The European Network of excellence
on the Geological Storage of CO_2

State-of-play on CO_2 geological storage in 32 European countries — an update

October 2021

CO$_2$GeoNet

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The information contained in this report represents the status as of 30th June 2021, apart from a few exceptions where more recent developments have been included, particularly on a European level.

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Terms and Abbreviations

ACT	Accelerating CCS Technologies; ACT is an international research programme to establish CO_2 capture, utilisation and storage (CCUS) as a tool to combat global warming, the research programme which was initiated with ERA NET co-funding and national funding of European countries.
BASRECCS	Regional Baltic CCS Network; network of regional CCS experts and stakeholders (operated as an association) aiming to support the implementation of CCS in the Baltic Sea Countries.
BECCS	Bioenergy with CO_2 capture and storage; as CCS but using biogenic fuel, i.e. plant material is used for energy generation and the CO_2 is captured and stored deep underground. BECCS has the potential of achieving negative CO_2 emissions.
Billion	1,000 million, 10^9
CCS	Carbon dioxide Capture and Storage; process consisting of the separation of CO_2 from industrial and energy-related sources, transportation and injection into a geological formation [deep underground], resulting in long-term isolation from the atmosphere (ISO 27917:2017).
CCU	Carbon dioxide Capture and Utilisation; process of separating (capturing) CO_2 from an industrial, manufacturing or energy-related process or from air, and using it directly or after conversion for use as material feedstock or product. CO_2 is utilised for many sectors including horticulture, basic chemicals and synthetic fuels.
CCUS	Carbon dioxide Capture, Utilisation and Storage; a combination of CCS and CCU where the CO_2 is stored for climate-relevant timescales (IPCC 2018). In the current report, the term CCUS refers to CCU and CCS (if no distinction necessary) and includes enhanced hydrocarbon recovery by CO_2 injection.
CDR	Carbon Dioxide Removal; removing CO_2 from the atmosphere for storage (geological or otherwise) via, for example, direct air capture and storage (DACCS) or capture of CO_2 from biomass combustion and storage (BECCS), also referred to as NET or Negative Emission Technologies.
CEM	Clean Energy Ministerial; a high-level global forum of energy ministers from 28 countries and the European Commission to promote policies and programs that advance clean energy technologies.

Climate neutrality Becoming “climate neutral” means here reducing greenhouse gas emissions as much as possible, while compensating for any remaining emissions such as from hard to abate sectors. Compensation can be by removing carbon from the atmosphere (e.g. by DACCS, BECCS or by natural carbon sinks), or through offsetting measures, which typically involve supporting climate-oriented projects.

CO_2-EGR Enhanced Gas Recovery; the recovery of gas additional to that produced through primary production, achieved by fluid injection or other means, here by injection of CO_2.

CO_2-EOR Enhanced Oil Recovery; the recovery of oil additional to that produced through primary production, achieved by fluid injection or other means, here by injection of CO_2.

$CO_{2\,eq}$ CO_2 equivalent; a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential by converting amounts of other gases to the equivalent amount of CO_2 with the same global warming potential.

CO_2 stream A flow of substances resulting from CO_2 capture processes, consisting overwhelmingly of CO_2. The CO_2 stream typically includes impurities and may include substances added to the stream to improve performance of CCS and/or to enable CO_2 detection (ISO 27917:2017).

CSLF Carbon Sequestration Leadership Forum; a ministerial-level international climate change initiative that is focused on the development of improved, cost-effective technologies for carbon capture and storage (CCS).

DAC Direct Air Capture; CO_2 is captured directly from the atmosphere with a technology/engineering solution.

DACCS Direct Air Capture with CO_2 storage; DACCS has the potential of achieving negative CO_2 emissions.

EC European Commission.

ECCSEL European Research Infrastructure for CO_2 Capture, Utilisation, Transport and Storage (CCUS); a European Research Infrastructure Consortium (ERIC) which is a full legal entity under EU law; a distributed, integrated research infrastructure, encompassing over 80 scientific facilities across Europe.

EERA	European Energy Research Alliance; energy research community in Europe; Membership-based, non-profit association that brings together 250 universities and public research centres from 30 countries.
ENeRG	European Network for Research in Geo-Energy; ENeRG was created in 1992 by European organisations involved in research and technology development focused on fossil energy sources, especially oil and gas.
EU	European Union.
EU ETS	EU Emissions Trading System; cap and trade system for greenhouse gases including CO_2 emissions from electricity and heat generation, energy-intensive industry and commercial aviation emissions, set up in 2005, that operates in EU Member States and Iceland, Liechtenstein, Norway and UK.
FP7	Seventh Framework Programme; European Commission funding programme.
Geological storage of CO_2	CO_2 is trapped in geological formations as a free gas/dense-phase fluid/mineral form.
GCCSI	Global CCS Institute; international think tank that aims to accelerate the deployment of carbon capture and storage. Membership includes governments, global corporations, private companies, research bodies and non-governmental organisations.
GeoERA	"Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe"; H2020 ERA-NET Co-fund Action. This means that it is not a single research project but rather a research programme that is established and run by a group of 33 national and 15 regional geological survey organisations from Europe.
GHG	Greenhouse gas.
Gt	10^9 t, 10^6 kt, 1000 Mt
H2020	Horizon 2020; European Commission Funding programme.
IEA	International Energy Agency; an autonomous inter-governmental organisation within the OECD framework that works with governments and industry to shape a secure and sustainable energy future for all. IEA provides authoritative analysis, data, policy recommendations, and real-world solutions to help countries provide secure and sustainable energy.

IEAGHG — IEA Greenhouse Gas R&D Programme; IEA's Technology Collaboration Programme formed in 1991 aiming to assess the role that technologies can play in reducing GHG emissions from both the power system and from industrial processes. Currently the Programme is supported by its 37 members, comprising 18 Contracting Parties and 19 multinational Sponsors. Funding for the Programme is provided by the members.

IMO — International Maritime Organisation; IMO is the United Nations' specialised agency responsible for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships.

IPCC — Intergovernmental Panel on Climate Change; the United Nations body for assessing the science related to climate change.

kt — 1000 t, 10^{-3} Mt

LT-LEDS — Long-Term Low GHG Emission Development Strategies to the mid-century (LT-LEDS or LTS) are invited by the UNFCCC under the Paris Agreement and set out longer-term plans than the NDCs.

MI — Mission Innovation; intergovernmental platform that brings together governments, public authorities, corporates, investors and academia; global initiative to catalyse action and investment in research, development and demonstration to make clean energy affordable, attractive and accessible to all this decade. MI aims to accelerate progress towards the Paris Agreement goals and pathways to net zero.

Mineral Storage — Reacting minerals with CO_2 in order to store CO_2 as minerals such as carbonates (ex-situ or in-situ).

Mt — 10^6 t, 1000 kt, 10^{-3} Gt

NDCs — Nationally Determined Contributions (submitted to the UNFCCC).

NECP — National Energy and Climate Plan (submitted to European Commission).

NSBTF — North Sea Basin Task Force; Task Force that aims to develop common principles for managing and regulating the transport, injection and permanent storage of CO_2 in the North Sea sub-seabed. Composed of public and private bodies from Norway, the United Kingdom, the Netherlands, Germany and Flanders.

Oxyfuel Combustion — A CO_2 capture process based on burning a fuel using pure oxygen, or a mixture of oxygen and recirculated flue gas instead of air.

PCC	Post-combustion capture: capturing CO_2 after the CO_2-generating process, typically using an amine based scrubbing process.
Pre-Combustion Capture	Separating CO_2 from the raw fuel before combustion by means of a gasification process.
PCI	Projects of Common Interest; key cross-border infrastructure projects that link the energy systems of EU countries – see 2020 list of selected projects.
RFCS	Research Fund for Coal and Steel; funding programme of the European Commission.
SET-Plan	Strategic Energy Technology Plan; European initiative launched in 2007 by EC to accelerate the development and deployment of low-carbon technologies, through cooperation amongst EU countries, companies, research institutions, and the EU itself.
UNFCCC	The United Nations Framework Convention on Climate Change.
ZEP	Zero Emission Platform; a European Technology and Innovation Platform (ETIP) under the European Commission's Strategic Energy Technologies Plan (SET-Plan) and technical adviser to the EU on the deployment of CCS and CCU.

Executive summary

The role of CO_2 capture and storage (CCS) within the portfolio of available greenhouse gas (GHG) emission-reduction options is currently under discussion in many European countries. Several full-chain CCS projects are evolving, particularly around EU-supported Projects of Common Interest for large-scale, cross-border CO_2 transport infrastructures in the North Sea area. Promising developments are also evident in other European regions. These recent developments motivated the CO_2GeoNet Association to prepare an update on the state-of-play on geological storage of CO_2 in Europe. This update builds on the 2013 report "State of play on CO_2 geological storage in 28 European countries" (Rütters et al. 2013) that was published under the "Pan-European Coordination Action on CO_2 Geological Storage" (FP7 CGS Europe project). For the current report, reflecting the state-of-play as of 30th June 2021, contributions using a questionnaire were collected from 32 European countries – 25 EU Member States (excluding Malta and Luxemburg) as well as Bosnia and Herzegovina, Iceland, Norway, Switzerland, Turkey, UK and Ukraine. In addition to the countries covered in the 2013 report, information is now included on Bosnia and Herzegovina, Cyprus, Iceland, Switzerland, and Ukraine; no information was obtained on Serbia for this report. The completed questionnaires are provided in the report annex. Contributors were asked to provide information on the following topics:

1) national policies and climate-protection strategies;
2) national legislation and regulations;
3) national storage options, potential and capacity;
4) large-scale and demonstration CCS projects, pilot and test sites for CO_2 capture, transport and storage;
5) research activities with respect to CO_2 storage;
6) national actors driving CCS forward, public awareness and engagement.

The main findings from the national contributions in the context of the European CCS landscape are as follows:

- **National policies and climate-protection strategies:** Since 2013, many important policy developments at international and EU levels have been made, and many European countries adopted new policies and measures to address the 2030 and 2050 climate objectives. To date, all 27 EU Member States submitted their final integrated National Energy and Climate Plans (NECP) for the period from 2021 to 2030. The national long-term strategies to meet the Paris Agreement commitments and the Energy Union objectives with a perspective covering at least 30 years have been provided by 20 EU Member States[1]. In most Member States' NECPs, CCS is mentioned as one of several options under consideration for decarbonising industry and/or power

[1] Information provided by the EC website as of September 2021.

generation or as a negative emission technology (when combined with bioenergy generation or direct air capture). Planned activities in the individual Member States relating to CCS differ significantly, ranging from support for research activities, national capacity assessments and feasibility studies to an implementation of specific large-scale CCS projects. Since the first state-of-play assessment prepared in 2012, focus has shifted in most European countries from CO_2 capture on fossil-fired power stations to capture on other emitters (e.g. cement, steel and chemical industry, waste incineration, geothermal plants and hydrogen production). Some countries favour CO_2 capture and use (CCU) over CCS.

- **National legislation and regulations**: The EU Directive 2009/31/EC on the geological storage of CO_2 ("EU CCS Directive") has been transposed into national legislation in all EU Member States, Norway and the UK. In Iceland, the Government has adopted the transposition, including the necessary adaptations to the conditions and requirements for CO_2 mineral storage in basalt formations. As of June 2021, the geological storage of CO_2 is permitted in 19 of the 32 countries studied, though some countries exclude specific regions or impose limitations of the amount of CO_2 that could be injected annually. In the other 13 countries studied, CO_2 storage is *de facto* prohibited (9 countries) or neither allowed nor prohibited since it is not covered by specific laws (4 countries). A comparison between the present-day situation and the situation in 2012 shows no clear trend: for example, while in Sweden and the Czech Republic a previously implemented ban of CO_2 geological storage was lifted, CO_2 storage has recently been forbidden in Lithuania.
  Across Europe there is very limited experience with licencing procedures for CO_2 storage. Only Norway has practical experience with operational industrial-scale CO_2 storage sites (Sleipner, Snøhvit) that were regulated under the Norwegian Acts relevant for emissions from petroleum activities[2]. Recently, storage licences according to the provisions of the EU CCS Directive have been awarded for the Sleipner (in 2017) and Snøhvit (in 2018) sites as well as for prospective new storage sites in Norway, the Netherlands and the UK. Several storage licences and permits based on different national laws and regulations (e.g. mining or geothermal) were granted to smaller-scale and pilot projects in France, Germany, Iceland and Spain. As few projects have moved forward to exploration and characterisation to date, the experience with awarding exploration permits and licences for CO_2 storage sites is also limited.

[2] Emissions from Norwegian petroleum activities are regulated through several acts, including the Petroleum Act, the CO_2 Tax Act on Petroleum Activities, the Sales Tax Act, the Greenhouse Gas Emission Trading Act and the Pollution Control Act.

- **National storage options, potential and capacity**: The level of knowledge, the quality of datasets and the format of presentation differ significantly from country to country. Detailed and comprehensive national storage atlases and databases are available in Norway, the UK, Spain and the Nordic countries (Nordic CO_2 Storage Atlas), less detailed or partial assessments have been performed in many other countries, while in some countries, particularly in Eastern and South-Eastern Europe, only basic assessments have been carried out. Cyprus has not yet performed any assessment of CO_2 storage potential. The most up-to-date pan-European overview of national storage capacities is provided by the CO_2StoP database, although a significant part of the underlying data is now 10 or more years old since it was collected during the FP6 EU GeoCapacity project (2006–2008). Although these figures do not reflect the recent changes and updates performed at national and regional levels that have been reported by 25 countries, they clearly indicate that Europe has sufficient geological storage capacity to be able to deploy CCS at scale. The prevailing storage options considered in Europe are saline aquifers (25 countries) and depleted / depleting hydrocarbon fields (22 countries). Offshore is the preferred location of storage sites in most countries with a coastline. Five countries also report storage capacity in coal seams, but this option has not been investigated or developed over the last few years. Iceland has been the pioneer and promoter of in-situ mineral storage of CO_2 in mafic and ultramafic rocks, especially basalts. Estonia and Finland report zero storage capacity based on their unfavourable geology.

- **Large-scale and demonstration CCS projects; pilot and test sites for CO_2 capture, transport and storage**: In Europe, two large-scale CO_2 storage sites are currently in operation, namely Sleipner since 1996 and Snøhvit since 2008, both in the Norwegian Sector of the North Sea. On a pilot scale, the Icelandic Carbfix pilot project has developed CO_2 geological storage in basaltic rocks by rapid mineralisation ("mineral storage") and has been in operation since 2014. This technology is now being used by the Carbfix Company on a larger scale capturing and storing CO_2 from a geothermal power plant as well as directly from the atmosphere. No other pilot injection sites are currently in operation. The pilot injection projects at Ketzin (saline aquifer, Germany), Lacq (depleted gas field, France) and K12-B (depleted gas field, The Netherlands) finished as planned. The injection pilot project at Hontomín, Spain, was put on hold in 2018 due to political and administrative reasons.
  Reasonable development has been observed since the publication of the first State of Play report in terms of preparation for Projects of Common Interest (PCI) and full-chain or CCS cluster projects, often being interlinked with PCI as nuclei. Five PCI for cross-border CO_2 transport network development that are establishing transport connections towards evolving offshore storage sites have qualified for EU financial support: (1) CO_2-Sapling project (UK); (2) CO_2TransPorts (NL, BE); (3) Northern Lights project (NO); (4) Athos project (NL); (5) Ervia Cork project (IE). New proposals for PCIs

are also under development.
Commercial-scale CO_2-driven enhanced oil recovery (CO_2-EOR) is ongoing in Hungary, Turkey and Croatia. CO_2-EOR is also considered an option in Austria, the Czech Republic, Latvia, Lithuania, Poland and Romania which might help to kick-start broader CCUS activities, whereas Denmark, for example, plans to prohibit CO_2-EOR activities in line with phasing out oil and gas production by 2050.
In several European countries, test facilities are available for developing and optimising CO_2 capture technologies at different scales. Over the last few years, focus has shifted from capturing flue gases from fossil-fuelled power plants to pilots for capture on industrial facilities (in particular cement plants and steel mills) addressing, amongst other issues, process integration. In October 2020, the world's largest CO_2 transport test facility opened at the Equinor premises in Porsgrunn, Norway.

