture, where it supports plant growth and enhances agricultural productivity.³⁷⁹

9.4.4. Carbon Transport and Storage

Several European countries are actively supporting CCS and CCUS through dedicated funding mechanisms and policy instruments. Some of them will be described in the following pages.

In Norway, in 2025, the government is co-financing the Longship project with over €1.7 billion in public investment. This flagship initiative includes capture from industrial sources (e.g., Norcem cement plant) and permanent offshore storage via the Northern Lights infrastructure³⁸⁰.

In the Netherlands, the Porthos project will transport CO₂ from the Port of Rotterdam to offshore storage in depleted gas fields, supported through the SDE++ scheme, which compensates for the cost gap between CCS and conventional alternatives. In 2021, the project received approval for up to €2.1 billion in operating subsidies over 15 years³⁸¹.

In Denmark, the government has merged its CCUS and Green Strategic Reserve (GSR) schemes to allocate DKK 38 billion (around €5 billion) in funding to CCS deployment, including tenders in 2024 and 2025 to contract over 2.3 MtCO₂/year of capture capacity starting from 2029³⁸².

In the United Kingdom, the government launched the CCUS Cluster Sequencing Process, selecting two initial industrial clusters (HyNet North West and East Coast Cluster) that are eligible for funding through the £1 billion CCS Infrastructure Fund and Contracts for Difference (CfDs) for CO₂ transport and storage services³⁸³.

³⁷⁸ Source: European Climate, Infrastructure and Environment Executive Agency: FReSMe project

³⁷⁹ Source: The Netherlands Organization for Applied Scientific Research TNO. *CO₂ reduction in the Netherlands: measures and innovations*.

³⁸⁰ Source: Government Press Release. *Longship goes into operation – A Global Breakthrough for Carbon Capture and Storage*. Web reference accessed in June 2025: https://www.regjeringen.no/en/aktuelt/longship-goes-into-operation-a-global-breakthrough-for-carbon-capture-and-storage/id3109272/?utm_source=chatgpt.com

³⁸¹ Source: Porthos CO₂ Transport & Storage. *Dutch government supports Porthos customers with SDE++ subsidy reservation*. 2021. Web reference: https://www.porthosco2.nl/en/dutch-government-supports-porthos-customers-with-sde-subsidy-reservation/?utm_source=chatgpt.com

³⁸² Source: Danish Energy Agency. *Danish Energy Agency presses the start button for billion-dollar tendering procedure for carbon capture and storage*. 2024. Web reference accessed in July 2025: https://ens.dk/en/press/danish-energy-agency-presses-start-button-billion-dollar-tendering-procedure-carbon-capture?utm_source=chatgpt.com

³⁸³ Source: Government of the UK. October 2021 update: Track-1 clusters confirmed. 2021. Web reference accessed in July 2025: https://www.gov.uk/government/publications/cluster-sequencing-for-carbon-capture-usage-and-storage-ccus-deployment-phase-1-expressions-of-interest/october-2021-update-track-1-clusters-confirmed?utm_source=chatgpt.com

These examples demonstrate how tailored financial instruments—including grants, operating subsidies, and risk-sharing mechanisms—are critical to de-risking investment and accelerating deployment. Such mechanisms offer valuable insights for designing Lithuania’s future support schemes for CCSU.

At EU level, the Innovation Fund supports large-scale CCSU demonstration projects through grants and projects like the previous commented. To summarize, in Europe there are a total of 43 active projects in development that are expected to store about 141 million tons of CO₂ by 2030. 19 are in the territory of the European Union, and by 2030 a total of 42 million tons of CO₂ are expected to be stored³⁸⁴. The main ones are located in:

Norway

- Longship (& Northern Lights).
- Sleipner.
- Barents Blue (& Polaris).
- Snovit.
- Smeaheia.
- Trudvang.
- Luna.
- Havstjerne.
- Poseidon (NO).

United Kingdom

- Acorn.
- Caledonia Clean Energy.
- Zero Carbon Humber.
- Hynet.
- Net Zero Teosside.
- South Wales Industrial Cluster.
- Bacton Thames Net Zero Initiative.
- Poseidon (UK).
- Viking CCS.
- Orion.
- Solent Cluster.

Netherlands

- Porthos.

³⁸⁴ Source: International Association of Oil & Gas Producers. *CO₂ storage projects in Europe*. 2024. Web reference accessed in May 2025: <https://iogpeurope.org/key-topics/carbon-capture-use-storage/>

- Aramis.
- L10 CCS.

Iceland:

- Orca.
- Silverstone.
- Coda Terminal.
- Mammoth.

Denmark

- Greensand.
- Bifrost.
- Stenlille demo CO₂-storage.
- Norne.
- Ruby.
- ACCSION.

Croatia

- Petrokemija Kutina.
- Bio-Refinery Project.
- CCGeo.
- CO₂ EOR Project Croatia.
- Geothermal CCS Project.

Other projects in Europe

- ANRAV (Bulgaria).
- CO₂-SPICER (Czech Republic).
- Pycasso (France-Spain, Cancelled).
- Prinos CCS (Greece).
- MOL-Hungary CCS Project (Hungary).
- Callisto (Ravenna CCS, Italy).

<u>Norway</u>

The Norwegian Offshore Directorate has performed the “CO₂ Atlas for the Continental Shelf” declared three main atlas for the storage of CO₂³⁸⁵.

³⁸⁵ Source: RIIS, Fridtjof; HALLAND, Eva. *CO₂ Storage Atlas of the Norwegian Continental Shelf: Methods Used to Evaluate Capacity and Maturity of the CO₂ Storage Potential*. Energy Procedia 63, pp. 5258-5265. 2014. <https://doi.org/10.1016/j.egypro.2014.11.557>

- North Sea
- Norwegian Sea
- Barents Sea

The storage potential of the North Sea aquifers is significantly greater compared to other areas. This is partly because the North Sea contains key aquifers across various stratigraphic levels, whereas in the Norwegian and Barents Seas, the primary focus for CO₂ injection will be the Jurassic formations.

The injectivity of the aquifers analysed and the sealing capabilities of their cap rocks are regarded as satisfactory or good, primarily due to the exclusion of low-quality reservoir formations from the assessment. Some of these formations are outlined in the geological description sections.

The sealing properties in the Barents Sea are generally considered somewhat weaker compared to other regions. This is explained in the literature and attributed to the area's Cenozoic and Quaternary uplift history, as well as widespread signs of hydrocarbon seepage.

In conclusion, the Norwegian Sea and Barents Sea offer ample storage capacity for CO₂ captured from local sources, while the Norwegian North Sea also has the potential to accommodate CO₂ from northern Europe.

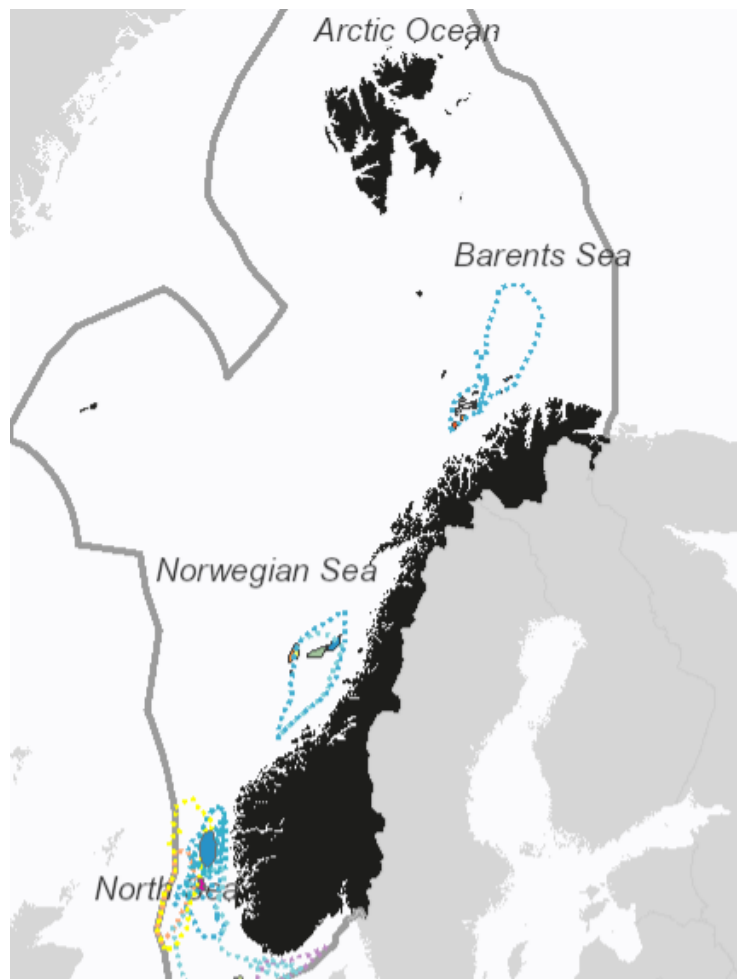


Figure 58: Storage opportunities in Norway. From Atlas of the Norwegian Continental Shelf.

Now we are about to discuss the geological conditions of the North Sea and what make them viable for CO₂ storage.

The North Sea:

Structural Framework: The North Sea's basic structure results from Upper Jurassic/Lower Cretaceous rifting, influenced by older structural elements.

Carboniferous-Permian: Major rifting with volcanism led to the deposition of sandstones (Rotliegendes) and thick evaporates (Zechstein). Overlying sediments caused salt movement (halokinesis), important for creating closed structures and hydrocarbon traps in the southern North Sea.

Triassic: Significant N-S to NE-SW rifting with coarse fluvial sediments along rift margins, transitioning to finer river and lake deposits in the basins' centres. A marine transgression marks the transition to the Jurassic.

Jurassic: Following the marine transgression, a volcanic dome formed over the Viking Graben, Central Graben, and Moray Firth Basin, causing uplift and rifting. Deltaic systems developed, and significant shale sequences accumulated, creating the primary source rock and important seals like the Draupne Formation.

Cretaceous: Rifting ceased, and thermal subsidence followed. The Upper Cretaceous saw contrasting lithologies—chalk to the south and siliclastic sediments to the north.

Cenozoic: Palaeocene/Eocene saw major earth movements and sea floor spreading in the North Atlantic. Deposition of chalk continued into the Early Palaeocene, with uplift producing submarine fans. By the Miocene, a deltaic system formed. Major uplift and glacial erosion during the Quaternary buried Jurassic source rocks, allowing hydrocarbon generation and effective seals.

Storage options in the North Sea

A) Saline aquifers

Theoretical Storage Capacity: The evaluation of the North Sea's theoretical CO₂ storage capacity identifies two aquifers with significantly higher potential than others: the Utsira-Skade Formation aquifer and the Bryne-Sandnes Formation aquifer.

Utsira Formation: Currently used by the petroleum industry for CO₂ storage, structures like the Sleipner injection site are categorized in the 3rd level of the maturation pyramid. Only about 25% of the total pore volume in the Utsira-Skade aquifer is considered suitable for storage, due to the aquifer's shallow top.

Bryne-Sandnes Formation: This aquifer has lower maturity than the Utsira Formation. Reservoir quality and seal integrity need to be carefully assessed at any proposed storage site. It is located in a salt basin, and closed structures created by salt tectonics may be ideal for CO₂ injection.

Johansen-Cook Formation: While this aquifer has a smaller pore volume than the previous two, it possesses good reservoir and seal properties. A potential storage site in the Johansen Formation has been recently evaluated by Gassnova and is included in the 3rd step of the maturation pyramid.

Evaluated aquifers	Average depth (m)	Bulk volume (Gm ³)	Pore volume (Gm ³)	Average permeability (mD)	Open/closed	Storage efficiency (%)	Storage volume (GRm ³)	Density in reservoir (kg/m ³)	Storage capacity (Gt)
Utsira Formanijon and Skade	1,000	2,500	530	>1,000	Open	4.0%	21.00	750	15.77
Bryne/Sandnei Formations	1,700	5,000	440	150	Half open	4.5%	20.00	690	13.60
Sognefjord Delta East.	1,750	550	110	300	Half open	5.5%	5.90	690	4.09
Statfjord Gp East	2,400	1,100	120	200	Half open	4.5%	5.40	660	3.59
Gassum Formation	1,700	650	76	450	Half open	5.5%	4.20	680	2.85
Farsund Basin	2,000	860	82	150	Half open	4.0%	3.30	700	2.30
Johanssen and Cook Formation	1,700	N/A	91	300	Faults	3.0%	2.70	650	1.78
Fiskebank Formation	1,600	100	25	1,000	Half open	5.5%	1.40	700	0.96
Stord basin, Jurassic model	1,450	270	16	5 - 20	Half open	0.8%	0.14	710	0.10
Hugin East	1,700	19	2	500	Half open	5.5%	0.13	700	0.09

Table 19: Features of some aquifers for potential capture of CO₂. Extracted from the CO₂ Atlas for the Continental Shelf.

B) Abandoned oil or hydrocarbon fields:

According to the January 2024 Risk Level Norwegian Petroleum Activity (RNNP) Report, a total of 488 wells in 16 fields on the Norwegian Continental Shelf (NCS) are listed as temporarily abandoned or temporarily plugged and abandoned, including inactive wells. This accounts for 22% of the total well stock on the NCS, which is 2,245 wells.

Some fields have been pressure-depleted, with calculations based on material balance, accounting for the volumes of oil, condensate, and gas produced. Some fields, like those in a namely Ekofisk area, have low permeability chalk reservoirs, which require long wells with advanced completions for efficient injection rates. These fields also offer enhanced oil recovery (EOR) potential, as remaining hydrocarbons might be mobilized during CO₂ injection. Storage capacities for producing fields are projected for 2030 and 2050, based on production data.

On the other hand, the Frigg field has been specifically studied due to its large storage potential. Many large fields in the Lower-Middle Jurassic Statfjord, Brent, and Sleipner (currently in production) aquifers are in regions with weak to moderate overpressure, though some parts have been depleted due to production. Areas with high overpressure are unsuitable for CO₂ injection. Also, fields with low permeability require specialized injection techniques.

Norwegians estimate that the main future CO₂ storage potential is tied to both abandoned and currently producing fields, with projections for 2030 and 2050.

Projects in the Area: North Sea

Overview of the Sleipner Project:

The Sleipner Project, operated by Statoil, represents the first commercial-scale initiative for geological CO₂ storage in a saline formation. Located approximately 250 km off the Norwegian coast in the North Sea, it captures CO₂ (around 9%) from the Sleipner West Gas Field, separating and injecting it into a deep saline sandstone formation situated 800 meters below the seabed. The Saline Aquifer CO₂ Storage (SACS) project was established to oversee and advance research and monitoring of this storage process. Since its inception in 1996, the operation has injected approximately 1 million tons of CO₂ annually, with more than 7 million tons injected by early 2005. By the project's end, an estimated total of 20 million tons of CO₂ is expected to be stored.

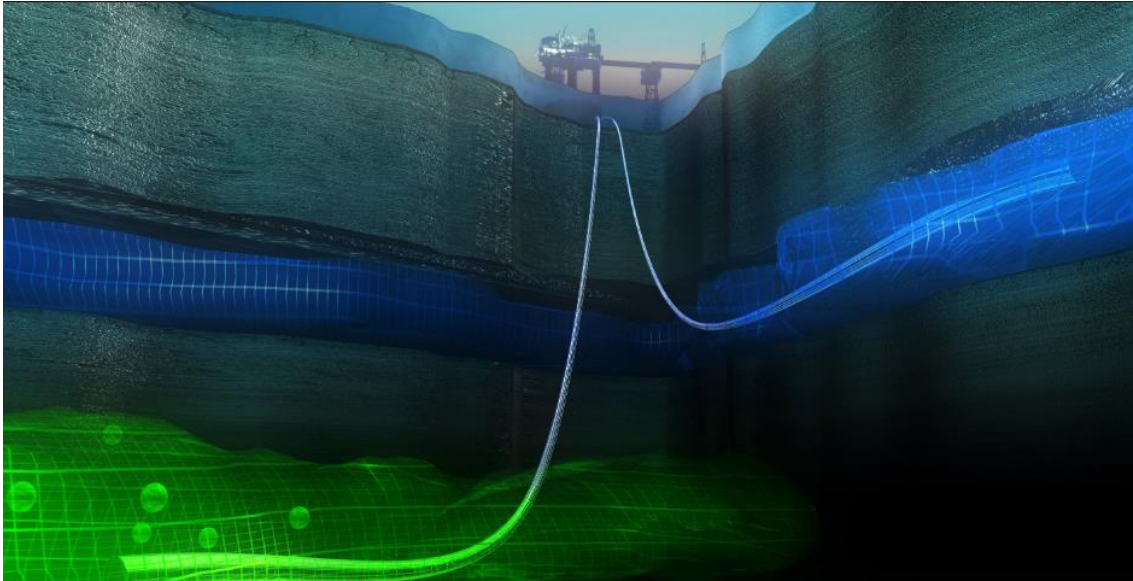


Figure 59: Visualization of carbon storage at Sleipner. Source: Equinor.

Geological Characteristics:

The storage formation is a brine-saturated, unconsolidated sandstone layer located 800–1000 meters below the sea floor, interspersed with thin shale layers that influence the distribution of CO₂. With an estimated capacity of 1–10 gigatons of CO₂, the formation is topped by a thick, extensive shale caprock that serves as a reliable seal to prevent CO₂ leakage. Seismic surveys have confirmed the integrity of the caprock and the containment of the CO₂ plume.

Phases of the Project:

The Sleipner project is divided into three phases.

- Phase-0 focused on gathering and evaluating baseline data, completed in 1998.
- Phase-1, completed after three years of CO₂ injection, involved assessing the reservoir geology, reservoir simulation, geochemistry, monitoring requirements, and geophysical modelling.
- Phase-2 began in 2000, emphasizing data interpretation and model validation to understand CO₂ behaviour in the reservoir.

Monitoring and Long-term Predictions:

Seismic time-lapse surveys have been critical for tracking the CO₂ plume within the formation. These surveys demonstrate the effectiveness of the caprock in sealing the formation and preventing leakage. The CO₂ plume currently spans an area of approximately 5 square kilometres. Long-term simulations predict that the CO₂ will dissolve into the pore water over time, increasing its density and reducing the risk of future leakage.

DENMARK

In Denmark, several projects have been or are under development.

- Greensand.
- Bifrost.
- Stenlille demo CO₂-storage.
- Norne.

- Ruby.
- ACCSION.

1) **Project Greensand (Nini Field. Off-shore)**

This project started in June 2020, and it is performed in an abandoned oil reservoir: The Nini Field. In the initial phase of the project, CO₂ storage at the Nini Field is deemed competitive. With third-party certification confirming a storage potential of 0.5 million tonnes per annum (Mtpa) at Nini West, it is plausible that the adjacent Nini Main reservoir could store roughly double that amount. Consequently, the Nini A Platform could support storage capacities ranging from 0.5 to 1.5 Mtpa. Preliminary business case analyses indicate that the associated storage costs are economically viable.

Last updates revealed that the pilot project's initial offshore CO₂ injection was successfully carried out during the winter of 2022/2023. A total of 4,000 tons of CO₂ was injected into the depleted Nini West oil field, showcasing the complete value chain across international borders. The operation spanned 90 days and involved seven CO₂ shipments to the Nini site ³⁸⁶.

Petersen et al. 2022³⁸⁷ revealed the full geological and caprock features of the site. This is in the Siri Canyon. The reservoirs of most Danish oil and gas fields consist of Cretaceous–Danian Chalk, mainly in the Danish Central Graben, except for this Siri Canyon. The Siri Canyon extends eastward from the Central Graben to the Stavanger Platform area, located in a geologically stable region with low seismic activity.

Formed during the Palaeocene, the canyon transported glauconitic sand to the Central Graben and was later filled with Palaeocene–Miocene marls, mudstones, and fine-grained glauconitic sandstones from turbidite flows ³⁸⁸. Sandstone bodies within the Palaeocene–Eocene Rogaland Group were deposited in deep-water mudstones. Post-depositional fluidization created complex sandstone geometries. The older sandstones are sealed by the Rogaland Group, while younger ones are capped by the Horda and Lark Formations, which together form a one-kilometre-thick seal³⁸⁹.

With respect to the caprock, the ISO27914, 2017³⁹⁰, is usually consulted. Normally, these are briefed in: (1) stratigraphy, lithology, thickness and lateral continuity of the primary seal, (2) mineralogy, organic matter content and composition, porosity and permeability of the primary seal, and (3) capillary entry pressure and seal capacity.

³⁸⁶ Source: SZABADOS, A.; POULSEN, S. R. *The CCS greensand project: CO₂ pilot injection and monitoring*. 2023.

³⁸⁷ Source: PETERSEN, Henrik I.; SPRINGER, Niels; WEIBEL, Rikke; SCHOVSBO, Niels H. *Sealing capability of the Eocene–Miocene Horda and Lark formations of the Nini West depleted oil field – implications for safe CO₂ storage in the North Sea*. 2023. International Journal of Greenhouse Gas Control 118 (103675). 2022.

³⁸⁸ Source: NIELSEN, Ole Bjørsløv; RASMUSSEN, Erik Skovbjerg; THYBERG, Brit Inger. *Distribution of Clay Minerals In the Northern North Sea Basin During the Paleogene and Neogene: A Result of Source-Area Geology and Sorting Processes*. 2022. <https://doi.org/10.2110/jsr.2015.40>

³⁸⁹ Source: SVENDSEN, Johan Byskov; HANSEN, Henrik Juhl; STÆRMOSE, Thomas; ENKILDE, Michael Kragh. *Sand remobilization and injection above an active salt diapir: the Tyr sand of the Nini Field, Eastern North Sea*. Basin Research 22(4). 2010.

³⁹⁰ ISO27914. *Carbon dioxide capture, transportation and geological storage – geological storage*. ISO 2017, 59 pp. 2017.

Risk factor	Risk factor value ranges		
	High risk	Moderate risk	Low risk
Caprock strength	Weak	Moderate	Strong
Caprock thickness	≤ 3 m	3- 30 m	≥ 30 m
Number of caprocks	None	One	Multiple
Caprock heterogeneity	Significant	Moderate	Low risk
Caprock permeability	$> 10^{-15} \text{ m}^2$	$10^{-18} - 10^{-15} \text{ m}^2$	$< 10^{-18} \text{ m}^2$
Caprock lateral extend/ storage zone thickness	< 25	25 - 100	>100
Caprock dip	$\geq 8^\circ$	$2^\circ - 8^\circ$	$\leq 2^\circ$

Table 20: Risk matrix for the project Greensand.³⁹¹

In September 2024, DNV, a leading independent energy expert, certified the first CO₂ storage site for Denmark's Project Greensand, achieving a significant milestone in carbon capture and storage (CCS) efforts.

2) Project Bifrost (Off-Shore)

The project Bifrost targets the Harald field in the North Sea, which comprises two developed gas reservoirs: the Harald West sandstone and the Harald East chalk. Bifrost aims to showcase the potential for repurposing existing wells for CO₂ injection and storage in the sandstone reservoir

Additionally, a key objective of Project Bifrost is to assess the viability of CO₂ storage in chalk reservoirs. Success in this area could significantly expand geological storage capacity in Danish waters, allowing other chalk fields within the DUC to be converted for CO₂ storage as their production phases out ³⁹².

Project Bifrost introduces an innovative CO₂ transport solution using ships instead of pipelines to deliver CO₂ to the Harald fields. In this approach, CO₂ is cooled to a cryogenic state (-30°C to -20°C) and transported offshore via liquid CO₂ tankers, each with a capacity of 12,000 m³. Three such tankers are needed to achieve the target injection rate of 3 million tonnes annually³⁹³ (Bifrost, 2024).

The CO₂ is transferred to a Floating Storage & Injection Unit (FSIU) with a 30,000 m³ capacity, connected to the Harald platform by a flexible pipeline and a combined power and optical fibre link. At the FSIU, the CO₂ is heated and pressurized, arriving at the platform at 0°C and up to 150 bars. High-pressure pumps on the platform then increase the pressure to 350 bars for injection into geological reservoirs (Figure 60).

³⁹¹ Source: BRUNO, Michael S.; LAO, Kang; DIESSL, Julia; CHILDERS, Bill; XIANG, Jing; WHITE, Nicky; VAN DER VEER, Ellen. *Development of Improved caprock Integrity Analysis and Risk Assessment Techniques*. Energy Procedia 63. Pp.4708-4744. 2014. <https://doi.org/10.1016/j.egypro.2014.11.503>

³⁹² Source: PREVOST, Mathieu; GENIN, Alexia; LADENBURG, Jacob; FROST, Jesper Kok; SOYTAS, Ugur; LANG, Rasmus; HEIN, Malene; VEST, Malene Rod; ANDERSEN, Simon Ivar; NICK, Hamidreza M. *Bifrost, an Innovative CO₂ Transportation and Storage Project in Denmark*. Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16). 2022.

³⁹³ Bifrost. *Project Bifrost Climate change mitigation by geological storage of CO₂ in depleted gas fields*. 2024.

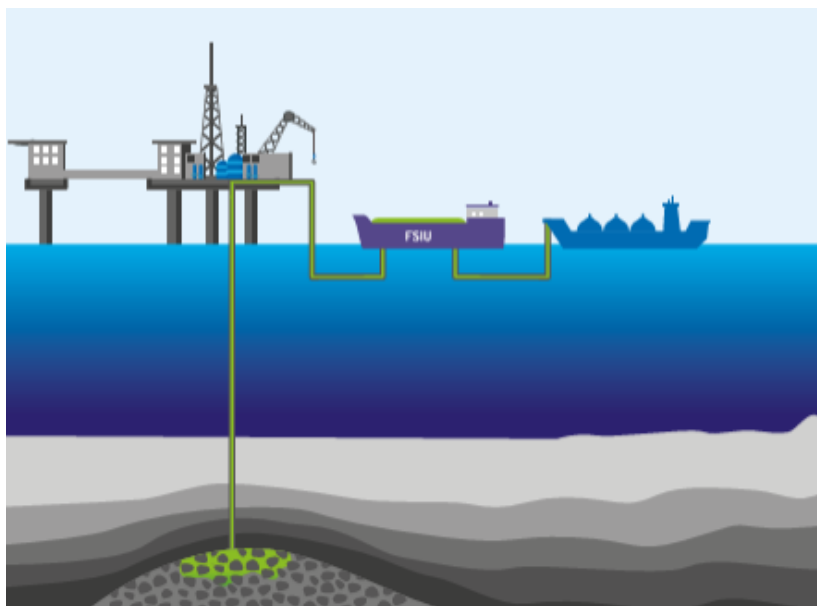


Figure 60: The conditions for using chalk formations as a CO₂ storage formation³⁹⁴.

3) Norne (ONSHORE)

Project Norne aims to establish a CO₂ transportation and storage network utilizing pipeline infrastructure and LCO₂ ships. This system will transport CO₂ from European emitters to onshore geological formations in Denmark for permanent storage. Initially, the project will involve Denmark, Sweden, Belgium, and the UK but can extend benefits to any country capable of exporting LCO₂ by ship.

The initial phase of Project Norne involves developing two distinct storage facilities: Project Fyrkat and Project Trelleborg. Project Fyrkat will feature a storage site at the Gassum Structure in Northern Jutland, supported by pipeline infrastructure and an LCO₂ reception facility at the Port of Aalborg. Project Trelleborg will include a storage site at the Havnsø Structure in Western Zealand, along with its pipeline infrastructure and an LCO₂ reception facility at the Port of Kalundborg. Both sites are geologic formations within the Gassum Formation.

The Havnsø Structure's proximity to the Stenlille Structure, where a pilot CCS project is underway, presents opportunities for shared transportation and storage infrastructure, as well as flexibility between sites to handle downtime or CO₂ surges.

On the one hand, the primary reservoir of the Havnsø formation is made up of siliciclastic sandstones from the Upper Triassic to Lower Jurassic Gassum Formation, with an expected net-sand thickness of around 100 meters. These sandstones extend laterally and are found across the Danish Basin³⁹⁵

On the other hand, The Gassum Formation is widely recognized for its high-quality reservoir properties. The Upper Triassic – Lower Jurassic Gassum Formation, found across Denmark, is utilized for geothermal energy extraction and natural gas storage, and is now being considered for Carbon Capture Storage (CCS). Its thickness ranges from 50 to 200 meters and is relatively consistent. The formation consists of 5 to 30 meters of alternating fluvial and shoreface sandstones with excellent reservoir

³⁹⁴ Source: BONTO, M.; WELCH, M.J.; LÜTHJE, M.; ANDERSEN, S.I.; VESHAREH, M.J.; AMOUR, F.; AFROUGH, A.; MOKHTARI, R.; HAJIABADI, M.R.; ALIZADEH, M.R.; LARSEN, C.N.; NICK, H.M. *Challenges and enablers for large-scale CO₂ storage in chalk formations*. Earth-Science Reviews 222(103826). 2021.

³⁹⁵ Source: BECH, Niels; LARSEN, Michael. *Storage of CO₂ in the Havnsø aquifer - a simulation study*. Geological Survey of Denmark and Greenland. Ministry of the Environment. 2005.

properties (15–35% porosity, permeability up to several Darcies), interspersed with marine and lagoonal muds on a meter scale³⁹⁶.

The infrastructure for the project Norne includes:

- LCO₂ reception facilities at Aalborg (4 Mtpa) and Kalundborg (4 Mtpa), planned expansion to 12 Mtpa by 2030, with potential expansion to 8 Mtpa at Aalborg based on negotiations.
- Horizontal storage bullets for intermediary CO₂ storage at reception sites.
- High-pressure compression equipment at reception sites and pipeline tie-ins for CO₂ entry.
- 80 km trunkline (508 mm) from Aalborg to Gassum Structure, with local emitter connections.
- 20 km trunkline (406 mm) from Kalundborg to Havnsø Structure, with local emitter connections

In brief, this project will be developed in Onshore – Saline Aquifers (Gassum & Havnsø Structures). Project Norne plans to provide a currently planned 12 Mtpa of LCO₂ reception capacity and 10 Mtpa transportation capacity per trunkline via to injection wells with an estimated 0.75 to 1 Mtpa injection rate per well, drilling new wells as necessary for scale.

4) ACCSION

Additionally, the Danish government has proposed a comprehensive national CCS strategy aimed at eliminating at least 3.2 million tonnes of CO₂ per year by 2030 through carbon capture and storage technologies³⁹⁷. The strategy includes the development of a large-scale, safe, and cost-effective CO₂ storage network, both onshore and offshore, supported by substantial public investment (approximately DKK 38 billion). This long-term plan reinforces Denmark's role as a European leader in CCS and provides a relevant model for other countries, including Lithuania, particularly in designing short and cost-efficient CCS value chains.

The ACCSION project, led by Air Liquide and Cementir Holding Group, aims to establish one of the first complete carbon capture and storage (CCS) value chains in Europe. The project will capture CO₂ emissions from the Aalborg Portland cement plant in Denmark, transport the CO₂ by ship to a permanent geological storage site, and is expected to reduce emissions by up to 1.5 million tonnes of CO₂ per year by 2029. Supported by the EU Innovation Fund, ACCSION serves as a scalable model for cost-effective, nearshore CCS solutions in Europe.

³⁹⁶ Source: WALTHER, Florian; SMIT, Harald; GREGERSEN, Ulrik; LORENTZEN, Mads; BREDESEN, Kenneth; PEDERSEN, Gunver; HOVIKOSKI, Jussi; VOSGERAU, Henrik. *Seismic Geomorphology of the Upper Triassic – Lower Jurassic Gassum Formation – Improved Reservoir Characterization in the Stenlille (Denmark) CCS Demonstration Site*. Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16). 2022.

³⁹⁷ Source: Danish Energy Agency. *CCS in Denmark: Status and Perspectives*. 2024. Available at: <https://ens.dk/media/4760/download>

UNITED KINGDOM AND IRELAND

UNITED KINGDOM

27 out of 37 exploration licenses for CO₂ storages in Europe are in the United Kingdom. Most of them, are in the North Sea. The British Geological Survey (GVS) created, following the methodology for evaluation of CO₂ storage found in Bachu et al.³⁹⁸, the following map, including sources and CO₂ reservoirs storages.

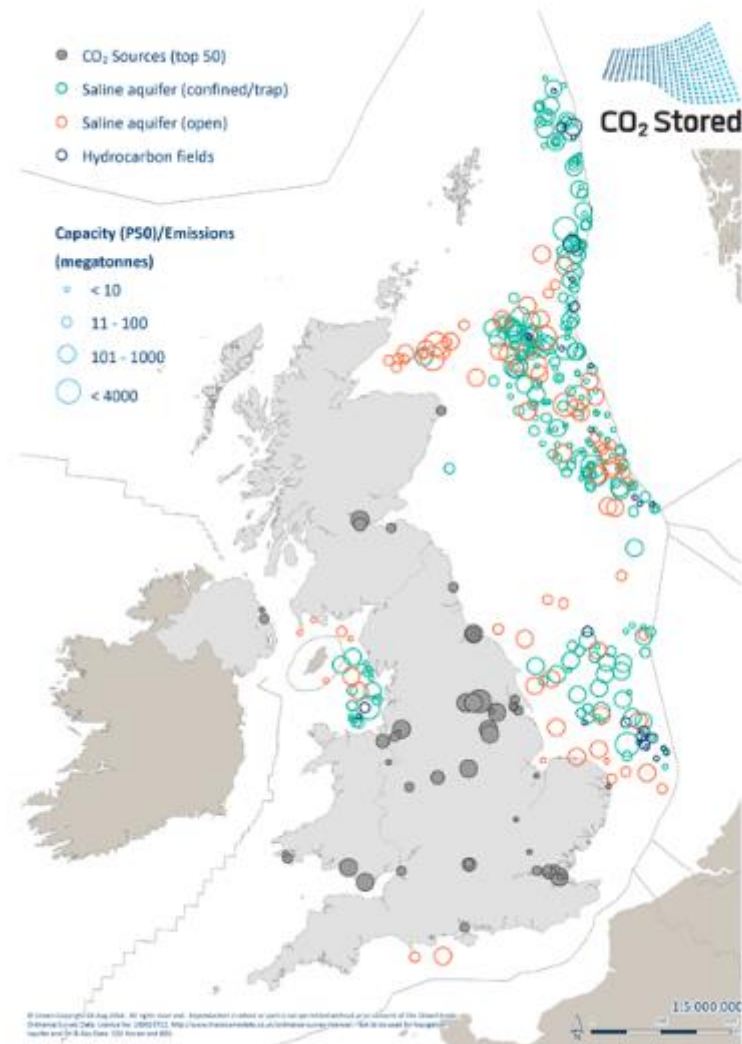


Figure 61: CO₂ storage capacity estimation. From CO₂ Stored © BGS/UKRI.

³⁹⁸ Source: BACHU, Stefan; BONIJOLY, Didier; BRADSHAW, John; BURRUSS, Robert; HOLLOWAY, Sam; CHRISTENSEN, Niels Peter; MATHIASSEN, Odd Magne. CO₂ storage capacity estimation: Methodology and gaps. International Journal of Greenhouse Gas Control 1(4), pp. 430-443. 2007.

Acorn Project

Acorn plans to utilize one of the UK's most well-characterized and advanced geological CO₂ storage sites, located over 100 kilometres off the northeast coast of Aberdeenshire and buried 2.5 kilometres beneath the North Sea seabed. Acorn is expected to store at least 5 million tonnes of CO₂ per year by 2030, and is designed to service multiple emitters around Scotland, the UK and Europe³⁹⁹.

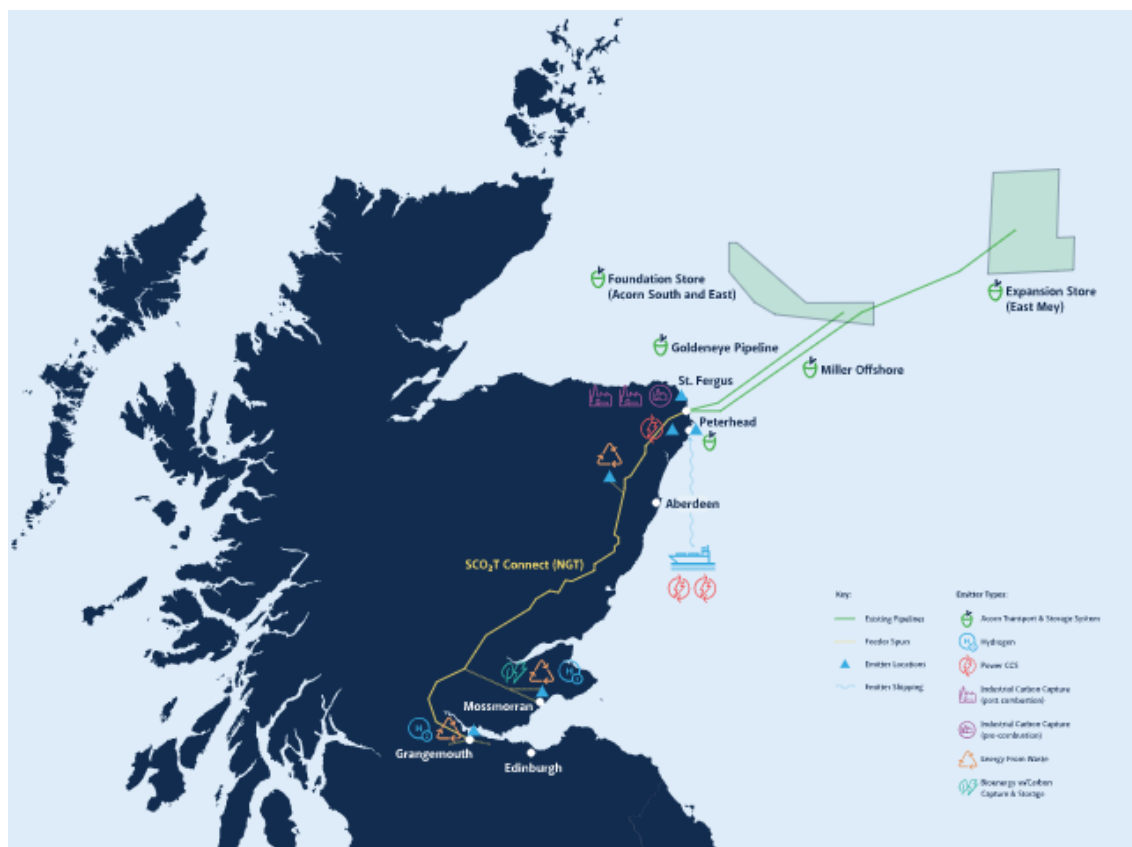


Figure 62: Scheme of the Acorn project⁴⁰⁰.

The geology of the formation can be found in Allen et al.⁴⁰¹; while the seal is described in AlNajdi et al.⁴⁰².

³⁹⁹ Source: ALCALDE, Juan; HEINEMANN, Niklas; MABON, Leslie; WORDEN, Richard H.; DE CONINCK, Heleen; ROBERTSON, Hazel; MAVER, Marko; GHANBARI, Saeed; SWENNENHUIS, Floris; MANN, Indira; WALKER, Tiana; GOMERSAL, Sam; BOND, Clare E.; ALLEN, Michael J.; HASZELDINE, R. Stuart; JAMES, Alan; MACKAY, Eric J.; BROWNSORT, Peter A.; FAULKNER, Daniel R.; MURPHY, Steve. *Acorn: Developing full-chain industrial carbon capture and storage in a resource- and infrastructure-rich hydrocarbon province*. Journal of Cleaner Production 1 October 2019, pp. 963-971. 2019.

⁴⁰⁰ Web reference from the Acorn Project. Accessed: May 2025. <https://www.theacornproject.uk/>

⁴⁰¹ Source: ALLEN, Michael J.; FAULKNER, Daniel R.; WORDEN, Richard H.; RICE-BIRCHALL, Elliot; KATIRTSIDIS, Nikolaos; UTLEY, James E.P. *Geomechanical and petrographic assessment of a CO₂ storage site: Application to the Acorn CO₂ Storage Site, offshore United Kingdom*. International Journal of Greenhouse Gas Control 94(102923). 2020.

⁴⁰² Source: ALNAJDI, N.A.; WORDEN, R.H.; UTLEY, James E.P. Compositional controls on the Lower Cretaceous Rodby Shale pore structure and surface area: a planned CCS top seal caprock for the Acorn storage site. International Journal of Greenhouse Gas Control 137(104219). 2024.

The storage site reservoir is the Captain Sandstone, part of the Lower Cretaceous Valhall Formation within the Cromerknoll Group, which is interbedded with shales ⁴⁰³. The Captain Sandstone regionally dips 1 to 2° to the southeast with a steep ramp of 20° at its northwestern extent. The Captain Sandstone consists of the Upper and Lower Captain separated by the Mid-Captain Sola Shale. It is primarily composed of thick-bedded, fine to medium-grained sandstones deposited by high-density turbidity currents. The unit's thickness reaches up to 143 m in the centre but thins to the north and south, with an average thickness of 54 m, while the Mid-Captain Sola Shale averages 15 m. Average permeability of the Captain Sandstone is about $2.1 \times 10^{-12} \text{ m}^2$.

The primary caprock sealing the reservoir is the Rodby Shale Formation, which is the focus of this study as the top seal for the Captain Sandstone CO₂ storage site. The Rodby Shale's lithology is primarily composed of marls and calcareous claystones, varying in colour from light and medium grey to pale and greyish red⁴⁰⁴. The shales have an average porosity of 13.75%, an average permeability of $2.2 \times 10^{-19} \text{ m}^2$.

Viking CCS

Viking CCS is in the other important CO₂ storage in the North Sea in UK seas. The project aims to store 11 MtCO₂/year by 2030 and over 12 MtCO₂/year by 2034, and has a total maximum storage capacity of over 300 MtCO₂ in the depleted Viking gas fields⁴⁰⁵. The site has been widely explored and main features can be found in Heinemann et al.⁴⁰⁶ and is mainly formed by the Bunter Sandstone.

The average thickness of the Bunter Sandstone is taken to be 140 m and an average depth of 1,500 m. Rock properties are uniform throughout the model: horizontal permeability is 250 mD, while vertical permeability is 25 mD based on a generic vertical to horizontal permeability ratio of 1:10; and porosity is 18%⁴⁰⁷.

The Bunter Sandstone seal is primarily formed by overlying lithologies, including the Röt Halite of the Dowsing Dolomitic Formation, which is typically 50–100 m thick in the central study area but absent or thinner towards the southern and southeastern margins. Halite is typically considered an excellent seal due to its near-zero permeability and its ability to self-seal if fractured. This seal is further enhanced by a thick layer of mudstones and evaporites from the Haisborough Group, both of which are effective sealing lithologies. The total seal thickness generally exceeds 200 m, reaching over 500 m in a north-south band through the centre of the basin.

⁴⁰³ Source: TUCKER, Owain; TINIOS, Lynsey. Experience in Developing the Goldeneye Storage Permit Application. *Energy Procedia* 114, pp. 7466-7479. 2017.

⁴⁰⁴ Source: CRITTENDEN, S.; COLE, J.; HARLOW, C. The early to middle Cretaceous lithostratigraphy of the central North Sea (UK sector). *Journal of Petroleum Geology* 14(4). 1991. <https://doi.org/10.1111/j.1747-5457.1991.tb01033.x>

⁴⁰⁵ Viking CCS 2023. *Harbour's Viking and Acorn CCS Projects Awarded Track 2 Status*. Press Release, <https://www.harbourenergy.com/news-and-media/latest-news/2023/harbour-s-viking-and-acorn-ccs-projects-awarded-track-2-status/>

⁴⁰⁶ Source: HEINEMANN, Niklas; WILKINSON, Mark; PICKUP, Gillian E.; HASZELDINE, R. Stuart; CUTLER, Nick A. CO₂ storage in the offshore UK Bunter Sandstone Formation. *International Journal of Greenhouse Gas Control* 6, pp. 210-219. 2012. <https://doi.org/10.1016/j.ijggc.2011.11.002>

⁴⁰⁷ Source: HOLLOWAY, Sam; VINCENT, Ceri J.; BENTHAM, Michelle S.; KIRK, Karen L. *Top-down and bottom-up estimates of CO₂ storage capacity in the United Kingdom sector of the southern North Sea basin*. *Environmental Geosciences* 13 (2), pp. 71-84. 2006. <https://doi.org/10.1306/eg.11080505015>

IRELAND

The research of Lewis et al.⁴⁰⁸ revealed the potential in Northern Ireland (and in Ireland). The main hubs were:

1. Moneypoint (Co. Clare) & Cork - Kinsale Head Gas Field, North Celtic Sea
2. Kilroot (Co. Antrim) - Closed structures in the Portpatrick Basin

The **Kinsale Head Gas Field (1)** has a quantified storage capacity of a 330 Mt. The Kinsale Head field's primary reservoirs are Early Cretaceous. The Agone Sandstone Member ('A' Sand) in the Selbourne Group is sealed by the Gault Formation claystone. Below it, the Bream Sandstone Member and upper Wealden Group ('B' Sand) reservoirs are separated from the Agone Sandstone by ~15m of claystone⁴⁰⁹. The trap mechanism of the Kinsale Head field is a simple structural trap that was formed in the Tertiary inversion. The features of the field are presented below.

	Kinsale Head		Corrib
	Agone Sandstone	Bream Sst / Wealden Grp	
Water depth (m)	90	90	350
Depth to top reservoir (m TVDss)	838	905	3,300
Depth to top reservoir (m bml)	748	815	2,950
Gas-water contact (m TVDss)	902	966	3,601
Area (km2)	109	109	15 (gas field)
Vertical structural closure (m)	91	91	560 (310 m gas)
Caprock lithology	Mudstone	Mudstone	Halite
Caprock thickness (m)	45	15	78 - 777
Gross sand thickness (m)	38	-	381+
Net-to-gross (%)	82	7 m sand	72
Average porosity (%)	20	22	8.5
Average permeability (mD)	420	280	15.2
Sw (%)	24.6	29.9	-
Formation water salinity (g/l)	-	92	326
Formation water density (g/cm ³)	.	1.06	1.24
Reservoir temperature (°C)	29.4	32.2	112
Initial reservoir pressure (MPa)	92 (1336.8 psia)	-	-40.7 (-5,900 psia)
Pressure gradient (kPa/m)	-10 (hydrostatic)	-	-11 (slight overpressure)
Gas composition	C ₁ > 99%		C ₁ 94% C ₂ 3% N ₂ 3%
Formation volume factor- Gas	101		272
Original gas-in-place (Bcm)	52.1 (1.84 Tcf)		34.0 (1.2 Tcf)
Recoverable gas (Bcm)	50.1 (1.77 Tcf)		24.6 (870 Bcf)
Carbon Storage Potential			
CO ₂ density at reservoir condition (kg/m ³)	720		740
Assumed discount factor	0.90		0.65
CO ₂ storage capacity (Mt = 10 ⁶ tonnes)	321		44

Table 21: Representative Properties for Kinsale Head and Corrib gas field⁴¹⁰.

⁴⁰⁸ Source: LEWIS, Deirdre; BENTHAM, Michelle; CLEARY, Tom; VERNON, Richard; O'NEILL, Nick; KIRK, Karen; CHADWICK, Andy; HILDITCH, David; MICHAEL, Karsten; ALLINSON, Guy; NEAL, Peter; HO, Minh. *Assessment of the potential for geological storage of carbon dioxide in Ireland and Northern Ireland*. Energy Procedia 1(1), pp. 2655-2662. 2009.

⁴⁰⁹ Source: SHANNON, Patrick M.; ENGLISH, Kara L.; HANRAHAN, Michael. *The Stratigraphic Nomenclature of the Irish Offshore Basins*. Department of Communication, Climate Action and Environment, PAD Special Publication 2/21. 2021.

⁴¹⁰ Source: ENGLISH, Joseph M.; ENGLISH, Kara L. *Carbon Capture and Storage Potential in Ireland — Returning Carbon Whence It Came*. First Break 40(5), pp.35-43. <https://doi.org/10.3997/1365-2397.fb2022035>

The **Portpatrick Basin (2)** has a demonstrated CO₂ storage capacity of 37 Mt in a selected area of the formation known as Sherwood Sandstones, but the full formation is esteemed to have another 630 Mt. Some researchers studied the potential of CO₂ storage of this formation⁴¹¹, revealing that the Sherwood Sandstone Group is a Permo-triassic aquifer of 300 m of thickness, mainly horizontal (1-2° dip) able for injection. The observed permeability of the aquifer was observed in 0.65-1.6 m/day in the shallow and 0.18 m in the deep, while a mathematical modelling revealed that permeability can reach 1.3-10 m/day in the shallow and 0.1-1.8 m/day in the deep. The caprock is the Mercia Mudstone Group (non-aquifer), from the Triassic, with 300 m thickness, overlying the Sherwood/aquifer formation with extremely poor observed permeabilities of 10⁻⁵ m/day, but crossed by a single fault.

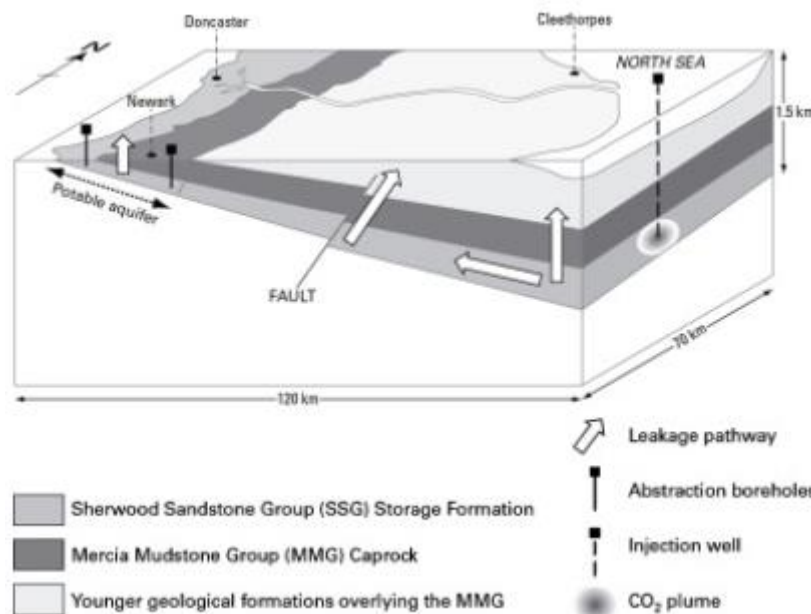


Figure 63: Schematic of the hydrogeological system present in the Portpatrick Basin. Extracted from Bricket et al., 2012.

NETHERLANDS

The Porthos project

There are three sites currently having storage permits. One is in Norway, which is the abovementioned Sleipner, the only current operational storage, but there are another 2 licenses of storage available, and these are the Porthos project in the Netherlands.

The Porthos initiative involves capturing CO₂ emissions from Rotterdam's industrial sector and storing them in depleted gas reservoirs beneath the North Sea. Construction has commenced near Rozenburg, including a 30-kilometer onshore pipeline and an additional 20 kilometres extending offshore. The project aims to begin operations in 2026 and to end by 2042. Porthos has a target of injecting 5 Mt CO₂ per year by 2030, but several scenarios including accelerated injection rates have been evaluated to reach 10; 14,5 and 19.5 Mt CO₂⁴¹².

⁴¹¹ Source: BRICKER, S.H.; BARKWITH, A.; MACDONALD, A.M.; HUGHES, A.G.; SMITH, M. *Effects of CO₂ injection on shallow groundwater resources: A hypothetical case study in the Sherwood Sandstone aquifer, UK*. International Journal of Greenhouse Gas Control 11, pp. 337-348. 2012. <https://doi.org/10.1016/j.ijggc.2012.09.001>

⁴¹² Source: WILDENBORG, Ton; LOEVE, Daniël; NEELE, Filip. *Large-scale CO₂ transport and storage infrastructure development and cost estimation in the Netherlands offshore*. International Journal of Greenhouse Gas Control 118 (103649). 2022. <https://doi.org/10.1016/j.ijggc.2022.103649>

The Porthos project consists of injecting CO₂ in three reservoir compartments in the P18-A field (P18-2, P18-4 and P18-6). It consists of an abandoned gas field in Triassic sandstones⁴¹³.

The geology is widely described in Arts et al.⁴¹⁴. The reservoir rocks of the P18-4 field are part of the Main Buntsandstein Subgroup, characterized by a cyclic sequence of (sub-)arkosic sandstones interbedded with clayey siltstones, with a total thickness of approximately 200 meters. The main sealing formations of the P18 fields consist of siltstones, claystones, evaporites, and dolostones from the Solling Claystone Member, the Röt Formation, the Muschelkalk Formation, and the Keuper Formation, which rest unconformably above the reservoir.

CROATIA

According to a report performed by Clear Air Task Force in 2023 project CO₂⁴¹⁵, the point source fossil CO₂ emissions in the country are attributed mainly to Energy (54% - 3.306 MtCO₂/year), cement & lime industry (28% - 1.715 MtCO₂/year), oil refineries (12% - 0.716 MtCO₂/year) and others (6% 0.324 MtCO₂/year). Nevertheless, Croatia has an estimated storage capacity of 4.2 GtCO₂, enough to store 693 years of Croatia's yearly point source emissions. There are 4 Gt of capacity in 6 saline aquifers, while the storage in depleted hydrocarbon fields is estimated into 175 Mt in 17 hydrocarbon fields.

In recent years, Croatia has made notable progress in advancing its carbon capture and storage (CCS) network. However, despite these efforts, there are currently no spatial plans specifically designated for CO₂ storage (except the EOR project, which is mainly focused on Enhanced Oil Recovery) at either the county or national level, even though some projects have been initiated. This process could be expedited by leveraging existing studies from hydrocarbon and geothermal projects as references and applying the insights gained from their development.

Projects in development:

A) Geothermal CCS project (Early development).

This is a project specifically designed for capture of CO₂ produced by cement plants. It aims to establish a robust CO₂ transport and storage system, featuring two wells, a CO₂ injection facility, and a geothermal power plant that supplies renewable electricity for the operation while also providing excess heat to the surrounding community.

The feasibility study has been approved in January 2023. It is in early development and the intention is to start in 2029.

In the initial stage, CO₂ will be sourced from the Našice cement plant's CO₂NTESSA project and a cement plant in Beremend, Hungary. The captured CO₂ will be stored at the Bockovci-1 site, where it will be injected into a structure within the Drava saline aquifer, which has a storage capacity of 26 million tonnes. Using a single injection well during this phase, the project has the potential to store 630,000 tonnes of CO₂ annually, totalling 15.77 million tonnes over a 25-year period.

B) Petrokemija Kutina (Advanced development)

⁴¹³ NORCE Norwegian Research Centre AS. *Porthos CCS Storage permit review. Final technical assessment and recommendations*. Technical Report. 2021.

⁴¹⁴ Source: ARTS, R.J.; VANDEWEIJER, V.P.; HOFSTEE, C.; PLUYMAEKERS, M.P.D.; LOEVE, D.; KOPP, A.; PLUG, W.J. *The feasibility of CO₂ storage in the depleted P18-4 gas field offshore the Netherlands (the ROAD project)*. International Journal of Greenhouse Gas Control 11 (Supplement), pp. 10-20. 2012. <https://doi.org/10.1016/j.ijggc.2012.09.010>

⁴¹⁵ Source: Clear Air Task Force. *Carbon Capture & Storage in Croatia*. 2023.

A pilot full-chain CCS project is underway at the Petrokemija ammonia production plant in Kutina (Croatia), where natural gas serves as the primary feedstock. The project involves capturing CO₂ and transporting it through the existing pipeline network for storage in two depleted oil and gas fields near Ivanić Grad, located 41 km east of Zagreb. The initiative aims to capture, transport, and inject 190,000 tonnes of CO₂ annually.

Following a thorough analysis of options to reduce CO₂ emissions from the Petrokemija plant, two nearby oil and gas reservoirs were identified as potential solutions, along with the ongoing Enhanced Oil Recovery (EOR) project in the Ivanić and Žutica oil fields, which are located slightly farther from the facility.

The project design basis includes the major facilities provided as follows:

- **CO₂ supply system:** The CO₂ supply system will be located at the Petrokemija ammonia production facility.
- **Transport System:** The transport system includes two segments of CO₂ pipeline. The first segment connects the ammonia production facility to an existing, unused natural gas pipeline (approximately 3 km). This pipeline runs from Kutina to the Ivanić Ethane facility near the Ivanić oil field. Both pipelines, having been inactive for some time, will need testing and potential refurbishment. Additionally, a new 3 km connecting pipeline will be constructed to link the facility at Petrokemija Kutina with the natural gas pipeline.
- **Injection System:** The injection system at the Ivanić oil field is already in place, requiring no additional work.
- **Monitoring System:** A monitoring system is operational, covering both the Ivanić oil field and the entire City of Ivanić-Grad.

Additionally, and related to this project, several oil and gas fields of varying sizes were discovered and brought into production in the Sava depression. Some of the smaller fields have already become economically unviable, leading to a halt in production. These fields are potential candidates for CO₂ storage, provided that the conditions in each field are suitable for CO₂ injection. As part of this project, two oil fields, Voloder and Mramor Brdo, were assessed as potential CO₂ storage sites due to their proximity to the petrochemical plant. These sites could be used as pilot locations for further research, and based on the findings, they may be put into operation. If conditions are favourable, these sites could even be expanded into demonstration or industrial-scale CO₂ storage facilities.

C) CCGeo: Closed Carbon Geothermal Energy (In development 2022-2026)

The CCGeo project seeks to generate near-zero carbon electricity and heat from gas dissolved in water extracted from geothermal wells ⁴¹⁶. To achieve this, the project develops a closed-loop geothermal power plant utilizing the process of Internalization of Carbon Compounds (ICC). By integrating this innovative technology into a geothermal plant, the project will establish the foundation for scaling up the efficient use of low-temperature geothermal resources and showcase the potential to nearly eliminate all greenhouse gas (GHG) emissions typically associated with conventional technologies.

D) CO₂ EOR Project

At present in Croatia, there is one CCUS project using CO₂ for enhanced oil recovery (EOR), which was developed by the oil and gas company INA and started operations in 2014. The CO₂ source is at the

⁴¹⁶ EU Innovation Fund. *CCGeo: Closed Carbon Geothermal Energy, Project Summary*. 2021. Available online: https://climate.ec.europa.eu/system/files/2022-07/if_pf_2021_ccgeo_en.pdf

natural gas processing plant (NGPP) Molve, serving the gas fields of Molve, Kalinovac, Stari Gradac, Gola, etc., in northern Croatia. The process chart of the CO₂ EOR project is shown in Figure 64. These natural gas fields in northern Croatia contain high volume fractions of CO₂: from 9% in Stari Gradec up to 23.8% in Molve and 53.6% in Gola. The wet sour gas is dehydrated and sweetened in the NGPP Molve. The CO₂ stream is compressed up to 30 bar and transported through an 88 km long and DN500 size pipeline to the compression and liquefaction unit CLU Etan, which is 14 km from the site of the EOR project (Ivanić Grad and Žutica-North). The pressure drop across the pipeline is less than 1 bar. At the CLU Etan, the CO₂ stream is compressed to 90 bar, liquefied, and finally pumped to 200 bar. The liquid CO₂ is distributed to water-alternating-gas (WAG) injection wells and pumped into the oil fields. The injection capacity is 600,000 standard cubic meters of CO₂ per day (Sm³/day), which is equivalent to 0.41 Mtpa.

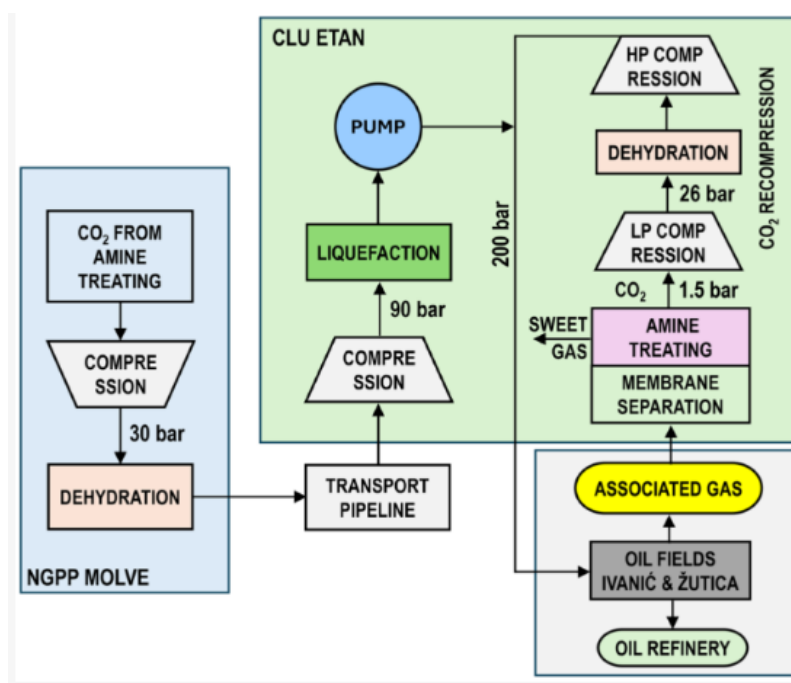


Figure 64: The CO₂ EOR project in northern Croatia. Extracted from Bleich et al.⁴¹⁷.

Thus, a gas treatment plant located in Molve Municipality, 640,000 m³/day of CO₂ are produced from the natural gas purification process. The CO₂ is compressed to 30 bar, dehydrated, and then transported via an 88 km long onshore pipeline to the Fractionation Facilities in Ivanić Grad. From there, the CO₂ is further compressed, liquefied, and transported at 200 bar for injection into the mature oil fields of Ivanić and Žutica for Enhanced Oil Recovery.

9.5. Recommendations for the development of national support measures

Experience from the OECD, the IEA, the IPCC, the European Commission, the Global CCS Institute and the World Bank on the development of carbon capture, utilization, transport and storage projects worldwide has allowed them to provide some recommendations for the successful implementation of this technology in other countries.

Some of the main recommendations are the following:

⁴¹⁷ Source: BLEICH, Paolo; WOLF, Igor; SENČIĆ, Tomislav; BONEFAČIĆ, Igor. *Current Status of Enhanced Oil Recovery Projects Using Carbon Dioxide (EOR CO₂) in Croatia*. Engineering Proceedings 61(1), 19. 2024. <https://doi.org/10.3390/engproc2024067019>

- It is essential to develop regulation which makes attractive investing in CCUS projects, and which clearly define the procedures to carry out these projects, the regulation which should be followed, liabilities of the project developer, geological formations where it is allowed to develop the projects.
- Currently, carbon storage is forbidden in Lithuania. For this reason, it is necessary to develop a new regulatory framework which includes detail on the methodology to measure and count captured, transported and stored carbon dioxide in order to enable CO₂ export for the purpose of permanent storage.
- Besides, the use of carbon capture, utilization and storage technologies could be promoted if the captured emissions can be offset with obligations in carbon emission reduction, and in the need for using carbon allowances in the European Trading System.
- Another relevant action to develop carbon capture, utilization and storage projects in Lithuania should be investing in mapping and evaluating storage resources, to reduce the risk of further private investments.
- It is necessary to develop transport infrastructure networks, such as pipelines and shipping routes, to connect capture sites and storage reservoirs.
- The correct integration of the new CO₂ infrastructure with existing energy systems is essential to make sure that systems do not interfere, and that synergies are fully identified and used.
- Regional CO₂ hubs and clusters can be developed, to share infrastructure costs and make sure that infrastructures are optimally used.
- Carbon capture, utilization and storage technologies should be considered in National Energy and Climate Plans (NECP) and other policies related to decarbonization and reducing the impact of climate change on Lithuania.
- Apart from having a favourable regulation, it is important to set clear, ambitious and realistic targets related to the CO₂ storage capacity, in the mid and long term. Targets are defined by the government, but they should be aligned with Lithuania's international commitments (for example, the Paris Agreement, or the NECPs), and also need to be discussed with experts and the industry, to make sure they are achievable. Based on past experiences, it is better to offer a slow growth path, with stable investments along the period, than sharp increases and stops in the yearly investments. Having a manageable and stable workload allows the development of local project developers and component manufacturers.
- International cooperation should be encouraged on the regulatory side, this is, collaborating with other governments to develop standards and regulation which are compatible, but also signing agreements to develop common infrastructures to invest in carbon storage. Besides, cooperation between private partners should be also promoted. Due to the large investments needed, it is very advisable that needed costs are shared by many partners.
- The administrative and permitting procedures need to be as easy as possible, and approvals should be obtained quickly. Delays and administrative burdens should be minimized. Normally, a waiting period for a resolution longer than 90 days is considered as excessive.