- **Research activities with respect to CO_2 storage**: 31 out of 32 countries that responded to the questionnaire reported having at least one research institution carrying out CO_2 storage-related research; some countries reported more than fifteen institutions actively engaged. Fourteen of these countries reported hosting large-scale CCS research infrastructure, ranging from test sites to laboratory facilities. Over the past few years there has been a significant rise in the development of new testbeds, for example, the UK GeoEnergy Test Bed (GTB) and the Norwegian Svelvik CO_2 FieldLab, the establishment of a network of European CCS research facilities (ECCSEL), and the strengthening of cooperation in the European Energy Research Alliance (EERA) that build upon and complement existing research infrastructures and test centres.
  Nearly all assessed European countries are or have been involved in one or more CO_2 storage-related research projects funded through Horizon 2020, FP7, RFCS and regional programmes since 2012. The bulk of these projects are coordinated by countries of western Europe and Scandinavia and indicate particularly strong collaborative links between some countries such as Denmark, France, Germany, Italy, The Netherlands, Norway, Spain, and the UK. A few non-European countries are active in EU-funded research projects on CO_2 storage including Canada, China, the USA, Japan, Australia, and the United Arab Emirates.
  On the national level, it is difficult to compare efforts beyond a qualitative assessment of research project numbers and topics because budget figures for projects are not readily available. A few countries have national research programmes addressing or dedicated to CCS or to specific parts of the CCS process chain. In all, 18 countries reported having conducted or being in the process of carrying out one or more nationally funded projects since 2012, ranging from development of test sites to PhD support. The topical focus of recent CO_2 storage-related national research projects in Europe appears to be on storage capacity assessment (16 out of 18 countries) and modelling of subsurface storage processes (14 countries), with less attention given to well technologies, social acceptance, and complex management (addressed by 8, 8

and 9 countries, respectively). In some countries, research activities have focused on CO_2 capture and utilisation rather than on geological storage.

- **National actors driving CCS forward, public awareness and engagement**: In many of the European countries studied, overall awareness of and knowledge about CCS technology is still low to very low and CCS is often perceived as a "risky technology" due to its unfamiliarity. Striking exceptions are Iceland and Norway where high and very high awareness levels, respectively, and neutral to positive attitudes towards CCS were reported. In areas where storage pilot and demonstration projects were planned or implemented, early, open and transparent public awareness and engagement campaigns resulted locally in a mostly favourable public opinion towards the application of CO_2 storage in these areas (e.g. in Hontomín/Spain, Ketzin/Germany, Cork/Ireland).
  In several countries, media and political interest in CCS technology has (slightly to moderately) increased recently, in particular due to the negotiations on national CO_2 emission-reduction targets and measures to achieve these. In some countries, the perception of CCS technology is reported to be more positive for CO_2 capture on industrial facilities, geothermal plants or waste incinerators than for capture on (fossil-fired) power plants. Also, capture on bioenergy plants or direct CO_2 capture from the air, with the potential of achieving "negative" CO_2 emissions, appears to increase public acceptance of the overall process chain including geological storage.

In conclusion, the information compiled in this report reveals clear progress in Europe since 2012 in bringing CCS back onto national agendas to help to meet climate targets. This includes a move from research to implementation, developing CCS networks with hubs and clusters, the emergence of companies and sites offering a "CO_2 transport and storage service" and PCI creating nuclei/stimuli to advance projects. Updates of national storage capacity assessments have been reported by the majority of countries that responded to the questionnaire, underlining the necessity for preparation of a consolidated and up-to-date European CO_2 storage atlas to encompass these recent data as well as to collect new data. The wide range of activity and knowledge levels across Europe underpins the continued need for pan-European knowledge exchange, technology transfer and cooperation on all aspects of CCS – legislation and regulation, research and development, large-scale infrastructure and project planning and advancement – to rapidly deploy CO_2 capture, transport and storage at the scale required for significant CO_2 emission reduction in Europe.

Chapter 1: Introduction

This CO_2GeoNet report summarises the state-of-play of CO_2 geological storage in 32 European countries as of 30th June 2021. In a few specific cases, more recent information has been included to reflect developments after this date, in particular on a European level. The report highlights the current status of national policy and regulations around CO_2 capture and storage as well as advancements in geological storage assessments and practical demonstration of CO_2 capture and storage (CCS) in each country and across Europe since 2012. This report was collated from responses to a questionnaire focused on CO_2 storage, completed by CO_2GeoNet Members and institutions from outside the Association across Europe (Fig. 1).

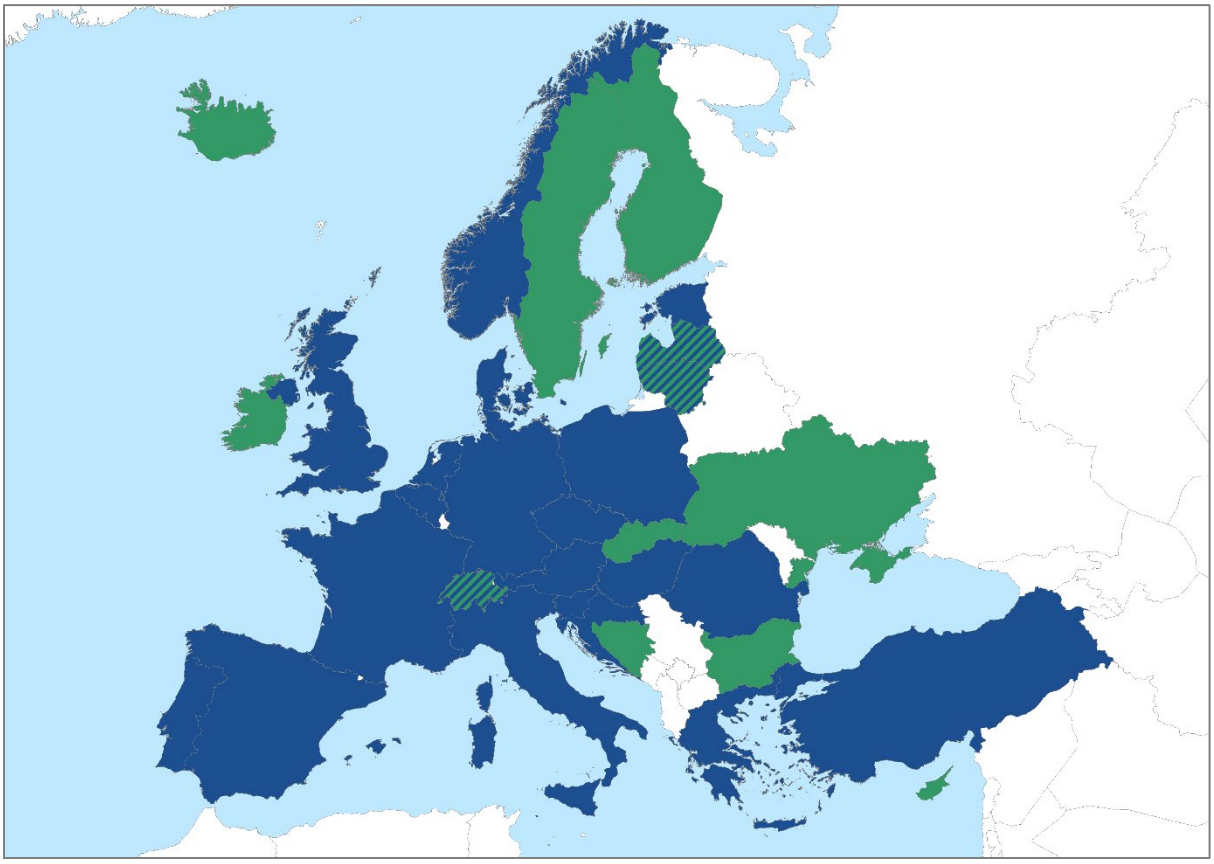

Figure 1: European countries covered in this report (blue: countries represented in the CO_2GeoNet Association, green: countries covered by institutions outside the Association; stripes: countries represented in the Association, but contribution provided by a non-member institution, or non-CO_2GeoNet countries covered by an Association member).

The first "State of play on CO_2 geological storage in 28 European countries" report was published in 2013 under the Pan-European Coordination Action on CO_2 Geological Storage (FP7 CGS Europe project) and was based on responses to a questionnaire similar to the one used for the current report to collect data from contributors.

The road to emission reduction and avoiding the worst impacts of climate change starts with international agreements and goals. The Paris Agreement signed at the United Nations Framework Convention on Climate Change (UNFCCC) 21st Conference of the Parties (COP21) represented a key milestone in defining climate goals. The Paris Agreement was adopted by 196 Parties at COP 21 in Paris on 12th December 2015 and entered into force on 4th November 2016. By 22nd April 2016, the Paris Agreement had been signed by all countries considered in this report and the European Union. Ratification (or approval/acceptance, depending on national requirements) has been completed by all of the countries considered here. The overarching goal of the Paris Agreement is to limit global warming to well below 2°C, preferably to 1.5°C, compared with pre-industrial levels. This agreement was informed by the IPCC Fifth Assessment Report (AR5) that sets out scenarios for climate change impacts and mitigation. The Paris Agreement requires each country to outline and communicate their planned post-2020 actions to meet the agreed climate targets, known as their Nationally Determined Contributions (NDCs). NDCs are recorded by the UNFCCC.

The International Energy Agency (IEA) assessed pathways to achieve global climate targets in the Energy Technology Perspectives (ETP) report series, which includes the 2 Degrees Scenario (2DS) and more recently the Sustainable Development Scenario, and in the recent Net Zero by 2050 report. The IPCC Assessment reports and IEA reports all emphasise the requirement for national supporting policies and global collaboration in order to meet the Paris Agreement climate goals, and the urgent requirement to massively scale up efforts to curb emissions. The IEA reports show the key role for CCS in a sustainable future, alongside further energy efficiency improvements, an increased use of renewable energy and other low carbon technologies. The ETP scenarios clearly indicate that the longer we wait to act, the more negative emissions through carbon dioxide removal (CDR) will be needed to meet climate goals.

Multiple CCS concepts are developing, with CO_2 captured from different types of facilities (energy plants – fossil-fuelled, geothermal or bioenergy (BECCS), industrial facilities – chemical, steel, cement plants, production of "blue" hydrogen from natural gas), or directly from the air (Direct Air Capture and Storage - DACCS). Apart from geological storage and mineral storage, captured CO_2 may be utilised for a wide range of applications (CCU) including the production of basic chemicals and synthetic fuels, and horticulture (e.g. increase CO_2 concentration in greenhouses). The injection of CO_2 into depleting oil reservoirs to enhance oil recovery (CO_2-EOR) or gas recovery (CO_2-EGR) are examples of CO_2 utilisation and storage. Each of these types of utilisation has a specific CO_2 emission-reduction potential that mainly depends on the permanence of CO_2 “storage” in the final product, the scale of application and the overall lifecycle carbon footprint of the technology.

During 2018, the European Commission (EC) set out its vision for a climate-neutral European Union (EU) and the objective of making the EU climate neutral by 2050, which was endorsed by the EU leaders in 2019. During 2020, as part of the European Green Deal, which aims for Europe’s economy and society to become climate neutral by 2050, the European Commission proposed the first European Climate Law in order to enshrine the 2050 climate-neutrality target into law. By the end of 2019, EU Members States were required to set out their National Energy and Climate Plans (NECPs) for the period 2021–2030 and their National Long-Term Strategies to achieve the vision of carbon neutrality by mid-century. Current NECPs target the original 40% emission-reduction target for 2030 and will need to be updated to meet the recently set 2030 target of 55% reduction compared to 1990 levels. The EC strategy to become climate neutral by 2050 was submitted to the UNFCCC during 2020. As Europe is moving towards climate neutrality, many countries are now discussing the role of CCS in Europe and in each country.

The European Strategic Energy Technology Plan (SET Plan) continues to accelerate the development and deployment of low-carbon technologies through cooperation amongst EU countries. SET Plan Action 9 is focused on developing full-chain commercial-scale CCS projects, cross-border infrastructures, preparation of new CO_2 storage sites and promoting new pilot projects on CO_2 capture, utilisation and storage. To achieve Action 9, the SET-Plan CCS and CCU Implementation plan set out research and innovation activities, first published in 2017 and recently updated in 2020 to reflect the raised ambition of a carbon-neutral Europe by 2050. CCS research and development in Europe is being supported through the European Commission’s Horizon 2020 and Horizon Europe research programmes at various scales and technology readiness levels. The first industrial projects can be supported by the EC Innovation Fund. The development of CCS hubs and clusters in Europe is currently being advanced with EC support for larger-scale transport infrastructure as Projects of Common Interest (PCI).

International agreements on standardisation will help build confidence in the safe operation of CO_2 capture, transport and storage facilities. The International Standards Organisation (ISO) produced standards for CO_2 capture, transport and geological storage through ISO/TC 265 for design, construction, operation, environmental planning and management, risk management, and related activities. CO_2 geological storage is handled by two standards already published, i.e. “Carbon dioxide capture, transportation and geological storage — Geological storage (ISO 27914:2017)” and “Carbon dioxide capture, transportation and geological storage — Carbon dioxide storage using enhanced oil recovery (CO_2-EOR) (ISO 27916:2019)”. Additional standards and technical reports are in preparation.

During 2019, significant progress was made to remove one of the barriers to larger-scale CCS networks including offshore CO_2 transport and storage: a Provisional Application of the 2009 Amendment of Article 6 of the London Protocol was allowed, which means that cross-border transport of CO_2 for the purpose of geological storage in sub-seabed geological formations is now permissible with agreement between the Parties concerned (see also IEAGHG 2021).

The Global CCS Institute (GCCSI) report "Global status of CCS 2020" observed a yearly increase in new facilities under development from 2018 to 2020, part of the recent resurgence of CCS. The report indicates 65 large-scale commercial CCS facilities, of which 26 are operating. These 26 facilities currently capture around 40 Mt CO_2 per year, most of which is used in hydrocarbon reservoirs for enhanced oil recovery, with only five projects targeting dedicated storage in deep saline aquifers. The report also noted increased engagement in CCS projects from the financial and environmental, societal, and governance sectors.

The above-described recent developments in national and European climate-protection ambitions and the yet to be fully exploited potential of CCS (and CCU) for CO_2 emission reduction and net carbon removal from the atmosphere motivated the CO_2GeoNet Association to provide an update of the current situation and recent developments on the geological storage of CO_2 in Europe to inform and stimulate ongoing discussions on the national measures to reach the envisaged emission-reduction targets towards climate neutrality, including the role of CCS. This report addresses the following aspects:

- European and national policies and climate-protection strategies.
- National and international legislation and regulations with respect to CO_2 geological storage.
- Assessment of storage options, potential and capacity in Europe.
- Large-scale and demonstration CCS projects; pilot and test sites for CO_2 capture, transport and storage.
- CO_2 storage research activities on a national, regional and European level.
- National actors driving CCS forward, public awareness and engagement.

Activities on CCU and CO_2-EOR in different European countries are considered to some extent in this report to provide a broader overview on the options, potentials and current activities of CCUS technologies – however, the focus of this report is clearly on CCS and in particular on the geological storage of CO_2.

Chapter 2: European and national policies and climate-protection strategies

2.1 European policies and climate-protection strategies

Since 2012, many important policy developments at international and EU levels have been made, and many European countries have adopted new policies and measures to address the 2030 and 2050 climate objectives. The EU aims to be climate-neutral by 2050, i.e. to become an economy with net-zero greenhouse gas (GHG) emissions. The EC set out its vision for a climate-neutral EU in November 2018, which was endorsed by the European Council in December 2019. Becoming the first climate-neutral continent by 2050 is the overarching objective of the European Green Deal – the EU's main new growth strategy to transition the EU economy to a sustainable economic model. In addition, the EU has recently re-defined its 2030 climate ambition, now aiming to cut GHG emissions by at least 55%. To bring the EU's climate and energy legislation in line with this updated 2030 goal, the EC proposed the Fit for 55 package in July 2021. The transition to climate neutrality concerns nearly all EU policies and is in line with the Paris Agreement objective to keep the global temperature increase to well below 2°C and pursue efforts to keep it to 1.5°C. To write into law the European Green Deal's main objective, the European Commission proposed, on 4th March 2020, the first European Climate Law enshrining the 2050 climate-neutrality target. The included provisions complement the existing policy framework, i.e. the 2030 climate and energy framework, and propose a legally binding target of net-zero GHG emissions by 2050. The European Climate Law (Regulation (EU) 2021/1119) was approved by the European Parliament on 24th June 2021 and by the European Council on 28th June 2021 and entered into force on 29th July 2021.