Similarly, the procedure should be transparent: project developers should be informed about the detailed path that has to be followed to obtain the total approval of the project, including each step, requirements, rules, and times. It is very advisable to offer updated information about the state of each request. The “one-stop-shop” approach is very advisable, what involves

that the management of licences and permits is centralized and depends on a sole administration.

- Lack of financing and funds can be a problem for CCUS project developers. Although making funds available is not responsibility for the policy makers, but for investment funds and banks, there are some actions which can be carried out:
 - Creation of national funds, like these which can be used to support renewable energy, with financing and co-financing.
 - Agreements with international funding organizations, such as development banks or the World Bank, to obtain financing for these projects.
- Citizens, organizations, NGOs support and acceptance of the technology is essential to make sure that projects can be developed in time. Even if a project obtains all required permits, if the local government, social organizations or inhabitants mostly reject the project, it will be very difficult to carry it out. For this reason, it is essential that the opinion of citizens and local stakeholders is considered. Besides, citizens usually express concerns about the safety of carbon capture and storage, their environmental impact, effects on water quality, possibility that the technology generates earthquakes, or even the perception that CCUS is a technology which will slow down the removal of fossil fuels.

To obtain the support by local citizens, some actions which can be developed are:

- Carry out awareness and information campaigns, using a clear and not-technical language, to make sure that citizens are well informed about the project. These campaigns should include information about the benefits, risks, and the economic rationale of the project.
 - Create a bi-directional communication channel: It is necessary not only to inform citizens and organizations, but also make sure that their worries are well received and addressed.
 - Make sure that a part of the economic benefits of the project are locally distributed. New taxes can be created to make sure that part of the benefit is shared with the community, or the project developer can support social, economic, or cultural activities, as well as the development of public infrastructures.
 - To engage early and continuously communities, local government, NGOs and inhabitants to make sure that the project is accepted.
- It is advisable to develop common designs and standards, if possible, at an international level. Having a common accepted technology allows that countries exchange equipment, and that equipment manufactured by different companies is compatible.
 - It is essential to have a highly skilled workforce in Lithuania, specialized in geology, industrial, mining or energy engineering, chemistry, physics, mathematics, modelling and other subjects, to offer highly specialized professionals to the companies which will invest in CCUS. Specialized training programs should be developed in universities, and academic partnerships with relevant education institutions along the world are needed.
 - Investing in research and development, as the number of existing CCUS projects is limited, and it lacks experience and knowledge along the world. Some actions which can be made are:

- To develop small-scale demonstration projects to evaluate the feasibility of CCUS technologies in local contexts.
- To collect information and data from these pilot projects, to refine technologies, and improve the public knowledge and awareness on the technology.
- To invest in advanced capture technologies, enhancing energy efficiency and scalability.
- To carry out investments in the improvement of the efficiency of the technology, to reduce energy intensity and costs.
- To put focus on emerging technologies, such as direct air capture, and combining bioenergy with CCUS, to reduce emissions.
- To make sure that lessons learnt, and knowledge is freely exchanged with other countries, to identify best practices and knowledge gaps.
- To offer incentives to R&D&I activities, such as tax deductions for investments, subsidies, accelerated depreciation of assets used in R&D&I.
- To create technological centres and hubs specialized in CCUS.
- To promote the participation of local specialists in international R&D&I projects, consortia, and associations.
- To develop calls for subsidies to carry out CCUS R&D activities.
- To promote the collaboration between the public and the private sectors. For example, the collaboration between universities, which have an important knowledge and R&D&I capabilities, and the industry, which knows better the real needs and priorities is very fruitful.
- To promote the development of cluster structures. Clusters are horizontal collaborative structures and networks which act on a specific industry, trying to join forces to make an industry succeed. A cluster can be made up by entrepreneurs, scientists, politicians, project developers, component manufacturers, academia, universities, certification, financing, insurance, logistics and consulting companies.

Clusters are focused on promoting the vertical cooperation among partners, developing all phases of the industry, sharing knowledge, carrying out R&D&I projects and training activities, identifying business opportunities, promoting collaborative business frameworks, standardization and requirements for process and equipment, internationalization and so on.

9.6. Recommendations for international partnerships in R&D&I

9.6.1. International partnerships in R&D&I based on the European Union

Considering that Lithuania makes part of the European Union, there is plenty of opportunities for the country to establish partnerships in R&D&I with other European countries, under the support of any of the EU programmes focused on R&D&I for low-carbon industrial technologies.

Although the European Commission budget is low compared to the combined national budgets of all European countries, the European R&D&I budget is very important compared to the total combined national public funding for R&D&I, and especially in competitive funding. Indeed, the European

Commission budget allocates around 8% of the funds to R&D&I, while the average investment in R&D&I stood at 2.24% in 2023⁴¹⁸.

The Multiannual Financial Framework 2021-2027⁴¹⁹ of the European Commission allocates a total amount of €₂₀₂₁ 93,720 million for the period 2021-2027 for research and innovation, from which, €₂₀₂₁ 86,123 million are invested in the Horizon Europe Programme. The rest is divided into the Euratom Research and Training Programme, with €₂₀₂₁ 1,981 million along this period, and €₂₀₂₁ 5,610 million for the International Thermonuclear Experimental Reactor (ITER).

Additionally, the programme InvestEU Fund, with €₂₀₂₁ 3,068 million, and the Innovation Fund, with around €40,000 million for the period from 2020 to 2030 are available for R&D&I investments. The European Fund for Strategic Investments (EFSI), through the European Regional Development Fund (ERDF) can be also used to support R&D&I and industrial investments.

The Multiannual Financial Framework 2028-2034⁴²⁰, which was proposed by the European Commission on July 16th, 2025, and is now being negotiated between the Parliament and the EU Member States, is expected to reach €₂₀₂₅ 1,763,056 million. From this amount, €₂₀₂₅ 450,508 million are allocated to the European Competitiveness Fund, focused on competitiveness, research and innovation.

The following is a description of the main R&D&I programmes which are centrally managed by the European Commission:

- **Horizon Europe**⁴²¹: The European Commission has developed different Framework Programmes for Research and Technological Development (FPs), since 1984. Until now, there have been 9 Framework Programmes. The last programmes have been the Horizon 2020 (Framework Programme 8), with a total budget of around €80 billion, and Horizon Europe (Framework Programme 9), whose budget is €95.5 billion. The Horizon 2020 programme lasted between 2014 and 2020, while the Horizon Europe programme will last from 2021 to 2027.

These programmes provide grants for research and innovation projects, using open and competitive calls for proposals. The European Commission regularly publishes the Work Programmes for the different Clusters, where the main topics where the European Commission is interested in focusing efforts are included. Most projects need to be carried out by a consortium of at least three different partners, in most cases from different European countries. Consortia can be made by any entity in the European Union, including research institutions, universities, but also public entities such as ministries and municipalities, and, more remarkably, private entities (SMEs and large companies).

⁴¹⁸ Source: Eurostat. GERD by sector of performance. Percentage of gross domestic product (GDP). Last update May 2nd, 2025.

⁴¹⁹ Source: European Commission. Multiannual Financial Framework. <https://www.europarl.europa.eu/factsheets/en/sheet/29/multiannual-financial-framework>

⁴²⁰ Source: European Commission. *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. A dynamic EU budget for the priorities of the future- The Multiannual Financial Framework 2028-2023*. July 16th, 2025. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52025DC0570>

⁴²¹ Source: European Commission. Horizon Europe.

In the Horizon Europe programme, the Pillar 2 Global Challenges and European Industrial Competitiveness includes clusters such as Health; Culture, Creativity and Inclusive Society, and Climate, Energy and Mobility. In particular, Horizon Europe Cluster 5 (Climate, Energy and Mobility) and Cluster 4 (Digital, Industry and Space), have promoted some relevant CCUS projects.

The grant is provided as a subsidy from the European Commission to cover the expenses incurred by the entities in the development of the project, including personal costs, other direct costs (equipment, travels, subcontracting), and over costs.

It can be mentioned that the Horizon 2020 programme supported almost 35,000 projects, which involved around 40,000 organizations. It also led to the publication of almost 4,000 patents and trademarks, and supported 33 Nobel Prize winners⁴²². From them, 1,522 projects were related to low-carbon technologies in energy-intensive industries. These projects received grants for €3.86 billion.

Since 2020, the total amount from Horizon Europe funds allocated to carbon removal projects has been €15 million⁴²³.

Inside the Horizon Europe programme, €10.1 billion have been allocated to the European Innovation Council (EIC). Its objective is to support game changing innovations, from the earlier research activities, to proof-of-concept, technology transfer, and financing and scale up for start-ups and SMEs. From this budget, €7 million will be spent in carbon removal projects.

In the Multiannual Financial Framework 2028-2034 of the European Commission, the Horizon Europe programme will continue having a relevant role to promote research and innovation. Specifically, a budget of €₂₀₂₅ 175,002 million have been allocated to this fund.

- **LIFE Climate Change Mitigation and Adaptation⁴²⁴:** The LIFE programme is a European funding instrument focused on the environment and climate action. It was created in 1992, and similarly to the Horizon Europe programme, there have been different funding periods: LIFE I (1992-1995), LIFE II (1996-1999), LIFE III (2000-2004, then extended to 2006), LIFE + (2007-2013), LIFE 2014-2020, and LIFE 2021-2027.

In the last programme, there are four sub-programmes, with a total budget of €5,430 million: Nature and biodiversity; Circular economy and quality of life; Climate change mitigation and adaptation, and Clean energy transition. Specifically, the LIFE Climate Change Mitigation and Adaptation sub-programme has a budget of €905 million. From this amount, €30 million are allocated to carbon removal projects.

⁴²² Source: European Commission. Report from the Commission to the European Parliament and the Council. Ex post evaluation of Horizon 2020, the EU framework programme for research and innovation. Brussels, January 29th, 2024.

⁴²³ Source: European Commission. *Public funding for permanent carbon removal in the EU*. January 28th, 2025. Brussels.

⁴²⁴ Source: European Commission. EU Action. EU funding for climate action. LIFE Climate Change Mitigation and Adaptation. https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/life-climate-change-mitigation-and-adaptation_en

- **Innovation Fund:** The Innovation Fund is one of the largest funding programmes of the world, focused on the development of net-zero and innovative technologies. It finances the EU climate policy, especially industry and energy. Funds come from the EU Emissions Trading System, with approximately 530 million ETS allowances.

The total available budget for the fund will, therefore, depend on the carbon allowance price. Considering an average price of €75/ton CO₂, the total available budget would be €40,000 million from 2020 to 2030. For the period 2028-2034, the Multiannual Financial Framework allocates a budget of €₂₀₂₅ 35,470 million to this fund.

The Innovation Fund supports projects focused on innovative low-carbon technologies and processes in energy-intensive industries, including products which can replace carbon-intensive ones, carbon capture and utilisation (CCU), construction and operation of carbon capture and storage (CCS) facilities, innovative renewable energy generation, and energy storage.

Projects asking for support should be highly innovative, but be mature enough to have a solid planning, business model and financial and legal structure. The objective of the Fund is to share the risk of the project between the project developer and the European Commission.

The Innovation Funds support projects which can be included in the European REPowerEU Plan, the Hydrogen Bank, the Green Deal Industrial Plan, or the Net-Zero Industry Act.

In some cases, the Innovation Fund supports projects with grants through calls for proposals (similarly to Horizon Europe grants), and in other cases, it is based on competitive bidding procedures (auctions). Auctions are an innovative market-based instrument, which are based on offers from the interested promoters, which offer goods or services. In the Innovation Fund, what is auctioned is the level of subsidy for a specific activity or product.

The projects which ask for the lowest public subsidy for a decarbonization product or activity, and fulfil with the rest of conditions of the bid, win the subsidy. After a review of the eligibility and quality of the bid, bids are ranked from lowest to highest, and support is provided in this order, until it is exhausted. Auctions have been successfully used for projects focused on the production of Renewable Fuels of Non-Biological Origin (RFNBO), particularly hydrogen.

By February 2024, the Innovation Fund had supported 26 industrial carbon management projects, with the European Hydrogen Bank, with grants totalling €3.3 billion. The total amount of the Innovation Fund which will be allocated to carbon dioxide removal projects is €656 million³⁶⁰.

It can be also mentioned that the European Commission allowed Lithuania and Austria to allocate State aids to support auctions for the production of renewable hydrogen of the European Hydrogen Bank. More specifically, the Republic of Lithuania has allocated €36 million of State aids, while Austria will offer €400 million to renewable hydrogen projects in these countries. It is estimated that the equivalent of 112,000 tonnes of hydrogen will be produced in Austria, and 13,000 tonnes of renewable hydrogen in Lithuania⁴²⁵.

⁴²⁵ Source: European Commission. Press corner. *Commission approves a €400 million Austrian State aid scheme, and a €36 million Lithuanian state aid scheme, to support renewable hydrogen production*. March 10th, 2025.

- **Modernisation Fund⁴²⁶:** The Modernisation Fund is focused on the modernisation of energy systems, and the improvement of energy efficiency in 13 lower-income EU Member States: Bulgaria, Czechia, Estonia, Greece, Croatia, Latvia, Lithuania, Hungary, Poland, Portugal, Romania, Slovenia and Slovakia.

It was created in 2018, and is operative during the period 2021-2030. It supports investment in 6 priority areas:

- Generation and use of energy from renewable energy sources, including renewable hydrogen.
- Heating and cooling from renewable sources.
- Reduction of the overall energy use through energy efficiency, including industry, transport, building, agriculture and waste.
- Energy storage and modernisation of energy networks, including demand-side management, district heating, grids for electricity transmission, and the increase of interconnections between Member States.
- Support for low-income households, including rural and remote areas, to address energy poverty, while heating systems are modernized, and infrastructure for zero-emission mobility is created.
- Just transition in carbon-dependent regions to support redeployment, reskilling and upskilling of workers, training, education, job-seeking initiatives and start-ups.

Funds for the Modernisation Fund come, similarly to the Innovation Fund, from the auctioning of EU ETS carbon allowances. The Fund is operated by each Member State, although the European Investment Bank (EIB) and the European Commission confirm that projects are eligible and classify them according to their priority.

Nationally, each European country receives the European Structural and Investment funds (ESIF), which are managed jointly by each country and the European Commission. The use of the funds and the project selection is carried out by the Member States. ESIF support projects in five areas: research & innovation, digital technologies; supporting the low-carbon economy; sustainable management of natural resources and small businesses.

One of the main ESIF funds is the European Regional Development Fund (ERDF). These funds support the territorial cohesion in the European Union, by investing in the less developed European countries and regions. Each Member State selects the projects which receive funding, and the priority areas.

Lithuania is using the ERDF funds to support several research and innovation initiatives, not only on the sustainable energy field, but in other fields. For example, it is possible to mention the R&D Implementation Scheme (SMART), or the Information Technologies for the Development of Science and Knowledge Society (Impact-driven programme).

As a summary, the following table offers a view of the main funding programmes focused on R&D&I, along with the amounts which are allocated to carbon removal projects:

⁴²⁶ Source: European Commission. EU Action. EU funding for climate action. Modernisation Fund. https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/modernisation-fund_en

Funding programme	Total amount (€ million)	Amount allocated to carbon removal projects (€ million)
Horizon Europe	95,500	15
from which:		
European Innovation Council	10,100	7
LIFE programme	5,430	30
Innovation fund	40,000	656
Total	140,930	701

Table 22: Summary of the main funding programmes focused on R&D&I

9.6.2. International partnerships in R&D&I based on collaborations between the European Union and third countries.

The initiatives described before are developed by the European Commission, and they are intended for projects developed by European entities, in European countries (although they are specific projects which involve third countries).

However, there are also R&D&I programmes which are developed by the European Union with third countries.

- **Breakthrough Energy Catalyst partnership (EU BEC partnership)⁴²⁷:** The EU-Catalyst partnership was launched on November 3rd, 2021, and involves the Horizon Europe and the Innovation Fund, from the European Commission, and the Bill Gates Foundation Catalyst. Bill Gates is the founder of Breakthrough Energy, and during the Glasgow COP26, agreed with the European Commission and the European Investment Bank to mobilize funding in emerging climate technology projects located in the EU-27. The total funds which are made available are up to €840 million, between 2023 and 2027.

Projects asking for support should have high potential for impact, and a cost-down trajectory. Focus technologies are:

- Clean Hydrogen (Delegated Act Compliant), to decarbonize industry and transport.
- Long Duration Energy Storage, to provide cleaner and more reliable power along with heat.
- Sustainable Aviation Fuel to power aviation.
- Direct Air Capture to remove CO₂ from the atmosphere.
- Industrial decarbonization of cement, steel, plastics, textiles and fertilizers.

There are two different types of projects which can receive support:

- **Demonstration Projects:** Small projects in an early development stage (TRL 5-7), with budgets between €30 million and €100 million.

⁴²⁷ Source: EU- Breakthrough Energy Catalyst Partnership. Accelerating the Deployment of Emerging Climate Technologies in the EU. <https://www.breakthroughenergy.org/our-work/catalyst/eu-catalyst-partnership/>

- Large First-Of-A-Kind (FOAK) Projects: Projects focused on emerging climate technology scale-up & market creation, with a TRL higher than 6, and a budget between €100 million and €1,000 million.

Other important initiatives for collaborations in R&D&I, and to obtain funds for research projects are the following:

- **World Bank:** The World Bank is an international financial institution, made by 189 countries, and provides loans and grants to the governments of low- and middle-income countries. Loans can be used to reduce poverty and inequality, or to protect the environment.

The institution offers loans at reduced rates or zero rate to member countries, as well as grants to the low-income countries. Their objectives include the human development (education, health), public administration, agriculture and rural development (for example, irrigation and rural services), environmental protection (for example, to reduce pollution), infrastructure (construction of roads, power plants), large industrial projects, development of the private and public sector, or to improve the governance of countries.

These projects are funded by funds provided by countries, other multilateral institutions, commercial banks, credit institutions based on exports, or private investors.

The Public-Private Partnership Resource Center (PPPRC), formerly known as the Public-Private Partnership Legal Resource Center (PPPLRC) and the Public-Private Partnership in Infrastructure Resource Center for Contracts, Laws and Regulations (PPPIRC), is specialized on providing legal resources and guidance on public private partnerships, especially on innovative and emerging topics, particularly on sustainability.

There is a public private partnership focused on carbon capture and storage (CCS). This partnership has carried out some research on the topic of carbon capture and storage, for example, the assessment “Carbon Capture and Storage in Developing Countries: A Perspective on Barriers to Deployment”⁴²⁸.

- **European Bank for Reconstruction and Development:** The European Bank for Reconstruction and Development (EBRD) is another international financial institution, founded in 1991, and with headquarters in London. The bank is owned by 75 countries, along with the European Commission and the European Investment Bank.

The objective of the EBRD is to promote transition to open, market-based economies, and is focused on socially and environmentally sustainable projects. The activity of the bank is to promote the development of more than 30 countries, in central Europe, central Asia, the southern and the eastern mediterranean.

In the fourth quarter of 2024, the bank had €42.1 billion of operating assets, and €25.3 billion available capital. By December 2024, it had €25.7 billion investment in energy efficiency, climate change and sustainable resource finance.

⁴²⁸ Source: KULICHENKO, Natalia; EREIRA, Eleanor Ereira. 2012. *Carbon Capture and Storage in Developing Countries: A Perspective on Barriers to Deployment*. Washington, D.C.: World Bank. DOI: 10.1596/978-0-8213-9609-4. ISBN (paper): 978-0-8213-9609-4, ISBN (electronic): : 978-0-8213-9610-0.

From 2006, the Bank has developed the Green Economy Transition (GET), whose objectives are to advance the transition to an environmentally sustainable, low-carbon and climate-resilient economy, and to prevent economies from being locked into carbon-intensive, climate-vulnerable and/or environmentally damaging pathways.

Among the projects which are funded by the EBRD, some of them are included in the category climate change mitigation, or reduction of greenhouse gas emissions. These projects include those which reduce the GHG emissions into the atmosphere, such as renewable energy, energy efficiency, or lower-carbon and efficient energy generation, and projects related to carbon capture, sequestration and storage.

However, the Bank does not fund carbon capture and utilization for enhanced oil recovery, as it is considered as part of the activities in the upstream fossil-fuel industry, which is not supported by the Bank. Carbon capture of emissions is also eligible for funding if the CO₂ is permanently stored, or used replacing raw materials, and demonstrating a substantial reduction in relative GHG emissions, or carbon intensity. Single use of captured CO₂, without further conversion is not eligible⁴²⁹.

- **European Investment Bank:** The European Investment Bank (EIB) is the European Union's investment bank. It is the largest multinational financial institution in the world, and is owned by the 27 member states of the European Union. It was established in 1958 by the Treaty of Rome, and is headquartered in Luxembourg.

The European Investment Bank funds projects which support the European Union priority objectives, particularly climate change, infrastructure, energy, SMEs, innovation, regional development, and so on. Although its activity is focused on the European Union countries, particularly the less developed regions, it is active in 140 countries around the world.

One of the main focuses of the European Investment Bank is on environmental projects, including these aimed at reducing the impact of climate change, and just transition. The Bank foresees to invest 1 trillion euros in these projects from 2020 to 2030, and since the end of 2021, it has not provided any financing to fossil fuel projects.

The Bank is also supporting carbon capture, storage and use projects. For example, in April 2025, the Bank granted a loan of €260 million to Stockholm Exergi to build the first large-scale bioenergy plant with carbon capture and storage (BECCS) in Värtaverket, Sweden. This plant is expected to be able to capture up to 800,000 tonnes of carbon dioxide per year, equivalent to the total yearly emissions from the road traffic in Stockholm⁴³⁰. After its capture, the carbon dioxide will be temporarily stored, and then it will be transported to Norway by boat. There, it will be stored in the bedrock under the North Sea.

- **Asian Development Bank (ADB):** The Asian Development Bank, headquartered in Metro Manila, Philippines, is the regional development bank for Asia. It was created on December 19th, 1966, and

⁴²⁹ Source: European Bank for Reconstruction and Development. *1731: Annexes to Implementing the Green Economy Transition – Technical Guide*. March 2024.

⁴³⁰ Source: European Investment Bank. *Sweden: EIB finances ground-breaking carbon capture plant in Stockholm*. April 4th, 2025.

has as members the members of the UN Economic and Social Commission for Asia and the Far East, and non-regional developed countries. Currently, it has 69 members, from which, 50 are from Asia and the Far East.

Its objective is to reduce the poverty in Asia and the Pacific, promoting the inclusive economic growth, environmentally sustainable growth and regional integration. It offers support as loans, grants and knowledge sharing in the following topics: Agriculture and Food Security, Climate Change, Digital Technology, Education, Energy, Environment, Finance Sector, Gender Equality, Governance, Health, Transport, Social Development, Urban Development and Water.

By the end of 2024, the Bank committed US\$24.3 billion from its own resources, along with US\$14.9 billion in cofinancing in collaboration with its partners⁴³¹.

In particular, the Asian Development Bank created, as part of the Clean Energy Financing Partnership Facility, the Carbon Capture and Storage Fund. This fund was led by Australia since its creation in July 2009, and this country was the only member until the United Kingdom joined in December 2012.

The fund offers financing to all ADB developing member countries, although initial priority was given to China, India, Indonesia and Viet Nam.

It funds the following projects:

- Capacity development to accelerate the physical deployment of carbon capture and storage demonstration projects.
- Geological investigations and environmental studies related to potential carbon dioxide storage sites.
- Undertaking community awareness and support programmes.
- **Norway-EU Agreement:** Norway is among the countries which have made largest efforts in research on the carbon capture and storage. The European Union and Norway have formed a Green Alliance to collaborate in clean energy, industrial transition and joint climate action, as well as environmental protection efforts. This alliance will be useful to ensure that the Paris Agreement is successfully implemented. Among the priority areas, it is foreseen to collaborate on climate adaptation, carbon pricing, carbon removals, and carbon capture, transport, utilisation and storage.

Apart from the European Union, some European countries have signed individual agreements with Norway. For example, in 2021, Norway and the Netherlands signed an agreement to collaborate in energy topics in the North Sea, including carbon capture and storage. In 2022, a new agreement was signed between Norway and Belgium, and in 2023, Denmark and Norway signed it.

In 2022 and 2023, Denmark, Belgium and the Netherlands signed arrangements for the transport and storage of captured carbon across borders. In April 2024, Denmark, Belgium, the Netherlands and Sweden established an arrangement for cross-border transport of CO₂ with Norway.

⁴³¹ Source: Asian Development Bank. Main Report 2024.

- **Global standards:** It can be also mentioned that Lithuania, as part of the European Union and the OECD, can actively participate in different associations and partnerships to expand the knowledge transfer and sharing on carbon capture, utilisation, transport and storage.

An example of this can be the Society of Petroleum Engineers (SPE), an international association made by specialists in the oil and natural gas sectors, with an international aim. As part of its activities, the SPE has developed the CO₂ Storage Resources Management System (SRMS), a document which establishes internationally accepted capacity and resources evaluation standards to quantify the storable CO₂ in different deposits.

- **Global CCS Institute:** The Global CCS Institute is an international think tank, with the mission of accelerating the deployment of carbon capture and storage (CCS), as quickly and cost effectively as possible.

The institute is made up by specialists of countries along the world, and its members include governments, global corporations, private companies, research bodies and non-governmental organizations. It has headquarters in Melbourne (Australia), and offices in Abu Dhabi, Beijing, Brussels, London, Tokyo and Washington DC.

It offers global and complete data and information on all aspects of carbon capture and storage.

9.6.3. General recommendations for international partnerships in R&D&I

To take benefit of these opportunities for establishing international collaborations for R&D&I, and to make sure that all the parties which make the investment in the actions are fairly benefitted from them, there are some recommendations that can be done, to define the kind of projects where the focus will be put⁴³²:

- Select the most relevant technologies or capacities which should be developed.
- Define and use clear standards.
- Create fair and equitable partnerships, considering a fair share of funding, work, task, responsibilities, and sharing of benefits.
- Use structures, processes and relationships which have shown to be successful in other projects and initiatives.
- Create flexible approaches to deal with project changes and budgets.
- Administer programmes efficiently in time: the project selection should not take long, funds should be disbursed quickly, reporting should be easy and clear.
- Ensure that quality assurance mechanisms are applied in the grant management, and to control project results and activities.
- Focus on the creation of new capacities for institutions and professionals.

⁴³² Based on O’SULLIVAN, Fionn; LÓPEZ GÓMEZ, Fabiola; MARCET PUIG, Anna; SHELLEY, Josh. *What works in international R&I collaboration? An evidence review. Research Paper Number 2024/004*. Department for Science, Innovation and Technology. April 2023.

- Make sure that the project results are effectively communicated, and are available for the target audiences.
- Create opportunities for the collaboration between professionals, including mentoring, alumni communities and secondments.
- Offer opportunities for learning-by-doing through joint design of research, implementation of field research and joint opportunities for presenting results.
- Make sure that the research objectives are aligned with industrial and social needs.
- Involve stakeholders in the definition of the research objectives, and engage them during the research process.
- Present research outputs to the specific audience.
- Make all research results publicly available, by using open access journals and open repositories.
- Be swift to promote research in subjects which become specially interesting.
- Make sure that the programmes encourage gender balance, while the most qualified professionals are benefitted.

9.6.4. Carbon Capture, Utilisation, Transport and Storage

High quality research, innovation, and demonstration ecosystems are important for Lithuania to accelerate in their efforts to decarbonise their industrial sector. Carbon capture technologies remain capital-intensive and complex, hence, active participation in international R&D&I partnerships are a good pathway to bridge the gap on Lithuania's expertise and technology readiness.

Horizon

Several R&D&I programmes funded under Horizon 2020 provide tested models for accelerating carbon capture technologies across the value chain. These include not only technology pilots but also knowledge-sharing platforms, professional networks, and policy advisory structures – all of which are relevant for early-stage development of CCUS in Lithuania.

Projects such as H2020 IMPACTS9 focused on aligning stakeholders across Europe to implement the SET Plan for CCUS and sharing knowledge between members on the deployment of these technologies. These initiatives facilitated technical development and integration of societal, regulatory and policy perspectives.

Similarly, H2020 STRATEGY CCUS highlighted the importance of tailoring scenarios to regional and national contexts and assessing the lifecycle emissions such that the positive impact of the technologies can be shared with the stakeholders.

Horizon 2020 projects have employed standardised KPIs such as LCOE, cost of CO₂ avoided, capture rates, and TRLs to benchmark progress. For Lithuania, engaging in similar frameworks would enhance clearer tracking of technology performance and integration potential.

Innovation Fund

The European Innovation Fund has emerged as a major driver for scaling CCUS technologies, with several large-scale projects underway. While none of the currently funded CCS projects are in the Baltic region, the funding mechanisms and partnership models (e.g. CO2LLECTInnovation, INNOZHERO) offer clear templates for engagement. Many of these projects are also industry centric, hence very relevant and applicable to the current situation in Lithuania.

Projects that blend hydrogen production with carbon capture – such as Sustainable Hydrogen and Recovery of Carbon (SHARC) – also hold relevance for Lithuania, especially if national strategies begin to emphasise low-carbon hydrogen or bioenergy-CCS pathways. As these projects mature, future cross-border initiatives in transport or storage infrastructure could become more accessible.

SET Plan (Strategic Energy Technology Plan)

The SET Plan provides long-term policy direction and international commitment structures that Lithuania should continue to monitor and align with. Action 9 of the SET Plan outlines key targets for CCUS development by 2030, including cost reduction, scale-up of demonstration activities, and integration into industrial clusters.

LIFE Programme

The LIFE Programme is one of the financial instruments of the European Union dedicated to environmental and climate projects, including those entered on carbon capture. Lithuania is already participating on the LIFE Programme with 2 active projects LIFE IP EnerLIT and LIFE SIP Vanduo, but has not yet launched specific carbon capture projects under this programme.

This programme offers an opportunity to fund R&D projects focussed on the development of CCS technologies that facilitate the shift to a low carbon energy system in Lithuania, aligning with the LIFE Programme's objectives for climate change mitigation, and supporting the establishment of a national carbon capture platform that provides a collaborative framework for stakeholders to advance CCS solutions.

9.7. Recommendations for international partnerships in project development

The development of integrated carbon capture, transport and storage chains requires large quantities of capital, expertise, and enough CO₂ emissions to benefit from economies of scale. As such, international partnerships between neighboring countries can allow these projects to be feasible by sharing common infrastructure and expanding the network of available CO₂ sources and storage sites.

In Lithuania, this vision is realized through the participation of national companies in the CCS Baltic Consortium project. This project is extensively described in chapter 9.2.

Currently Lithuania participates in Nordic-Baltic CCUS dialogue on the Networking Group on CCUS hosted by the Nordic Committee of Senior Officials for Energy Policies, aimed at sharing knowledge, aligning strategies, and advising collective action on CCUS matters.

An example of international cooperation for CCS are the agreements signed in April 2024 by Denmark, Norway, Sweden, Belgium, and the Netherlands, where each signed Memorandums of Understanding (MoUs) with Norway to enable cross-border CO₂ transport and geological storage in Norwegian subsurface reservoirs. These agreements follow the first agreement on energy cooperation around the North Sea, including carbon and storage, signed by Norway and the Netherlands in 2021. A similar agreement was signed in 2022 between Norway and Belgium, and in 2023 another agreement by Norway and Denmark, and a joint declaration with Sweden in 2022. In 2022 and 2023, Denmark, Belgium (the Federal State, as well as the regions of Flanders and Wallonia), and the Netherlands signed agreements to transport and store carbon dioxide across borders.

There are, currently, parallel agreements for the cross-border carbon transport between Denmark, Belgium, the Netherlands and Sweden each with Norway, and between Sweden and Denmark. These agreements are expected to contribute to the creation of an open carbon capture and storage market in the North Sea, using geological structures in Norway and Sweden.

Reaching a similar agreement between Lithuania and Norway could strengthen institutional and policy alignment for CCUS in Lithuania, aligning with the complex regulatory frameworks of Nordic states. Fostering cooperation within mechanism like the Nordic-Baltic Eight to build policy cohesion across environmental and energy frameworks.

Latvia and Estonia are the primary candidates for the joint development of shared infrastructure for offshore storage sites as the Baltic Sea region offers significant geological storage potential, the Cambrian Deimena Regional stage sandstones in the E6 structure, located in Latvia approximately 80 km from the Port of Klaipėda has an estimated storage capacity of about 365 Mt of CO₂. Additionally, Latvia hosts several onshore geological formations with substantial storage potential in the Dobeļe Structure, located in southwestern Latvia, with an estimated storage capacity of 150 Mt of CO₂ and the Blidene and North-Blidene Structures, situated in the same region, which collectively offer a combined storage capacity of approximately 252.6 Mt of CO₂. However as of the 2030s, only offshore geological sequestration is considered to be feasible. Onshore sequestration still needs some additional research and analysis, and for this reason it will become viable only in the longer term, this is, 2040-2050.

There is a number of advantages which can be found in cooperating with other countries in the development of international partnerships for shared carbon transport and storage infrastructures:

- Shared use of infrastructure, such as pipelines, compressors, or so on. For example, onshore pipelines could transport carbon dioxide along Estonia, Lithuania and Latvia, and put all the gas

in a common port, where it would be compressed and transported in a sole pipeline to the geological storage.

- Geological storage structures are located in international or shared national waters. For this reason, agreements need to be reached between different countries to make a common use of these structures.
- The combination of the produced carbon dioxide volumes by several countries can make huge investment in carbon capture and storage be more profitable, due to economies of scale: installing a pipeline with a higher transport capacity is cheaper than installing parallel smaller pipelines, for example.

Some recommendations which can be made to develop such cooperations include:

1. It is necessary to develop standardized measurement, reporting and verification of emissions methodologies for carbon capture, sequestration and storage. This will make carbon amounts transported and stored by all countries transparent and comparable.
2. The signature of memoranda of understanding or collaboration agreements is the first step to start collaborating in the development of such projects.
3. All participating countries should have developed robust and comparable national regulations on carbon capture and storage, aligning with international standards.
4. Platforms to exchange common knowledge, technical expertise, research findings and lessons learnt are essential to make sure that research and development efforts are focused on the most interesting topics, and that parallel research is not carried out on the same topics. This can be achieved with international conferences, workshops, and online repositories.
5. Investing countries can develop training programmes for engineers, scientists and policymakers, to build the workforce needed to develop and operate carbon capture and storage technologies.
6. Financial efforts can be shared by countries to take profit of economies of scale.

Regarding financing, the European Commission has created the Connecting Europe Facility, or CEF. It is a funding instrument which supports the development of high performing, sustainable and efficiently interconnected trans-European networks in the fields of transport, energy and digital services.

CEF supports large international projects which are considered strategic, offering financial instruments such as guarantees and project bonds. These projects leverage their use of EU budget, and are also considered as movers for further funding from the private sector and other public sectors⁴³³. CEF supports energy, transport and digital projects.

Among them, CEF Energy is investing in connecting the energy infrastructure of EU countries, and creating a connected, modern, secure and smart energy network. In this programme, priority corridors and thematic areas are selected, and some projects are selected as Projects of Common Interest (PCIs). The total budget for the period 2021-2027 in the CEF Energy programme amounts to €5.84 billion. Until now, CEF Energy has funded 149 actions, in 107 PCIs, with a total financial support of €4.7 billion.

⁴³³ Source: European Commission- European Climate, Infrastructure and Environment Executive Agency. About the Connecting Europe Facility. https://cinea.ec.europa.eu/programmes/connecting-europe-facility/about-connecting-europe-facility_en#cef-energy

10. Regulation of CCUS and other innovative technologies

10.1. Regulatory framework for CCUS in international law: General provisions

CCS is recognized as a crucial technology for mitigating the effects of climate change by reducing atmospheric emissions of CO₂. Over the past two decades, various international legal and policy frameworks have emerged to govern aspects of CCS, reflecting a growing consensus on its importance while highlighting the need for robust regulations to ensure environmental integrity and public safety.

Despite the absence of a singular, comprehensive international treaty dedicated exclusively to CCS, multiple international agreements, protocols, and conventions address CCS in some form. These range from broader climate change treaties under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC) to specialized frameworks related to marine protection, environmental impact assessment, and the law of the sea. This section examines the general provisions relevant to CCS regulation as outlined in the attached document, focusing on the principal treaties, amendments, and guidelines that shape the international regulatory landscape.

1. CCS Under the United Nations Framework Convention on Climate Change and Related Agreements

The United Nations Framework Convention on Climate Change (UNFCCC)⁴³⁴ was adopted in 1992 as a framework for international cooperation on climate change, seeking to stabilize greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.⁴³⁵ While the text of the UNFCCC does not explicitly mention CCS, it establishes the foundation for subsequent decisions and mechanisms under which CCS is recognized. By encouraging Parties to adopt policies that reduce GHG emissions, the UNFCCC provides a high-level legal basis for the development and deployment of CCS as part of national mitigation strategies.

Adopted in 1997, the Kyoto Protocol^{436, 437, 438, 439, 440, 441}

⁴³⁴ Lithuania ratified the agreement on March 24th, 1995.

⁴³⁵ Source: The United Nations. United Nations Framework Convention on Climate Change (UNFCCC), Art. 2. Objective. https://unfccc.int/sites/default/files/convention_text_with_annexes_english_for_posting.pdf

⁴³⁶ Source: The United Nations Framework Convention on Climate Change (UNFCCC). *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. (1997) <https://unfccc.int/documents/2409>.

⁴³⁷ Lithuania ratified the agreement on January 3rd, 2003.

⁴³⁸ Source: The United Nations Framework Convention on Climate Change (UNFCCC). *Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities*. Proposal by the President. Durban Climate Change Conference. Publication date December 8th, 2011. UNFCCC. Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol. <https://unfccc.int/documents/7064>

⁴³⁹ Source: The United Nations Framework Convention on Climate Change (UNFCCC). *Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities*. Proposal by the President. Publication date December 8th, 2011. Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol. <https://unfccc.int/documents/7064>

⁴⁴¹ Source: The United Nations Framework Convention on Climate Change (UNFCCC). *Doha Amendment to the Kyoto Protocol* (2012) https://unfccc.int/files/kyoto_protocol/application/pdf/kp_doha_amendment_english.pdf.

The Paris Agreement^{442, 443}, adopted in 2015, sets the overarching goal of limiting global warming to well below 2°C, with efforts to remain under a 1.5°C increase above pre-industrial levels. While it does not explicitly detail CCS, it offers a supportive framework that can include CCS to achieve each Party's Nationally Determined Contributions. Article 6 of the Paris Agreement supports voluntary cooperation among countries through market and non-market mechanisms, potentially allowing CCS-related emission reductions to be transferred or credited internationally.

The United Nations 2030 Agenda for Sustainable Development⁴⁴⁴ includes Sustainable Development Goal (SDG) 13, which calls for urgent action to combat climate change and its impacts. While CCS is not explicitly mentioned within the SDGs, the Agenda highlights technology transfer and financial mechanisms as critical components of global climate action. In this context, CCS can be integrated into national strategies aligned with SDG 13, leveraging international cooperation, technological capacity-building, and financial support to ensure responsible deployment.

The Intergovernmental Panel on Climate Change (IPCC) is a United Nations body established in 1988⁴⁴⁵. The IPCC provides a critical scientific basis for CCS regulation by periodically assessing the technology's effectiveness, risks, and potential role in meeting various mitigation pathways. Although the IPCC does not create binding regulations, its reports inform policy decisions and international negotiations:

1. Special Report on Carbon Dioxide Capture and Storage (SRCCS, 2005) is a foundational document that evaluates CCS technologies, covering capture processes, transport methods, storage options, and cost analyses⁴⁴⁶. It underscores the significant potential of CCS to reduce CO₂ emissions, while also highlighting concerns about leakage and long-term monitoring.
2. Sixth Assessment Report (AR6) – working Group III (2022) reinforces the necessity of CCS for decarbonizing “hard-to-abate” sectors such as heavy industry and discusses pathways consistent with 1.5°C or 2°C warming limits.⁴⁴⁷

⁴⁴² Source: The United Nations Framework Convention on Climate Change (UNFCCC). *Paris Agreement* (2015) http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

⁴⁴³ Lithuania ratified the agreement on February 2nd, 2017

⁴⁴⁴ Source: The United Nations Framework Convention on Climate Change (UNFCCC). *United Nations 2030 Agenda for Sustainable Development* (2015) <https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf>.

⁴⁴⁵ Source: The Intergovernmental Panel on Climate Change. <https://www.ipcc.ch/>

⁴⁴⁶ Source: The Intergovernmental Panel on Climate Change. METZ, Bert; DAVIDSON, Ogunlade; DE CONINCK, Heleen; LOOS, Manuela, MEYER, Leo. *Special Report Carbon Dioxide Capture and Storage*, 2005. Cambridge University Press, UK. pp 431. Available from Cambridge University Press, The Edinburgh Building Shaftesbury Road, Cambridge CB2 2RU ENGLAND <https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/>

⁴⁴⁷ Source: The Intergovernmental Panel on Climate Change. SHUKLA, P. R.; SKEA, J.; SLADE, R.; AL KHOURDAJIE, A.; VAN DIEMEN, R; MCCOLLUM, D.; PATHAK, M.; SOME, S.; VYAS, P.; FRADERA, R.; BALKACEMI, M.; HASIJA, A.; LISBOA, G.; LUZ, S.; MALLEY, K. *Climate Change 2022: Mitigation of Climate Change Working Group III Contribution to the IPCC Sixth Assessment Report* https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Citation.pdf

3. AR6 – Synthesis Report (2023) - concludes that a wide deployment of CCS (alongside renewables, efficiency, and other measures) is crucial to keep global temperature increases within targeted thresholds.⁴⁴⁸

These IPCC assessments guide the design of regulatory frameworks by identifying the key environmental and technological aspects that must be monitored, the potential risks of large-scale CCS deployment, and strategies to mitigate those risks.

2. Marine Environment Frameworks

United Nations Convention on the Law of the Sea (UNCLOS)⁴⁴⁹⁴⁵⁰ role in carbon dioxide (CO₂) storage is specific yet significant. It governs CO₂ storage activities involving aircraft⁴⁵¹⁴⁵²

The London Convention (1972)⁴⁵³ and its 1996 Protocol⁴⁵⁴⁴⁵⁵—often referred to collectively as the London Protocol—were originally established to prevent marine pollution by controlling dumping at sea. In 2006, an amendment to the Protocol explicitly permitted CO₂ stream dumping into sub-seabed geological formation.⁴⁵⁶

In 2009, Contracting Parties adopted another amendment (to Article 6) addressing transboundary CO₂ export for sub-seabed storage.⁴⁵⁷ Since an insufficient number of Parties have ratified this amendment, the Protocol's Contracting Parties introduced a provisional application mechanism in 2019 to allow

⁴⁴⁸ Source: The Intergovernmental Panel on Climate Change. Climate Change 2023. LEE, H. And ROMERO, J. *Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647 <https://www.ipcc.ch/report/ar6/syr/>

⁴⁴⁹ Source: United Nations Convention on the Law of the Sea https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf

⁴⁵⁰ Lithuania ratified the agreement on November 12th, 2003.

⁴⁵² Source: European Commission: Directorate-General for Energy, Fraunhofer Institute for Systems and Innovation Research ISI, Guidehouse, McKinsey & Company, TNO, Trinomics, Utrecht University, BOLSCHER, H., GUEVARA OPINSKA, L., FINESSO, A., RYCROFT, L., NEELE, F.WILDENBORG, T. *EU regulation for the development of the market for CO₂ transport and storage*. Publications Office of the European Union, 2023, p 11-12 <https://data.europa.eu/doi/10.2833/093881>

⁴⁵³ Source: International Maritime Organization. *Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter* (This text contains all the amendments which entered into force) <https://www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx>

⁴⁵⁴ Source: International Maritime Organization. London Protocol (1996) to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972) <https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/PROTOCOLAmended2006.pdf>.

⁴⁵⁵ Lithuania is not a party.

⁴⁵⁶ Source: International Energy Agency. *Carbon Capture and Storage and the London Protocol. Options for Enabling Transboundary CO₂ Transfer*, 2011, IAE <https://www.iea.org/reports/carbon-capture-and-storage-and-the-london-protocol>.

⁴⁵⁷ Source: Source: International Energy Agency. *Carbon Capture and Storage and the London Protocol. Options for Enabling Transboundary CO₂ Transfer*, 2011, IAE <https://www.iea.org/reports/carbon-capture-and-storage-and-the-london-protocol>.

nations willing to participate in transboundary CCS to do so without waiting for the full ratification process.⁴⁵⁸

Under the London Protocol, the International Maritime Organization (IMO) has adopted Specific Guidelines for the Assessment of Carbon Dioxide for Disposal into Sub-Seabed Geological Formations (2012)⁴⁵⁹. These guidelines provide a standardized approach for:

- Evaluating potential environmental impacts of storing CO₂ in subsea reservoirs.
- Selecting appropriate storage sites to minimize risks of CO₂ leakage.
- Ensuring regulatory compliance with broader marine pollution rules.

Additionally, a Risk Assessment and Management Framework⁴⁶⁰ outlines procedures for identifying and mitigating any adverse effects of CO₂ injection into sub-seabed formations. By adhering to these guidelines, CCS project developers can meet international marine protection standards and demonstrate responsible environmental stewardship.

3. Regional instruments

The 1992 Helsinki Convention^{461 462}, formally known as the Convention on the Protection of the Marine Environment of the Baltic Sea Area, is a modernized successor to its original 1974 counterpart. Though adopted in 1992, it officially came into force in 2000. The parties to the convention are Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Sweden, Russian - as well as the European Union. The agreement governs activities within the Baltic Sea region and aims to reduce and ultimately eliminate pollution to help restore the sea's ecological health and maintain its natural balance. A key provision of the convention (Article 11) is its strict ban on waste disposal into the sea or seabed. The term "dumping" is broadly interpreted to cover any intentional release of waste materials or other substances from ships, aircraft, or human-made offshore structures. Notably, this definition also includes the intentional sinking or abandonment of such structures. Importantly, the convention does not carve out any exceptions for storing carbon dioxide beneath the seabed. Unlike the London Protocol or the OSPAR Convention, which have been updated to allow for sub-seabed CO₂ storage

⁴⁵⁸ Source: International Maritime Organization. *Resolution Lp.3(4) on the Amendment to Article 6 of the London Protocol* (Adopted on October 30th, 2009) [https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/LCLPDocuments/LP.3\(4\).pdf](https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/LCLPDocuments/LP.3(4).pdf)

⁴⁵⁹ Source: International Maritime Organization. *2012 Specific Guidelines for the Assessment of Carbon Dioxide for Disposal Into Sub-Seabed Geological Formations*. Adopted on November 2nd, 2012 (LC 34/15, Annex 8) <https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/2012%20SPECIFIC%20GUIDELINES%20FOR%20THE%20ASSESSMENT%20OF%20CARBON%20DIOXIDE.pdf>

⁴⁶⁰ Source: International Maritime Organization. *Risk Assessment and Management Framework for CO₂ Sequestration in Sub-Seabed Geological Structures* (CS-SSGS) <https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/CO2SEQUESTRATIONRAMF2006.doc>

⁴⁶¹ Source: Baltic Marine Environment Protection Commission (Helsinki Commission- HELCOM). *Convention on the Protection of the Marine Environment of the Baltic Sea Area*. 1992. <https://helcom.fi/about-us/convention/>

⁴⁶² Source: LEVINA, Ellina. *Thought Leadership – CO₂Storage Permitting Process in the European Union: A Guide*. The Global CCS Institute. December 10th, 2024. <https://www.globalccsinstitute.com/resources/publications-reports-research/thought-leadership-co2-storage-permitting-process-in-the-european-union-a-guide/>

under certain conditions, the Helsinki Convention remains unchanged in this regard. As a result, the geological storage of CO₂ in the Baltic Sea remains prohibited.

The OSPAR Convention, established in 1992 by 15 Northern European countries and the European Community, is recognized as one of the most comprehensive and stringent legal frameworks for protecting the marine environment. It is a regional convention important to the EU. In response to a 2006 report on ocean acidification, the OSPAR Commission acknowledged the importance of carbon capture and storage as part of an effective strategy to reduce greenhouse gas emissions. Consequently, OSPAR adopted a decision permitting the safe storage of CO₂ in geological formations, supported by detailed guidelines for risk assessment and management. At the same time, it prohibited the storage of CO₂ in the water column or directly on the seabed, citing potential environmental risks.

4. Environmental Impact Assessment Frameworks

The Espoo Convention^{463 464} on Environmental Impact Assessment in a Transboundary Context aims to prevent and minimize environmental damage by requiring states to notify and consult each other on all major projects under consideration that are likely to have significant adverse environmental impact across boundaries. Although CCS is not explicitly listed in the annexes of the Espoo Convention, many CCS activities—especially those involving transboundary CO₂ pipelines or storage sites near national borders—may fall under its scope. This implies that:

- Project proponents must assess the potential environmental impacts of CCS installations.
- Neighbouring states likely to be affected by leakage or pipeline accidents should be informed and consulted prior to project approval.

No specific amendments have been adopted under the Espoo Convention solely for CCS, but the existing provisions remain applicable, reinforcing the principle of preventive action and international cooperation.

The Protocol on Strategic Environmental Assessment (SEA Protocol)^{465, 466} to the Espoo Convention, which entered into force in 2010, extends the concept of environmental assessments to plans and programs with significant environmental impacts. Large-scale CCS initiatives—such as national strategies for carbon transport and storage networks—could trigger this requirement if they have substantial environmental implications. As a result, states are expected to:

- Assess the cumulative impacts of implementing CCS across multiple regions or sectors.
- Integrate environmental considerations into the earliest stages of planning.
- Engage the public and concerned authorities in the decision-making process.

In conclusion, despite the regulatory progress achieved thus far, challenges remain: the global regulatory framework for CCS is fragmented, with no single international agreement fully consolidating

⁴⁶³ Source: United Nations. *Convention on Environmental Impact Assessment in a Transboundary Context*. 1989-
<https://treaties.un.org/pages/showdetails.aspx?objid=080000028002887c>

⁴⁶⁴ Signed February 25th, 1991, entry into force September 10th, 1997. Date of effect in Lithuania April 11th, 2001.

⁴⁶⁵ Source: United Nations. *Protocol on Strategic Environmental Assessment to the Convention on Environmental Impact Assessment in a Transboundary Context*. 2003.
https://treaties.un.org/doc/Publication/CTC/Ch_XXVII_4_b.pdf

⁴⁶⁶ Signed May 21st, 2003, entry into force July 11th, 2010. Lithuania ratified the agreement on March 22nd, 2011.

the rules, leading to overlapping or complementary coverage across various treaties and conventions; additionally, transboundary uncertainties continue to complicate cross-border initiatives, as evidenced by the slow ratification of certain London Protocol amendments and the inconsistent incorporation of CCS considerations within the Espoo and SEA Protocol processes.

10.2. Strategic objectives and legal framework for CCUS in the European Union

The EU has articulated a series of strategic objectives to scale up the deployment of CCUS technologies, anchored in its broader climate policy agenda, including the 2040 interim target of a 90% net reduction in greenhouse gas emissions relative to 1990 levels. To translate these goals into practice, the EU has also developed a complex legal and regulatory framework designed to support CCUS implementation while safeguarding environmental and public interests. This chapter reviews the EU's strategic direction for CCUS and critically examines the existing legal instruments that govern its deployment. It situates CCUS within the evolving landscape of European climate governance, addressing both the opportunities and the regulatory challenges.

Strategic Objectives for Carbon Capture, Utilisation and Storage in the European Union

The European Union has committed to an ambitious pathway toward achieving climate neutrality by 2050, with the overarching objective of fostering a sustainable, equitable, and prosperous society. An important component of this transition is the widespread implementation of CCUS technologies, which are essential for both reducing emissions in hard-to-abate sectors and enabling atmospheric carbon removal. This part of the study examines key European Union strategic documents that outline the principal priorities for the development and integration of CCUS across the region. They are:

- Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society 18 COM/2024/63 final.⁴⁶⁷
- Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Towards an ambitious Industrial Carbon Management for the EU COM/2024/62 final.⁴⁶⁸

Communication from the Commission Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society. The European Commission's strategy for reaching climate neutrality by 2050 includes an important role for CCUS. To support its proposed 2040 climate target—a 90% net reduction in greenhouse gas emissions compared to 1990—the Commission calls for scaling up CCUS along with other key low-carbon technologies. To hit the 2040 climate target, the EU will need to start rolling out carbon capture technologies much earlier. These technologies won't just reduce emissions—they'll also help remove CO₂ from the atmosphere, working alongside natural solutions like forests and soils to reach the ambitious 90%

⁴⁶⁷ Source: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society. COM/2024/63 final <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2024%3A63%3AFIN>

⁴⁶⁸ Source: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Towards an ambitious Industrial Carbon Management for the EU COM/2024/62 final <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2024:62:FIN>

emissions reduction goal. Achieving this will require a mix of approaches, including BioCCS (carbon capture from biomass), direct air capture, and other emerging methods. CCUS technologies—which store captured carbon underground or reuse it in industry—are particularly important for sectors that lack cleaner alternatives. These systems can also help build new carbon-based supply chains, replacing fossil inputs with biobased or recycled materials. To unlock the full potential of these technologies, the EU needs a strong policy and investment framework. That’s why the Commission is also launching a dedicated strategy for industrial carbon management.

Towards an ambitious Industrial Carbon Management for the EU.⁴⁶⁹ The Commission released its Industrial Carbon Management Communication, outlining how these technologies can help reduce emissions by 90% by 2040 and reach climate neutrality by 2050. As part of this, the EU plans to develop 50 million tonnes of CO₂ storage capacity by 2030, scaling up to 280 million tonnes by 2040, based on climate target impact assessments. The Communication lays out a clear EU-level strategy: building the infrastructure and legal framework needed to create a functioning CO₂ single market. This includes potential new rules (CO₂ transport and storage regulatory package) for transport and storage, ensuring fair access, setting quality standards for CO₂, and providing incentives for investment. The Commission’s Joint Research Centre has also published a report detailing infrastructure needs and investment priorities⁴⁷⁰. In addition, the EU will map out storage sites, guide permitting procedures, and create tools to connect CO₂ producers with storage providers and users. Plans also include integrating carbon removals into the ETS and creating rules for how captured CO₂ can be used in products while still counting toward climate goals.⁴⁷¹

To conclude, reaching climate neutrality by 2050 will require the European Union to fully integrate both natural and industrial carbon removal methods into its climate strategy. The Commission’s Industrial Carbon Management initiative represents a significant step forward, outlining how CCUS technologies can support the 2040 reduction target while laying the foundation for long-term emissions removal. Developing the necessary infrastructure, legal frameworks, and market conditions will be essential to ensure fair access, encourage investment, and enable the widespread use of these technologies.

A Review of the Legal Framework for Carbon Capture, Utilisation and Storage in the European Union

The successful deployment of CCUS relies not only on technological advancements and industrial investment, but also on the establishment of a coherent regulatory framework. At the European Union level, a range of interrelated legal instruments—covering areas such as emissions trading, liability, infrastructure development, and environmental protection—collectively shape the regulatory environment for CCS. This section briefly reviews the key EU regulations and directives that govern the implementation and oversight of CCS activities. These include:

⁴⁶⁹ Source: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Towards an ambitious Industrial Carbon Management for the EU COM/2024/62 final <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2024:62:FIN>

⁴⁷⁰ Source: TUMARA, D.; UIHLEIN, A.; HIDALGO GONZÁLEZ, L. *Shaping the future CO₂ transport network for Europe*, Publications Office of the European Union, Luxembourg, 2024, doi:10.2760/582433, JRC136709. <https://publications.jrc.ec.europa.eu/repository/handle/JRC136709>

⁴⁷¹ Source: Commission sets out how to sustainably capture, store and use carbon to reach climate neutrality by 2050 https://ec.europa.eu/commission/presscorner/detail/en/ip_24_585

- Regulation (EU) 2024/1735 of the European Parliament and of the Council of 13 June 2024 on establishing a framework of measures for strengthening Europe's net-zero technology manufacturing ecosystem and amending Regulation (EU) 2018/1724.
- Directive 2004/35/EC of the European Parliament and of the Council of 21 April 2004 on environmental liability regarding the prevention and remedying of environmental damage.
- Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006.
- Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment.
- Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Union and amending Council Directive 96/61/EC (Text with EEA relevance).
- Regulation (EU) 2023/956 of the European Parliament and of the Council of 10 May 2023 establishing a carbon border adjustment mechanism.
- Commission Implementing Regulation (EU) 2023/1773 of 17 August 2023 laying down the rules for the application of Regulation (EU) 2023/956 of the European Parliament and of the Council as regards reporting obligations for the purposes of the carbon border adjustment mechanism during the transitional period.
- Regulation (EU) 2022/869 of the European Parliament and of the Council of 30 May 2022 on guidelines for trans-European energy infrastructure, amending Regulations (EC) No 715/2009, (EU) 2019/942 and (EU) 2019/943 and Directives 2009/73/EC and (EU) 2019/944, and repealing Regulation (EU) No 347/2013.
- Regulation (EU) 2024/1679 of the European Parliament and of the Council of 13 June 2024 on Union guidelines for the development of the trans-European transport network, amending Regulations (EU) 2021/1153 and (EU) No 913/2010 and repealing Regulation (EU) No 1315/2013.

Net Zero Industry Act⁴⁷². The Net-Zero Industry Act is designed to strengthen Europe's ability to manufacture clean technologies and their critical components at scale. It targets the challenges that currently limit industrial growth in the net-zero sector, aiming to boost competitiveness, attract investment, and expand market opportunities for green technologies within the EU. One of the central goals of the Net Zero Industry Act is to ensure that, by 2030, at least 40% of the EU's annual deployment needs for clean technologies are met by domestic manufacturing. The Net Zero Industry Act focuses on developing a European market for CO₂ storage services by 2030. A key measure includes establishing an EU-wide injection capacity of 50 million tonnes of CO₂ per year in strategically selected storage sites.

⁴⁷² Source: Consolidated text: Regulation (EU) 2024/1735 of the European Parliament and of the Council of 13 June 2024 on establishing a framework of measures for strengthening Europe's net-zero technology manufacturing ecosystem and amending Regulation (EU) 2018/1724. ELI: <http://data.europa.eu/eli/reg/2024/1735/2024-06-28>.

This target will be met through contributions from oil and gas companies operating within the EU, proportionate to their market presence.⁴⁷³ On May 22nd, 2025, the European Commission specified the European oil and gas companies which are obliged to contribute to the development of the capacity of 50 million tonnes of CO₂ per year⁴⁷⁴. It has to be noted that all Lithuanian oil and gas companies were excluded from this obligation, as their production volumes of crude oil and gas made less than 5% of the cumulative Union production volumes of crude oil and natural gas in the period from January 1st, 2020 to December 31st, 2023. By setting these ambitions, the regulation aims to eliminate one of the major roadblocks in scaling up CCS—especially for high-emission industries where emissions are difficult to eliminate. Ultimately, the Net Zero Industry Act positions CCS as a practical and financially viable solution in the EU's path toward climate neutrality.

Environmental Liability Directive⁴⁷⁵⁴⁷⁶. Operators of CCS storage sites are legally bound to take steps to prevent and address environmental damage linked to their sites, as stated in Articles 5 and 6. Additionally, Article 14 compels Member States to foster the development of financial security tools and markets, enabling operators to meet their liability obligations through appropriate guarantees. It also introduces flexibility, allowing phased implementation, financial cap limits, and exemptions for low-risk activities. It also permits exemption from liability in cases where operators are not at fault, are not negligent, or where force majeure applies.⁴⁷⁷ We can see interaction between the Environmental Liability Directive, the CCS Directive, and national laws. Notably, civil actions, as well as private injury, fall under each country's civil law system and are not constrained by the CCS Directive or the Environmental Liability Directive. The CCS Directive further reiterates that operators must carry out both preventive and remedial measures as mandated by the Environmental Liability Directive. While the directive may need refining, it currently includes critical elements such as interim losses and compensatory remediation—which could become significant long-term financial burdens for CCS initiatives.⁴⁷⁸ Experts have also pointed out a lack of clarity in Article 34 of the CCS Directive, which amended the Environmental Liability Directive. This article extends Environmental Liability Directive provisions to the "operation" of CCS storage sites, but what exactly constitutes "operation" remains

⁴⁷³ Source: European Commission- Industry-Sustainability. *The Net-Zero Industry Act: Making the EU the home of clean technologies manufacturing and green jobs*. https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en

⁴⁷⁴ Source: European Commission. *Document 32025D1479. Commission Decision (EU) 2025/1479 of 22 May 2025 specifying the pro rata contributions to the Union CO₂ injection capacity objective by 2030 from entities holding an authorisation as defined in Article 1, point 3, of Directive 94/22/EC of the European Parliament and of the Council*. ELI: <http://data.europa.eu/eli/dec/2025/1479/oj>

⁴⁷⁵ Source: European Commission: Directorate-General for Energy, Fraunhofer Institute for Systems and Innovation Research ISI, Guidehouse, McKinsey & Company, TNO, Trinomics, Utrecht University, BOLSCHER, H., GUEVARA OPINSKA, L., FINESO, A., RYCROFT, L., NEELE, F.WILDENBORG, T. *EU regulation for the development of the market for CO₂ transport and storage*. Publications Office of the European Union, 2023, p 11-12 <https://data.europa.eu/doi/10.2833/093881>

⁴⁷⁶ Source: European Commission. *Consolidated text: Directive 2004/35/EC of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage*. ELI: <http://data.europa.eu/eli/dir/2004/35/2019-06-26>

⁴⁷⁷ Source: MAKUCH, Zen; SLAVINA, Georgieva; ORAAE-MIRZAMANI, Behdeen. *Innovative Regulatory and Financial Parameters for Advancing Carbon Capture and Storage Technologies*. *Fordham Environmental Law Review* 32 (1) (2020):pages 1–45. <https://www.jstor.org/stable/26984191>.