Practical measures to help achieve the EU climate neutrality are included in the "Clean Energy for all Europeans Package" – a set of eight legislative Acts on the energy performance of buildings, renewable energy, energy efficiency, governance, and electricity market design. According to provisions included in this Package, each EU country is required to establish an integrated 10-year National Energy and Climate Plan (NECP) for 2021–2030. The NECPs outline how EU countries are going to achieve their respective targets related to the common EU energy and climate targets for 2030. The NECPs have now been finalised for all 27 EU Member States. In addition, the Member States were required to submit their first national long-term strategies (covering the period up to 2050) to the Commission by 1st January 2020. The strategies describe how the Member States plan to achieve the GHG emissions reductions needed to meet their commitments under the Paris Agreement and the EU climate-neutrality objectives. The long-term strategies have to be consistent with Member States' NECPs. At the time this report was written, national long-term strategies had been submitted by 20 out of the 27 Member States. In the countries outside the EU, other national legislations, programmes and mechanisms have been implemented, which also aim to achieve climate goals resulting, inter alia, from the Paris Agreement.

On the European level, CCS is considered an important technology to achieve the EU climate objectives. For example, the Commission's publication "Going climate-neutral by 2050" counts CCS as one of seven major strategic building blocks of the strategic vision for a climate-neutral Europe. CCS is deemed necessary "as a potential avenue to produce hydrogen, as a mechanism for eliminating certain difficult-to-reduce emissions from industry and, combined with sustainable biomass, to create CO_2 removal technologies" (DG CLIMA 2019).

The study ´Review of Carbon Capture Utilisation and Carbon Capture and Storage in future EU decarbonisation scenarios´ (Butnar et al. 2020), commissioned by the SET Plan Implementation Working Group 9, reviews the role of CCS and CCU in Europe in published decarbonisation scenarios consistent with the 1.5°C and 2°C global temperature targets. The considered scenarios indicate that CCS is essential for Europe to reach net-zero CO_2 emissions by 2050, which is consistent with the 1.5°C global target. To achieve a target of below 2°C, most scenarios suggest a prominent role for CCS. This strongly implies that Europe needs large-scale CCS deployment to meet future GHG emission-reduction targets. In the 1.5°C scenarios reviewed by Butnar et al. (2020), the median rate of CO_2 capture by CCS is 230-430 Mt CO_2/year in Europe in 2030, increasing to 930-1,200 Mt CO_2/year by 2050. In the 2°C scenarios, the median rate of CO_2 captured by CCS is lower with 35-100 Mt CO_2/year in Europe in 2030, increasing to 600-930 Mt CO_2/year by 2050. In addition, there is a significant role for carbon dioxide removal (CDR) technologies, for example, by energy generation from biomass with CCS (BECCS), in the scenarios, ranging from 150-230 Mt CO_2/year by 2050 in the 2°C scenarios to 400 Mt CO_2/year by 2050 in the 1.5°C scenarios (Butnar et al. 2020).

2.2 National policies and climate-protection strategies

The above-mentioned and other related strategic documents issued by the countries covered in this report have been analysed with reference to the inclusion of CCS in national energy and/or climate protection plans and strategies. When analysing the 27 NECPs submitted by EU Member States to the EC, it was found that 20 mention plans and possibilities for the use of CCS technology as a CO_2 emission-reduction option. In some countries, only one part of the CCS chain (i.e. capture) is being considered.

In the case of long-term strategies, as of September 2021, 20 out of 27 countries had reported to the EC. CCS technology (sometimes in combination with CCU) is included in the long-term strategies of Italy, Lithuania, Latvia, the Netherlands, Slovakia, Spain, Sweden, Austria, Finland, France, Germany, Greece, Hungary. It should be noted, however, that in the majority of cases these strategies mention a possible consideration of CCS without detailed specification and without clear implementation plans. This includes CCS being solely considered, inter alia, in GHG emission-reduction scenarios or indicated as an option for specific industry sectors with an assumed cost reduction and with a need for further research on implementation, or CO_2 use but not storage or CO_2 capture where the CO_2 is exported for storage.

Overall, the foreseen activities with respect to CCS in the individual Member States differ significantly. They range from support for research activities, national storage capacity assessments and feasibility studies to implementation of specific large-scale CCS projects. Since 2012, the focus of CCS application has shifted in many countries from capture at fossil-fired power plants to capture at industrial facilities and other alternative emitters/sources, for example, waste incineration plants or geothermal energy production.

In countries where CCS is considered an (important) element of the transition to a low or zero-emission economy, its implementation also involves the need to cooperate with other countries. Establishing framework programmes and/or bi- or multilateral collaborations are declared as an aim, for example, by Belgium, Croatia, Denmark, Estonia, Germany, and Sweden. This collaboration also may include countries outside the EU. There are very visible activities in this area included in NECPs and long-term strategies of the Nordic countries that mention, for example, the "Nordic Energy Research" as a platform for co-operative energy research and policy development.

The provisions of the Paris Agreement invite Parties to communicate by 2020 to the UNFCCC Secretariat their mid-century "long-term low GHG emission development strategies (LT-LEDS)". At the end of September 2021, such strategies or their drafts had been prepared and communicated by Hungary, Slovenia, France, Switzerland, Denmark, Austria, Netherlands, Sweden, Spain, Belgium, Latvia, Norway, Finland, Slovakia, Portugal, Ukraine, United Kingdom, Czech Republic, and Germany, i.e. by 19 countries of the 32 countries covered by this report, and by the European Union. In EU Member States, these long-term strategies are expected to be consistent with Member States' NECPs for the period 2021–2030 and the national long-term strategies prepared under the "Clean Energy for all Europeans Package".

Figure 2 shows the countries covered in this report and indicates those with policies that refer in some way to the possibility of using CCS.

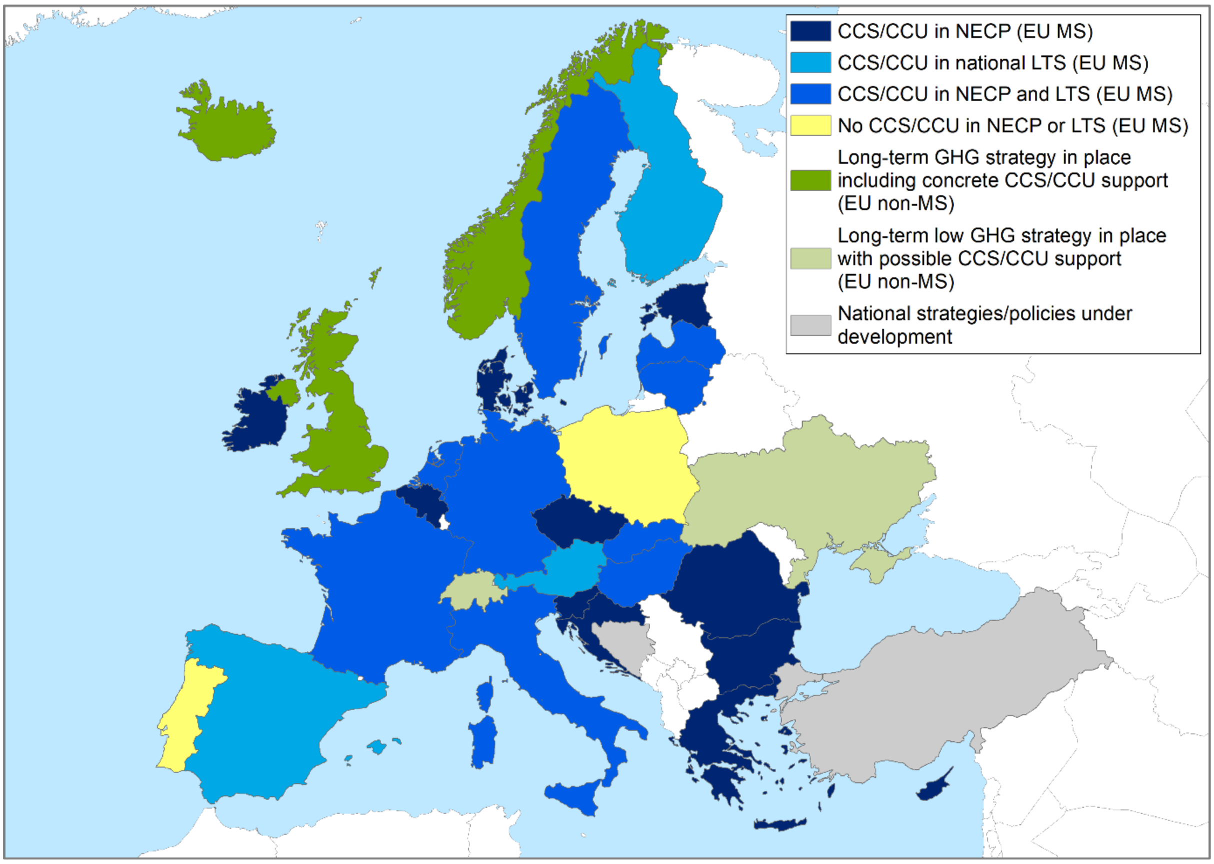

Figure 2: Countries with an indication of the role of CCS in national decarbonisation policies including national integrated national energy and climate plans for the period from 2021 to 2030 and/or long-term GHG emission-reduction strategies (EU Member States) and other national long-term GHG emission-reduction strategies (EU non-members).

When analysing the main objectives related to the low/zero-emission goals included in all the above-mentioned documents, differences between the targets of individual countries are clearly visible. For instance, for the reduction of non-Emissions Trading System (ETS) GHG emissions by 2030 compared with 2005, the highest reduction targets of 40% or more are set in Denmark, Finland, France, Germany, Iceland, Norway, Portugal and Sweden. Emission-reduction targets between 30 and 36% are set by Austria, Belgium, Ireland, Italy, and the Netherlands. When it comes to the lowest reduction targets, up to 10% is indicated by Croatia, Hungary, Latvia, Lithuania and Poland. Targets for the share of renewable energy sources in the final energy consumption in 2030 of more than 40% are reported for Austria, Denmark, Estonia, Finland, Latvia, Lithuania, Portugal and Spain. In the case of energy security, which refers to reduced reliance on imported fossil fuels, in some countries quantified objectives are not set. 100% renewable electricity generation by 2030, 2040 and 2050 is indicated by Austria, Sweden and Denmark, respectively.

These examples show the wide variation in goals defined in strategic documents by individual countries that reflect their present-day characteristics of, for example, national economic structure, energy mixes, domestic energy sources, and gross domestic product (GDP) level.

Chapter 3: National and international legislation and regulations with respect to CO_2 geological storage

3.1 National legislation and regulations

The EU Directive 2009/31/EC on the geological storage of CO_2 (often called the "EU CCS Directive") was transposed into national legislation in all Member States considered in this study between 2010 and 2014 (information on Malta and Luxemburg has not been included as no partners were identified to provide updates). Norway, a member of the European Economic Area (EEA), transposed the EU CCS Directive in 2014. In Iceland (EEA member), the Government has adapted the transposition of the Directive to allow for the conditions and requirements of mineral storage, i.e. to enable the subsurface storage of CO_2 in basalt formations. Turkey (EU membership candidate), Bosnia and Herzegovina (potential candidate for EU membership), as well as Switzerland and Ukraine have no dedicated national legislation in place for geological storage of CO_2. In Turkey, there are no regulatory barriers that directly prevent the usage of the subsurface for CO_2 storage; in particular, if a field could be used technically as a storage medium, for other energy activities and at the same time for petroleum production, CO_2 storage operations are allowed. In Bosnia and Herzegovina, only gas storage has been regulated to date. In Switzerland, the 26 Cantons have sole sovereignty over the subsurface and are responsible for defining the regulatory framework for geological CO_2 storage if deemed necessary.

As of June 2021, the geological storage of CO_2 is currently permitted in 19 of the 32 countries studied by provisions according to the EU CCS Directive or other national legislation and regulations. Some countries excluded certain regions or imposed certain limitations as follows:

Permitted:
UK, Spain, Portugal, Norway, Netherlands, Iceland, Hungary, France, Czech Republic and Romania.

Permitted with regional exceptions or limitations:

- Italy (excluding seismic/volcanic areas),
- Croatia (state may exclude certain areas),
- Belgium (Brussels region & North Sea area: storage geologically not possible, Flemish and Walloon regions: permitted),
- Sweden (only offshore),

- Greece and Cyprus (CO_2 storage not allowed in the water column or if the storage complex extends beyond Hellenic or Cypriot territory[3], respectively),
- Greece (in addition to the above, storage is prohibited in underground aquifers),
- Poland (permitted only for demonstration projects in specified areas; see also below),
- Slovak Republic (exploration only allowed in defined areas, see also below) and
- Bulgaria (the size of the exploration area for each individual CO_2 storage site is limited to 5,000 km^2 on land and 20,000 km^2 on the continental shelf and in the exclusive economic zone in the Black Sea; ICF International 2013).

Prohibited: The geological storage of CO_2 is prohibited in 9 of the 32 countries studied: Slovenia, Lithuania, Latvia, Ireland, Finland, Estonia, Austria and Denmark (exception: EOR operations allowed offshore). In Germany, de facto CO_2 storage has been prohibited since 2017 (see also below). In many countries where CO_2 storage is prohibited, an exception from Article 2 of the Directive is included in the national laws for activities with a total foreseen amount of less than 100,000 t CO_2 stored so that injection for research purposes, development or testing of new products or processes is permissible. In contrast, Denmark and Slovenia prohibit any CO_2 injection in the subsurface (see also below).

Not defined: CO_2 storage is currently neither permitted nor prohibited in Ukraine, Turkey, Switzerland and Bosnia and Herzegovina as no dedicated legislation exists in these countries.

A comparison between the present-day situation and the situation in 2012 shows no clear trend of development (Figs. 3&4). Nevertheless, the following aspects are notable:

- Five additional countries transposed the EU CCS Directive after 2012 and the collation of the Rütters et al. 2013 report, making CO_2 storage now permitted within this legal framework in Norway, Croatia, Poland, Iceland and parts of Belgium. Note that in Norway, the Sleipner and Snøhvit projects were first regulated under the Norwegian Acts pertaining to Petroleum Activities and the Pollution Control Act prior to the transposition of the EU CCS Directive and their re-licencing in 2017 and 2018, respectively.
- CO_2 storage is now also permitted in Sweden and the Czech Republic. In Sweden, CO_2 storage was temporarily forbidden until 2013. According to the new laws, as of 2014 (with some amendments in the following years), larger-scale CO_2 storage is now permitted offshore in Sweden. In the Czech Republic, the time limit prohibiting CO_2 storage projects exceeding 100 kt CO_2 expired on 1st January 2020, so that CO_2 storage is now permitted.

[3] Including each country's exclusive economic zone and continental shelf.

- In contrast, in Lithuania, CO_2 storage has been prohibited since 1st July 2020 by a new law. Similarly, Slovenia has prohibited CO_2 storage since November 2013 (also applying to CO_2 injection for research purposes).
- In Germany, the national CO_2 storage law in principle permits CO_2 geological storage, but de facto CO_2 storage is prohibited as the deadline for filing CO_2 storage permits under this law expired on 31st December 2016. In addition, the German Federal States are given the right to ban CO_2 storage in their territory and some states have used this power. A first evaluation of the national storage law in 2018 did not result in any adaptations. The next evaluation is due in 2022.

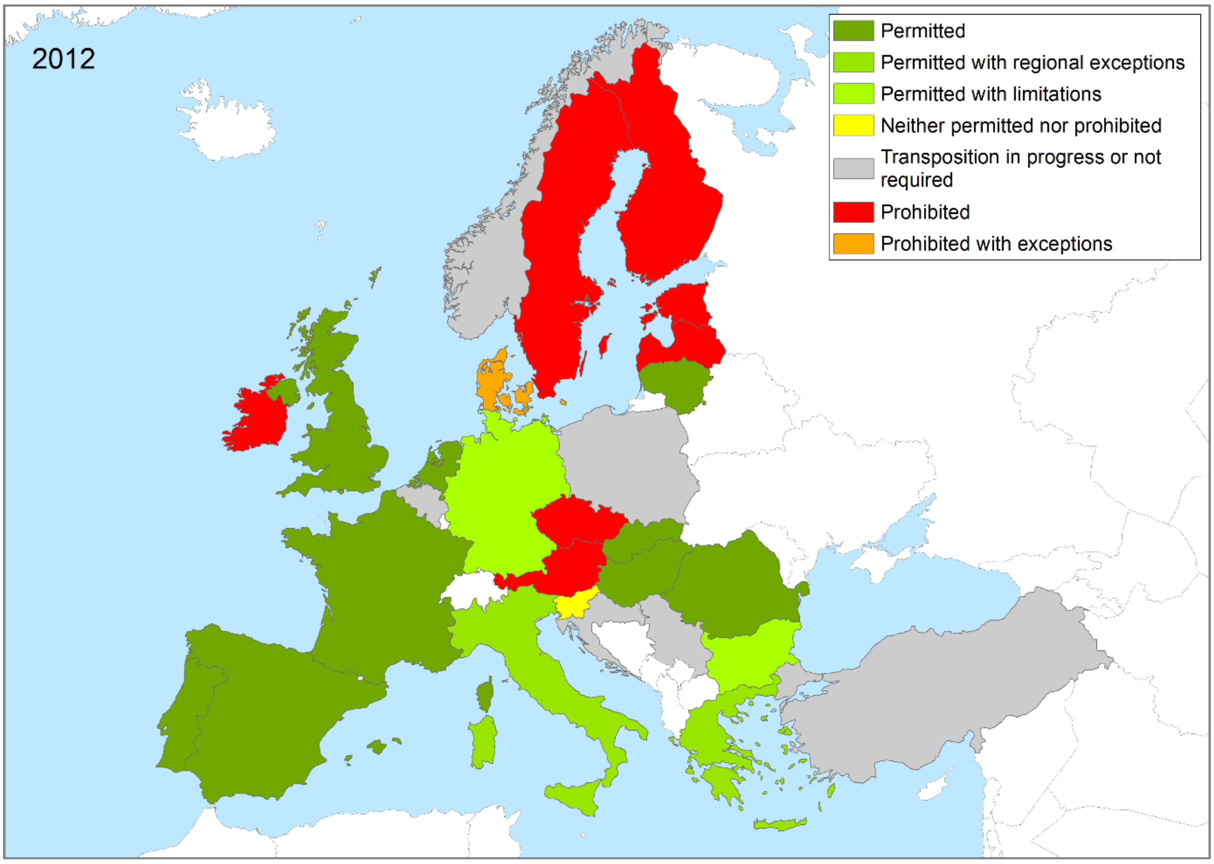

Figure 3: CO_2 storage permissibility with respect to national legislation in European countries as of 2012 (cf. Rütters et al. 2013).