⁴⁷⁸ Source: WEBER, Viktor. *Regulation of CCS Storage Sites in Norway and Compliance with EEA Law*. Trondheim Conference on CO₂ Capture, Transport and Storage. 2021. <https://sintef.brage.unit.no/sintef-xmllui/handle/11250/2786920?show=full&locale-attribute=no>

vague. The term might only refer to the active injection phase, or it might be interpreted more broadly to include the entire lifecycle of a project—from the initial site selection to post-closure monitoring and transfer of responsibility. Lastly, experts emphasize the need for more precise and enforceable requirements in relation to financial security, particularly under Article 14.⁴⁷⁹

The CCS Directive^{480, 479, 475}. The European Union introduced legislation known as the CCS Directive, aimed at ensuring the safe and environmentally responsible geological storage of carbon dioxide. This directive sets out a comprehensive regulatory framework governing how exploration and storage activities are permitted within the EU. This legislation outlines clear rules for how sites should be selected, permitted, operated, and ultimately decommissioned, with a strong focus on ensuring both safety and environmental integrity. Notably, the directive does not extend to carbon capture and utilisation technologies. A fundamental aspect of the CCS Directive is the autonomy it grants to Member States, allowing them to designate specific areas suitable for CO₂ storage—or to completely exclude the option of CCS within their national borders. As several countries have chosen to opt out, the legal landscape for CCS across the EU remains fragmented, with significant variation between national frameworks. At the time of reporting, geological storage of carbon dioxide is allowed in all Member States, Iceland and Norway except in Germany, Estonia, Ireland Cyprus, Latvia, Austria, Finland and Slovenia. In Lithuania the geological storage of carbon dioxide has been prohibited since July 2020.⁴⁸¹

EU Environmental Impact Assessment Directive⁴⁸². The Environmental Impact Assessment Directive lays out the legal requirements for evaluating how certain public and private sector projects might affect the environment. It ensures that environmental considerations are factored into the decision-making process before projects are approved. Annex III of the directive outlines the criteria used to determine whether a project must undergo a formal Environmental Impact Assessment. These include:

- The specific nature and scale of the project,
- Where the project will be located,
- The scope and seriousness of any potential environmental consequences.

CCS projects are generally subject to this assessment process. This applies not only to the storage component but can also extend to the capture and transportation stages, depending on certain thresholds and conditions across the CCS value chain. In particular, the directive mandates an

⁴⁷⁹ Source: European Commission: Directorate-General for Energy, Fraunhofer Institute for Systems and Innovation Research ISI, Guidehouse, McKinsey & Company, TNO, Trinomics, Utrecht University, Bolscher, H., GUEVARA OPINSKA, L., FINESO, A., RYCROFT, L., NEELE, F.WILDENBORG, T., *EU regulation for the development of the market for CO₂ transport and storage*. Publications Office of the European Union, 2023, p. 12 <https://data.europa.eu/doi/10.2833/093881>

⁴⁸⁰ Source: Consolidated text: Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006 ELI: <http://data.europa.eu/eli/dir/2009/31/2018-12-24>

⁴⁸¹ Source: The European Commission. *Report from the Commission to the European Parliament and the Council on Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide*.

COM/2023/657 final <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2023%3A657%3AFIN>

⁴⁸² Source: The European Commission. *Consolidated text: Directive 2011/92/EU of the European Parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment (codification)* ELI: <http://data.europa.eu/eli/dir/2011/92/2014-05-15>

Environmental Impact Assessment when CO₂ is captured from a facility that already requires such an assessment and the capture volume reaches or exceeds 1.5 million tonnes per year. Similarly, if the project involves constructing CO₂ pipelines with a diameter greater than 800 millimetres and stretching over more than 40 kilometres for geological storage, an Environmental Impact Assessment is also compulsory.⁴⁸³

Annex I and **Annex II** of the Environmental Impact Assessment Directive list the types of projects that are subject to assessment. Projects listed in **Annex I** always require an Environmental Impact Assessment because they are likely to have significant environmental effects. Projects in **Annex II** are not automatically subject to EIA but must be **screened** by Member States to determine whether an EIA is needed, based on their size, nature, and potential environmental impact. Categories include. Member States use **screening criteria** (Annex III) to decide if a project under Annex II requires an EIA.

Large CO₂ pipelines with a diameter of more than 800 mm and a length of more than 40 km, constructed to transport CO₂ streams for geological storage (including associated booster stations), fall under Annex I, point 16(b) of the EIA Directive. These projects automatically trigger a full Environmental Impact Assessment before any authorization can be granted. The construction of CO₂ storage sites—i.e., geological storage facilities covered by Directive 2009/31/EC—is listed under Annex I, point 22. As part of Annex I, these storage installations also require a full EIA. Facilities designed for the capture of CO₂ streams intended for geological storage that either originate from installations already in Annex I or capture at least 1.5 Mt of CO₂ per year are considered Annex I, point 23 projects. Consequently, they always necessitate a full Environmental Impact Assessment

Smaller-scale CO₂ projects fall under Annex II, where they are subject to a screening process to determine whether a full EIA is required. CO₂ capture installations that do not meet the Annex I threshold (i.e., capture less than 1.5 Mt/year) are included under Annex II, point 3(j). These projects must undergo screening according to Annex III criteria and may require a full EIA if significant environmental effects are likely. CO₂ transport pipelines that fail to meet the size criteria of Annex I—meaning those with diameter ≤ 800 mm or length ≤ 40 km—are captured under Annex II, point 10(i). Similarly, these pipelines must go through screening, and if the assessment reveals potential significant impacts, a full EIA is required.

Strategic Environmental Assessment Directive^{484, 485}. It aims to promote sustainable development by ensuring that environmental considerations are integrated into the preparation, adoption, and implementation of certain public plans and programmes. It applies specifically to those likely to have significant environmental effects, particularly in sectors such as agriculture, energy, transport, water management, tourism, and land use planning. The Strategic Environmental Assessment Directive requires an environmental assessment for plans and programmes prepared by public authorities and governed by legislative or regulatory frameworks. This includes those that set the framework for future development consent under the Environmental Impact Assessment Directive or under the Habitats Directive. Plans not explicitly listed may also be subject to assessment if likely to have significant

⁴⁸³ Source: LEVINA, Ellina. *Thought Leadership – CO₂Storage Permitting Process in the European Union: A Guide*. The Global CCS Institute. December 10th, 2024. <https://www.globalccsinstitute.com/resources/publications-reports-research/thought-leadership-co2-storage-permitting-process-in-the-european-union-a-guide/>

⁴⁸⁴ Source: The European Commission. Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment ELI: <http://data.europa.eu/eli/dir/2001/42/oj>

⁴⁸⁵ Source: European Commission. *Assessment of the certain effects of plans and programmes on the environment (SEA)*. <https://eur-lex.europa.eu/legal-content/EN/LSU/?uri=celex:32001L0042>

environmental impacts. Key steps in the process include scoping, preparing an environmental report, public and authority consultations, decision-making, and post-adoption monitoring. The directive allows for screening procedures to determine whether certain smaller-scale plans or amendments require full assessment. Strategic Environmental Assessment applies to CO₂ capture, storage, and transportation projects primarily at the planning and programme level, rather than individual projects. Its application depends on whether public plans or programmes related to CO₂ infrastructure are likely to have significant environmental effects and whether they set the framework for development consent of projects.

EU ETS directive^{486 487}. The European Union Emissions Trading System (EU ETS) operates on a “cap-and-trade” model. The “cap” refers to the upper limit placed on total greenhouse gas emissions allowed from sectors covered by the system. This limit is tightened each year to align with the EU’s broader climate goals, ensuring a steady reduction in emissions. Each emission allowance under the system permits the release of one tonne of CO₂ equivalent. These allowances are either auctioned off or traded between companies. As the cap shrinks annually, fewer allowances enter the market, increasing their value and reinforcing the system’s environmental effectiveness. Companies covered by the ETS must measure and report their annual emissions, then surrender a corresponding number of allowances to match those emissions. Failing to comply results in substantial penalties. Although most allowances are auctioned, a portion is distributed free of charge to certain companies, particularly in sectors vulnerable to international competition. Organizations may buy, sell, or save unused allowances depending on their emissions performance. If a company reduces its emissions, it can either bank the leftover allowances for future use or sell them. All these transactions are tracked through the Union Registry. The cost of allowances is set by supply and demand in the EU carbon market, which operates under strict supervision. The yearly reduction in the cap reinforces the limited availability of allowances, helping maintain a meaningful carbon price. This price serves as a financial signal, motivating companies to reduce emissions efficiently and invest in cleaner alternatives. It also directly impacts how much revenue is generated from auctions. Most of the proceeds from the ETS go directly to national governments, who are expected to reinvest these funds in projects that support renewable energy, boost energy efficiency, or develop low-carbon technologies. Additionally, part of the revenue funds EU-wide programs like the Innovation Fund and the Modernisation Fund, which support innovation and help drive the continent’s shift to a greener economy. A new emissions trading system—referred to as ETS2—will be established under this directive to target carbon emissions resulting from fuel use in buildings, road transport, and smaller industrial sectors that fall outside the scope of the original EU ETS. While full implementation of ETS2 is planned for 2027, the system will begin with emissions monitoring and reporting in 2025.⁴⁸⁸

⁴⁸⁶ Source: Consolidated text: Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Union and amending Council Directive 96/61/EC. ELL: <http://data.europa.eu/eli/dir/2003/87/2024-03-01>

⁴⁸⁷ Source: European Commission. Climate Action. *About the EU ETS*. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/about-eu-ets_en

⁴⁸⁸ Source: The International Energy Agency. Directive (EU) 2023/959 establishing a system for greenhouse gas emission allowance trading within the Union. <https://www.iea.org/policies/21250-directive-eu-2023959-establishing-a-system-for-greenhouse-gas-emission-allowance-trading-within-the-union>

Carbon Border Adjustment Mechanism (CBAM) Regulation.⁴⁸⁹ The Carbon Border Adjustment Mechanism officially came into effect on October 1st, 2023, marking a major shift in how the EU addresses carbon leakage. Beginning January 1st, 2026, importers bringing in certain carbon-intensive goods—such as steel, aluminium, cement, ammonia, and hydrogen—will be required to purchase and submit CBAM certificates. One certificate must be surrendered for each tonne of embedded emissions, calculated in CO₂ equivalents, associated with the production of those imported products. The cost of these certificates will mirror the price of allowances in the EU ETS, ensuring alignment between domestic and imported goods. However, CBAM defines emissions differently than the ETS. Under CBAM, emissions are only counted if greenhouse gases are released into the atmosphere during the production process. This means that any CO₂ that has been captured and either permanently stored underground (via geological storage) or chemically locked into products is not treated as an emission. Consequently, such CO₂ does not trigger a CBAM certificate obligation. This interpretation is clearly outlined in the Commission’s Implementing Regulation (EU) 2023/1773⁴⁹⁰, as well as in the official CBAM guidance for importers, issued on August 17th, 2023. These documents clarify that, to be excluded from the emission count, it must be proven through monitoring and documentation that the CO₂ is permanently prevented from re-entering the atmosphere—either through geological storage or chemical fixation.

TEN-E Regulation⁴⁹¹. It plays a central role in connecting energy systems across EU Member States. Cross-border energy infrastructure is essential for facilitating the energy transition. The updated version of TEN-E now includes provisions for projects related to both CO₂ transport and storage. This covers dedicated CO₂ pipelines, as well as associated fixed infrastructure such as liquefaction facilities, buffer storage units, and conversion stations that prepare carbon dioxide for further transport. These facilities are intended to support the movement of CO₂ via pipelines or other dedicated methods, including ships, trucks, trains, and barges. However, while TEN-E acknowledges these various transport modes, only CO₂ pipeline transport is formally included within its scope; the other methods fall outside its regulatory coverage. Among the policy’s thematic priorities, one key focus is the creation of a cross-border CO₂ network. This priority area specifically aims to develop infrastructure that enables the transportation of captured carbon emissions from industrial sources across national borders.⁴⁹²

In its 2022 revision, the TEN-E framework was explicitly updated to align with the European Green Deal objectives and to incorporate new infrastructure categories needed for decarbonisation. Notably, CO₂

⁴⁸⁹ Source: The European Commission. CBAM Regulation. Regulation (EU) 2023/956 of the European Parliament and of the Council of 10 May 2023 establishing a carbon border adjustment mechanism. ELI: <http://data.europa.eu/eli/reg/2023/956/oj>

⁴⁹⁰ Source: The European Commission. Consolidated text: Commission Implementing Regulation (EU) 2023/1773 of 17 August 2023 laying down the rules for the application of Regulation (EU) 2023/956 of the European Parliament and of the Council as regards reporting obligations for the purposes of the carbon border adjustment mechanism during the transitional period. ELI: http://data.europa.eu/eli/reg_impl/2023/1773/2024-10-31

⁴⁹¹ Source: Consolidated text: Regulation (EU) 2022/869 of the European Parliament and of the Council of 30 May 2022 on guidelines for trans-European energy infrastructure, amending Regulations (EC) No 715/2009, (EU) 2019/942 and (EU) 2019/943 and Directives 2009/73/EC and (EU) 2019/944, and repealing Regulation (EU) No 347/2013, ELI: <http://data.europa.eu/eli/reg/2022/869/2025-02-05>

⁴⁹² Source: The European Commission: Directorate-General for Energy, Fraunhofer Institute for Systems and Innovation Research ISI, Guidehouse, McKinsey & Company, TNO, Trinomics, Utrecht University, Bolscher, H., GUEVARA OPINSKA, L., FINESSO, A., RYCROFT, L., NEELE, F.WILDENBORG, T., *EU regulation for the development of the market for CO₂ transport and storage*. Publications Office of the European Union, 2023, p. 12 <https://data.europa.eu/doi/10.2833/093881>

networks, as priority areas, were added as a priority thematic area under TEN-E, alongside smart electricity grids and smart gas grids.⁴⁹³ This means that proposed cross-border CO₂ transportation projects (for example, pipeline networks linking multiple Member States or connecting onshore sources to offshore European storage hubs) can be recognised as Projects of Common Interest. The legal effect of Projects of Common Interest status is significant. Projects on the EU Projects of Common Interest list benefit from streamlined permitting procedures and regulatory incentives under EU law. According to the TEN-E Regulation, Projects of Common Interest are to be treated by Member States as top priority infrastructure: authorities must ensure a coordinated permitting process with an absolute maximum duration of 3½ years, and such projects should receive the “highest national significance” status to avoid undue delays. Moreover, Projects of Common Interest are eligible for funding from the EU’s *Connecting Europe Facility* (CEF), and regulators are empowered to allocate costs across borders for these projects in a fair manner.⁴⁹³ Equally, the TEN-E Regulation provides for Projects of Mutual Interest which extend similar support to infrastructure developed with non-EU countries. This is pertinent for CO₂ transport, as some storage destinations (e.g. under the North Sea) involve cooperation with neighbouring countries like Norway.

On January 30th, 2025, the European Commission released the outcomes of its Connecting Europe Facility (CEF) funding call, originally initiated in April 2024. Approximately €1.25 billion has been awarded to finance 41 cross-border energy infrastructure projects, specifically addressing electricity, hydrogen, and carbon dioxide (CO₂) infrastructure. These projects were recognized in 2024 as Projects of Common Interest and Projects of Mutual Interest under the TEN-E policy. From the allocated funds, €250 million support nine preparatory studies and three specific CO₂ infrastructure projects. These include the Prinos CO₂ storage facility in northern Greece, the North Sea L10 CO₂ storage site on the Dutch continental shelf, and the Norne CO₂ facility located in Denmark.⁴⁹⁴

TEN-T Regulation⁴⁹⁵. It defines the network and sets out the requirements for infrastructure to ensure a coherent quality throughout the EU. The purpose of the infrastructure requirements for the TEN-T network are twofold. They ensure that transport infrastructure users can count on an efficient, reliable and high-performing infrastructure wherever they are in the EU. This important for our economic development and competitiveness and the cohesion of the EU. The requirements also ensure the development of more sustainable forms of transport. They make sure that our infrastructure can help reduce emissions from transport and is resilient against the impacts of climate change. They also promote digitalisation and improve multimodality⁴⁹⁶. “The trans-European transport network shall demonstrate European added value by contributing to the objectives laid down in the following four

⁴⁹³ Source: The European Commission: Energy, Climate Change, Environment. Trans-European Networks for Energy. EU policy for planning cross-border energy infrastructure. https://energy.ec.europa.eu/topics/infrastructure/trans-european-networks-energy_en#:~:text=The%20revised%20TEN,it%20introduces

⁴⁹⁴ Source: Global CCS Institute. *CO₂ Infrastructure Projects Listed Among the 41 Cross-border Energy Infrastructure Projects Awarded Funding Under the CEF-E Programme*. February 4th, 2025. <https://www.globalccsinstitute.com/news-media/latest-news/co2-infrastructure-projects-listed-among-the-41-cross-border-energy-infrastructure-projects-awarded-funding-under-the-cef-e-programme/>

⁴⁹⁵ Source: Regulation (EU) 2024/1679 of the European Parliament and of the Council of 13 June 2024 on Union guidelines for the development of the trans-European transport network, amending Regulations (EU) 2021/1153 and (EU) No 913/2010 and repealing Regulation (EU) No 1315/2013 Art. 4(2) <https://eur-lex.europa.eu/legal-content/EN/AUTO/?uri=CELEX:32024R1679>

⁴⁹⁶ Source: The European Commission- Transport Themes- Infrastructure and Investment. Trans-European Transport Network (TEN-T). https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_en

categories: (a) sustainability through: (i) promotion of zero and low emission mobility in line with the relevant Union CO₂ reduction targets;^{494, 495.}

The reviewed EU regulations and directives, spanning environmental liability, emissions trading, infrastructure development, and environmental impact assessments, collectively establish a multifaceted regulatory landscape that supports CCUS while addressing potential legal, financial, and environmental risks. Key legislative instruments, such as the CCS Directive and the Net-Zero Industry Act, provide crucial regulatory scaffolding to promote safe CO₂ storage and to stimulate investment in domestic clean technology production. Nonetheless, the fragmented implementation across Member States and the need for greater legal precision—particularly regarding liability, financial security, and long-term site management—highlight areas where regulatory refinement is still required.

10.3. CO₂ storage in the EU: Legal framework

The recent Commission Communication on the EU's climate target for 2040 highlighted the need for 450 million tonnes of CO₂ per year to be captured and either stored or utilised by 2050⁴⁹⁷. To meet its climate goals and achieve net-zero emissions by 2050, the European Union is placing increasing importance on carbon capture and storage. This process involves capturing carbon dioxide emissions—especially from industries that are hard to decarbonize like cement production, and storing them underground instead of releasing them into the atmosphere.

Industrial Carbon Management -Future Perspectives

In 2024 the Commission adopted the Communication „Towards an ambitious Industrial Carbon Management for the EU“⁴⁹⁸. It emphasises a growing need to build enough CO₂ storage capacity to meet future demand. Only a few EU countries have started the permitting process for storage sites, yet many others plan to begin capturing emissions as early as 2025. This urgency calls for early coordination between companies and permitting authorities, and for clear, consistent rules across Europe to streamline the approval process. To help identify suitable storage locations, the EU is also creating a digital atlas of potential sites. This inventory will include geological data like seismic activity and well samples, allowing investors to better understand where they can safely and effectively store CO₂. Each site will be rated on how "ready" it is for storage, making it easier for industry to plan. Looking further ahead, the EU wants to significantly expand storage capacity—reaching at least 250 million tonnes of CO₂ per year by 2040. To make this happen, it will be essential for countries to recognize CO₂ storage as a strategic priority, offer financial support where needed, and design detailed plans for reducing emissions in each industrial sector.

⁴⁹⁷Source: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society. COM/2024/63 final <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2024%3A63%3AFIN>

⁴⁹⁸ Source: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Towards an ambitious Industrial Carbon Management for the EU COM/2024/62 final. Pages 10-13. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2024:62:FIN>.

The Commission foresees to⁴⁹⁹:

1. *develop, with Member States, by early 2026 at the latest, a platform for demand assessment and demand aggregation for CO₂ transport or storage services, with the aim of matching CO₂ suppliers with storage and transport providers and providing contract and procurement transparency*
2. *aim to create and make available by early 2026, in cooperation with the geological services of the EEA, an investment atlas of potential CO₂ storage sites based on a common storage readiness level format.*
3. *use the knowledge-sharing Platform for industrial CCUS projects to develop together with industry sectoral roadmaps for industrial carbon management.*
4. *develop, with Member States, by 2025 step-by-step guidance for permitting processes for net-zero strategic projects for CO₂ storage, notably regarding:*
 - a. *the transfer of responsibility from operators back to the competent authorities and the corresponding financial security and financial mechanism requirements;*
 - b. *transparency on the permitting requirements and risk-based approaches to facilitate final investment decisions by storage operators.*

Member States should^{498, 499}:

1. *include in their updated National Energy and Climate Plans their assessment of capture needs and storage capacity/options and identify actions to support the deployment of a CCS value chain.*
2. *by 2025, ensure that they have transparent processes in place for storage permit applicants to engage with the competent authorities during the preparatory phase.*
3. *from 2024 onwards, support the development and roll out of cooperative net-zero strategic projects under the NZIA to create full carbon capture, transport and storage value chains, including across borders.*
4. *by 2025 at the latest, enable their geological services to contribute existing data and to generate new data to contribute to an EEA-wide investment atlas of potential CO₂ storage sites.*

CCS Directive

One of the cornerstones of Europe's approach to CO₂ storage is the CCS Directive. It establishes a comprehensive legal framework to ensure that any long-term storage of CO₂ underground is done in an environmentally safe way. In fact, the directive explicitly defines “*environmentally safe geological storage*” of CO₂ as “*the permanent containment of CO₂ in such a way as to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health*” (CCS Directive, Article 1).

⁴⁹⁹ Source: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Towards an ambitious Industrial Carbon Management for the EU COM/2024/62 final p10-13 <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2024:62:FIN>

The directive's primary focus is on making sure only appropriate sites are used to store CO₂, and that companies have the proper permits. *Member States* that decide to allow CO₂ storage must first assess potential storage locations in their territory. This means countries need to survey their geological formations (deep saline aquifers, depleted oil/gas fields, etc.) and identify where there is capacity to store CO₂ safely. According to the directive, a site can only be selected and approved as a storage location if detailed analysis shows "no significant risk of leakage, and no significant environmental or health risks exist" (Article 4(4)). In other words, regulators will only authorize a CO₂ storage site if they are confident the CO₂ will stay contained and not pose any serious danger to the environment or human health. Before any company can begin storing CO₂, it must go through a rigorous permitting process. There are typically two key permits: an exploration permit and a storage permit.

- Exploration permit: This allows a company to explore a specific underground area to determine if it is suitable for CO₂ storage. The company can perform tests like seismic surveys or even small-scale CO₂ injections to gather data. The directive requires that exploration permits be granted only after the site has undergone a positive assessment by the authorities.
- Storage permit: If the exploration phase shows that the site is viable and safe, the company must then apply for a storage permit to inject and store CO₂ there. Importantly, the Directive gives the European Commission oversight on these permits as well: before a country issues a storage permit, it must notify the Commission, which can review and if necessary *require changes or even reject* the permit to ensure EU laws are uniformly upheld.

Once a site is up and running, the CCS Directive imposes strict rules to maintain safety and environmental protection. The operator of the storage site must continuously monitor the injected CO₂ and the surrounding environment. A key component of the Directive is its treatment of third-party access. Specifically, Article 21 obligates EU Member States to guarantee access to CO₂ transport systems and storage facilities for entities that do not control the infrastructure. However, operators may be allowed to deny such access in situations where there are technical incompatibilities—such as when the quality or composition of the CO₂ stream doesn't meet required standards.

Typically, CO₂ initiatives must secure permits—such as exploration or storage authorizations—granted and monitored by national regulators to ensure projects adhere to relevant safety and environmental standards. These projects must also undergo a thorough Environmental Impact Assessment which obliges developers to evaluate and address possible environmental and societal impacts related to CO₂ capture, transport, and storage.

To support the consistent application of the CCS Directive, the European Commission released four nonbinding Guidance Documents. These documents provide best practices and technical advice for implementing the Directive throughout the EU. However, they're not official legal texts and don't carry any legal weight on their own. The four guidance papers are:

1. Guidance document 1. CO₂ storage life cycle and risk management framework⁵⁰⁰.

⁵⁰⁰ Source: European Commission. Directorate- General for Climate Action. *Guidance document 1. CO₂ storage life cycle and risk management framework*. 2024, https://climate.ec.europa.eu/document/download/951d14ea-ce0f-4753-92dd-35ba88920888_en?filename=ccs-implementation_gd1_en.pdf

2. Guidance document 2. Characterisation of the storage complex, CO₂ stream composition, monitoring and corrective measures⁵⁰¹.
3. Guidance document 3. Criteria for transfer of responsibility to the competent authority⁵⁰².
4. Guidance document 4. Financial security and financial contribution⁵⁰³.

As a new version of the guidelines was adopted recently in 2024, it is worth a more in-depth discussion.

Guidance Document 1 – lays out a comprehensive approach to managing risks throughout all phases of a CO₂ storage project. It breaks a project into key stages (site assessment, site characterization, development, operation, closure, and post-closure stewardship) and describes what should happen at each stage to ensure safety. A core message of this guidance is that risk management must be continuous and site-specific. Operators should identify potential hazards (like possible CO₂ leaks, seismic events, or well failures) and evaluate the likelihood and impact of each. It introduces tools like risk matrices to determine which risks are significant. The principle of “as low as reasonably practicable” is emphasized – meaning that all significant risks should be reduced as much as possible without being unrealistic or excessively costly.

Legislative context⁵⁰⁰

The CCS Directive establishes a legal framework for the geological storage of CO₂. It specifies that environmentally safe CO₂ geological storage means the permanent containment of CO₂ in such a way as to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health (CCS Directive, Article 1). This document provides guidance to operators and competent authorities on how to interpret and implement the obligations for risk management related to the following requirements in the CCS Directive:

- Article 4(4): A geological formation shall only be selected as a storage site, if under the proposed conditions of use there is no significant risk of leakage, and if no significant environmental or health risks exist.
- Annex I, Step 3.3: Risk assessment:
- Hazard characterisation – site-specific risk identification
- Exposure assessment – based on the hazards identified.
- Effects assessment – based on the hazards identified.
- Risk characterisation – based on the hazard, exposure and effects assessment.

⁵⁰¹ Source: European Commission. Directorate- General for Climate Action. *Guidance document 2. Characterisation of the storage complex, CO₂ stream composition, monitoring and corrective measures*. 2024 https://climate.ec.europa.eu/document/download/6f19cb98-b791-466d-8f3c-32c5bb12be2d_en?filename=ccs-implementation_gd2_en.pdf

⁵⁰² Source: European Commission. Directorate- General for Climate Action. *Guidance document 3. Criteria for transfer of responsibility to the competent authority*. 2024 https://climate.ec.europa.eu/document/download/f647725c-e86f-4bea-b698-48c6b0390ad3_en?filename=ccs-implementation_gd3_en.pdf

⁵⁰³ Source: European Commission. Directorate- General for Climate Action. *Guidance document 4. Financial security and financial contribution*. 2024. https://climate.ec.europa.eu/document/download/9a6b221d-642e-499e-a5a0-298ce1068b21_en?filename=ccs-implementation_gd4_en.pdf

Apart from the ban on storing CO₂ storage in the water column and the requirements set out in the Water Framework Directive 2000/60/EC², the CCS Directive is not prescriptive regarding the type of storage option or formation that can be used for geological storage. The CCS Directive allows for storage in sedimentary and igneous aquifers, hydrocarbon fields, coal seams, and in principle other options such as salt caverns. However, the CCS Directive is prescriptive on the required characteristics of a suitable storage complex. It states that all prospective storage sites must meet the requirement in Article 4(4): under the proposed conditions of use there is no significant risk of leakage, and no significant environmental or health risks. However, from a risk perspective, knowledge from previous operations at the storage site can be leveraged to demonstrate conformance with this requirement.

There may also be circumstances where CO₂ is injected into the subsurface as part of enhanced hydrocarbon recovery (EHR) operations, or as part of geothermal operations (e.g. re-injection of produced CO₂, or using CO₂ as a geothermal working fluid). If the primary aim of such operations is the permanent and environmentally safe storage of CO₂, a risk-based approach suited for CO₂ storage projects should be used. This is also reflected in Recital 20 in the CCS Directive which states that ‘the provisions of the CCS Directive should apply if EHR is combined with geological storage of CO₂.

In Europe, EHR is typically permitted under the regulations governing petroleum exploration and production, which may not require compliance with all requirements of the CCS Directive. Similarly, geothermal operations are generally permitted under regulations specific to geothermal energy projects with no requirement to ensure the containment of any re-injected CO₂ or CO₂ used as working fluid. If the operators of a geothermal installation capture and reinject CO₂ underground to reduce GHG emissions, they will need to apply for CO₂ storage permit in accordance with Directive 2009/31/EC in addition to any other permit needed for their operation. This, however, does not apply in the cases where the CO₂ reinjection is configured in a closed cycle system, being contained within the system for the entire operation, including geothermal systems that reinject exclusively CO₂ originating from the same aquifer.

Guidance Document 2 - focuses on the technical evaluation of the storage site and the CO₂ stream itself. The first part of this guidance deals with site characterization: it details how an operator should thoroughly study the geology of the proposed storage site and its surrounding area. This includes collecting extensive geological and geophysical data and building three-dimensional (3D) models of the underground rock formations. By running simulations of CO₂ injection in these models, operators can predict how the CO₂ plume will move and ensure that the site can handle the injected volumes without leaks or pressure problems. The second part covers the CO₂ stream quality and monitoring plans. It makes clear that the CO₂ being injected should consist mostly of CO₂ itself and not be used to dump other industrial waste gases – any impurities in the stream must be within acceptable limits so they don’t compromise storage safety. Monitoring isn’t only during active injection; it continues for years *after* injection has ceased to ensure the CO₂ remains securely in place.

Legislative context

This section provides guidance to operators and competent authorities on how to interpret and meet the obligations stipulated by Article 4(2) and Article 4(3) in the CCS Directive. Article 4(2) states that Member States that intend to allow geological storage of CO₂ in their territory must assess the storage capacity available in parts or in the whole of their territory. Article 4(3) states that ‘the

suitability of a geological formation for use as a storage site must be determined through a characterisation and assessment of the potential storage complex and surrounding area pursuant to the criteria specified in Annex I'.

Annex I to the CCS Directive sets out the specific criteria to be met to characterise and assess the potential storage complex and surrounding area. It requires operators to complete the assessment according to best practice at the time of the assessment. Best practice may vary depending on site-specific considerations. The steps to carry out during the site characterisation process in Annex I include:

1.Data collection.

- Sufficient data must be collected to construct a volumetric and three-dimensional static (3D)-earth model for the storage site and storage complex, including the caprock, the surrounding area and hydraulically connected areas.

2.Three-dimensional (3D) static geological modelling.

- Using the data collected in Step 1, a three-dimensional static geological earth model, or a set of such models, of the candidate storage complex, including the caprock and the hydraulically connected area and fluids must be built using computer reservoir simulators.

3.Characterising storage dynamic behaviour, sensitivity and risk assessment.

- The process to characterise storage dynamic behaviour must be based on dynamic modelling. It must comprise multiple time-step simulations of CO₂ injection into the storage site using the three-dimensional static geological earth model(s) in the computerised storage complex simulator constructed.
- Multiple simulations must be carried out to identify the sensitivity of the assessment to assumptions made about parameters. The simulations must be based on altering parameters in the static geological earth model(s) and changing rate functions and assumptions in the dynamic modelling exercise. The risk assessment must factor in any significant sensitivity.
- The risk assessment must include the following steps:
 - hazard characterisation
 - exposure assessment
 - effects assessment
 - risk characterisation

Guidance Document 3 focuses on the conditions for transferring responsibility for a CO₂ storage site from the operator to the competent authority, as laid out in Article 18 of the CCS Directive. This handover can happen only once it's proven that the stored CO₂ is safely and permanently contained. The guidance outlines how to demonstrate that the behaviour of injected CO₂ matches predictions, that no leakage has occurred for at least ten years, and that the site is moving toward long-term stability. It also provides advice on what documentation and evidence should be included in the transfer report, including model conformity, monitoring results, and the effectiveness of trapping mechanisms.

The minimum post-closure monitoring period is usually 20 years, though it can be shortened if safety can be proven earlier. Additionally, the site must be physically sealed, injection facilities removed, and all relevant data and models handed over to the authorities for ongoing stewardship.

Legislative context

After a storage site is closed, the operator remains liable for monitoring, reporting, taking corrective measures and surrendering allowances in the event of leakage, until these obligations are transferred to the competent national authorities in accordance with Article 18 of the CCS Directive.

This guidance clarifies the following obligations:

1. Article 18(1)(a), 18(1)(d) and 18(2)(a)-(c): Submission of a transfer report documenting that the following conditions have been met:
 - all available evidence indicates that the stored CO₂ will be completely and permanently contained;
 - the storage site has been sealed and the injection facilities have been removed;
 - the actual behaviour of the injected CO₂ conforms to the modelled behaviour;
 - there is no detectable leakage;
 - the storage site is evolving towards a situation of long-term stability.
2. Article 18(1)(b): A minimum period determined by the competent authority has elapsed. This minimum period is to be no shorter than 20 years, unless the authority is convinced that the criterion in 18(1)(a) is met before the end of that period.

Guidance Document 4 provides detailed instructions on the financial aspects required under the CCS Directive for CO₂ storage projects. It focuses on two key financial obligations: financial security and financial contribution. Financial security ensures that storage site operators can cover the costs of obligations such as monitoring, corrective measures, and potential permit withdrawal scenarios, without burdening taxpayers. This must be valid throughout the project's life until the site is safely handed over to the competent authority. The amount of financial security should reflect site-specific risks, be periodically reviewed, and may include a mix of financial instruments like insurance, trust funds, or bank guarantees. Separately, the financial contribution is a one-time payment the operator must make before transferring site responsibility to cover post-transfer monitoring and any unexpected issues. This amount is based on anticipated costs over at least 30 years. The document aims to strike a balance—protecting public interests while keeping CCS projects financially feasible for developers.

Legislative context

Article 19 of the CCS Directive requires that Member States ensure that, when applying for a storage permit, the potential operator must provide proof that adequate provisions can be established, by way of financial security or any other equivalent, based on arrangements to be decided by the Member States.

1. Article 19(3) states that the financial security will remain valid and effective:

- after a storage site has been closed in accordance with Article 17(1) points (a) or (b), until the responsibility for the storage site is transferred to the competent authority in accordance with Article 18(1) to (5); and
- after the withdrawal of a storage permit by Article 11(3);
 - until a new storage permit has been issued; and
 - where the site is closed in accordance with Article 17(1)(c), until the transfer of responsibility in accordance with Article 18(8), provided the financial obligations referred to in Article 20 have been fulfilled.

2. Article 19(2) requires that the financial security should be periodically adjusted to take account of changes to the assessed risk of leakage and the estimated costs of the obligations under the permit issued under the CCS Directive.

3. Article 19(1) clarifies that the amount of the required financial security is to be based on the estimated cost of meeting the obligations arising out of the permit, as well as obligations arising from the ETS Directive.

In summary, these four Guidance Documents act as a toolkit to accompany the CCS Directive. They help translate high-level legal requirements into practical steps, methodologies, and checks for those involved in CCS projects.

Environmental Impact Assessment Directive

Even with strong regulations and guidance for CO₂ storage operations, each project must also comply with the EU's broader environmental protection laws. The most important of these is the Environmental Impact Assessment Directive. Certain infrastructure projects—like those involving CO₂ storage—must undergo an environmental impact assessment. . Annex I and Annex II of the Environmental Impact Assessment Directive list the types of projects that are subject to assessment. Projects listed in Annex I always require an Environmental Impact Assessment because they are likely to have significant environmental effects. Projects in Annex II are not automatically subject to EIA but must be screened by Member States to determine whether an EIA is needed, based on their size, nature, and potential environmental impact. Categories include. Member States use screening criteria (Annex III) to decide if a project under Annex II requires an EIA. For CO₂ storage, the assessment is a key step in securing a permit.

In countries such as the Netherlands, authorities require a broad evaluation that looks at the entire CO₂ value chain—capture, transport, and storage. Developers are expected to plan the environmental impact assessment alongside other permit-related documentation, ensuring everything is ready within the same timeframe. It's also essential to identify early on whether the proposed site is near protected areas, like Natura 2000 zones or archaeological sites, as this can influence the scope of the assessment. For CO₂ storage in particular, environmental concerns vary depending on whether the site is onshore or offshore. Common issues include nitrogen emissions, air and water quality, biodiversity, noise, and the impact on the geology deep below the surface. Since storage often occurs more than 500 meters underground, where environmental law gives way to mining regulations, developers must also assess

how CO₂ injection might alter subsurface rock formations or risk leaks through wells, faults, or weak cap rocks.⁵⁰⁴

EST directive and Monitoring Regulation

Under the Monitoring Regulation, any CO₂ captured for storage can be deducted from the installation's reportable emissions, provided it is transferred for permanent storage at an eligible site. This is formalized in Article 49 of the Monitoring Regulation, which allows operators to subtract CO₂ *“transferred out of the installation to any of the following installations:*

(i) a capture installation for the purpose of transport and long-term geological storage in a storage site permitted under Directive 2009/31/EC;

(ii) a CO₂ transport infrastructure with the purpose of long-term geological storage in a storage site permitted under Directive 2009/31/EC;

(iii) a storage site permitted under Directive 2009/31/EC for the purpose of long-term geological storage.”

By including capture installations and CO₂ transport infrastructure in this list, the regulation ensures that captured CO₂ remains deductible even if it goes first to an intermediate compression or transport facility before reaching the final storage site.

Main Legal Issues in Developing CO₂ Storage Projects under the EU Law Framework

The development of CO₂ storage projects in the European Union is a critical component of climate strategy, but it comes with significant regulatory and technical challenges. This overview highlights the key legal, procedural, and operational hurdles that project developers must overcome to ensure safe and effective long-term CO₂ storage.

Launching a CO₂ storage project in the EU requires navigating a complex legal framework. In addition to the CCS Directive, developers must comply with laws on environmental assessments, land use, water, and mining. The permitting process is often slow due to the uniqueness of each site, which demands fresh technical and safety reviews. While these safeguards ensure safety, they also lengthen timelines. To address this, new EU policies aim to streamline permitting. Until then, project developers must be ready for a detailed and sometimes lengthy approval process.

A major issue is who holds responsibility if something goes wrong decades after CO₂ has been stored. Under the CCS Directive, operators are liable during injection and post-closure phases and must eventually prove the site is permanently safe before transferring responsibility to the state. To ensure this, they must provide financial security and contribute to long-term monitoring costs. This system safeguards the public but increases project costs and risk for companies.

Because stored CO₂ must remain underground for centuries, long-term monitoring is essential. The CCS Directive requires continuous oversight during operation and reduced but sufficient monitoring after closure. Emerging technologies like satellite sensors may improve detection, but funding and institutional commitment are needed to sustain oversight for decades. Transferring site control to public authorities adds further complexity, as they must ensure data continuity and maintain

⁵⁰⁴ Source: LEVINA, Ellina. *Thought Leadership – CO₂ Storage Permitting Process in the European Union: A Guide*. The Global CCS Institute. December 10th, 2024. <https://www.globalccsinstitute.com/resources/publications-reports-research/thought-leadership-co2-storage-permitting-process-in-the-european-union-a-guide/>

monitoring standards. Though the legal framework is strong, turning these requirements into long-term practice remains a challenge.

10.4. CO₂ geological storage in Lithuania: Legal challenges and strategic perspectives

Lithuania chosen a notably cautious stance toward geological storage of CO₂. While some European countries actively explore or already have implemented geological storage projects, Lithuania has taken a clear stance against allowing such projects within its borders. This chapter examines Lithuania's current laws and strategic reasoning behind its prohibition of geological CO₂ storage. It also provides recommendations on strengthening Lithuania's regulatory and policy framework regarding CO₂ storage.

Legal Regulations on Geological CO₂ Storage in Lithuania

Lithuania's laws explicitly forbid geological storage of CO₂ in various environments, including underground geological structures, aquifers, the water column, and geological formations beneath the seabed. Previously, Lithuania's Law on Geological Storage of Carbon Dioxide⁵⁰⁵ outlined conditions under which storage might have been permitted. However, amendments introduced in 2019 to the Law on Subsurface⁵⁰⁶ Art. 14 banned any form of geological CO₂ storage by clearly stating: "the injection and/or storage of carbon dioxide in natural and/or artificial subsurface cavities or aquifers is prohibited." This amendment came into force on July 1st, 2020, completely ending the possibility of geological CO₂ storage in Lithuania.

This regulation is consistent with EU law and international commitments. CCS directive allows member states the flexibility to opt-out of geological CO₂ storage. Additionally, Lithuania supports regional environmental commitments, having ratified the Helsinki Convention, which explicitly prohibits CO₂ storage beneath the Baltic Sea. Also, Lithuania has not yet ratified the London Convention or its London Protocol, which aims to create favourable conditions for CO₂ sub-seabed geological formation. This regulatory approach places Lithuania in a position prioritizing environmental caution and safety above potential climate benefits or economic incentives.

The updated National Energy Independence Strategy (2024)⁵⁰⁷ clarifies Lithuania's strategic intentions, stating explicitly that the country will not pursue domestic geological CO₂ storage. However, Lithuania remains committed to broader European climate objectives through regional cooperation, infrastructure development, and participation in international transport of CO₂ to offshore storage locations. Clauses 198 and 199 of this strategy specifically address the development of export terminals and transportation networks for CO₂ storage outside Lithuanian jurisdiction.

Although the environmental aspects related to geological CO₂ storage and liability for potential damages are critically important and widely debated—both in the scholarly literature and in discussions concerning the implementation of EU and national legal frameworks—the fact remains that, as previously noted, Lithuania has prohibited geological CO₂ storage within its territory. Consequently, engaging in deeper discussions on this issue may be premature.

⁵⁰⁵ Source: Lietuvos Respublikos anglies dioksido geologinio saugojimo įstatymas, 2011 m. birželio 28 d. Nr. XI-1550 (Suvestinė redakcija nuo 2018-07-01) <https://www.e-tar.lt/portal/lt/legalAct/TAR.3BB20C9F088C/asr>

⁵⁰⁶ Source: Lietuvos Respublikos žemės gelmių įstatymas (1995 m. liepos 5 d. Nr. I-1034 (Suvestinė redakcija nuo 2023-07-01) <https://www.e-tar.lt/portal/lt/legalAct/TAR.13E108ED3981/asr>)

⁵⁰⁷ Source: Lietuvos Respublikos Seimas nutarimas Dėl Nacionalinės darbotvarkės „Nacionalinė energetinės nepriklausomybės strategija“ patvirtinimo 2012 m. birželio 26 d. Nr. XI-2133

<https://www.e-tar.lt/portal/lt/legalAct/TAR.E151BC09AE62/asr>

This approach strategically positions Lithuania to actively engage with EU climate targets while preserving national environmental integrity. It indicates a preference for international cooperation and logistical support for CO₂ storage over domestic geological storage projects, reducing local environmental risks.

10.5. Recommendations for Lithuania's Regulatory and Strategic Framework

Helsinki Convention. Given Lithuania's commitment to the Helsinki Convention, ongoing active involvement in regional discussions and potential amendments is essential. The Helsinki Convention currently prohibits the dumping of waste into the Baltic Sea. This ban has been interpreted to include the storage of CO₂ in geological formations beneath the seabed. As a legally binding regional agreement, it means that even if Lithuania were willing to pursue offshore CO₂ storage, it would not be permitted unless the convention is amended. Lithuania can maintain its support for this ban, both in its national policies and during discussions within the convention's governing body. At the same time, Lithuania has an opportunity to engage in constructive regional dialogue about what the future might hold. In June 2023, some Baltic Sea states began informal talks on possibly amending Article 11 of the convention to allow for CO₂ storage, recognizing the current legal barrier⁵⁰⁴. Any such change would require unanimous agreement among all contracting parties.

Lithuania should support scientific studies to assess environmental risks, contribute national data, and help define under what conditions—if any—regional CO₂ storage could be acceptable and play an active role in regional dialogues, promoting comprehensive scientific and environmental impact assessments on any proposed changes to this article.

London Protocol. While Lithuania maintains a prohibition on domestic geological storage, ratification of the London Protocol and its amendments could significantly enhance its international collaboration capabilities. The 2009 amendment explicitly enables cross-border CO₂ transport and storage agreements, contingent on mutual consent among involved countries. Ratifying this Protocol would clarify Lithuania's legal position, facilitating future CO₂ export initiatives without requiring domestic storage.

It's important to emphasize that although the London Protocol and its subsequent amendments support the idea of CO₂ storage beneath the seabed, they do not compel any country to permit such storage within its own territory. The relevant provision clearly states:

“Carbon dioxide streams referred to in paragraph 1.8 may only be considered for dumping, if:

1. disposal is into a sub-seabed geological formation; and
2. they consist overwhelmingly of carbon dioxide. They may contain incidental associated substances derived from the source material and the capture and sequestration processes used; and
3. no wastes or other matter are added for the purpose of disposing of those wastes or other matter.”

The wording “may only be considered” underscores that ratifying the protocol does not obligate a country to establish its own CO₂ storage infrastructure. As such, joining the protocol would not conflict with Lithuania's national legislation or with its commitments under the Helsinki Convention, which currently prohibits CO₂ storage beneath the Baltic Sea. In fact, we can see that other countries bound by the Helsinki Convention—such as Finland and Estonia—have ratified both the London Protocol and its 2009 amendment.

Guidelines for CO₂ Storage Research Initiatives. Another essential recommendation is for Lithuania to develop clear guidelines allowing limited research-based or small-scale CO₂ injection activities. Although Lithuania currently bans all forms of injection, the Art. 2(2) of the CCS directive provides exemptions for research injections under certain conditions (less than 100 kilotonnes). Clear guidelines will enable Lithuanian researchers to participate in international research collaborations without conflicting with domestic prohibitions, fostering scientific advancement while maintaining strict environmental safeguards.

10.6. CO₂ transportation in the EU: Legal framework

This part of the study explores the evolving legal and regulatory framework governing the transportation of CO₂ within the European Union and under international law, in the context of advancing industrial carbon management and achieving climate neutrality. It begins by analysing recent EU policy initiatives—such as the European Commission’s communications on industrial carbon management and energy infrastructure—which underscore the urgency of developing robust CO₂ transport systems, including pipelines and maritime shipping. The discussion then turns to the Net Zero Industry Act, which formally recognises all CO₂ transport modes and sets the groundwork for a more integrated and legally supported infrastructure. Following this, the analysis shifts to international law, particularly the London Protocol and its amendments, which address the legal conditions for cross-border CO₂ shipment and storage. The paper then critically examines EU law, especially the EU ETS and the CCS Directive.

Towards an Ambitious Industrial Carbon Management for the EU

The European Commission's communication, *"Towards an Ambitious Industrial Carbon Management for the EU"*⁵⁰⁸ clearly articulates that transport infrastructure for CO₂ is central to enabling the successful deployment of industrial carbon management technologies. A critical aspect highlighted is the complexity involved in establishing this infrastructure. Key issues identified include substantial upfront investment requirements, lengthy planning and permitting procedures, uncertainty surrounding future CO₂ volumes, and coordination challenges inherent to cross-border value chains. Particularly noteworthy is the emphasis placed on the importance of developing specialized CO₂ shipping capacity in the short term, with pipelines expected to become the predominant transport mode by 2040.

The communication also addresses the necessity of standardizing the quality and specifications of CO₂ streams to ensure interoperability and prevent fragmentation of the emerging transport market. To address current regulatory shortcomings, the Commission recommends initiating comprehensive preparatory efforts starting in 2024, aiming to establish an integrated, EU-wide regulatory framework covering technical standards, market structures, cross-border network planning, and investment incentives.

Financial implications are also thoroughly considered. The document estimates that approximately €12.2 billion will be required by 2030 to develop adequate CO₂ transportation networks, with significantly greater investment needs expected thereafter. Furthermore, the strategic integration of existing infrastructure—such as repurposing gas pipelines—and ensuring compatibility with electricity,

⁵⁰⁸ Source: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Towards an ambitious Industrial Carbon Management for the EU COM/2024/62 final <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2024:62:FIN>

gas, and hydrogen networks are recommended to optimize overall system efficiency and cost-effectiveness.

The Commission foresees to:

- from 2024, initiate preparatory work in view of a proposal for a possible future CO₂ transport regulatory package; it will consider issues including market and cost structure, cross-border integration and planning, technical harmonisation and investment incentives for new infrastructure, third-party access, competent regulatory authorities, tariff regulation and ownership models.
- from 2024, work towards proposing an EU-wide CO₂ transport infrastructure planning mechanism in cooperation with Member States and the CCUS Forum stakeholder platform. The work related to network planning will also assess to what extent it is possible to reuse/repurpose existing infrastructure for CO₂ transport and storage, when considering the priority for infrastructure needs of renewable gases, and if so, what regulatory changes are needed.
- from 2024, consider, in close engagement with industry, nominating European coordinators to support the early development of (cross-border) infrastructure projects.
- develop emissions accounting rules in the context of the EU ETS to enable all means of transport of CO₂, and ensure liability for leakage.
- work with the European standardisation bodies to establish minimum standards for CO₂ streams to be used in a network code, applicable to all industrial carbon management solutions, and in addition in cooperation with Member States to consider guidelines on 'incidental associated substances' to ensure the integrity of the infrastructure and reservoirs.
- promote through the International Maritime Organization the development of any necessary guidelines on safe transportation of CO₂ by sea.

Although ministers from several European Union member states called on the European Commission to introduce a regulatory framework for cross-border CO₂ transport by 2025, the Commission has opted to postpone the initiative. The regulatory framework for the CO₂ market and infrastructure in the EU is expected in the second half of 2026.

Grids, the Missing Link - An EU Action Plan for Grids

The European Commission's communication titled "Grids, the Missing Link - An EU Action Plan for Grids"⁵⁰⁹ action Plan identifies electricity grids as essential for integrating various energy systems, including the rapidly expanding infrastructure required for CO₂ transport. The document explicitly emphasizes the importance of coordinated infrastructure planning across electricity, hydrogen, and CO₂ networks, recognizing the interdependencies essential for achieving an efficient energy transition. This integrated planning is vital as it supports the acceleration of projects designed to transport

⁵⁰⁹ Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Grids, the missing link - An EU Action Plan for Grids COM/2023/757 final <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2023%3A757%3AFIN&qid=1701167355682>

captured carbon to storage and utilization sites. However, the report highlights considerable hurdles in implementing these infrastructures. It acknowledges delays and complexities in the permitting process, funding shortfalls, and issues related to public acceptance as significant barriers to developing effective CO₂ transportation networks. The Commission’s action-oriented approach is underscored by proposals for clearer regulatory frameworks, improved long-term planning, and strengthened cross-border coordination.

Net Zero Industry Act

The Net Zero Industry Act formally recognizes CO₂ transportation infrastructure as a key component of the EU’s strategy for net-zero technologies. It explicitly includes all modes of transport—not just pipelines, but also ships, road, and rail—as eligible means for transporting CO₂ to storage facilities. This broad definition is important because previous EU climate legislation focused mostly on pipelines, creating legal uncertainty for other transport methods.

“‘CO₂ transport infrastructure’ means the network of pipelines, including associated booster stations, for the transport of CO₂ to the storage site, as well as any ships, road or rail transport modes, including liquefaction devices and temporary storage facilities if needed, for the transport of CO₂ to the harbour facilities and storage site;” (Article 3(29)).

To support the achievement of the Union’s CO₂ injection capacity target, both the EU and its Member States are required to undertake all reasonable efforts to develop the necessary CO₂ transport infrastructure, including cross-border connections. This development must consider the economic and environmental advantages of locating capture and storage sites in close proximity. In line with this objective, Member States are obliged to adopt appropriate measures to ensure access to CO₂ transport networks and geological storage facilities, particularly where such access is economically viable or where a customer is prepared to bear the associated costs, in accordance with Article 21 of CCS directive. Furthermore, in cases where CO₂ is captured and initially transported within one Member State but is ultimately stored in another, Member States must coordinate their efforts to facilitate such transboundary operations. (Article 22)

London Protocol⁵¹⁰: The 2006 and 2009 Amendments

In 2006, a significant development under the London Protocol occurred when Australia, the United Kingdom, Norway, France, and Spain jointly proposed an amendment to Annex 1. This revision explicitly permitted the disposal of captured CO₂ streams into sub-seabed geological formations, provided that these streams consist almost entirely of CO₂ and contain no other waste materials. Entering into force in 2007, the amendment marked a critical step in legitimising offshore carbon storage under international environmental law.

In the aftermath, the International Maritime Organization examined the implications of cross-border CO₂ transfers for CCUS. The International Maritime Organization secretariat observed that Article 6 of the Protocol was originally designed to prevent parties from exporting waste to non-signatory states—primarily to avoid regulatory loopholes. However, it acknowledged that the provision, as it stood, could

⁵¹⁰ Source: Slaughter and May. *Regulatory Barriers to a European Market for CO₂ Transport by Ship*. February 15th, 2024. <https://www.slaughterandmay.com/insights/importedcontent/regulatory-barriers-to-a-european-market-for-co2-transport-by-ship/>

obstruct CCUS deployment by broadly prohibiting the transboundary movement of CO₂ for sub-seabed storage, including transfers between contracting parties themselves.

To address this, an amendment was adopted in 2009, introducing a new paragraph to Article 6. This provision authorised the export and import of CO₂ intended for offshore geological storage, under two primary conditions:

Firstly, States involved in such transactions must enter into a formal agreement or arrangement delineating the responsibilities for permitting and oversight. Where exports are destined for non-contracting parties, these arrangements must incorporate regulatory safeguards consistent with the Protocol—especially those in Annex 2. In its 2013 Guidance on the Implementation of Article 6.2 on the Export of CO₂ Streams for Disposal in Sub-seabed Geological Formations for the Purpose of Sequestration (LC 35/15, Annex 6)⁵¹¹, the International Maritime Organization offered a detailed interpretation of the obligations imposed on both contracting and non-contracting parties under the London Protocol. This guidance delineates the procedural and legal responsibilities associated with cross-border CO₂ export activities. Specifically, it affirms that when a CO₂ stream is loaded onto a vessel within the territory of a contracting party, that party bears responsibility for issuing the necessary permits. Moreover, this obligation extends to cases where a vessel flying the flag of a contracting party is loaded with CO₂ in a non-party territory for the purpose of transporting it to another state. In such instances, the contracting party remains accountable for ensuring that the legal and environmental safeguards contained within any agreement or arrangement—particularly those related to permitting—are fully consistent with the objectives of the Protocol. Where CO₂ is transferred to a non-party state for storage, the contracting party must assume complete responsibility for guaranteeing that the bilateral arrangement reflects an appropriate and enforceable allocation of regulatory duties. This requirement is intended to uphold a uniform standard of environmental protection, even when a non-party receives and stores carbon dioxide originating from a contracting party. It is also recognised that bilateral agreements are necessary solely for the purpose of CO₂ storage, and that vessels transporting CO₂ may transit through the territorial waters of third-party states without obligating those states to issue formal declarations or conclude bilateral agreements.

Secondly, all such agreements must be reported to the IMO.

This 2009 Amendment enables nations without domestic offshore storage capacity to participate in CCUS initiatives within a legal international framework. However, its formal entry into force remains pending, contingent on ratification by two-thirds of the Protocol's contracting parties (36 states). As of now, only ten parties—Norway, the United Kingdom, the Netherlands, Iran, Finland, Estonia, Sweden, Denmark, Belgium, and the Republic of Korea—have ratified the amendment.

Recognising the urgency of advancing CCUS capabilities, contracting parties adopted a resolution in October 2019 permitting provisional application of the 2009 Amendment. Under this mechanism, states may implement the amendment's provisions prior to their formal ratification. According to the International Maritime Organization, several countries—Belgium, Norway, the Netherlands, Denmark, Sweden, the Republic of Korea, and the United Kingdom—have begun doing so.

Nonetheless, some legal experts argue that this provisional approach may not be ideal. They contend that the parties could have instead issued an interpretive declaration clarifying that Article 6 does not

⁵¹¹ Source: International Maritime Organization. *Report of the Thirty-Fifth Consultative Meeting and the Eight Meeting of Contracting Parties*. Parties, LC 35/15 October 21st, 2013. https://www.umweltbundesamt.de/sites/default/files/medien/381/dokumente/london_protocol_-_lc_35-15_-_report_of_the_thirty-fifth_consultative_meeting_and_the_eight_meeting_of_the_contracting_parties.pdf

apply to the transboundary movement of CO₂ for storage purposes—thereby eliminating the need for a formal amendment altogether.

Regardless, the 2019 resolution effectively dismantled the final significant international legal obstacle to CO₂ export and storage. The first bilateral agreement under the amended Article 6 was concluded between Belgium and Denmark on September 26th, 2022. Other states have since expressed intentions to formalise similar arrangements—such as Belgium and Norway, Norway and Sweden, and the United Kingdom and Norway.⁵¹²

Notably, the amended Article 6 permits a range of international legal arrangements to satisfy its requirements. In September 2022, the European Commission released a legal assessment affirming that EU and EEA law frameworks are sufficient to constitute such arrangements under the revised Article 6. From the Commission’s perspective, bilateral agreements among EU/EEA member states should be limited to residual issues not addressed by EU law⁵¹³. The Belgium-Denmark agreement serves as a practical example of this hybrid approach.

The Belgium–Denmark agreement established the legal framework under the London Protocol to allow international CO₂ transport. A key outcome of this agreement is Project Greensand, which demonstrates how captured carbon dioxide from Belgium can be legally shipped and permanently stored beneath the seabed off the coast of Denmark. Greensand Future is a CO₂ storage project located in the Danish North Sea. The facility is expected to begin storing carbon dioxide by late 2025 or early 2026, potentially becoming the first operational CO₂ storage site in the European Union designed to directly support climate change mitigation efforts. Initially, Greensand Future aims to store 400,000 tonnes of CO₂ per year, with plans to gradually expand that capacity to 8 million tonnes annually by 2030. A Final Investment Decision was made in December 2024, unlocking over \$150 million in investment to develop infrastructure across the CCS value chain. In March 2023, Project Greensand carried out a pilot operation, successfully transporting liquefied CO₂ from a chemical plant in Antwerp, Belgium, to the Danish North Sea. The pilot involved 23 partners from industry, government, and academia and received DKK 197 million (€26.5 million) in funding from Denmark’s Energy Technology Development and Demonstration Program. In November 2024, INEOS signed a multi-year agreement with Royal Wagenborg for CO₂ transport. The Dutch shipping company will supply a newly built CO₂ carrier for Greensand operations.⁵¹⁴

Also, Denmark, Belgium, the Netherlands, and Sweden have each signed Memoranda of Understanding with Norway to support the cross-border transportation of CO₂ for permanent geological storage. In addition, Sweden and Denmark have agreed on a separate bilateral arrangement to boost collaboration in CO₂ transport and storage. These agreements were finalized on April 15 during the informal meeting of EU Energy Ministers, held in Brussels on April 15–16, 2024. The primary goal of these arrangements is to overcome legal and logistical barriers currently hindering the deployment of CCS. They build on a

⁵¹² Source: HAKIREVIC PREVLJAK, Naida. *Danish-Belgian CCS agreement paves way for creating ‘actual market’ for maritime transport of CO₂*. October 3rd, 2022. Offshore Energy, available. <https://www.offshore-energy.biz/danish-belgian-ccs-agreement-paves-way-for-creating-actual-market-for-maritime-transport-of-co2/>

⁵¹³ Source: European Commission. *Services analysis paper for the Information Exchange Group (IEG) under Directive 2009/31/EC. The EU legal framework for cross-border CO₂ transport and storage in the context of the requirements of the London Protocol. Analysis paper final 0930*. September 30th, 2022. https://climate.ec.europa.eu/document/dfbbc90c-071e-4088-ada2-7af467084b30_en.

⁵¹⁴ Source: NS Energy. *Greensand Future CCS. Denmark*. 7th February, 2025. https://www.nsenergybusiness.com/projects/greensand-future-ccs-denmark/?utm_source=chatgpt.com&cf-view&cf-view

growing number of prior agreements, declarations, and initiatives across Europe aimed at enabling CO₂ storage—particularly in the North Sea—on behalf of exporting countries. Notably, the signatories are also among the countries that have accepted the 2009 amendment to Article 6 of the London Protocol and have declared its provisional application⁵¹⁵.

From this perspective, any remaining barriers under the London Protocol appear to stem more from political inertia than from legal complexity. In other words, it is not the structure of the Protocol that obstructs CO₂ shipping for storage, but rather the lack of coordinated political action—namely, the failure to ratify the 2009 Amendment or establish bilateral frameworks.

The regime for shipped CO₂ under the EU ETS^{516, 517}

EU ETS, which extends across the European Economic Area, obliges operators of regulated installations to acquire and surrender allowances equivalent to their CO₂ emissions—unless the CO₂ is captured and permanently stored as part of a CCUS process. The EU ETS was originally designed with an exclusive focus on pipeline-based CO₂ transport and did not foresee the possibility of maritime shipment to storage sites.

Under the Monitoring Regulation, operators are required to account for both direct and fugitive emissions from their facilities. However, the Regulation also permits the deduction of CO₂ emissions from an operator's total, provided that the CO₂ is captured from a regulated activity and transferred to a capture facility, transport infrastructure, or storage site within the EU or EEA for the purpose of long-term geological storage. The European Commission clarified—following a query from the Norwegian Environment Agency—that the use of maritime vessels to transport captured CO₂ does not affect an operator's right to deduct these emissions, provided the CO₂ is ultimately delivered to a storage site or pipeline network. However, CO₂ emissions lost due to leakage during transport remain the responsibility of the emitter and cannot be excluded from ETS calculations⁵¹⁸.

One of the most significant updates in the Monitoring regulation⁵¹⁹ is the recognition of non-pipeline transport modes in the CO₂ transport framework. Earlier EU ETS rules (under Directive 2003/87/EC Annex I) explicitly listed only “transport of CO₂ in pipelines” as an ETS activity. Now, the implementing

⁵¹⁵ Source: Global CCS Institute. *Five Northern European Countries Strengthen Cooperation on Cross-border CO₂ Transport and Storage*, April 25th, 2024. <https://www.globalccsinstitute.com/news-media/latest-news/five-northern-european-countries-strengthen-cooperation-on-cross-border-co2-transport-and-storage/>

⁵¹⁶ Source: Slaughter and May. *Regulatory barriers to a European Market for CO₂ Transport by Ship*. February 15th, 2024. <https://www.slaughterandmay.com/insights/importedcontent/regulatory-barriers-to-a-european-market-for-co2-transport-by-ship/>

⁵¹⁷ Source: FRATTINI, Linda; BECATTINI, Viola; MAZZOTTI, Marco. *Main current legal and regulatory frameworks for carbon dioxide capture, transport, and storage in the European Economic Area*. International Journal of Greenhouse Gas Control, 136, 2024, 104172, ISSN 1750-5836, <https://doi.org/10.1016/j.ijggc.2024.104172>.

⁵¹⁸ Source: See Letter from the Norwegian Ministry of Climate and Environment to the European Commission, DG CLIMA, ‘*The Norwegian CCS Demonstration Project – Request for Legal Clarifications Related to the ETS Directive and the MR-Regulation*’ (July 7th, 2019). In response, see Letter from the European Commission, Directorate-General, Climate Action to the Ambassador of Norway to the European Union” (Ref. Ares(2020)3943156 – 27/07/2020), cited in Weber (2021), p. 394. At the time of writing, the latter letter is not available online.