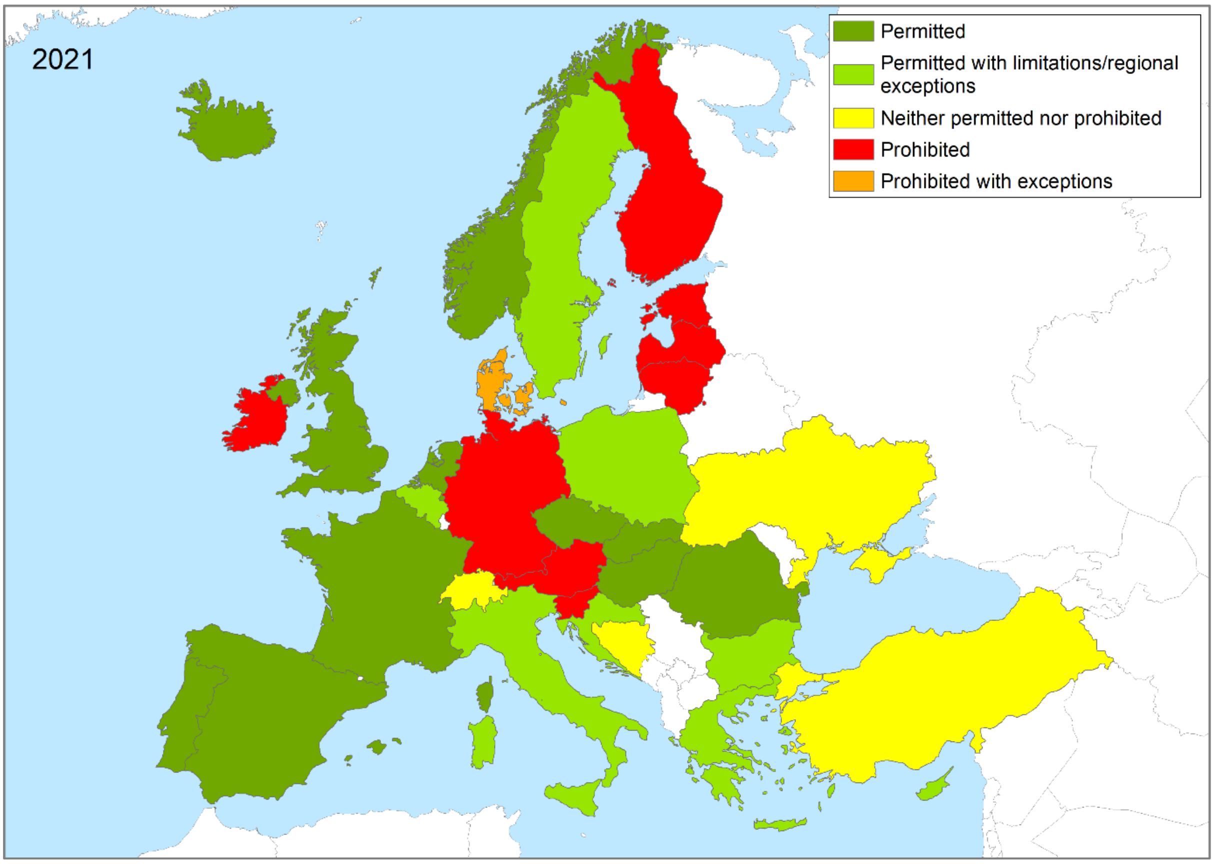

Figure 4: CO_2 storage permissibility with respect to national legislation in European countries as of 2021; note that in the 2021 representation the categories "permitted with regional exceptions" and "permitted with limitations" used in the Rütters et al. 2013 report are combined.

The specificities of the legal situation in the following countries is explained in more detail below:

- In Slovakia, the national CO_2 Storage Act generally enables CO_2 storage, but at the same time, other regulations significantly limit possible locations of CO_2 storage sites by protecting priority areas for other subsurface uses such as geothermal energy recovery or exploitation of hydrocarbons and mineral resources as well as areas for national parks.

- In Poland, only CCS for demonstration purposes[4] is allowed. Further limitations arise from the Implementing Acts to the Polish Geological and Mining Law stipulating that only offshore storage is allowed, with further limitations. As a result, at present the only available place where CO_2 storage may be permissible is the Cambrian reservoir within the exclusive economic zone of Poland.
- In Austria, the national CO_2 storage law is evaluated every five years. The evaluation in 2018 did not result in any changes, i.e. CO_2 storage is still prohibited in Austria.
- Denmark plans to permit large-scale offshore and onshore storage during 2022. The EU CCS Directive is implemented in the Danish Subsurface Act, but Denmark has since 2011 had a moratorium for CO_2 storage both onshore and offshore except in the case of EOR projects in Danish hydrocarbon fields in the North Sea. This moratorium also affected CO_2 injection for research purposes (< 100 kt). Permission for an injection of up to 100 kt CO_2 (research projects) is expected to be approved during 2022 and permission for injections of more than 100 kt CO_2 (large scale) is expected to be approved in autumn 2022.
- In Ireland, currently CO_2 storage is not permitted on Irish territory, its exclusive economic zone and its continental shelf. The national law is currently under review with plans to permit CO_2 storage.

Depending on the country-specific governmental and administrative organisation, CO_2 storage is regulated on a national/federal/state level (15 countries) or at regional level (4 countries) by the designated authorities/agencies. For 13 countries, no information was available or the relevant authority is not defined. In many countries where authorities are defined it is the (national or regional) mining authorities or hydrocarbon agencies that are often sub-ordinate to the (national or regional) ministries responsible for economy, energy or the environment. In some countries, several ministries are each responsible for regulating specific parts of the CCS chain. The exact structural organisation of agencies, departments and ministries is unique in each country.

In many of the countries studied, ownership of the subsurface lies with the state or the people collectively (e.g. Bosnia and Herzegovina, Croatia, Cyprus, Czech Republic, Italy, Slovenia, Spain, Sweden, Turkey, Ukraine). In some of the countries studied, the state has the right and/or the responsibility to define prospective areas for CO_2 storage, and it can also decide to exclude areas from any CO_2 storage activity. In several other countries (e.g. in Austria, Belgium's Brussels and Walloon regions, Germany, Latvia), the individual landowners own the land down to the earth's centre. In this case, the landowner's claim often does not include

[4] "Demonstration projects" involve capture on power generation with a minimum capacity of 250 MW or 500 kt CO_2 captured and stored annually on industrial plants as defined in the European Commission Decision 2010/670/EU of 3rd November 2010.

hydrocarbons and the geological structures bearing them (Austria) or “freely mineable” resources (Germany), which are deemed as national resources/state property. Permits and concessions for these are managed by agencies or mining authorities, as in countries where the subsurface is owned by the state. In contrast, in Latvia, storage permits from many landlords would be required to enable onshore CO_2 storage.

There is very limited experience with licencing procedures for CO_2 storage across Europe. Only Norway has practical experience with industrial-scale CO_2 storage sites in operation, and only three countries have awarded storage licences according to the provisions of the EU CCS Directive – Norway, the Netherlands and the UK. Several storage licences and permits based on different laws and regulations (e.g. mining or geothermal) were granted to smaller-scale and pilot projects in France, Germany, Iceland and Spain. Denmark reports one declined storage licence pre-application from 2011. Since few projects have reached the site characterisation phase, the experience with awarding exploration permits and licences is also limited in Europe (less than 10 countries).

3.2 International legislation and regulations

Various international agreements and regulations are relevant for the implementation of CCS projects in Europe and worldwide. The "Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972" ("London Convention" or LC) was one of the first global conventions to protect the marine environment from human activities and to prevent pollution of the sea by dumping of wastes and other matter. It has been in force since 1975. The “London Protocol” (LP) was agreed during 1996 prohibiting all dumping except for some acceptable wastes (specified in the so-called “reverse list”). The Protocol entered into force in 2006. An amendment to Article 6 of the London Protocol was adopted in 2009 allowing for the export of CO_2 streams for geological storage. For the amendment to come into force, a ratification by two thirds of the contracting parties is required. However, ratification, i.e. approval from all signatories, had not been achieved a decade after the amendment was adopted (cf. Tab. 1) so the amendment still is not in force. To overcome this barrier to the implementation of CCS projects involving transboundary transport of CO_2, a provisional application of this amendment was accepted at the LC 41/LP 14 meeting of the contracting parties in October 2019, thus, cross-border CO_2 transport to offshore storage sites is now permissible based upon agreements or arrangements between the countries concerned. In more detail, this means that countries who wish to allow cross-border transport of CO_2 for injection and permanent storage under the seabed must currently deposit a Unilateral Declaration of the Provisional Application of the 2009 Amendment to the London Protocol Article 6 to the Secretary-General of the International Maritime Organisation (IMO), i.e. both the importing and exporting country must deposit the declaration. This procedure is only possible for parties to the London Protocol.

Table 1: Status of ratification (or respective act depending on national constitutional requirements) of different international treaties and regulations relevant for CO_2 storage operations.

Country	London Convention & London Protocol		OSPAR	HELCOM
	Status as of 10th September 2021	Ratification of 2009 LP Amendment		
Austria	Non Party		(x)	
Belgium	Protocol Party		x	
Bosnia and Herzegovina	Non Party			
Bulgaria	Protocol Party		(x)	
Croatia	Convention Party		(x)	
Cyprus	Convention Party		(x)	
Czech Republic	Non Party		(x)	
Denmark[1]	Protocol Party		x	x
Estonia	Protocol Party	x	(x)	x
Finland	Protocol Party	x	x	x
France	Protocol Party		x	
Germany	Protocol Party		x	x
Greece	Convention Party		(x)	
Hungary	Convention Party		(x)	
Iceland	Protocol Party		x	
Ireland	Protocol Party		x	
Italy	Protocol Party		(x)	
Latvia	Non Party		(x)	x
Lithuania	Non Party		(x)	x
The Netherlands[2]	Protocol Party	x	x	
Norway	Protocol Party	x	x	
Poland	Convention Party		(x)	x
Portugal	Convention Party		x	
Romania	Non Party		(x)	
Slovak Republic	Non Party		(x)	
Slovenia	Protocol Party		(x)	
Spain	Protocol Party		x	
Sweden	Protocol Party	x	x	x
Continued on next page				

Table 1: *(continued)* Status of ratification (or respective Act depending on national constitutional requirements) of different international treaties and regulations relevant for CO_2 storage operations.

Country	London Convention & London Protocol		OSPAR	HELCOM
	Status as of 10th September 2021	Ratification of 2009 LP Amendment		
Switzerland	Protocol Party		x	
Turkey	Non Party			
Ukraine	Convention Party			
United Kingdom	Protocol Party	x	x	
European Union	n/a	n/a	x	x

[1]: With territorial exclusion with respect to Greenland and Faroes
[2]: For the European Part of the Netherlands
x: Approval/ Party
(x): Party under European Union signature.

The OSPAR Convention (1992), its name being derived from the original 1972 Oslo ("OS") and 1974 Paris ("PAR") Conventions, is a mechanism by which 15 governments and the EU (and as such all its Member States; see Tab. 1) cooperate to protect the marine environment of the North-East Atlantic. The OSPAR Convention is the result of the combination, up-dating and extension of the Oslo Convention against dumping and the Paris Convention for the prevention of marine pollution from land-based sources. During 2007, the OSPAR Commission adopted amendments to the Annexes of the Convention to allow the storage of CO_2 in geological formations under the seabed (Decision 2007/2), while the storage of CO_2 streams in the water column or on the seabed was prohibited (Decision 2007/1).

Likewise, for the protection of the marine environment in the Baltic Sea area, the Convention on the Protection of the Marine Environment of the Baltic Sea Area ("Helsinki Convention") was signed in 1974 by all Baltic Sea coastal countries. It forms the foundation of the Baltic Marine Environment Protection Commission, an intergovernmental organisation also known as the Helsinki Commission (HELCOM) (Tab. 1). The Helsinki Convention "seeks to protect the Baltic Sea from all sources of pollution […], to preserve biological diversity and to promote the sustainable use of marine resources". With this line, it prohibits the disposal of waste under the Baltic Sea. As yet, no amendment has been made to the Convention to explicitly exclude anthropogenic CO_2 from the list of wastes. In addition, established regional organisations such as HELCOM will play an important role in regional marine spatial planning (here: for the Baltic Sea area) to potentially implement CO_2 storage while ensuring protection and sustainable use of the marine environment (cf. Langlet 2018).

Chapter 4: Assessment of storage options, potential and capacity in Europe

The first joint European research on assessment of CO_2 storage potential was performed within the project "The underground disposal of carbon dioxide", funded by the 3rd EU Framework Programme JOULE 2 in 1993–1995. The first European numbers for possible geological storage capacity with an order of magnitude of 800 billion tonnes of CO_2 (800 Gt CO_2), mainly far offshore in the North Sea, were reported by Holloway (1996). These estimates of geological capacities were, as it was stated, "broad-brush" numbers, but nevertheless encouraging and thus led to further work.

The JOULE 2 study combined with the commencement of the Sleipner project in 1996, was the inspiration for the GESTCO study ("European potential for geological storage of CO_2 from fossil fuel combustion") that was carried out in 2000–2003. GESTCO was a 3-year EU-FP5 project covering eight countries (Norway, Denmark, UK, Belgium, Netherlands, Germany, France and Greece). Results were published in the project summary report (Christensen & Holloway 2004).

Within the CASTOR project ("CO_2 from Capture to Storage", EU-FP6, 2004–2008), a small part enabled initiation of collaborative activities around CO_2 storage capacity assessment between the GESTCO countries and some of the – at that time – new EU Member States and Candidate Countries of Central and Eastern Europe. The first CO_2 storage potential data from the Czech Republic, Poland, Slovakia, Hungary, Romania, Slovenia, Croatia and Bulgaria were collected and integrated in a database and Geographic Information System (GIS). Data were collected on possible geological storage locations, such as aquifers, oil and gas fields and coal seams, as well as local CO_2 emission point sources. Based on the data and assumptions, a first estimate of geological storage capacity was calculated, proving that generally 20 years' worth of all CO_2 emissions from point sources in the studied region could be stored in geological sites (Scholtz et al. 2006).

In 2006–2008, the above-mentioned activities were followed by EU GeoCapacity ("Assessing European capacity for geological storage of carbon dioxide"), an EU-FP6 project that has been the most comprehensive activity on mapping pan-European CO_2 storage potential to date. EU GeoCapacity covered 25 countries. Comprehensive country reports were produced, containing assessments of geological structures suitable for CO_2 geological storage, CO_2 point emission sources and existing infrastructure data (oil and gas pipelines). Storage potential was evaluated on the basis of a unified methodology; the level of detail, however, differed from country to country, depending on the amount and quality of available data. Archive, re-evaluated, as well as newly derived data were used. The main result is a GIS-linked, pan-European database of CO_2 storage potential. The database includes both public and confidential data; therefore, it could not be made freely available in the public domain. Project reports, publications and presentations are still available on the project website. Conservative storage capacity estimates for Europe are provided in the final report, accounting for 96 Gt (96,000 Mt) of CO_2 in deep saline aquifers, 20 Gt (20,000 Mt) of CO_2 in depleted hydrocarbon fields and 1 Gt (1,000 Mt) of CO_2 in unmineable coal beds. Considering the emissions reported by the European Environment Agency for 2019 (587 Mt $CO_{2\,eq}$ per year for industrial emissions; EEA 2020) and the conservative estimate for CO_2 storage in saline aquifers and hydrocarbon fields reported by EU GeoCapacity (116 Gt), if 1/10 of the reported geological storage capacity could be used, then two decades' worth of industrial emissions from Europe could be stored. It is worth noting that the EU GeoCapacity project strongly recommended collection of new data and further work to fully assess storage capacity in Europe. In particular, it was noted that data for saline aquifers, where the largest storage capacity is expected to lie, is extremely sparse.