⁵¹⁹ Source: European Commission. Commission Implementing Regulation (EU) 2024/2493 of 23 September 2024 amending Implementing Regulation (EU) 2018/2066 as regards updating the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council ELI: http://data.europa.eu/eli/reg_impl/2024/2493/oj

regulation anticipates CO₂ being transported by ship, road tanker, or railcar to storage, and it ensures these modes are covered in monitoring and accounting.

Article 49⁵²⁰

Transferred CO₂

1. The operator shall subtract from the emissions of the installation any amount of CO₂ originating from the activities covered by Annex I to Directive 2003/87/EC that does not originate from zero-rated carbon and that is not emitted from the installation, but transferred out of the installation to any of the following installations:

- (i) a capture installation for the purpose of transport and long-term geological storage in a storage site permitted under Directive 2009/31/EC;
- (ii) a CO₂ transport infrastructure with the purpose of long-term geological storage in a storage site permitted under Directive 2009/31/EC;
- (iii) a storage site permitted under Directive 2009/31/EC for the purpose of long-term geological storage.

Article 3

Definitions

(55) ‘CO₂ transport’ means the transport of CO₂ for geological storage in a storage site permitted under Directive 2009/31/EC;

(63) ‘CO₂ transport infrastructure’ means an infrastructure as defined in Article 3(29) of Regulation (EU) 2024/1735; (‘CO₂ transport infrastructure’ means the network of pipelines, including associated booster stations, for the transport of CO₂ to the storage site, as well as any ships, road or rail transport modes, including liquefaction devices and temporary storage facilities if needed, for the transport of CO₂ to the harbour facilities and storage site;)

The CCS Directive

The CCS Directive primary focus is on the safe and environmentally sound storage of CO₂ (detailing requirements for site selection, permits, monitoring, closure, and post-closure responsibilities), The CCS Directive also contains important provisions related to the transport of CO₂ for storage. Firstly, the Directive’s scope covers the capture, transport, and storage sequence – it mandates that captured CO₂ streams must meet certain criteria (mostly CO₂ with no significant contaminants) before being transported and injected, to ensure no adverse environmental effects (Article 12, CCS directive) directive.

Notably, an amendment introduced by Directive CCS modified EU waste law to clarify that CO₂ transported for geological storage is *not* classified as “waste”. Specifically, Regulation (EC) No

⁵²⁰ Source: European Commission. Commission Implementing Regulation (EU) 2024/2493 of 23 September 2024 amending Implementing Regulation (EU) 2018/2066 as regards updating the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council ELI: http://data.europa.eu/eli/reg_impl/2024/2493/oj

1013/2006⁵²¹ (Art. 1(3)(h)) on waste shipments was amended to *exclude CO₂ captured and transported for the purposes of geological storage* from its scope. Additionally, in its proposal to amend Directive 2008/98/EC⁵²² on waste, the European Commission aims to ensure legal clarity by incorporating changes from CCS directive. These changes concern the exclusion of CO₂ that is captured, transported for the purpose of geological storage, and subsequently stored, from the scope of Directive 2008/98/EC. This will be achieved by replacing Article 2(1)(a) of Directive 2008/98/EC. These legal changes are crucial: it removed a potential barrier to transboundary CO₂ movement by ensuring that shipping CO₂ to a storage site would not trigger the complex restrictions that apply to hazardous waste shipments. In parallel, the EU and its Member States addressed international legal obstacles by supporting the amendment of the London Protocol to allow cross-border export of CO₂ for sub-seabed storage. A scenario already being realized through projects like the Northern Lights initiative (where CO₂ from several EU countries is planned to be shipped to offshore storage in the North Sea).

However, the CCS directive itself focuses on CO₂ transportation by pipelines. The CCS Directive sets out market access rules for CO₂ transportation networks and storage sites to ensure open and fair usage of infrastructure. Article 21 of the Directive obliges Member States to guarantee that potential users can obtain access to CO₂ transport networks and storage sites in a transparent and non-discriminatory way for the purpose of geological storage. In other words, if a pipeline or storage facility has available capacity, its operator should not unjustifiably refuse to transport or store someone else's captured CO₂. The Directive instructs Member States to apply objectives of "fair and open access," existing or reasonably foreseeable capacity in the network and storage. This framework is analogous to third-party access principles in energy markets – it prevents CO₂ transport and storage from becoming closed monopolies and encourages efficient use of shared pipelines and reservoirs. Operators of CO₂ transport networks or storage sites may refuse access only on legitimate grounds, chiefly lack of capacity or incompatibility of CO₂ stream specifications, and they must provide a reasoned justification for any refusal.

Even then, the Directive pushes for expansion of capacity where feasible: if access is denied due to capacity constraints, the operator is required to make "*necessary enhancements*" (e.g. increase pipeline throughput or develop additional storage capacity) if it is economic to do so and if the prospective user is willing to bear the cost (Art 21(4), CCS directive).

Article 22 of the CCS Directive requires Member States to have independent dispute resolution mechanisms so that any disagreements over access (including cross-border disputes) can be settled, according to the Directive's access criteria. Moreover, Article 24 calls for cooperation in case of transboundary CO₂ transport or storage, mandating that authorities in the concerned Member States coordinate to fulfil the Directive's requirements jointly. In summary, the CCS Directive provides a common legal basis for CO₂ transport operations across the EU, emphasizing fairness with third-party access rules.

In conclusion, the evolving legal framework governing CO₂ transportation in the European Union reflects a growing recognition of its pivotal role in achieving climate neutrality and supporting large-scale deployment of CCS technologies. Among the most significant provisions is the Net Zero Industry Act's inclusive definition of CO₂ transport infrastructure, which—crucially—extends legal recognition

⁵²¹ Source: Regulation (EC) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on shipments of waste, ELI: <http://data.europa.eu/eli/reg/2006/1013/2025-01-01>

⁵²² Source: Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives, ELI: <http://data.europa.eu/eli/dir/2008/98/2024-02-18>

to all modes of transport, including shipping, road, and rail, alongside pipelines. This broad scope addresses longstanding legal ambiguity and enables more flexible infrastructure development. Equally important are the access and coordination requirements enshrined in the CCS Directive, particularly Articles 21, which guarantee open, transparent, and non-discriminatory access to CO₂ networks and storage sites. On the international level, the 2009 Amendment to the London Protocol and the subsequent 2019 resolution on provisional application mark critical advances in facilitating cross-border CO₂ transfers for sub-seabed storage, although further ratifications are still needed. Finally, the European Commission's clarifications under the EU ETS have helped ensure that CO₂ transported by ship remains eligible for emissions deductions, though further legislative amendments are advisable for full legal certainty. Collectively, these instruments form an increasingly coherent regulatory environment—one that is essential for scaling up industrial decarbonisation and realising the EU's climate objectives.

Standardization⁵²³

The EU plans to approve standards in 2026 and to address standardization by aligning ongoing efforts with both international and European priorities. Currently, international standardization is being developed under ISO/TC 265⁵²⁴, with a primary focus on CCS. Meanwhile, CEN/TC 474 will expand its work to include CCU.

While CCS and CCU are global challenges best addressed through international standards, certain areas—such as CO₂ stream quality and utilization—reflect specific European needs. CEN/TC 474 provides a platform for European stakeholders to develop European Standards, which may later be proposed for adoption by ISO at the global level.

This standardization effort covers the entire lifecycle of CCUS projects, including design, construction, commissioning, operation, inspection, maintenance, and decommissioning. It also addresses key areas such as occupational health and safety, environmental protection, risk management, lifecycle assessment, CO₂ composition and measurement, and monitoring. Furthermore, the initiative aims to develop a harmonized carbon accounting system. This will build on existing methodologies and chain-of-custody models to ensure clear, reliable, and transparent communication about CO₂ and other greenhouse gas transactions—whether physical (e.g., CO₂ as a commodity or feedstock) or administrative (e.g., carbon credits or carbon take-back obligations)—between businesses, governments, and consumers. For more detailed information, please refer to the article by Ingvild Ombudstvedt and Lena W. Østgaard⁵²⁵.

Recently, on the 11 of June 2025 was published, TC 474 - CO₂ capture, transportation, utilization, storage and carbon accounting⁵²⁶

⁵²³ Source: CEN-CENELEC. *The launch of European Standardization on carbon capture, utilization and storage*, February 20th, 2024 <https://www.cenelec.eu/news-events/news/2024/brief-news/2023-02-20-ccus/>

⁵²⁴ Source: ISO- International Organization for Standardization. *ISO/TC 26 Carbon dioxide capture, transportation, and geological storage* <https://www.iso.org/committee/648607.html>

⁵²⁵ Source: OMBUDSTVEDT, Ingvild and Østgaard, Lena. *CEN/TC 474; A New Wind for Standardization?* (December 20, 2024). Proceedings of the 17th Greenhouse Gas Control Technologies Conference (GHGT-17) October 20th-24th, 2024, Available at SSRN: <https://ssrn.com/abstract=5065305> or <http://dx.doi.org/10.2139/ssrn.5065305>

⁵²⁶ Source: CEN EN ISO 27913:2025. *Carbon dioxide capture, transportation and geological storage- Pipeline transportation systems (ISO 27913:2024). WG 2- Pipeline Transportation.* <https://standards.iteh.ai/catalog/tc/cen/4d35d503-d9be-4bce-be27-32e1743857b8/wg-2>

This document specifies the requirements and recommendations for the transportation of CO₂ streams from the capture site to the storage facility where it is primarily stored in a geological formation or used for other purposes (e.g. for enhanced oil recovery or CO₂ use).

This document applies to the transportation of CO₂ streams by:

- rigid metallic pipelines.
- pipeline systems.
- onshore and offshore pipelines for the transportation of CO₂ streams.
- conversion of existing pipelines for the transportation of CO₂ streams, and
- transportation of CO₂ streams in the gaseous and dense phases.

This document also includes aspects of CO₂ stream quality assurance, as well as converging CO₂ streams from different sources.

Health, safety and environment aspects specific to CO₂ transport and monitoring are also considered in this document.

Transportation of CO₂ via ship, rail or on road is not covered in this document.

The standards CEN/TC 474/WG CO₂ Streams and Quality, CEN/TC 474/WG 3 CO₂ Accounting, and CEN/TC 474/WG 4 Geological Storage have not yet been published.

10.7. Regulatory prospects for CO₂ transport in Lithuania: Insights from EU and International practice

Lithuania presently does not possess a CCS infrastructure, and, correspondingly, it has no established legal framework specifically addressing the transportation of CO₂. The national legislative system has not transposed the provisions of the EU CCS Directive concerning CO₂ transport. Nevertheless, a review of strategic policy documents and emerging project initiatives reveals that the development of CO₂ transport infrastructure will be indispensable to achieving the country's long-term decarbonization targets.

The revised 2024 National Energy Independence Strategy underscores the importance of expanding CO₂ transport infrastructure, reflecting Lithuania's increasing commitment to climate change mitigation. If justified by demand, the development of a dedicated CO₂ export terminal is envisaged. Such a facility would support the safe and effective transfer of captured CO₂ from across the region to offshore storage sites situated beyond Lithuania's territorial jurisdiction. The selection of transport modalities—such as pipelines, rail, or maritime tankers—will depend on various pragmatic considerations, including the volume of CO₂ to be moved, distances involved, and the economic feasibility of each transport method.

Significantly, the European Commission has designated the Lithuania–Latvia carbon capture and transportation initiative, led by the CCS Baltic Consortium⁵²⁷, as a Project of Common Interest. This recognition highlights the strategic importance of developing CCS infrastructure across the Baltic region.

⁵²⁷ Source: The CCS Baltic Consortium. <https://ccs-baltic.eu/news/>

Within this project framework, CO₂ emissions will be captured from cement manufacturing facilities operated by Schwenk Latvija in Latvia and Akmenės Cementas in Lithuania. The captured gas will then be transported through a newly constructed pipeline system to the Port of Klaipėda. National gas transmission system operators—Amber Grid (Lithuania) and Conexus Baltic Grid (Latvia)—will oversee and coordinate the land-based transport operations to ensure system efficiency. At Klaipėda Port, the CO₂ will be transferred into a multi-modal liquefied CO₂ export/import terminal managed by KN Energies. This facility is designed to handle CO₂ arriving in smaller quantities via trucks and rail wagons, offering logistical flexibility for medium-scale emitters.

The liquefied CO₂ will then be conveyed by ship to a permanent offshore storage site. Given the scale and scope of this initiative, Lithuania must now move to establish a regulatory framework governing CO₂ transport, particularly for pipelines and maritime shipping, including provisions addressing cross-border transportation. The subsequent sections assess relevant international regulatory practices and their applicability to the Lithuanian context.

Legal Approaches to CO₂ Transport Regulation⁵²⁸

Academic and policy literature identifies several core components for the regulation of pipeline-based CO₂ transportation:

- Strategic infrastructure planning, supported by clear regulatory responsibilities;
- Integration and unbundling across the CCS value chain;
- Determination of optimal infrastructure ownership models;
- Assurance of third-party access to the transport network;
- Transparent and economically viable tariff-setting mechanisms;
- Streamlined permitting procedures;
- Clearly defined technical and safety requirements for CO₂ transport systems.

Strategic Network Planning⁵²⁸

Effective planning for CO₂ pipeline infrastructure is essential during the early phases of CCS deployment, particularly in conditions of uncertainty surrounding CO₂ volumes and market dynamics. Forward-looking estimates of emissions and mapping of potential transport corridors are crucial in informing these decisions.

Pipeline system design should aim to exploit economies of scale, favouring higher-capacity investments from the outset to reduce long-term costs and risks. However, such strategies require early movers to commit substantial resources without assured volumes. To mitigate this, clustering emitters geographically can help stabilize throughput and distribute investment risks.

A further strategic decision involves choosing between the construction of new pipelines or the repurposing of existing gas pipelines. Reusing existing infrastructure can be significantly more cost-efficient—estimated at just 1–10% of the cost of new pipeline systems. Coordinated investment

⁵²⁸ Source: European Commission: Directorate-General for Energy, Fraunhofer Institute for Systems and Innovation Research ISI, Guidehouse, McKinsey & Company, TNO, Trinomics, Utrecht University, BOLSCHER, H., GUEVARA OPINSKA, L., FINESSO, A., RYCROFT, L., NEELE, F.WILDENBORG, T. *EU regulation for the development of the market for CO₂ transport and storage*. Publications Office of the European Union, 2023, p 11-12 <https://data.europa.eu/doi/10.2833/093881>

decisions across various CCS projects require high levels of information transparency, which justifies establishing a central coordinating authority or regulator. In the absence of formal coordination, voluntary platforms like the European CCUS Projects Network can facilitate project alignment and information exchange.

Infrastructure planning must also incorporate multi-modal transport alternatives, especially for smaller or geographically isolated emitters lacking direct pipeline access. Road, rail, and maritime links will be vital for ensuring equitable participation in the CCS network, particularly in landlocked or storage-limited Member States.

The regulatory model proposed under the Hydrogen and Decarbonised Gases Market Package could serve as a useful template. Specifically, the Ten-Year Network Development Plans (TYNDPs), as mandated by Articles 51 and 52 of the Recast Gas Directive (COM/2021/803), may offer a structured approach to long-term infrastructure planning and investment alignment with national climate policies.

Elements to be included in the planning are⁵²⁸:

- main infrastructure to be built over the 10 years period;
- information on all the investments that have been decided and those to be executed in the next three years;
- information on infrastructure to be decommissioned;
- provide a timeframe for the investment and decommissioning projects;
- be based on a joint scenario framework developed between relevant infrastructure operations;
- be consistent with the results of the common and national risk assessment under Art. 7 of Regulation (EU) 2017/1938 on measures to safeguard the security of gas supply;
- need to be in line with the integrated national energy and climate plan and its updates, and with the integrated national energy climate reports submitted in accordance with Regulation (EU) 2018/1999 and support the climate-neutrality objective set out in Article 2(1), of Regulation (EU) 2021/1119.

Institutional Roles: Regulator and Network Operator⁵²⁸

Institutional clarity is critical to successful network planning. A key consideration is whether infrastructure planning should be centralized under a public authority or left to private sector stakeholders. The literature supports the creation of a dedicated, independent regulatory body to guide infrastructure planning—mirroring models being developed for hydrogen markets. Article 70 of the Recast Gas Directive offers a basis for institutional arrangements that separate regulatory oversight from operational responsibilities, enhancing transparency and trust in the market.

In the UK, the Transport and Storage Company (T&SCo) model consolidates development, operation, and compliance functions within a single entity, while Ofgem is tasked with overseeing financial regulation to ensure long-term system viability.

Structuring the CCS Value Chain and Functional Unbundling⁵²⁸

Organizational design of the CCS value chain involves balancing integration against the benefits of functional separation. In the UK, the integrated T&SCo model simplifies participation for emitters. Conversely, the Norwegian Longship project showcases how state support can facilitate risk-sharing and system coordination.

An emerging alternative is the unbundled model, where emitters negotiate independently with storage and transport providers. Dutch projects like Porthos and Aramis embody this structure, which allows for more flexible contracting and clearer delineation of liabilities along the value chain—especially regarding emissions trading and regulatory obligations.

Infrastructure Ownership Models⁵²⁸

Ownership structures for CCS infrastructure vary significantly across jurisdictions, influencing state control and development strategies:

- The Netherlands employs a mix of public and public–private models.
- Norway maintains mixed ownership with significant government participation.
- Denmark ensures at least 20% state ownership in all storage ventures.
- The United States and the United Kingdom generally favour fully private models.

Each structure presents different incentives for investment, coordination, and regulatory influence.

Third-Party Access⁵²⁸

Ensuring third-party access to transport and storage infrastructure is vital once spare capacity exists. Without clear TPA provisions, dominant players may inhibit new entrants and limit innovation. Effective regulation should guarantee access that is non-discriminatory and transparent while ensuring infrastructure developers retain sufficient incentives.

Designing a TPA regime must address:

- Synchronization of capture, transport, and storage timelines;
- Volume-based incentives for cost efficiency;
- Accessibility for small-scale emitters;
- Investment security for first movers;
- Technical standards for CO₂ purity and compatibility.

Article 21 of the CCS Directive already obliges Member States to implement fair access mechanisms, balanced against capacity limitations and national emission targets.

Tariff Mechanisms⁵²⁸

Tariff regulation plays a key role in managing financial risks and investment returns. Pricing frameworks may include:

- Commodity-based charges per tonne transported.
- Capacity-based charges linked to reserved throughput.
- Connection fees for infrastructure development.

Choosing the appropriate model depends on the business context and public financing arrangements. For instance, capacity-based tariffs can stabilize revenues, while connection fees can recoup costs for isolated branches. Given the monopolistic nature of CCS networks, tariff models must allow for recovery of overcapacity costs and consider alternatives such as subsidies or regulated asset base (RAB) mechanism

Comparative Regulatory Approaches to CO₂ Pipeline Infrastructure in Europe and Beyond⁵²⁹

Some countries have already adopted legislation regulating CO₂ transportation. Examples are provided in the table below.

Table 23. A summary of key provisions in existing national regulatory frameworks for CO₂ pipeline transport⁵²⁹

	Status of network operators	Network access	Tariffs	Network planning
Denmark	The Ministry must grant permits to establish and operate CO ₂ pipeline facilities (onshore and offshore), excluding pipelines transiting the Danish Continental Shelf to or from other states.	The network operator must grant access on objective, transparent and non-discriminatory terms. Access can be refused based on incompatible technical specifications or insufficient capacity.	Standard tariff ranges are published, but ultimately negotiated with users. They must be reasonable, transparent, and based on clear principles. Tariffs may not cover repayment of investments already expected to deliver reasonable profit.	The Ministry must assess permit applications based on appropriate dimensioning, access, and transport capacity.
Wallonia/ Flanders	There is a distinct framework for regional network operators and local branches (accounting separation between these functions is required). A single network operator for each region is appointed by government. Local and regional operators must be legally distinct from emitters.	Network and local operators must grant fair and open access. Access can be refused based on incompatible specifications, lack of capacity, or other reasonable needs of the operator and other users.	Tariffs are to be objective, transparent, and non-discriminatory, based on actual costs and a reasonable profit margin. In Wallonia, the regulator adopts a pricing methodology. In Flanders, the need for such a methodology is to be reviewed before 2028 and every 5 years.	Network operators and local cluster operators must complete annual (Wallonia) or biennial (Flanders) 10-year development plans, including estimates of future capacity requirements, the need for national and cross-border connections and a corresponding investment programme. Flanders also requires short-term forecasts based on actual investments.

⁵²⁹ Source: LOCKWOOD, Toby. *Building Future-Proof CO₂ Transport Infrastructure in Europe*. Clean Air Task Force. February 21st, 2025. <https://www.catf.us/resource/building-future-proof-co2-transport-infrastructure-europe/>

	Status of network operators	Network access	Tariffs	Network planning
Netherlands	CO ₂ pipeline infrastructure requires permitting by the Ministry under a general energy and climate infrastructure regime. The Ministry has proposed that state-owned Energie Beheer Nederland cooperate in the development of all CO ₂ transport (and CO ₂ storage projects), under market-based conditions.	Third-party access to transport and storage infrastructure is based on the provisions in the Dutch implementation of the EU Directive on CO ₂ Storage (the Mining Act) and general Dutch and EU competition law.	Tariffs are negotiated between capture projects, transport and storage companies. The Ministry intends to explore options for closer market monitoring and potential additional rules.	No explicit requirements on infrastructure developers to plan for future network development.
United Kingdom	An economic licence to act as a transport and storage company (T&SCo) is granted by the Ministry and regulated by energy regulator Ofgem.	Users are selected by a government-led allocation process, and must apply for a connection to an existing delivery point or request a new one. The T&SCo must prepare an offer, including a construction plan.	Tariffs are regulated to provide a set rate of return on the T&SCo asset base, with components for booked and used capacity.	All network users provide regular short-term and long-term forecasts of CO ₂ delivery. Cluster expansion and the selection of additional clusters are managed through a government-led process.

Both Denmark and Belgium have enacted dedicated legislative frameworks to govern the development of CO₂ pipeline infrastructure. These frameworks establish systems of negotiated third-party access underpinned by comprehensive regulatory oversight—particularly with respect to tariff structures and infrastructure planning

In Denmark, the *Act on Pipeline Transport of CO₂* imposes stringent obligations on network operators. It requires adherence to specific negotiation deadlines, full disclosure of contractual terms with users, and transparent articulation of the methodologies used to calculate tariffs. These tariffs must reflect the actual services provided and may incorporate a risk-adjusted, market-based return on capital for excess capacity earmarked for third-party users.

In Belgium, the regional legal regime in Wallonia delegates authority to regulators to define tariff methodologies. The tariffs must be equitable and non-discriminatory, ensuring a balance between service quality and affordability for users, while simultaneously allowing operators to achieve a reasonable rate of return.

The Netherlands currently leads CO₂ pipeline deployment within the European Union. A prominent example is the publicly owned Porthos project—a 55-kilometre pipeline in the Port of Rotterdam,

designed with a transport capacity of 10 million tonnes per annum (Mtpa). Public ownership has enabled the project to operate with more flexible financial expectations, including the acceptance of lower returns. Conversely, the larger Aramis project—capable of transporting up to 22 Mtpa and led by private sector actors such as TotalEnergies and Shell—is structured on a fully commercial basis.

However, concerns about potential market failures have emerged due to Aramis’s regional monopoly, the vertical integration of its transport and storage components, and the relatively high benchmark tariffs (ranging from EUR 90.6 to 112.8 per tonne for combined transport and storage services). A government-commissioned expert evaluation concluded that while a competitive market may materialize over time, immediate regulatory intervention is necessary. Key recommendations include stricter supervision of access and pricing structures, as well as public support for alternative transport modes such as maritime shipping. The report also advises that any unanticipated cost overruns be shared between the state and the project developer to protect users from disproportionate tariff increases.

Considering these findings, the Dutch Ministry of Climate Policy and Green Growth has announced plans to intensify monitoring of market conditions and to evaluate the risks posed by high or volatile tariffs.

In France, the *Commission de Régulation de l’Énergie* (CRE) has undertaken an in-depth assessment of regulatory options for emerging CO₂ infrastructure. Recognizing the potential for long-term natural monopolies in critical parts of the CCS value chain—including pipelines, liquefaction plants, and offshore export systems—CRE distinguishes between “open” and “isolated” carbon transport networks. Open networks serve multiple large emitters and are geographically concentrated, whereas isolated networks cater to a smaller number of users located far from collection or storage hubs.

For open networks, CRE supports a negotiated third-party access framework, augmented by ex post regulatory reviews to ensure fairness and transparency in tariff-setting. However, as these systems expand and become more interconnected, the regulator anticipates that a transition toward more formalized tariff regulation will be required. For isolated networks, CRE advocates for greater public sector involvement and pre-established access conditions, while also warning against the risk of overbuilding capacity that may not align with foreseeable demand.

Germany’s draft carbon management strategy echoes this regulatory posture by proposing ex post tariff assessments as an initial safeguard against the misuse of market dominance. The strategy also calls for continuous regulatory oversight to mitigate monopoly risks over the long term.

Outside the European Union, the United Kingdom has adopted a more interventionist approach. It has established a system of regionally designated “transport and storage companies” which operate under a *regulated asset base* model. Drawing parallels with the gas sector, this model enables operators to charge users based on predetermined returns calculated on both actual usage and booked capacity.

The UK is also evaluating whether to extend similar regulatory standards to alternative, non-pipeline modes of CO₂ transport—particularly maritime shipping and related port infrastructure. Nevertheless, this approach imposes significant administrative and financial burdens on public authorities. Accordingly, the government has signalled its intention to eventually transition to a more market-oriented regime once initial investments and institutional frameworks have stabilized.

Across the EU’s leading CCS initiatives, the model of negotiated third-party access remains predominant. However, the degree of regulatory intervention varies by jurisdiction. Where legislation mandates transparency and clearly defines tariff-setting methodologies—as is the case in Denmark—

this approach provides interim protection against monopolistic behaviour, while simultaneously promoting the accelerated development of CO₂ transport networks from key industrial clusters. As CO₂ pipeline networks expand and increasingly span national borders, there will likely emerge a necessity in many jurisdictions to transition toward a more formalized, regulated third-party access framework. This is especially pertinent for onshore pipeline systems, which inherently function as natural monopolies. Such infrastructure should be designed with sufficient capacity to serve all potential users within a given region, thereby avoiding inefficiencies and unnecessary duplication through the construction of competing parallel pipelines.

To ensure equitable access and prevent excessive tariffs, while remaining flexible to uncertainties in network development, the EU regulatory framework and related legislation should⁵²⁹:

- In the near term, establish clear minimum regulatory criteria for localised infrastructure that is likely to become operational before the EU regulation comes into force, to be applied by national regulatory authorities.
- Require Member States to appoint a national regulatory authority for CO₂ transport, with the power to oversee access demands and tariffs.
- Establish a Europe-wide platform for coordination between national CO₂ regulators.
- Require operators of CO₂ pipelines to offer fair and reasonable tariffs and to publish those tariffs in a transparent manner, together with the methodology behind their determination.
- Require the sector regulator to regularly assess the potential for emerging monopolies for CO₂ transport and storage and ensure it has the power to introduce further tariff regulation where appropriate.
- Consider implementing a regulated third-party access regime as the default long-term approach for significant shared infrastructure, including major CO₂ trunklines and cross-border pipelines (onshore and offshore), CO₂ liquefaction terminals, and CO₂ storage sites without regional competition.

Special Considerations for Maritime Transport

For Lithuania, maritime shipping is of strategic significance due to the absence of national CO₂ storage capacity and the current lack of pipeline connectivity to foreign storage sites. Klaipėda's terminal infrastructure and shipping routes represent the only immediate means of transporting captured CO₂ for permanent offshore sequestration.

In this context, Lithuania's accession to the London Convention and its Protocols is highly relevant, as it governs the dumping and transport of wastes, including CO₂, into the maritime environment. Moreover, the transport of liquefied CO₂ by sea may soon be governed under the Convention on Hazardous and Noxious Substances, pending ratification by enough signatories. Proactive alignment with these international frameworks would ensure regulatory certainty and enable Lithuania to participate fully in cross-border CCS value chains.

10.8. Recommendations for Improving Lithuania's National CO₂ Transportation Legal Framework

Transpose the EU CCS Directive into National Law. To provide a solid legal basis for developing CO₂ transport infrastructure, Lithuania should fully transpose the EU CCS Directive (2009/31/EC) into its

national legislation. This will create a comprehensive regulatory foundation, clarifying the roles, obligations, and legal responsibilities associated with CO₂ transport, storage, and related infrastructure. Clear transposition will also facilitate regulatory alignment with EU practices, supporting cross-border cooperation and infrastructure interoperability.

The CCS Directive was transposed into the legal system of the Republic of Lithuania in 2011. Therefore, the scope of legal regulation in the CCUS field has fundamentally changed, and it is recommended to review the transposition of the Directive due to certain inaccuracies. Article 3 of the CCS Directive provides definitions with the aim of ensuring that specific terms are understood uniformly throughout the EU. Thus, the precise transposition of these terms into national law is of great importance. However, significant discrepancies can be observed between the terminology used in the Lithuania's Law on Geological Storage of Carbon Dioxide and the Directive. One example is as follows:

- CCS Directive: "**pipeline network**" means a pipeline, including associated pressurised parts, used to transport CO₂ to the storage site.
- National Law: Carbon dioxide **pipeline** (hereinafter – pipeline) – a pipeline, including associated pressure maintenance equipment, intended for transporting CO₂ to the storage site.

It is also possible that Article 22 of the CCS Directive, which relates to dispute resolution, has not been correctly transposed. The CCS Directive states:

1. Member States shall ensure that dispute settlement arrangements are in place, including the designation of a competent independent authority with access to all necessary information, in order to facilitate the expeditious resolution of disputes relating to access to transport networks and storage sites, taking into account the criteria referred to in Article 21(2) and the number of potential users of such access.

Meanwhile, Article 17(2) of the Lithuania's Law on Geological Storage of Carbon Dioxide provides:

"Disputes concerning the use of storage sites shall be examined and resolved by the courts of the Republic of Lithuania in accordance with the procedure established by the laws of the Republic of Lithuania."

Firstly, there is no mention of pipelines in the national provision. Secondly, courts do not guarantee the required prompt resolution of disputes.

Establish Dedicated National CO₂ Transportation Regulations. Lithuania should enact dedicated CO₂ transportation regulations clearly defining permitting procedures, operational responsibilities, and safety standards for all transportation modes, including pipelines, maritime shipping, rail, and road transport. Specifically, regulations should detail technical standards for pipeline integrity, liquefaction facilities, and safety protocols for maritime shipping, in line with the provisions outlined in the EU's Net Zero Industry Act and international maritime frameworks.

Set Clear Third-Party Access Rules and Tariff Structures. To avoid monopolistic behaviour and ensure fair market access, Lithuania should legislate clear, transparent, and non-discriminatory third-party access rules for CO₂ transport infrastructure. Regulations should mandate that operators publish tariff structures and methodologies transparently, ensuring fees reflect actual costs with a reasonable return on investments. This approach aligns with Article 21 of the EU CCS Directive and successful regulatory practices in Denmark and Belgium.

Create an Independent Regulatory Authority for CO₂ Infrastructure. Establishing an independent national regulatory authority is essential to oversee compliance, regulate tariffs, mediate disputes, and coordinate strategic infrastructure planning. Modelled after successful international examples, such as Denmark's and Belgium's regulatory frameworks, this authority should be empowered to regulate both economic and technical aspects of the CO₂ transport sector, ensuring consistent implementation of EU standards.

10.9. CO₂ capture and utilisation in the EU: Legal framework

CCU represents a novel approach to climate mitigation by converting captured CO₂ emissions into valuable products, including fuels, chemicals, and construction materials. By integrating CCU into its broader industrial and environmental strategies, the EU aims to reduce dependency on fossil carbon and foster a circular carbon economy. This chapter explores the strategic goals underpinning the EU's CCU agenda, outlines the evolving legal and regulatory framework, and concludes with reflections on the future trajectory of CCU policy development. However, it is worth mentioning that the regulation of CCU is primarily focused on promoting CO₂ utilization rather than solely on regulation of CO₂ utilization itself. Furthermore, the regulatory framework for CCU is notably complex, encompassing not only the utilization of CO₂ but also the sources of energy employed in these utilization processes. This chapter will concentrate more specifically on reviewing related regulatory developments.