In 2012–2013, the European Commission funded a targeted project titled CO_2StoP ("CO_2 Storage Potential in Europe") to establish a database of publicly available data on CO_2 storage potential in Europe. Due to the limited budget, only existing data were used. In all, 27 European countries were covered. In most cases, EU GeoCapacity data were used with the confidential data removed. Only a few countries provided updates, largely based on work funded at national level. CO_2StoP used an improved methodology for storage potential assessment, and a pan-European database was produced. Project results include the database, a GIS application (ESRI's ArcGIS 10) and a calculation engine capable of providing probabilistic estimates of CO_2 storage capacity. A Data Analysis/Interrogation Tool is also available, able to perform calculations of storage capacity, injection rates with stochastic analyses. The project report does not provide any overall storage capacity figures for Europe but rather a set of country-wide results based on calculations performed using the calculation engine with uncertainty intervals expressed mostly by minimum, maximum and mean values. The CO_2StoP database itself was first housed by the EC Joint Research Centre in Petten, the Netherlands, and was made broadly available to the public only in 2020. After an agreement was reached with EuroGeoSurveys, the association of European Geological Surveys, the database has become publicly available online on the EGDI map portal of EuroGeoSurveys (Fig. 5). The CO_2StoP database represents the most up-to-date pan-European dataset; however, much of the data collation took place more than a decade ago and does not reflect recent changes and updates performed on national and regional levels. Storage capacity updates that have taken place since the publication of the first State of Play report and June 2021 have been reported by 25 countries; details are provided in Annex I to this report. The updates range from thorough storage capacity assessments or re-assessments on country or even transnational levels, to updates focusing on selected regions or clusters of potential storage sites.

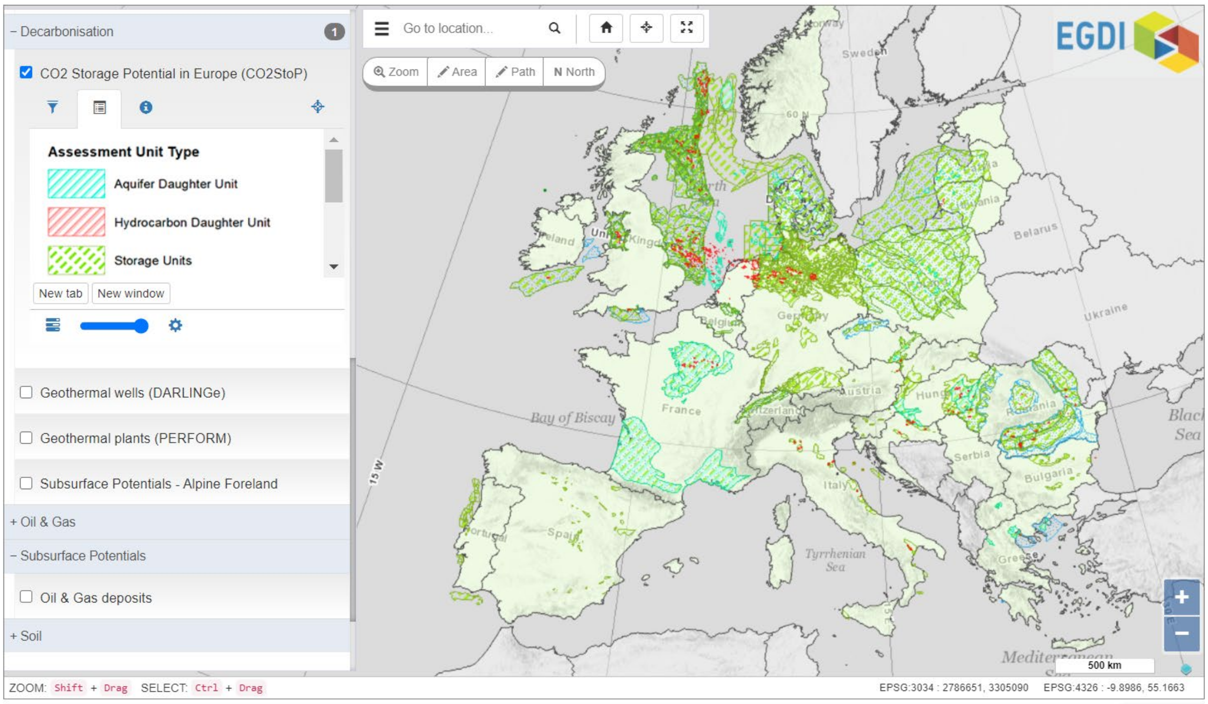

Figure 5: Overview map of the CO_2StoP database on the EGDI portal of EuroGeoSurveys.

Notable examples of new developments in storage capacity assessments since 2012 are as follows: The Nordic CO_2 Storage Atlas that was produced by NORDICCS – the Nordic CCS Competence Centre in 2011–2015 and that covers Denmark, Sweden, Norway and Iceland. National storage atlases/databases have been completed in three countries: The UK has finalised its national storage database CO_2 Stored, Norway has finished the work on the comprehensive CO_2 Storage Atlas of the Norwegian Continental Shelf, and Spain completed its Atlas of Subsoil Structures Susceptible to CO_2 Storage (AlgeCO_2).

Considering these recent developments (including the Nordic Atlas), together with earlier work, we can state that a comprehensive national CO_2 storage atlas (database, catalogue) is currently available for 8 European countries – Denmark, Germany, Iceland, Norway, Poland, Spain, Sweden and the UK. The level of detail and information provided varies significantly between the national databases/catalogues of these countries. For example, the Storage Catalogue of Germany does not include a quantification of CO_2 storage capacities.

In addition, significant developments of storage capacity assessment or re-assessment at a national level have also been achieved in other countries, in particular Hungary, Ireland, Italy and the Netherlands. Work on national storage capacity (re-)assessment is ongoing or has just finished in Denmark and Ukraine.

The developments listed above offer a strong argument for the value of a new pan-European CO_2 storage atlas, as recommended in the Position Paper by ENeRG, the European Network for Research in Geo-Energy, in 2012. The necessity to prepare a consolidated and up-to-date European Storage Atlas has also been reflected in the EU SET Plan Action No 9 CCS and CCU and its Implementation Plan, where the R&I Activity 4: ´Establish a European CO_2 Storage Atlas´ was included in 2017 with the intention of this work being completed by 2020. Unfortunately, this objective has not been achieved as of today and there are no indications that a European Storage Atlas could be available before 2025–2027, given that the estimated working time to complete such an activity is approximately three years.

The Annex to this report contains the questionnaire responses and provides an overview of the current status of CO_2 storage potential assessment in individual European countries. It is evident that the level of knowledge, quality of datasets and form of presentation differ from country to country, ranging from detailed national atlases and databases (Norway, the UK, etc.) to basic assessments or even no assessment in some countries, especially in Eastern and South-Eastern Europe. Two countries – Estonia and Finland – report zero storage capacity based on their unfavourable geology. The map in Figure 6 provides an overview of the current level of CO_2 storage capacity assessment in individual countries.

The prevailing types of structures considered for CO_2 storage in Europe are saline aquifers (25 countries) and depleted/depleting hydrocarbon fields (22 countries). Offshore sites are the preferred location for storage in most coastal countries, with a focus on the North Sea as a region where the largest European storage potential has been identified so far. Five countries report storage capacity in coal seams but this option has not been investigated or developed recently. In many countries the focus has been on one type of structure or geographical setting while other types or settings have not been evaluated in detail (such as aquifers in Ireland and the Netherlands, offshore structures in France, etc.).

Iceland is the pioneer and an advocate of in-situ mineral storage of CO_2 in mafic and ultramafic rocks, especially basalts, promoted by the dissolution of CO_2 in water before or during its injection (so-called “Carbfix technology”; Snæbjörnsdóttir et al. 2020). Carbfix has recently launched its “Mineral Storage Atlas“ that highlights suitable geological formations for mineral storage in Europe and worldwide. Altogether the worldwide mineral storage potential has been estimated at > 100,000 Gt CO_2. This approach has not been followed by other European countries yet, apart from Greece and Portugal, where the first steps are in progress towards an estimation of their national CO_2 storage potential for in-situ mineralisation.

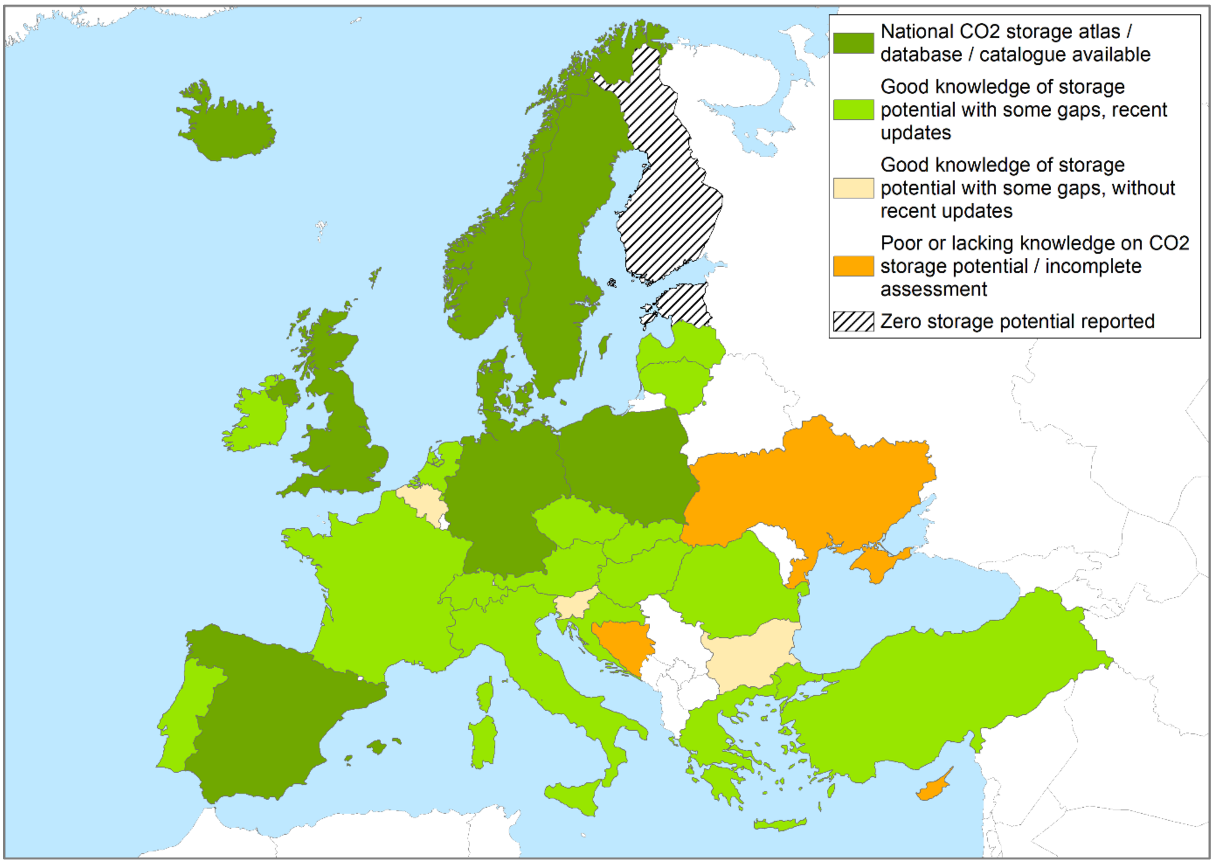

Figure 6: Status of CO_2 storage potential assessment in European countries.

Chapter 5: Large-scale and demonstration CCS projects; pilot and test sites for CO_2 capture, transport and storage

This chapter gives an update on developments since 2012 regarding CO_2 capture, transport and/or storage projects as well as new activities at all project scales (Tab. 2).

Table 2: Classification of CO_2 capture, transport and/or storage projects according to project size following GCCSI (2020) and Martínez et al. (2013b).

Scale	Definition
Large-scale projects	projects that enable CO_2 capture/injection rates of > 400 kt CO_2/year (800 kt/year on power)
demonstration projects	projects that have a capture/injection rate of < 400 kt/year with overall > 100 kt CO_2 captured/injected
pilot projects	with an overall amount of < 100 kt CO_2 captured/injected (over a few years)

This report focuses on storage projects. Capture and transport projects are included to complement the overview of projects and activities relevant for advancing CCS technology and its implementation.

5.1 Full-chain CCS projects and clusters

The realisation of large-scale CCS projects in Europe remains challenging: between 2010 and 2017 many projects were slowed down or cancelled due to financial restrictions, low public acceptance (of CCS in general and locally of specific projects) and lack of incentives. Recent initiatives at national level such as the Norwegian full-chain CCS project (Longship), as well as on EU level (e.g. the recently opened Innovation Fund) could unlock the potential of CCS in Europe. With a view to achieving its climate and energy targets for 2020 and beyond, the EU launched two major funding programmes in 2009 to support implementation of CCS and Innovative Renewables: the European Energy Recovery Programme (EEPR) and the NER300 programme. As the European Court of Auditors noted, neither programme succeeded in introducing CCS in the EU (European Court of Auditors 2018). Lupion and Herzog (2013) analysed factors and reasons for this: The political and economic realities in Europe have changed since the European CCS demonstration programme was set up in 2009. Cutbacks in public funds as result of the financial and economic crises, and a lack of comprehensive climate policies in most of the Member States were critical factors affecting the lack of advancement in CCS development in Europe. In addition, the combination of tight specifications of criteria for project assessment in the NER300 programme, the requirement of substantial co-funding from the actors, and a larger complexity and higher costs of CCS projects as compared to Renewable Energy Sources (RES) projects have proven fatal. Due to the collapse of the carbon price under the EU ETS (at that period close to only EUR 5/t CO_2) and without any other legal constraint or incentive, there was no rationale for economic actors to invest in CCS. Of the 33 proposals submitted by Member States in the NER300 second round only one CCS proposal (White Rose from the UK) addressed CCS (EC 2013). The failure to receive a significant number of CCS project applications under the NER300 second round again supports the reasons from Lupion and Herzog (2013) presented above.

The new EU **Innovation Fund for low-carbon technologies** was launched in 2020. The originally EUR 10 billion fund, which is financed by the EU's Emissions Trading Scheme (ETS) and replaces the NER300 programme, will run until 2030. An increase of this amount to EUR 20 billion has been proposed by the EC within the Fit for 55 Package in July 2021. The Innovation Fund offers grants (EUR 1.5-4.5 million) for small-scale projects (< EUR 7.5 million total capital costs) and for large-scale projects (> EUR 7.5 million total capital costs) aiming to support the commercial demonstration of innovative low-carbon technologies, including CCU and CCS. To date, two calls for proposals – one for small-scale and one for large-scale projects – have been run. In the small-scale call, among the 32 project applications that have been invited to start the grant preparation process, four include elements of CCUS (AggregaCO_2, CCGeo, Silverstone, and FirstBio2Shipping). The first call for large-scale projects was heavily oversubscribed with 311 eligible applications, of which 70 were selected for the 2nd stage. More than 20% of these 70 projects include at least one CCUS component but less than half of those include CO_2 storage (the majority relate to CO_2 utilisation). The first grants are expected to be awarded in early 2022. Further calls, both large-scale and small-scale, will follow.

The possibility to apply for grants from the Innovation Fund has been an additional stimulus for preparation of new CO_2 storage projects, mostly as part of full-chain CCS project development, in several countries, including those where CCS development has been lagging behind (e.g. full-chain CCS projects in Switzerland or the Czech Republic – in both cases proposals are currently in the early preparation phase with a view towards applying for this Innovation Fund).