Towards an ambitious Industrial Carbon Management for the EU.

The European Commission's approach to CCU is increasingly embedded in EU legislation and policy instruments as part of the broader strategy to decarbonise industry and transition toward climate neutrality. Several regulatory mechanisms have been introduced to support the deployment of CCU technologies, particularly in sectors where emissions are hard to abate and alternatives to fossil fuels are limited.

Several legislative measures explicitly support the integration of captured CO₂ into industrial applications. For instance, the EU ETS allows the allocation of up to 20 million free allowances from 2024 to 2030 to aircraft operators deploying renewable fuels of non-biological origin, which include synthetic fuels derived through CCU. Furthermore, under the ReFuelEU Aviation and FuelEU Maritime regulations, the use of CCU-based deploying renewable fuels of non-biological origin is incentivised in the aviation and maritime sectors respectively. These measures aim to ensure the environmental integrity of CCU fuels while avoiding double counting of carbon emissions within the ETS framework.

The 2023 revision of the EU ETS Directive also acknowledges that certain CCU products can achieve permanent carbon storage. The Commission is developing a delegated act to define the criteria for recognising this permanence, placing permanent CCU on equal regulatory footing with traditional CCS. Complementary to this, the EU carbon removal certification framework is set to validate industrial activities that store atmospheric or biogenic CO₂ in long-lasting products.

However, the Commission recognises the need for further measures to fully realise the climate benefits of CCU. In the chemical sector, where annual carbon demand is approximately 125 million tonnes (equivalent to 450 million tonnes of CO₂), over 90% of feedstock carbon is currently fossil-derived. Captured CO₂ could replace fossil feedstocks in the production of polymers, plastics, solvents, paints, and other chemical goods. Meeting this challenge requires accelerating the shift toward sustainable carbon cycles, fostering circular models, and integrating CO₂ as a renewable resource—while acknowledging the significant energy and cost implications of such transitions.

A robust regulatory and incentive framework is necessary to ensure traceability, environmental protection, and a clear price signal for carbon used across the CCU value chain. The upcoming 2026 review of the ETS is expected to examine critical accounting issues, such as whether emissions from non-permanent CCU products should be accounted for at the point of capture or at the point of release. This review will also explore the potential inclusion of municipal waste incineration and landfill processes within the ETS, further integrating CCU into broader waste and circular economy policies.

The Commission foresees to:

- assess demand pull options, in concertation with industries, to increase the uptake of sustainable carbon as a resource in industrial sectors in full consideration of the Commission's upcoming Biotech and Biomanufacturing initiative.
- use the knowledge-sharing Platform for industrial CCUS projects to co-develop with industries sector specific roadmaps on CCU activities.
- draw up a coherent framework to account for all industrial carbon management activities that accurately reflect the climate benefits across their value chains, and to incentivise the deployment of innovative and sustainable permanent and non-permanent CCU applications, while removing barriers.

EST directive and Delegated Regulation (EU) 2024/2620.

The EU ETS, established in 2005, is an important pillar of the EU's climate policy, operating on a cap-and-trade principle that limits emissions from major industrial sources. Under this scheme, companies must hold allowances for each tonne of CO₂ equivalent they emit, with the total cap gradually reduced to incentivize emission cuts.

The EU ETS explicitly supports CCS, recognizing securely stored CO₂ as non-emitted. A key legal milestone in the evolution of the EU ETS occurred with the 2017 Court of Justice of the European Union ruling in the *Schaefer Kalk* case (C-460/15). The court determined that CO₂ chemically bound in stable products, such as precipitated calcium carbonate, should not be treated as emitted, thus broadening the system's scope to include certain carbon capture and utilization applications. This challenged the existing Monitoring and Reporting Regulation, which did not previously allow for emission reductions via CCU. The ruling highlighted regulatory gaps and prompted calls for updates to reflect technological advancements. Recent developments, including the Fit for 55 package, indicate a regulatory shift toward broader acceptance of CCU, provided the CO₂ is permanently bound.

In 2023 the ETS Directive was revised to broaden its scope. This expansion effectively extends the exemption from the obligation to surrender emission allowances to greenhouse gas emissions that are deemed to be permanently chemically bound within products, thereby eliminating the risk of atmospheric release during typical usage.

Article 12(3b) of the ETS Directive states"

"3b. An obligation to surrender allowances shall not arise in respect of emissions of greenhouse gases which are considered to have been captured and utilised in such a way that they have become permanently chemically bound in a product so that they do not enter the atmosphere under normal use, including any normal activity taking place after the end of the life of the product."

Delegated regulation (EU) 2024/2620 elaborates the implementation of this 12(3b) Article of ETS Directive. It states, that to ensure climate integrity, the criteria for considering CO₂ permanently stored

require that the carbon remain chemically stable for several centuries or longer. This depends on the nature of the chemical bonds formed during the utilisation process and the expected use and disposal of the product. Products in which CO₂ is bound must not only be long-lived but must also avoid end-of-life treatment methods such as incineration, which would release stored carbon into the atmosphere. Mineral carbonates, such as calcium and magnesium carbonate, are highlighted as particularly effective carriers for permanent carbon storage. Their strong chemical bonds are resistant to degradation under normal environmental conditions, making them suitable for long-term use in products such as concrete, bricks, tiles, and other construction materials. These products typically have a life span extending over several decades to centuries, and are primarily managed through recycling, backfilling, or landfilling at end-of-life, rather than incineration. However, CO₂ contained in products that are frequently incinerated cannot be considered permanently stored, as the combustion process would reverse the chemical bonding and re-release CO₂ into the atmosphere. Therefore, permanence is closely tied to both product type and disposal route.

Delegated Regulation (EU) 2024/2620 also standardises definitions critical to CCU governance, such as „‘chemically bound’ means that CO₂ is chemically transformed so that the carbon atom is chemically fixated by strong bonds in a manner that prevents its global warming impact from occurring“.

Also, Delegated Regulation (EU) 2024/2620 sets out the requirements for the permanent capture and utilisation of CO₂ in products (Article 3).

“1. CO₂ shall be considered permanently chemically bound in a product where all of the following criteria are met:

- (a) It has become chemically bound in a product through an active and controlled utilisation process, which allows for the measurement and determination of the amount of CO₂ equivalent bound in the product during the utilisation process, excluding any carbon present in the material before the utilisation process or naturally absorbed from the atmosphere or other sources after the utilisation process; and*
- (b) It remains permanently chemically bound in a product so as to not enter the atmosphere under normal use of the product, including any normal activity taking place after the end of the life of the product, for a period of at least several centuries. In case of products with multiple normal use and end of life pathways, all such pathways need to be taken into account for the purposes of this paragraph. Products that during normal use, including any normal activity taking place after the end of the life of the product, may be exposed to high temperature combustion, such as during waste incineration, shall not be considered to permanently chemically bind CO₂ .”*

Annex I of the Delegated Regulation (EU) 2024/2620 also provides a list of products that are considered to permanently chemically bind CO₂. These include mineral carbonates used in the following construction products:

- (a) Carbonated aggregates used either unbound or bound in mineral-based construction products.
- (b) Carbonated constituents of cement, lime, or other hydraulic binders used in construction products.
- (c) Carbonated concrete, including precast blocks, pavers, or aerated concrete.
- (d) Carbonated bricks, tiles, or other masonry units.

In conclusion, the revised ETS Directive and its implementing Delegated Regulation (EU) 2024/2620 mark a significant advancement in the EU’s approach to climate governance, particularly in integrating

CCU into the broader framework of emissions reduction. The clear criteria set out for what constitutes “permanent chemical binding” and the exclusion of products likely to undergo incineration ensure the environmental integrity of the system, guarding against unintended emissions at end-of-life. Furthermore, the standardisation of key definitions and the detailed listing of eligible materials in Annex I, especially mineral carbonates used in durable construction products, provide regulatory clarity and legal certainty for industry actors.

Carbon Removal Certification Framework⁵³⁰. On November 19th, 2024, the Council of the European Union formally adopted a new regulation establishing the first EU-wide voluntary certification framework for permanent carbon removals, carbon farming, and carbon storage in products. This initiative, known as the Carbon Removal Certification Framework places primary emphasis on permanent carbon dioxide removal solutions. However, it also opens the door for product-based carbon storage, provided that the CO₂ is retained for a minimum of 35 years. This provision presents a significant opportunity for integration within the construction sector, where long-lasting materials can serve as stable carbon sinks.

Products meeting this durability threshold may meaningfully contribute to the EU’s climate targets under the Carbon Removal Certification Framework, especially when combined with comprehensive life-cycle assessments, sustainable manufacturing practices, and technological innovations aimed at improving product longevity and recyclability. Such an approach could help establish a long-term carbon sink within the built environment and support the transition toward a low-carbon construction industry.

The CRCF also introduces key definitions essential to its implementation. It defines:

- ‘permanent carbon removal’ means any practice or process that, under normal circumstances and using appropriate management practices, captures and stores atmospheric or biogenic carbon for several centuries, including permanently chemically bound carbon in products, and which is not combined with enhanced hydrocarbon recovery;
- carbon storage in products’ means any practice or process that captures and stores atmospheric or biogenic carbon for at least 35 years in long-lasting products, allows on-site monitoring of the carbon stored and is certified throughout the monitoring period;“.

Accordingly, the Carbon Removal Certification Framework allows for the recognition of both permanent and long-term temporary carbon storage in products. CO₂ utilisation may qualify as a carbon removal activity under the Carbon Removal Certification Framework if it meets one of the following criteria: (i) the CO₂ is stored for several centuries, (ii) it is **irreversibly chemically bound** within a product, or (iii) it is retained in durable goods for a minimum of 35 years. Importantly, the Carbon Removal Certification Framework in its current form explicitly excludes enhanced oil recovery from the list of acceptable carbon removal practices, reinforcing its focus on genuine climate mitigation.

Renewable Energy Directive and Delegated Regulation (EU) 2023/1185⁵³¹. CCU in the transport sector can contribute to meeting renewable energy quotas by enabling the production of synthetic fuels from

⁵³⁰ Source: European Commission: Carbon Removal Certification Framework - Regulation (EU) 2024/3012 of the European Parliament and of the Council of 27 November 2024 establishing a Union certification framework for permanent carbon removals, carbon farming and carbon storage in products.

⁵³¹ Source: TALUS, Kim; MADDAHI, Reza. *Carbon capture and utilization under EU law: impermanent storage of CO₂ in products and pre-combustion carbon capture*, The Journal of World Energy Law & Business, Volume 17, Issue 5, October 2024, Pages 295–308, <https://doi.org/10.1093/jwelb/jwae009>

captured CO₂, provided they meet the sustainability and greenhouse gas savings criteria established under EU regulations. The imposition of renewable energy quotas in the transport sector has become an important policy lever driving the adoption of CCU technologies, particularly in the production of electrofuels (e-fuels) derived from captured CO₂. Recent amendments to the Renewable Energy Directive and the introduction of the ReFuelEU Aviation and Maritime Regulations impose binding requirements on fuel suppliers, airlines, and maritime operators to reduce greenhouse gas emissions or increase the share of renewables by specified target dates. These mandates apply across the transport sector and include tailored obligations for the aviation and shipping sub-sectors.

As defined in Article 2 of Delegated Regulation (EU) 2023/1185, compliance with the established targets may be achieved through the deployment of renewable fuels of non-biological origin and recycled carbon fuels, provided that these fuels attain a minimum greenhouse gas emissions savings threshold of 70%. Furthermore, the Delegated Regulation (EU) 2023/1185 specifies the methodology for calculating Greenhouse Gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin, as well as from recycled carbon fuels, thereby ensuring consistency and transparency in assessing their environmental performance.

As of 2024, the scope of the EU ETS has been broadened to include the production of specific fuels, such as those derived from oil refining, the manufacture of carbon black, and the generation of hydrogen and synthesis gas. Notably, in the case of hydrogen, the regulation now encompasses all production methods—extending beyond traditional processes like steam methane reforming and partial oxidation—provided the facility has a daily output exceeding five tonnes.

In conclusion, the European Union has made significant strides in embedding CCU into its climate and industrial policy architecture. Key legislative instruments such as the revised ETS Directive, the Carbon Removal Certification Framework, and energy sector regulations reflect a shift toward integrating CCU within the broader climate neutrality agenda.

Nonetheless, further progress is needed to fully realise CCU's potential. This includes updating accounting rules to better capture the lifecycle impacts of non-permanent storage, integrating pre-combustion carbon removal technologies into the legal framework, and fostering market demand for CO₂-based products.

10.10. Carbon dioxide utilization in Lithuania: Strategic directions and emerging policy frameworks

In response to the European Union's evolving climate policies and the global imperative to reduce greenhouse gas emissions, Lithuania has developed a strategic approach to CO₂ utilization. While still at a formative stage, Lithuania's initiatives in this field reflect a growing commitment to integrating CO₂-based solutions into its broader energy and climate strategies.

According to the Lithuanian National Energy Independence Strategy⁵³², one of the key areas of focus is the valorisation of biogenic CO₂—carbon dioxide originating from renewable sources such as biomass and biogas. The strategy outlines the production of high value-added products from this biogenic CO₂, particularly synthetic green fuels like methane, methanol, synthetic diesel, and aviation fuel. These

⁵³² Source: Lietuvos Respublikos Seimas nutarimas Dėl Lietuvos Respublikos Seimo 2012 M. Birželio 26 D. Nutarimo Nr. XI-2133 „Dėl nacionalinės energetinės nepriklausomybės strategijos patvirtinimo“ Pakeitimo 2024 m. birželio 27 d. Nr. XIV-2856 <https://e-seimas.lrs.lt/portal/legalAct/lt/TAD/42fa9900352b11efb121d2fe3a0eff27?jfwid=>

fuels are expected to reduce Lithuania's dependence on fossil energy sources, contribute to energy security, and create new opportunities in both domestic and export markets.

By 2050, the strategy envisions that industrial sectors facing significant decarbonization challenges—commonly referred to as “hard-to-abate” sectors—will be required to balance their residual fossil-based emissions with equivalent CO₂ capture efforts. In alignment with circular economy principles, captured biogenic CO₂ from sources such as biomethane production, biofuels combustion, and municipal waste incineration is intended to be transformed into innovative fuels and chemical products. This approach not only supports climate targets but also adds economic value through the creation of sustainable industrial processes.

In terms of regulatory progress, Lithuania has begun integrating EU-level CCU provisions into national legislation. One notable example is the transposition of Article 12(3b) of the revised EU ETS, which recognizes CO₂ as “not emitted” if it is chemically bound in a product in such a way that it will not be released into the atmosphere during or after its use. This provision has been adopted into Lithuanian law via the Minister of Environment's Order No. D1-231⁵³³, providing a legal basis for recognizing permanent CO₂ utilization in products, thereby exempting such CO₂ from emissions allowance obligations.

In addition, Lithuania's Alternative Fuels Law⁵³⁴ introduces specific mandates for renewable fuel uptake. From 2030 onward, at least 16.8% of the total energy content of gasoline and diesel supplied to the domestic market must be derived from renewable sources. Within this quota, a minimum of 3.5 percentage points must be fulfilled using advanced biofuels and non-biological renewable liquid or gaseous fuels, such as those produced from captured CO₂.

Following the adoption of the Carbon Removal Certification Framework, which establishes a Union-wide certification framework for carbon dioxide removal, carbon farming, and carbon storage in products, Lithuania is preparing to designate specific national institutions to implement its provisions. According to the draft government resolution⁵³⁵, the Ministry of Environment is expected to oversee certification related to carbon farming in the forestry sector, ensuring the proper functioning of certification bodies and reporting any irregularities to the European Commission. The Ministry of Agriculture is anticipated to supervise carbon farming activities on agricultural land, facilitate access to advisory services for farmers, and ensure that key data is integrated into the national land parcel identification system. The Ministry of Economy and Innovation is proposed to be responsible for technological carbon dioxide removal, particularly in relation to industrial applications and innovations, while the Ministry of Energy is expected to manage certification procedures within the renewable

⁵³³ Source: Lietuvos Respublikos aplinkos ministro 2004 m. balandžio 29 d. įsakymas Nr. D1-231 „Dėl šiltnamio efektą sukeliančių dujų apyvartinių taršos leidimų skyrimo ir prekybos jais tvarkos aprašo patvirtinimo“ (Suvestinė redakcija nuo 2024-08-10) <https://www.e-tar.lt/portal/lt/legalAct/TAR.7DCD3695F015/asr>

https://www.infolex.lt/ta/43951#B_0

⁵³⁴ Source: Lietuvos Respublikos alternatyviųjų degalų įstatymas 2021 m. kovo 23 d. Nr. XIV-196 (Suvestinė redakcija 2025-05-01) <https://www.e-tar.lt/portal/lt/legalAct/b5c313d0986d11eb9fecb5ecd3bd711c/asr>

⁵³⁵ Source: Lietuvos Respublikos Vyriausybės nutarimo projektas Dėl pavedimo institucijoms vykdyti funkcijas įgyvendinant 2024 m. lapkričio 27 d. Europos Parlamento ir Tarybos Reglamentą (ES) 2024/3012, kuriuo sukurama Sąjungos ilgalaikio anglies dioksido absorbavimo, anglies kaupimo ūkininkavimo ir anglies saugojimo produktuose sertifikavimo sistema <https://e-seimas.lrs.lt/portal/legalAct/lt/TAP/5973dd30fdb811ef878bc971e70c4c04?positionInSearchResults=6&searchModelUUID=18ac2f3d-7766-4a67-bcb1-ad0f87a8c65e>

energy sector. In parallel, the National Accreditation Bureau is planned to carry out the accreditation of certification bodies, ensuring they meet EU standards of competence.

While Lithuania's CO₂ utilization sector remains emergent, these strategic and legislative developments reflect a broader effort to enable industrial decarbonization through innovation. Continued support through policy, investment, and international cooperation will be essential for the realization of these goals. As technology matures, CO₂ utilization could play a significant role in Lithuania's path toward climate neutrality and sustainable economic growth.

10.11. CO₂ capture from technological processes/air capture

Carbon removal has become an important pillar of the EU's climate strategy, especially for addressing residual emissions that cannot be eliminated through mitigation alone. This part examines the EU's policy framework designed to scale up industrial carbon removal, focusing on recent developments including the Carbon Removal Certification Framework and emerging technologies such as Direct Air Carbon Capture and Storage and Bioenergy with Carbon Capture and Storage. It also explores the challenges, costs, and institutional responses required to create a viable carbon removal ecosystem across Member States.

One of the main barriers to scaling up industrial carbon removal is the significant disparity between the high cost of carbon removal technologies and the relatively low price of carbon under the EU ETS. For example, while BioCCS projects are gradually approaching cost parity with CO₂ capture from fossil or industrial sources, more advanced solutions such as direct air capture remain prohibitively expensive, with projected costs ranging from €122 to €539 per tonne of CO₂—far exceeding current ETS carbon prices. This economic mismatch means that inclusion in the ETS alone will not make these technologies viable in the near term. Targeted public funding and policy support are therefore essential to bridge the cost gap, stimulate innovation, and accelerate technology development. Member States will need to actively engage in shaping and nurturing these emerging sectors, supported by tailored EU-wide instruments.⁵³⁶

The Commission foresees to:

- assess overall objectives for carbon removals needs in line with the EU's 2040 climate ambition and the goal to reach climate neutrality by 2050 and negative emissions thereafter.
- develop policy options and support mechanisms for industrial carbon removals, including if and how to account for them in the EU ETS.
- in parallel, boost EU research, innovation and early-of-a-kind demonstration for novel industrial technologies to remove CO₂ under Horizon Europe and the Innovation Fund.

The adoption of Carbon Removal Certification Framework, which was also discussed in the section devoted to CO₂ utilization, marks a significant step in formalising carbon removal within the EU policy architecture. The Carbon Removal Certification Framework introduces comprehensive quality standards and rules for monitoring, reporting, and verification of removals, which aim to unlock both public and private investment in this field. The regulation supports both nature-based and technological removal pathways. On the nature-based side, carbon farming offers incentives for land

⁵³⁶ Source: European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Towards an ambitious Industrial Carbon Management for the EU COM/2024/62 final p10-13 <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2024:62:FIN>

managers to adopt regenerative agricultural practices and forestry initiatives that increase carbon sequestration in soil and vegetation. Technological removals include permanent solutions such as Direct Air Carbon Capture and Storage and Bioenergy with Carbon Capture and Storage, and other methods that bind CO₂ in long-lived materials.⁵³⁷

Certification of these activities will follow a phased timeline:

- **2025:** Proposal of certification methodologies and implementing acts on verification and registries.
- **2026:** Start of certification and issuance of certified units.
- **2028:** Launch of the EU registry.

In late 2024 and early 2025, the Commission released and revised its draft methodologies for certifying removal activities. These drafts focus on four core quality criteria: additionality, accurate measurement, long-term storage, and environmental integrity. However, independent reviews by organisations such as the Oeko Institute have raised concerns that the methodologies do not meet international standards, including those of Article 6.4 of the Paris Agreement. To address these concerns and gather broader input, the Commission has engaged in stakeholder consultations and expert group meetings. These discussions have centred on practices such as agroforestry, peatland restoration, and tree planting. In May 2025, the European Commission organised workshops to explore demand-side frameworks for carbon credits generated under the Carbon Removal Certification Framework. These events sought to understand the preferences of potential buyers—including private companies and Member States—and to develop strategies for supporting market uptake⁵³⁷.

The main obligations for Member States would be to designate supervisory authorities and accrediting certification bodies in order to implement the storage certification process (Article 10 and 11), to establish a national register until the Union register will be created (Article 12 part 3). In Lithuania, a Government resolution has been adopted for the implementation of this regulation⁵³⁸.

⁵³⁷ Source: Clear Blue Markets. *EU Carbon Removal Certification Framework: Key Developments and Implications*, June 3rd, 2025. <https://www.clearbluemarkets.com/knowledge-base/eu-carbon-removal-certification-framework-key-developments-and-implications>

⁵³⁸ Source: Dėl pavedimo institucijoms vykdyti funkcijas įgyvendinant 2024 m. lapkričio 27 d. Europos Parlamento ir Tarybos reglamentą (ES) 2024/3012, kuriuo sukuriama Sąjungos ilgalaikio anglies dioksido absorbavimo, anglies kaupimo ūkininkavimo ir anglies saugojimo produktuose sertifikavimo sistema. TAR, 2025-06-19, Nr. 11093, <https://www.e-tar.lt/portal/lt/legalAct/b671d1b54ccb11f0b070ee7f1ceefc75>

11. Conclusions

This Feasibility Study analyses the feasibility of developing innovative technologies, mainly carbon capture, utilization and storage, but also other ones such as hydrogen and other innovative low-carbon technologies to reduce the greenhouse gas emissions in the more carbon intensive Lithuanian industrial companies, and, specifically, in the counties where there are more of these companies: Kaunas, Šiauliai, and Telšiai.

Firstly, it is remarkable that the Lithuanian economy is reducing greenhouse gas emissions, reaching in 2023 the lower greenhouse gas emissions without LULUCF in the period 1990-2023, with a fall of 65.8% during this period. Besides, the power sector is evolving to a higher participation of renewable energy sources, with an 71% in 2024. However, the power system still depends highly on imports, since the shutdown of the nuclear power plants of the countries.

To sustain industrial activity and competitiveness, it is crucial to continue expanding domestic renewable generation capacity and ensuring stable, cost-effective energy supply for key industries, while maintaining progress in decarbonization. It should be kept in mind that decarbonization targets should be made compatible with economic growth and keeping a strong industrial sector in Lithuania (and all the European Union).

Considering the received results, it becomes clear that while renewable electricity from solar PV and onshore wind remains the most mature and scalable pathway for decarbonization in Lithuania, the production of green hydrogen faces significant economic challenges under current conditions. Hydrogen nevertheless holds strong potential as a complementary solution, particularly for sectors that are difficult to electrify directly or that require energy carriers such as fuels and chemical feedstocks. Although today's cost levels of green hydrogen in Lithuania are far above those of grey and blue hydrogen, continued cost reductions in renewable electricity, together with improvements in electrolyser technologies and supportive policy frameworks, could gradually position green hydrogen as a viable option for deeper decarbonization and for the development of value-added derivatives in the longer term.

Hydrogen production is possible in Lithuania, based on two main technologies: steam methane reforming (SMR) and electrolysis. However, the cost of steam methane reforming is considerably lower (€2.68 per kg H₂ if carbon capture is not added to the process, and €3.40 per kg H₂ if carbon capture is used), than the use of electrolysis (€6.72 per kg H₂ if electricity is obtained from the grid, and €6.32 per kg H₂ if electricity is produced with renewable energy).

In the carbon capture, utilization and storage value chain, the first activity is carbon capture. While there are different technologies to capture carbon dioxide, the most advanced ones capture this gas from industrial processes and from the combustion of fossil fuels. The most cost-effective technology is post-combustion, which can be used in sectors such as cement and petrochemicals.

The captured carbon dioxide can be either utilized, or stored. Carbon utilization technologies focus on the use of carbon dioxide to produce new products, such as concrete, hydrocarbons, methanol, formic acid, methane, polymers, and so on. Its main disadvantage is its higher cost, compared to the use of traditional methods to produce these products.

Secondly, carbon storage is seen as a key alternative to reducing emissions to the atmosphere. The most feasible option remains geological storage in deep rock formations. However, Lithuania currently prohibits domestic geological storage under its regulatory framework. While this option may be

reevaluated in the future, in the short- to medium-term the most realistic pathway for Lithuania is to export captured CO₂ to established storage sites in the North Sea. Nordic countries, particularly Norway and Denmark, already operate large-scale offshore storage projects such as Northern Lights and Greensand, which are designed to receive CO₂ from across Europe, including the Baltic region. Both mentioned projects as well as lots of other in the North Sea will be in full capacity operation mode by 2030. Lithuania, through the planned Klaipėda CO₂ terminal and shipping connections, is well placed to integrate into the North Sea storage network, which represents the most practical and cost-effective solution in the short- to medium-term, given the uncertain legal, technical, and economic viability of domestic or regional Baltic storage options.

To store carbon, there are two main costs to be considered: transport costs and storage costs. As for transport costs, three main options can be considered: onshore pipeline, offshore pipeline and shipping. In general terms, offshore pipelines cost between 50% and 100% more than onshore pipelines, so they will only be used when the storage is in the sea. In the case of Lithuania, the most viable short- to medium-term solution is to develop a national CO₂ pipeline grid that collects emissions from major industrial sources across the country and delivers them to the Klaipėda port, from where CO₂ can be shipped efficiently to North Sea storage sites. Such a grid should also be designed to allow smaller emitters to connect and inject their CO₂, ensuring broader participation across sectors and improving overall system efficiency.

Comparing transport by pipeline and transport by shipping, the key questions are the distance to transport carbon dioxide, and the amounts to be transported. In general terms, pipelines are preferred for larger amounts of carbon dioxide and/or shorter distances. However, if only reduced amounts of carbon dioxide have to be transported, shipping can be chosen, as well as if distances are very long. Alternative transport solutions, such as developed transportation options via railroads and trucks can be also used for small CO₂ amounts, to ensure that smaller emitters also have viable opportunities.

Regarding the available geological formations for carbon dioxide storage in Lithuania, there are two main options: saline aquifers and oil fields. Specifically, the Cambrian reservoir includes two main structures, such as Syderiai saline aquifer, with a storage capacity of 21.5 Mt of CO₂, and Vaškai saline aquifer, with 8.7 Mt of CO₂. Additionally, the D11 saline aquifer in the Baltic Sea has an estimated capacity of 11.3 Mt of CO₂. Additionally, the Gargždai zone of uplifts could provide 31.3 Mt of CO₂ storage capacity. However, substantial changes to national regulation will be required before any practical exploration or demonstration activities on carbon storage in geological structures can be initiated.

Developing shared carbon storage projects with other Baltic countries is also a possible option for Lithuania. North Blidene, Blidene, Dobeles, and E6-E, located in the territory of Latvia, are structures with a combined average available capacity of 220.4 Mt of CO₂, and an optimistic estimate of 767.6 Mt of CO₂ based on preliminary scientific assessments. However, current Latvian regulation, similar to that of Lithuania, does not permit geological CO₂ storage even at the R&D or pilot scale. Therefore, before any joint activities can be pursued, both national regulatory frameworks would need to be amended to enable exploration, testing, and eventual deployment of such shared storage projects.

It should be noted that, as of the 2030s, only offshore geological sequestration could be considered feasible. Onshore sequestration will still require additional research and analysis and is expected to become viable only in the longer term (2040-2050).

Regarding regulation, Lithuania needs to enable industry decarbonization and provide clarity for market players on possibilities to reach EU climate goals. Geological storage in Lithuania and export possibilities should both be enabled, considering the current regulatory environment. Currently, captured carbon can only be transported to third countries. The European Union regulation supports carbon capture, utilization and storage, through the European Green Deal and the European Climate Law, as it can contribute to mitigate climate change.

Lithuania currently lacks a regulatory framework governing the CO₂ supply chain, including capture, transportation, terminals, and export options. This situation primarily stems from the absence of a unified EU-wide regulation. The European Commission is expected to present a proposal for a regulatory framework for the CO₂ market and infrastructure in the second half of 2026.

While Lithuania maintains a prohibition on domestic geological storage, ratification of the London Protocol and its amendments could significantly enhance its international collaboration capabilities. The 2009 amendment explicitly enables cross-border CO₂ transport and storage agreements, contingent on mutual consent among involved countries. Ratifying this Protocol would clarify Lithuania's legal position, facilitating future CO₂ export initiatives without requiring domestic storage. It's important to emphasize that although the London Protocol and its subsequent amendments support the idea of CO₂ storage beneath the seabed, they do not compel any country to permit such storage within its own territory. However, it should be noted that the scope of the London Protocol extends beyond CO₂ storage and transportation. Therefore, the possibility of ratification should be considered within a broader context.

Specifically, the European Union has a comprehensive regulatory framework for carbon storage, in the CCS Directive. This Directive also establishes a transparent and non-discriminatory access to any potential user to CO₂ transport networks. The CCS Directive was transposed into the legal system of the Republic of Lithuania in 2011. Therefore, the scope of legal regulation in the CCUS field has fundamentally changed, and it is recommended to review the transposition of the Directive due to certain inaccuracies.

For carbon capture and utilization, there is no specific regulation on these technologies. However, these projects can benefit from obtaining carbon allowances in the European Emission Trading System.

Research, development and Innovation (R&D&I) projects can also find support from European instruments such as the LIFE Climate Change Mitigation and Adaptation and the Innovation Fund. New investments in carbon capture, utilization and specially storage in Lithuania can also be funded by multilateral institutions, such as the World Bank, the European Bank for Reconstruction and Development, the European Investment Bank or the Asian Development Bank, or with the Connecting Europe Facility (CEF) from the European Union.

As a final conclusion, carbon capture, utilization and storage projects are still not fully feasible in a commercial way, considering the additional costs per tonne of CO₂, compared to the prices of the carbon allowance in the European Trading System. With a carbon capture cost which is between US\$20 and US\$100/tonne of CO₂, to which it is necessary to add transport costs (between US\$1.5 and US\$16/tonne of CO₂) and storage costs (between US\$1 and US\$20 per tonne of CO₂), the cost of the carbon allowance should be high to make these projects attractive for investors. However, allowances have reached a price around €80 per tonne in the period 2021-2023, and is expected to increase to €149 per metric tonne by 2030. A mechanism which avoided transferring these costs to the final user could encourage large emitters to invest in carbon capture, utilization and storage projects.