The level of CCS-related activities varies significantly among the assessed European countries. From the country-specific information in the Annex attached to this report, rapid developments in north-western Europe (especially in the North Sea region) can be seen, in contrast to no or very little tangible progress in development of CO_2 storage projects or project plans in Cyprus, Greece, Hungary, Latvia, Lithuania, Portugal, Slovakia, Slovenia and Ukraine. Reasons for the lack of progress may include i) CCS is not part of the national energy and climate-protection policies (due to CO_2 emission reduction by other means including, for example, an increased share of energy from nuclear power in some countries, ii) a lack of awareness of the technology, iii) insufficient geological storage capacity or iv) other socio-economic issues.

Strong growth has been observed in new full-chain CCS projects and/or low-carbon/zero-emission cluster initiatives. Some of these have been acknowledged by the EC as key cross-border infrastructure projects that link the energy systems of European countries, called "Projects of Common Interest (PCI)". These projects also have the right to apply for funding from the "Connecting Europe Facility (CEF)", which supports energy, transport, and digital infrastructure. Five projects focused on "cross-border CO_2 network development" are indicated in the 2020 PCI list:

(1) **CO_2-Sapling** project (CO_2 Shipping And PipeLine Infrastructure and North Sea ReGeneration) as the transportation infrastructure component of the Acorn full-chain CCS project and its follow-up international CO_2 transportation network to storage sites in the North Sea Basin reusing existing natural gas pipelines (UK, in further phases NL and NO);

(2) **CO_2TransPorts** aims to establish infrastructure that will facilitate large-scale CO_2 capture from the Ports of Rotterdam and Antwerp as well as the North Sea Port and transport of CO_2 for storage in the Dutch P18 gas fields (Phase 1) and other North Sea storage sites (Phases 2&3);

(3) **Northern Lights** project as a commercial transport connection project between several European capture initiatives (UK, IE, BE, NL, FR, SE) with CO_2 carried by ship to a storage site on the Norwegian continental shelf with plans for future expansion;

(4) **Athos** project (Amsterdam-IJmuiden CO_2 Transport Hub & Offshore Storage) for infrastructure to transport CO_2 from industrial areas in the Netherlands, the European mainland and Ireland to storage sites (depleted natural gas fields) in the Dutch section of the North Sea;

(5) **Ervia Cork** project in Ireland that proposes to repurpose onshore and offshore existing natural gas pipelines and construct new dedicated CO_2 pipeline-to-port facilities for the transport of CO_2 captured from heavy industry and two gas-fired power plants for storage in the offshore Kinsale gas field, in the first phase. The overall aim is to develop an open-access cross-border interoperable high-volume transportation structure. CO_2 storage is not yet permissible in Ireland but transboundary transport is possible. Ervia signed a MoU with the Northern Lights project in September 2019 and was awarded PCI status in November 2019.

These PCI projects are mainly focused on joint transport solutions, but are aiming to enable permanent geological storage of CO_2 in offshore subsurface structures. All five projects listed above were subsequently successful in applying for the CEF funding and obtained grants from the 2020 CEF Energy call for proposals. For example, the PORTHOS project will receive more than EUR 100 million for the development of a CO_2 transport network. An even larger portion of grant money of EUR 2.1 billion will be set aside for the PORTHOS project by the Dutch government[5]. These funds are reserved for contract-for-difference arrangements for four early suppliers of CO_2 to the PORTHOS transport and storage system. The final investment decision for the PORTHOS project is planned to be taken in the first quarter of 2022.

As an exemplar for national planning for full-scale projects, which are mostly linked to CO_2 storage options in the North Sea Area, it is worth highlighting the decision of the Norwegian Parliament to fund the Longship CCS project, taken in December 2020. The decision includes funding of the Northern Lights project – the transport and storage part of the Longship project. In its first stage (to be operational during 2024), the Longship project will include CO_2 capture at the NORCEM cement plant in Brevik (part of the Heidelberg Group) and at Fortum Oslo Varme's waste-to-energy plant at Klementsrud, Oslo, transport by ship to an onshore terminal near Bergen, subsequent offshore pipeline transport and storage in a saline aquifer at a depth of 2,600 m under the seabed. Additional emission sources in Norway and other countries will be subsequently added in later stages of the project.

In addition, some UK activities are also worthy of note. The UK Government Industrial Decarbonisation Challenge, IDC (part of the Industrial Strategy Challenge Fund, ISCF) aims to support decarbonisation technologies. GBP 171 million (approx. EUR 200 million) investment was provided in phase 2 for projects planning decarbonisation actions including the following:

(1) Scotland's Net Zero Infrastructure – NECCUS, which is an alliance of industry government and experts. This includes a CCUS and hydrogen hub focused around the Acorn project (also a PCI, see above), which aims to eventually develop the St Fergus Gas Terminal as a Hub for CCS.
(2) The Northern Endurance Partnership, which is linked to two projects that aim to decarbonise two industrial clusters in the UK:
(2a) Net Zero Teesside CCUS project, based in Teesside, is a full chain CCUS project comprising of a consortium of five OGCI members; BP, ENI, Equinor, Shell and Total.
(2b) The Zero Carbon Humber/Humber Industrial Decarbonisation Deployment project is focused around the Equinor-led Hydrogen to Humber (H2H) Saltend project that will establish the world's largest hydrogen production plant with CCS.

[5] See www.porthosco2.nl/en/dutch-government-supports-porthos-customers-with-sde-subsidy-reservation/

(3) HyNet North West is based on the production of hydrogen from natural gas in the North West of the country (Liverpool – Chester region). It includes the development of a new hydrogen pipeline and the creation of a CCS infrastructure.
(4) South Wales Industrial Cluster (SWIC) plans to create a decarbonised industrial zone deploying hydrogen and the development of CCUS.

Investment from the UK government continues with the GBP 1 billion (approx. EUR 1.17 billion) CCS Infrastructure Fund (CIF) that will support capital expenditure on transport and storage networks and industrial CCS projects. This action is part of the commitment set out in the Ten Point Plan for a Green Industrial Revolution issued during November 2020. Through the current Cluster Sequencing activity, two clusters were identified for support to achieve deployment by the mid-2020s ("Track 1"; The East Coast Cluster and Hynet in North Wales were named in October 2021 with ACORN on the reserve list). It is expected that two clusters will be identified for deployment by 2030 ("Track 2"), alongside reserve cluster(s). Funding for the clusters selected is not guaranteed, but "Track 1" projects will have the first opportunity to be considered for support through the CIF.

Other promising clusters under development include the Greensand project offshore Denmark, and the Ravenna CCS hub in Italy (Adriatic Blue project). In addition, numerous studies to assess new CCS project and cluster opportunities have been carried out in many European countries. To highlight some of these efforts, a few examples of regional assessment initiatives for clusters are included below:

- In the Baltic Sea region, a cluster of emission sources has been considered, including the four largest Estonian power plants, the Kunda Nordic Cement plant in Estonia and the Latvenergo TEC2 power plant in Latvia. The developed CCUS scenario includes mineral carbonation of CO_2 using oil shale ash produced in Estonia. Another planned cluster comprises, in addition to a cement plant in Estonia, also a cement plant in Lithuania and a storage site offshore Latvia (E6 structure). Both cluster concepts are at research level. The first project on mineral carbonation of CO_2 using oil shale ash mentioned above is currently under development by the environmental company Ragn-Sells in cooperation with Estonian universities.
- The STRATEGY CCUS project (funded through H2020) investigates, amongst other opportunities, start-up regions where CCUS clusters could develop in selected countries of Southern and Eastern Europe – France, Spain, Portugal, Croatia, Greece and Poland (more details are provided in Chapter 6).

For knowledge sharing and thereby driving CCS implementation forward, the **CCUS Project Network** represents and supports major industrial CCUS projects that are underway in Europe. The network was initiated as the European CCS Demonstration Project Network (2009–2018) and has since expanded and developed and now works closely with the European Commission to ensure that members' needs and interests are provided for while supporting the EU's climate action ambitions. At the time of writing, Northern Lights, Acorn, PORTHOS and other major CO_2 storage projects are network members.

A summary of current activities regarding planning and implementation of CO_2 capture, transport and storage projects in individual European countries is presented in Figure 7.

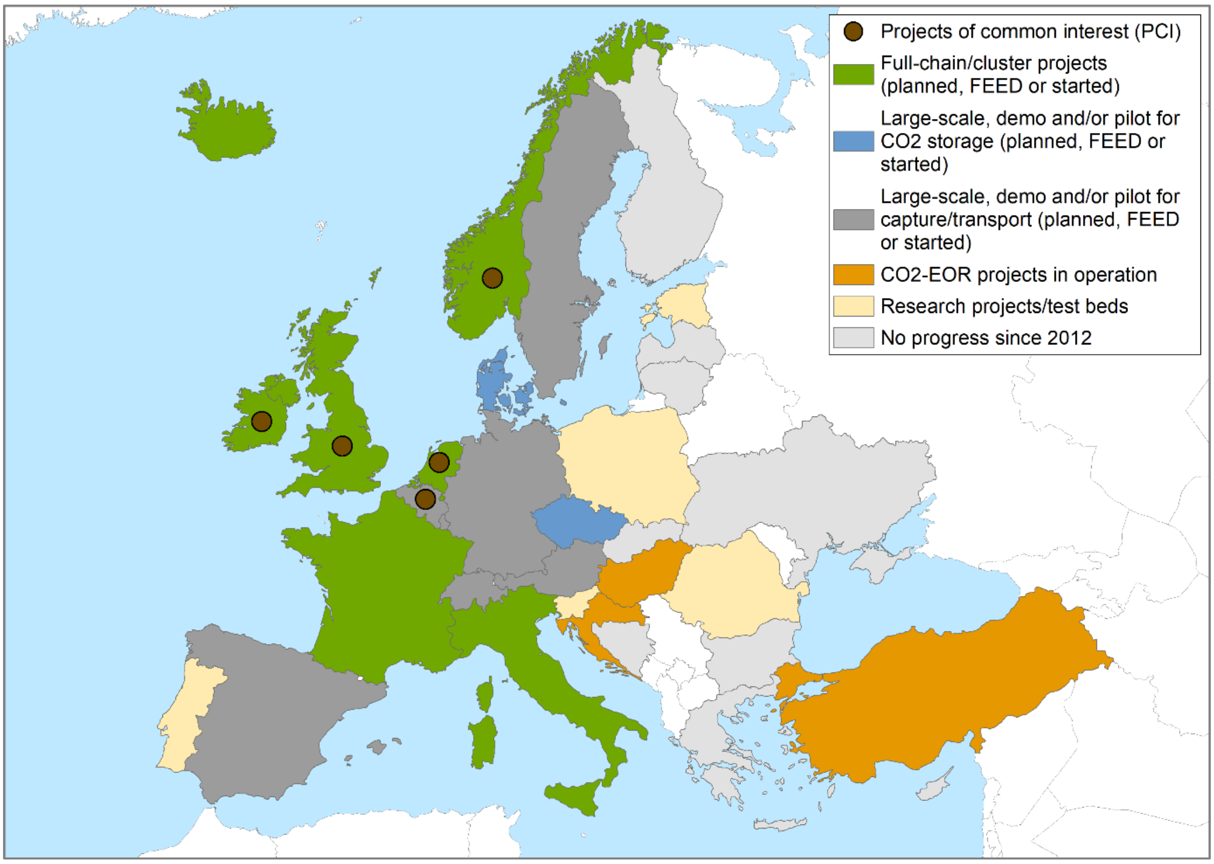

Figure 7: Current situation in Europe (as of 30th June 2021) regarding CO_2 capture, transport and storage projects on all scales and at all stages of planning and development, including full-chain/cluster projects and Projects of Common Interest (PCI). Note that country infills only reflect the most "advanced" project in the country, meaning for example, that countries that have full-chain projects in operation or advanced planning stage may also have CO_2 storage and/or capture projects in preparation or in operation.

In the following subsections, selected examples of CO_2 capture, transport and storage projects are presented to demonstrate progress in the assessed countries. Some of these projects have already been mentioned above as part of full-chain projects or PCI initiatives, but it is worth highlighting these individual national activities also here because of their targeted development in recent years.

5.2 CO_2 capture projects

The Norwegian projects at Sleipner and Snøhvit were the first pioneering activities in Europe with large-scale CO_2 capture or, more precisely, purification of natural gas from offshore gas production, from which the unwanted[6] CO_2 content had to be separated. Other than Sleipner and Snøhvit, no large-scale CO_2 capture projects (more than 400 kt CO_2/year on an industrial process or 800 kt/year on power generation) are in operation in Europe at the moment. There are, however, several projects under development, both early- and advanced-stage. A selection of these projects is included below:

In Dunkirk (northern France), a consortium of 11 European stakeholders including ArcelorMittal, Axens, IFP Energies nouvelles (IFPEN) and Total, has launched the 3D-DMX™ project to demonstrate an innovative process for capturing CO_2 from industrial activities. It is part of a larger comprehensive study dedicated to the development of the future European Dunkirk North Sea Capture and Storage Cluster, and is connected with storage options offered by the Norwegian Northern Lights project.

BECCS is being trialled at DRAX Power Station, North Yorkshire (UK). The first pilot project in partnership with Leeds-based C-Capture started in October 2018, with the first CO_2 captured during early 2019 (aim was to capture 1 t CO_2 per day). An additional pilot facility was installed onsite by Mitsubishi Heavy Industries Engineering Ltd. in late 2020, with the aim of capturing 300 kg CO_2/day. Following the pilot project, Drax Group and Mitsubishi Heavy Industries Engineering, Ltd. (part of Mitsubishi Heavy Industries Group) agreed a long-term contract for DRAX for a project that (at the date of writing) would be the largest deployment of negative emissions in power generation anywhere in the world. This could be online as early as 2024 with the aim of storing at least 8 Mt CO_2 per year by 2030.

In Norway, several capture projects with the specification to achieve capture rates of about 100 to 400 kt/year are in preparation. As part of the Norwegian Longship full-chain project, NORCEM's cement factory in Brevik aims to capture 400,000 t/year (or 50%) of CO_2 emissions from the plant and the capture facility at Fortum Varme's waste-incineration plant at

[6] The natural gas produced from the Sleipner field contained too much CO_2 to be marketable. Thus, it had to be separated. In addition, Norway has a tax for offshore CO_2 emissions making it cheaper to store than emit.

Klemetsrud, Oslo, aims to capture 400,000 t/year (or 90%) of CO_2 emissions from the plant. It is planned that both facilities will be connected to the Northern Lights PCI.

In recent years, Sweden's focus around CCS activities has been directed towards CO_2 capture and therefore several demonstration CO_2 capture projects have been established. For example, the pilot plant at PREEM's Lysekil refinery has recently started testing CO_2 capture from its hydrogen production unit with the aim of capturing around 500 kt CO_2 per year for transport and storage within the Northern Lights project. PREEM's ambition is to have a full-scale plant in operation by 2025. In addition, Stockholm Exergi AB inaugurated their test facility for bio-energy production with carbon capture and storage at their biofuel-fired combined heat and power plant in Värtan in 2019. In autumn 2020, Stockholm Exergi received additional funding from the Swedish Energy Agency to continue and expand research at the Värtan site. As of spring 2021, Stockholm Exergi is conducting an in-depth feasibility study with the aim of constructing a full-scale bio-CCS facility within four years (planned completion during 2025). In addition, Cementa has stated that they plan to capture around 1.8 Mt CO_2/year from their largest cement plant (in Slite, Gotland) in 2030 (although there are currently uncertainties around their environmental permit).

In Denmark, a new capture test pilot is under construction for the waste incineration facility in Copenhagen (EUDP 2020-I Net Zero Carbon Capture på ARC). The cement producer Aalborg Portland has also received funding to develop an integrated a CO_2 capture and synthetic fuel production facility (GreenCem, supported by EUDP).

A number of pilot projects for investigating capture-relevant issues include test centres, operated by the industry or scientific institutions as well as small-scale installations at industrial facilities or research institutions. Examples are indicated below:

Norway has two operational capture pilots/test centres:

1) The Technology Centre Mongstad (TCM), originally established as the first step in the development of a full-scale process to capture CO_2 from the combined heat and power plant (CHP) at Mongstad. Plans for full-scale capture were cancelled by the government in 2017, but the facility is now the world's largest test centre for CO_2 capture technologies. TCM Mongstad is operated by Equinor and owned by the Norwegian State through Gassnova with Equinor, Shell and Total as industrial partners.
2) The SINTEF AS CO_2 capture pilot plant at Tiller is a test facility for development of post-combustion CO_2 capture which has been active since 2010. It consists of a complete absorption and desorption plant with a CO_2 capacity of 50 kg CO_2/h. The facility is part of the European ECCSEL initiative (Quale et al. 2017).

In the Carbon2Chem project, CO_2 separation and purification for CO_2 utilisation is being tested and optimised at the Thyssen Krupp integrated iron and steel mill in Duisburg, Germany. In Germany, a post-combustion capture pilot facility is also in operation at the Niederaußem Test Centre for amine scrubbing (by RWE Power, BASF/Linde) that captures CO_2 from flue gases of the coal-fired Niederaußem power plant enabling capture rates of up to 7.2 t/day.

In the Netherlands, CO_2 is captured from the AVR (Afvalverbranding Rijnmond) waste incineration stack in Duiven for greenhouse horticulture usage; 100 kt/year has been captured since August 2019.

In Belgium, since 2016 the LEILAC1 project has investigated capture of process emissions from the calciner using CALIX direct separation technology at the HeidelbergCement plant in Lixhe. The pilot is operational and has the capacity to capture about 25 kt CO_2/year. Within the LEILAC 2 project (2020–2025), industrial upscaling is in progress: A demonstrator for the direct separation technology will be built at the HeidelbergCement plant in Hannover, Germany, which will capture about 20% of the plant's process emissions (about 100 kt CO_2/year).

In Spain, LafargeHolcim will start building a capture plant in its cement plant of Almeria at the end of 2022 using the Carbon Clean's technology. It will start capturing 10% of CO_2 emissions, subsequently ramping up to 100%. The final goal is to implement capture plants on all its four cement plants in the country.

In Iceland, a series of Carbfix projects have been running since 2007. CO_2 (and H_2S) has been captured at a geothermal power plant, dissolved in water and injected into basaltic rocks for mineral storage from 2014 onwards (see also 5.3). This operation has achieved over 70,000 t CO_2 and 30,000 t H_2S injected to date. Furthermore, in 2021 a pilot project started that is capturing 3,500 t CO_2 annually from a methane plant at a landfill site in Southwest Iceland.

The Swiss company Climeworks is pioneering in CO_2 capture from the atmosphere (Direct Air Capture, DAC) and achieved a technology readiness level for this method which is sufficient to enable large-scale application. After successful pilot operations under the EU-funded Carbfix2 project, Climeworks has commissioned a plant named "Orca" that combines Climeworks' direct air capture technology with subsurface storage of CO_2 in basaltic rocks. The plant comprises the world's first commercial direct air capture and storage (DACCS) chain removing 4,000 t CO_2 per year from the atmosphere. Another pilot project of direct air capture was started on the air-cooling units at the deep geothermal plant site of Balmatt in Mol, Belgium, in 2018.

The UK Government provided GBP 100 million (approx. EUR 117 million) for projects to help develop DAC and GHG removal in the UK and a second phase is planned to support the most promising technologies. It is anticipated that a new UK sustainable biomass strategy will be published during 2022, which is expected to consider recommendations on CCS and biomass use from the UK Committee on Climate Change's 2020 progress report.

The "Pilot-scale Advanced Capture Technology (PACT)" facility in the UK (part of the UK Translational Energy Research Centre, TERC) includes a solvent-based carbon capture plant enabling post-combustion capture research with different fuels and under different combustion conditions.

5.3 CO_2 transport projects

There is one CO_2 transport facility already in operation as part of a running large-scale CCS project; the 150 km-long pipeline for transporting CO_2 from the Melkeøya gas terminal to the offshore Snøhvit storage site in the Norwegian Barents Sea.

Another CO_2 pipeline in operation in Europe is part of the Croatian Ivanić EOR project, where CO_2 is brought via an 88 km-long pipeline from a gas processing facility at the gas condensate field Molve close to the Hungarian border, recompressed and injected through several wells into two oil reservoirs of the Ivanić and Žutica fields.

In the Netherlands, a CO_2 pipeline is operated by OCAP CO_2 B.V. to supply CO_2 to end users for greenhouse-based farming. Several hundred kt CO_2 per year come from a Shell refinery and from the bioethanol production plant by Alco and are delivered to more than 600 greenhouse farmers. In the future, the OCAP infrastructure may be connected with the Porthos CO_2 transport and storage network which is now under development as a PCI (see above).

As part of the Northern Lights CCS project, a new pipeline is planned from a storage terminal and pumping station at the premises of CCB Kollsnes AS near Bergen. From there, the CO_2 will be pumped through a 110 km-long pipeline and injected for permanent storage into the approved Aurora geological reservoir below the North Sea bed.

Various other transport scenarios, including pipelines and ships, are currently being developed as part of the CCS clusters described earlier. One example is the Swedish "Carbon Infrastructure Capture (Cinfracap)" project in which two refineries, two combined heat and power plants (CHPs), a port owner and a gas transport company analyse possible options for a shared CO_2 capture and transport infrastructure in western Sweden centred around the port of Gothenburg. After completion of the pilot study phase in March 2021, planning for a second project phase is underway.

5.4 CO_2 storage projects

Since publication of the Rütters et al. 2013 report, the number of operational European large-scale storage projects has not changed. The only two projects – Sleipner and Snøhvit offshore Norway that were established to store the CO_2 separated from the produced natural gas – continued their operation. No new large-scale projects have come online as of the date this new report was published. There are, however, several new projects under preparation. The most accelerated development and advanced progress is found in low-carbon/zero-emission clusters under development, in particular (but not only), the five projects with the PCI status described earlier.

The most advanced project under development is Northern Lights – the storage part of the Norwegian Longship CCS project. The project development plan has been approved and the preparation of the Aurora storage site in the North Sea, west of Bergen, is now in full flow, with the expectation of being operational in 2024.

Other noteworthy large-scale storage site developments include (non-exhaustive list):

- the Acorn storage site, ca. 100 km offshore Scotland, straddling multiple depleted oil and gas fields, with the Goldeneye gas field planned as the first storage site;
- the P18-2, P18-4 and P18-6 depleted gas fields offshore Rotterdam as storage sites for the PORTHOS project;
- the Endurance structure (saline aquifer) ca. 75 km offshore Eastern England as a storage site for CO_2 captured from the proposed Net Zero Teesside (NZT) and Zero Carbon Humber (ZCH) clusters;
- the Greensand project plans for storage in depleted North Sea oil fields, offshore Denmark.

Pilot-scale storage sites have not increased significantly in terms of project numbers. Only the Icelandic Carbfix pilot for in-situ mineral storage, which started at the Hellisheidi geothermal power plant in 2014, has successfully developed its activities, having stored around 70 kt CO_2 to date. As a part of the EU-funded GECO project, the feasibility of geothermal fluid re-injection will be further tested at pilot scale in different geological settings at sites in Germany, Turkey and Italy. A pilot plant storing CO_2 from a methane plant at a landfill came online in 2021, where 3.5 kt CO_2 is captured and injected annually in basalt formations in Southwest Iceland.

At the end of 2017, after a successful research period of about 13 years and injection of some 67 kt CO_2, the German Ketzin pilot injection site finished after a scheduled abandonment of all wells and disassembly of the surface facilities.

The Hontomín injection pilot in carbonate rocks in Northern Spain was operational from 2014. The Hontomín pilot project has, unfortunately, not achieved the planned amounts of CO_2 injected due to political and administrative reasons and was put on hold in 2018. No communication has been issued regarding future CO_2 injection at the site.

Efforts to develop new storage pilots (including those combined with EOR) have been registered in several countries (e.g. Croatia, Czech Republic, Italy, Latvia, Romania) but none have yet matured to a stage close to construction. The ENOS project report "Study on new pilot and demonstration project opportunities for CO_2 geological storage onshore in Europe" (Saftić et al. 2020) provides a portfolio of six conceptual case studies - suggested pilot projects - with a wide geographical spread (Croatia, Denmark, Hungary, Lithuania, Poland, Romania). If implemented, these pilot projects will bring significant knowledge and practical experience on CCS to European regions that so far have limited development of the technology, including the South-Eastern and Central Europe and the Baltic Sea region. Some of these suggested pilot projects are now undergoing further development.

5.5 CO_2-EOR

Commercial operations using CO_2 injection in hydrocarbon fields which have been in production for a long time, with the purpose of increasing oil production (CO_2-driven enhanced oil recovery or CO_2-EOR), have been ongoing in Hungary (since 1970s), Turkey (since 1980s) and Croatia (since 2010s). In all cases, the activities are run by national oil companies and use predominantly natural (geological) sources of CO_2, either produced directly for this purpose or separated from produced natural gas that contains a fraction of CO_2.

The possibility to use and store anthropogenic CO_2 captured during enhanced hydrocarbon recovery (i.e. not using natural CO_2 extracted from the subsurface) has only been considered in recent years. Oil produced by CO_2-EOR with anthropogenic CO_2 can have a significantly lower carbon footprint than, for example, oil imported to Europe from other parts of the world, as has been clearly demonstrated in the ECO-BASE project. Development studies on CO_2-EOR combined with CO_2 storage have been carried out in all three countries mentioned above. CO_2-EOR is also an option considered in Austria, the Czech Republic, Latvia, Lithuania, Poland and Romania, with studies and projects in different stages of assessment and planning (e.g. the ECO-BASE and ENOS project reports).

In general, CO_2-EOR could represent a good opportunity to kick-start broader CCUS activities in several countries (particularly of Central and Eastern Europe where depleting oil fields are present), provided the existing regulatory and financial barriers can be overcome and the CO_2 used is anthropogenic. This approach could follow the example of the USA and Canada where CO_2-EOR has enabled infrastructure development that has facilitated other CO_2 storage projects, and has supported the development of positive business cases for CO_2 storage projects as well as the development of relevant experience and expertise of CO_2 capture, transport and injection. In contrast, in some European countries, CO_2-EOR will not be allowed because it is not considered a CO_2 emission mitigation option and, accordingly, may meet public opposition. Denmark has even decided to phase out oil and gas production entirely by 2050 and plans to ban CO_2-EOR soon.

Chapter 6: CO_2 storage research activities on a national, regional and European level

The overview presented here includes projects active as of 30th June 2021, as well as projects completed between 2013 and 2021, which were not listed in the Rütters et al. 2013 State of Play report. Information was compiled from the country-based questionnaires and supplemented with information retrieved from organisation- and/or project websites where available. The map (Fig. 8) presents data from the 32 countries assessed through questionnaires, whereas some tables include also information on five additional countries participating in European research projects.

A total of 152 research institutions conducting CO_2 storage-related research (Fig. 8) were reported. Further details are presented in Table 7 and in the Annex.

The period from 2013 to 2021 witnessed an increased involvement in EU-funded research on CO_2 storage in countries in eastern and south-eastern Europe, while west and northwest European countries have expanded their activities in terms of number of projects and intra-European collaboration networks. According to the information received, current research “hot spots” are Norway, Poland, UK and Italy followed by France, The Netherlands, Portugal and Spain (Fig. 8). In contrast, in Germany, for example, less CO_2 storage research has been undertaken in recent years compared with the Rütters et al. 2013 assessment[7].

For the purpose of this report, projects are subdivided into:

a) EU projects funded through FP7 and H2020 programmes (6.1),
b) other multinational/regional efforts and initiatives funded or facilitated through European Energy Research Alliance (EERA), ERA-NET Co-fund “Accelerating CCS Technologies (ACT)”, regional networks, the Research Fund for Coal and Steel (RFCS), European Space Agency (ESA) and EU projects of particular regional significance (6.2), and
c) national research projects (6.3).

[7] In the current assessment “less research” means fewer research institutions reported as active in the annex, whereas the 2013 assessment also took other indicators into account (for details, see Rütters et al. 2013).

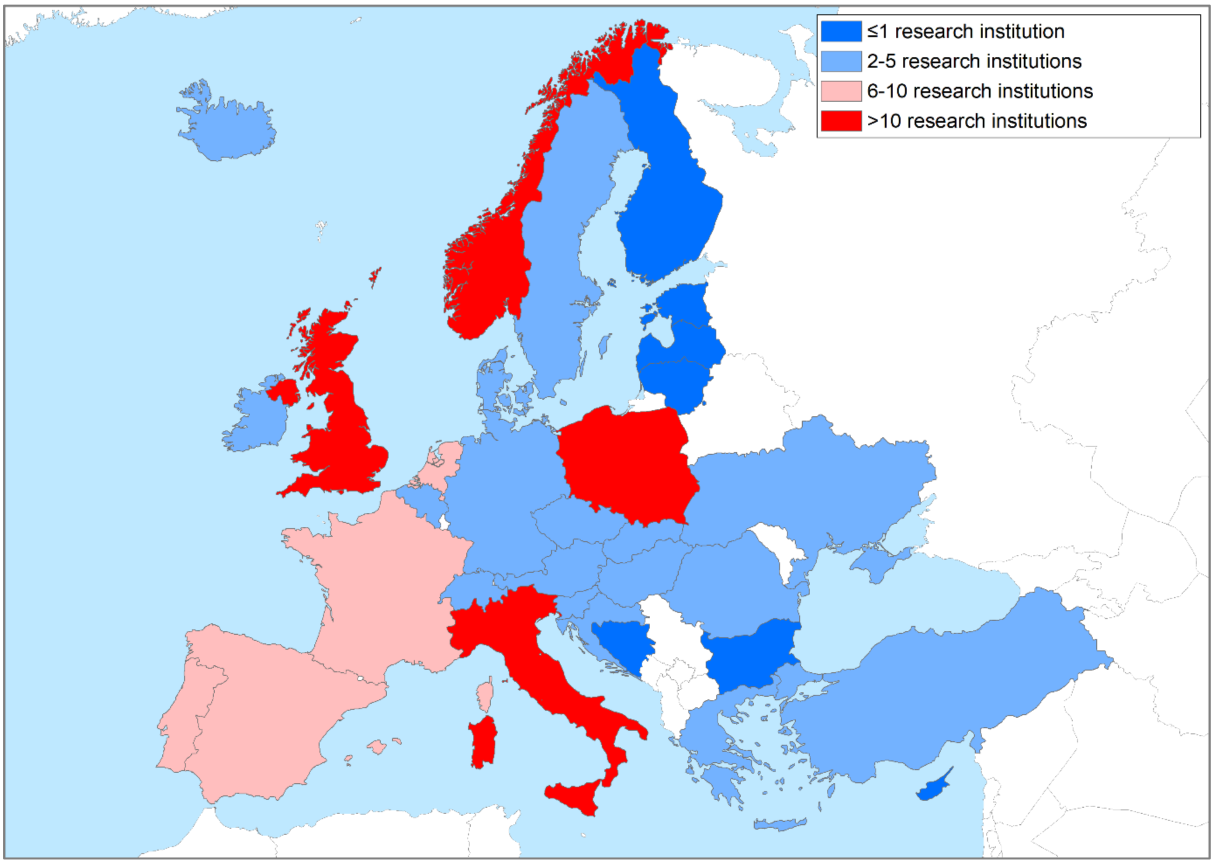

Figure 8: Geographical distribution of the 152 research institutions reported to be involved in CO_2 storage-related research in Europe given as the number of research institutions in each country involved in CO_2 storage research.

6.1 CO_2 storage research funded through FP7 and H2020

The CORDIS website provides information on 34 EU-funded projects addressing subsurface storage of CO_2. Table 3 lists the projects active as of June 30th 2021, as well as projects completed between 2013 and June 2021, which were not included in the Rütters et al. 2013 State of Play report. Table 4 provides an overview of the countries participating in each project.

Table 3: List of projects addressing subsurface storage of CO_2, supported through FP7 and H2020 funding, ongoing or completed after 2012, which were not included in the Rütters et al. 2013 report. Projects active as of 30th June 2021 are shown in bold typeface. Projects primarily focusing on storage are highlighted in blue; projects where aspects of subsurface storage are included but not the main focus are highlighted in green. Project are listed in alphabetical order of acronyms.

Acronym and project ID	Funded under	Coord.	Full project title	End date
3D 838031	**H2020-EU.3.3.2**	**France**	**DMX Demonstration Dunkirk**	**30.04.2023**
ACCSESS 101022487	**H2020-EU.3.3.2**	**Norway**	**Providing access to cost-efficient, replicable, safe and flexible CCUS**	**30.04.2025**
ACT 691712	**H2020-EU.3.3.2., 3 and 4**	**Norway**	**Accelerating CCS technologies as a new low-carbon energy vector**	**31.01.2021**
C4U 884418	**H2020-EU.3.3.2.**	**UK**	**Advanced carbon capture for steel industries integrated in CCUS Clusters**	**31.03.2023**
CarbFix2 764760	H2020-EU.3.3.2	Iceland	Upscaling and optimizing subsurface, in situ carbon mineralization as an economically viable industrial option	31.01.2021
CGS EUROPE 256725	FP7-ENERGY	France	Pan-European coordination action on CO_2 Geological Storage	31.10.2013
CHEERS 764697	**H2020-EU.3.3.2**	**Norway**	**Chinese-European emission-reducing solutions**	**30.09.2023**
CLEAN 846775	**H2020-EU.1.3.2.**	**UK**	**Carbon fracturing and storage in shale with wellbore infrastructure monitoring.**	**20.07.2022**
CLEANKER 764816	**H2020-EU.3.3.2**	**Italy**	**Clean clinker production by calcium looping process**	**31.03.2022**
CO2-REACT 317235	FP7-PEOPLE	France	Geologic carbon storage	28.02.2017
ConsenCUS 101022484	**H2020-EU.3.3.2**	**Nether-lands**	**Carbon-neutral clusters through electricity-based innovations in capture, utilisation and storage**	**30.04.2025**
DISCO2 STORE 101007851	**H2020-EU.1.3.3.**	**France**	**Discontinuities in CO_2 storage reservoirs**	**31.01.2025**
ECCSELERATE 871143	**H2020-EU.1.4.1.1.**	**Norway**	**ECCSEL ERIC – accelerating user access, growing the membership and positioning internationally to ensure long-term sustainability**	**31.12.2022**
ENOS 653718	H2020-EU.3.3.2.3	France	Enabling onshore CO_2 storage in Europe	31.08.2020
EPSKS 793007	H2020-EU.1.3.2.	UK	Efficient pore-scale kinetic simulation of gas flows in ultra-tight porous media	02.07.2020
GATEWAY 657263	H2020-EU.3.3.2.	Norway	Developing a pilot case aimed at establishing a European infrastructure project for CO_2 transport	30.04.2017
Continued on next page				

Table 3: (*continued*) List of projects supported through FP7 and H2020 funding.

Acronym and project ID	Funded under	Coord.	Full project title	End date
GATIPOR 647134	H2020-EU.1.1.	France	Guaranteed fully adaptive algorithms with tailored inexact solvers for complex porous media flows	31.08.2021
GECO 818169	**H2020-EU.3.3.2**	**Iceland**	**Geothermal emission control**	**30.09.2022**
GeoERA 731166	**H2020-EU.3.3.2 & EU.3.5**	**Nether-lands**	**Establishing the European geological surveys research area to deliver a geological service for Europe**	**28.02.2022**
GEoREST 801809	**H2020-EU.1.1.**	**Spain**	Predicting earthquakes induced by fluid injection	**31.01.2024**
IMPACTS 308809	FP7-ENERGY	Norway	The impact of the quality of CO_2 on transport and storage behaviour	31.12.2015
IMPACTS9 842214	**H2020-EU.3.3**	UK	**IMplementation Plan for Actions on CCUS Technologies in the SET Plan**	**28.02.2022**
LEILAC2 884170	**H2020-EU.3.3.2**	**France**	**Low emission intensity lime and cement 2: Demonstration scale**	**31.03.2025**
MIRECOL 608608	FP7-ENERGY	Nether-lands	Remediation and mitigation of CO_2 leakage	28.02.2017
OMNICS 653241	H2020-EU.1.3.2.	Denmark	Observing, modelling and predicting in situ petrophysical parameter evolution in geologic carbon storage system	09.03.2018
PilotSTRATEGY 101022664	**H2020-EU.3.3.2.**	**France**	**CO_2 geological pilots in strategic territories**	**30.04. 2026**
REALISE 884266	**H2020-EU.3.3.2**	**Norway**	**Demonstrating a refinery-adapted cluster-integrated strategy to enable full-chain CCUS implementation**	**30.04.2023**
S4CE 764810	H2020-EU.3.3.2	UK	Science for clean energy	31.12.2020
SECURe 764531	H2020-EU.3.3.2.	UK	Subsurface evaluation of carbon capture and storage and unconventional risk	31.05.2021
SSFZEP 826051	**H2020-EU.3.3**	**UK**	**Support stakeholders in zero emission fossil fuel power plants and energy intensive industry**	**31.10.2021**
SPM-RS 895406	**H2020-EU.1.3.2.**	**Norway**	**Smart proxy models for reservoir simulation**	**31.08.2022**
STEM-CCS 654462	H2020-EU.3.3.2.3	UK	Strategies for environmental monitoring of marine carbon capture and storage	29.02.2020
STRATEGY CCUS 837754	**H2020-EU.3.3.2.**	**France**	**Strategic planning of regions and territories in Europe for low-carbon energy and industry through CCUS**	**30.04.2022**
ULTIMATECO2 281196	FP7-ENERGY	France	Understanding the long-term fate of geologically stored CO_2	30.11.2015

Table 4: Overview of CO_2 storage-related research projects and participating countries funded through the FP7 and H2020 programmes. Data were compiled from country reports, in some cases supplemented by online sources. Countries marked in grey are not covered in detail in the report but are included here for completeness. Dark green: coordinator, light green: participant. For project details, see Table 3.

	Active as of 30th June 2021																			Completed 2013–June 2021, not in 2013 report												
Countries	3D	C4U	ACCSESS	CHEERS	CLEAN	CLEANKER	ConsenCUS	DISCO2STORE	ECCSELERATE	Gatipor	GECO	GeoERA	GEoREST	LEILAC2	REALISE	PiloSTRATEGY	S4CE	SPM-RS	STRATEGY CCUS	ACT	CarbFix2	CGS EUROPE	CO2 REACT	ENOS	EPSKS	GATEWAY	IMPACT	MIRECOL	OMNICS	SECURe	STEM-CCS	ULTIMATECO2
# of participating European countries	6	8	8	4	2	6	6	5	5	1	8	**32**	1	7	4	7	10	1	9	9	4	22	7	15	1	4	7	6	1	7	5	6
Albania												P																				
Austria												P										P		P							P	
Belgium		P		P				P				P		P								P										
Bosnia and Herzegovina												P																				
Bulgaria																						P										
Croatia												P							P			P		P								
Cyprus												P																				
Czech Republic												P										P		P								
Denmark	P						P					P			P								P						C	P		P
Estonia						P																P		P								
Finland						P						P					P					P										
France	C	P	P	P				C	P	C	P	P		C		C	P		C		P	C	C	C				P		P		C
Germany	P	P	P			P						P		P		P	P		P	P		P	P	P		P	P	P		P	P	P
Greece							P					P		P		P			P	P		P										
Hungary												P										P										
Iceland											C	P					P				C		P									
Ireland												P			P																	
Italy		P	P			C			P		P	P		P			P						P	P			P					P
Latvia												P										P										
Lithuania												P										P		P								
Luxemburg												P																				
Malta												P																				
Netherlands		P					C		P		P	C		P	P		P			P				P		P	P	C		P	P	
North Macedonia												P																				
Norway	P		C	C				P	C		P	P			C			C		C				P		C	C	P		P	P	
Poland	P		P	P								P				P	P		P			P								P		
Portugal												P				P			P			P										
Romania							P					P							P	P		P		P			P					
Serbia																	P					P						P				
Slovakia												P										P		P								
Slovenia												P										P		P								
Spain		P				P		P			P	P	C			P			P	P	P	P	P	P			P					
Sweden		P	P									P										P										
Switzerland	P		P		P	P		P						P			P			P	P											P
Turkey											P									P		P										
Ukraine												P																				
United Kingdom		C	P		C		P		P		P	P				P	C		P	P			P	P	C	P	P	P		C	C	P

6.2 Other multinational/regional CO_2 storage research projects

A total of 21 multinational/regional projects and initiatives addressing CO_2 storage have been or are funded and/or facilitated through ACT (Tab. 5), EERA, RFCS, ESA and regional networks. An overview of the projects and participating countries is shown in Table 6.

ACT (Accelerating CCS technologies) is an international initiative, initially co-funded as an ERA NET Co-fund through Horizon2020 and then entirely funded from national resources of participating countries. ACT supports research and innovation projects that can lead to accelerating and maturing safe and cost-effective CCUS technologies. Between 2017 and 2020, ACT has funded eleven storage-related research projects involving international collaboration (Tables 5 and 6). Key research topics addressed by these projects are monitoring, storage capacity assessment, and land planning/infrastructure. In addition, at the time of going to press, ACT announced that an additional 12 projects had been selected for funding from the recent 2020 call including four projects addressing aspects relating to CO_2 storage.[8]

Table 5: Storage-related projects supported by ACT.

Acronym	Full project title
ACORN	ACORN
ACTOM	ACT on Offshore Monitoring
ALIGN-CCUS	Accelerating Low carbon Industrial Growth through CCUS
DETECT	Determining the risk of CO_2 leakage along fractures in caprocks using an integrated monitoring and hydro-mechanical-chemical approach
DIGIMON	Digital monitoring of CO_2 storage projects
ECOBASE	Establishing CO_2 enhanced Oil recovery Business Advantages in South Eastern Europe
ELEGANCY	Enabling a Low-Carbon Economy via Hydrogen and CCS
Pre-Act	Pressure control and conformance management for safe and efficient CO_2 storage
REX-CO2	Reusing existing wells for CO_2 storage operations
SENSE	Assuring integrity of CO_2 storage sites through ground surface monitoring
SUCCEED	Synergetic Utilisation of CO_2 storage Coupled with geothermal Energy Deployment

[8] These four recently announced ACT projects are: CEMENTEGRITY (well cements for improved integrity and sealing), ENSURE (microseismic monitoring for compliance and public acceptance), RETURN (safe and cost-effective storage in depleted oil and gas fields) and SHARP (improved assessment of rock stress and failure scenarios).

EERA activities. The European Energy Research Alliance (EERA) is a research pillar of the European Strategic Energy Plan (SET-Plan) with the task of aligning R&D activities of individual research organisations with SET-Plan priorities. The EERA Joint Programme on Carbon Capture and Storage (JP CCS) has participants from 14 countries and works to coordinate national and European research and innovation programmes facilitating knowledge sharing and synergies. The JP CCS has sub-programmes (SPs) addressing CO_2 capture, transport and storage. The CO_2 storage SP is organised into three areas: monitoring, static modelling and dynamic modelling. Among the activities relevant for CO_2 storage, the JP CCS cooperates closely with the European CCS Research Infrastructure "ECCSEL" (see Chapter 6.3), and the European Zero Emissions Technology and Innovation Platform (ZEP). It supports H2020 CCS projects, continues to contribute to the SET-Plan, and builds collaborations outside Europe through participation in workshops and fact-finding missions facilitated by the European Commission.

RFCS activities. The Research Fund for Coal and Steel (RFCS) supports research and innovation projects in the areas of coal and steel. A complete list of projects funded through RFCS (2017–2020) is available on the RFCS website. RFCS funding policy is in line with the European Green Deal, supporting zero-carbon steel-production by 2030. RFCS funds a number of CCS-related projects including: COALBYPRO, which aims to develop new methods for management of coal/lignite by-products and handling CO_2 emissions from their combustion, ROCCS – Establishing a Research Observatory to unlock European Coal seams for Carbon dioxide Storage, and "LOWCARBONFUTURE – Exploitation of projects for a low carbon future steel industry". For country participation in these projects, see Table 6.

Baltic Region: The regional Baltic CCS network (BASRECCS) is a network of experts and stakeholders operating as an association. The association hosts an annual conference called the Baltic Carbon Forum (BCF). BASRECCS initiates, carries out and participates in regional projects and activities. For example the RouteCCS project (Routing Deployment of Carbon Capture, Use and Storage CCUS in the Baltic Sea Region) is coordinated by Uppsala University, organised by BASRECCS and funded by the Swedish Institute. The network has a task force on geological storage which plays a vital role in the CGS Baltic EUSBSR seed project which is currently developing a CO_2 geological storage project plan for the Baltic Sea Region (BSR). For participating countries, see Table 6.

North Sea: The Norwegian CCS Centre (NCCS) is an international research cooperation on CO_2 capture, transport and storage, co-financed by the Research Council of Norway, industry and research partners. The Centre supports achieving CO_2 storage in the North Sea, and realisation of a full-chain CCS project by 2022. For projects and participating countries, see Table 6.

Table 6: Overview of European, multinational and regional projects addressing CO_2 storage funded/ facilitated through GeoERA, RFCS, ESA, ACT and regional networks (ongoing projects are marked in green, completed projects in yellow). Data were retrieved from country reports, in some cases supplemented by online sources. Countries marked in grey are not covered in detail in the report but are included here for completeness. Dark green: coordinator, light green: participant.

	GeoERA projects		REGIONAL NETWORKS				RFCS projects			ESA	ACT projects granted 2019					ACT projects granted 2017					
Countries	GeoERA - GeoConnect3d	GeoERA - 3DGEO-EU	BASRCCS	RouteCCUS (BASRCCS)	NCCS	NORDIC CCS	COALBYPRO	LOWCARBONFUTURE	ROCCS	CCS SPACEMON	ACTOM	DIGIMON	REX-CO2	SENSE	SUCCEED	ALIGN CCUS	ELEGANCY	Pre-ACT	ACORN	ECOBASE	DETECT
# of participating European countries	16	7	9	7	7	4	4	5	3	2	3	7	5	5	5	5	7	5	3	5	3
Albania																					
Austria																					
Belgium																					
Bosnia and Herzegovina																					
Bulgaria																					
Croatia																					
Cyprus																					
Czech Republic																					
Denmark																					
Estonia																					
Finland																					
France																					
Germany																					
Greece																					
Hungary																					
Iceland																					
Ireland																					
Italy																					
Latvia																					
Lithuania																					
Luxemburg																					
Malta																					
Netherlands																					
North Macedonia																					
Norway																					
Poland																					
Portugal																					
Romania																					
Serbia																					
Slovakia																					
Slovenia																					
Spain																					
Sweden																					
Switzerland																					
Turkey																					
Ukraine																					
United Kingdom																					

Nordic Countries: The NORDICCS project (2011–2015) established a virtual carbon capture and storage (CCS) networking platform aiming to increase CCS deployment in the five Nordic countries through close collaboration between research institutions and industry. The project produced a web-based storage atlas, and investigated CCS scenarios for the region, particularly with respect to transport and centralised storage. For participating countries, see Table 6.

The European Space Agency (ESA) was involved in a feasibility study on satellite-based/supported site monitoring (Spacemon) in collaboration with Airbus, Axio and the British Geological Survey (2011–2013).

Promising CCUS start-up regions in Southern and Eastern Europe were developed in the H2020 project STRATEGY CCUS[9]. The eight regions, summarized below, are considered promising for the development of low-carbon energy and industry through CCUS:

- **Lusitanian Basin, Portugal:** CO_2 from industry and power generation is to be captured and stored. The anticipated storage capacity is 340 Mt CO_2 onshore and 1,600 Mt CO_2 offshore. Several co-generation biomass plants are under construction or planned, providing the potential for bioenergy generation with CCS (BECCS).
- **Ebro Basin, Spain:** The presence of geological structures with large, medium, and small storage capacity offers the potential for early onshore storage development. There are opportunities for several commercial CCU technologies. The presence of a transport network from Barcelona port could link CO_2 sources with storage sites and CO_2 utilisation opportunities.
- **Rhône Valley, France:** Capture is planned on several high, medium and small-scale CO_2 emitters. There is potential for early storage development in the south-east geological basin onshore, and offshore beneath the Mediterranean Sea. A Rhône Valley transport corridor could connect the region and neighbouring countries with large North Sea storage sites.
- **Paris Basin, France:** This region includes a range of small-to-medium emitters in the Paris and Orleans metropole areas. Potential CO_2 storage sites include onshore depleted hydrocarbon fields and deep saline aquifers. Potential storage capacity in 2009 was estimated at 60-140 Mt CO_2. The potential exists to connect CCUS clusters to large North Sea storage sites. Captured CO_2 can be used in existing greenhouses (CO_2SERRE project; Gravaud et al. 2021), or permanently stored in the subsurface, in some cases as part of geothermal projects (CO_2-DISSOLVED).

[9] The description of the STRATEGY CCUS regions is included here because of their regional and multinational relevance.

- **Northern Croatia:** This region covers the Zagreb and the Croatian part of the Pannonian basin. Geological CO_2 storage capacity in deep saline aquifers and depleted hydrocarbon fields has been evaluated at 2.7 Gt CO_2 by the long-since finished FP6 projects CASTOR and EU GeoCapacity. Additional storage capacities are being assessed for ongoing CO_2-EOR projects and CO_2-EOR candidates. Two future hubs are envisaged – Eastern cluster and Central cluster, with CO_2 in the Eastern cluster to be transported to the Beničanci oil field and Bokšić gas field in eastern part of the Drava depression for enhanced recovery.
- **West Macedonia area, Greece:** Plans for CO_2 capture focus on the Kozani and Ptolemaida industrial areas with small-to-large-scale emitters. Five (coal/lignite-fired) power plants account for around 30.5 Mt CO_2 emitted each year. High CO_2 storage potential exists in the Mesohellenic Trough, in north-western Greece. Capacity of the Pentalofos and Eptachori Formations is estimated at 1.02 and 0.13 Gt CO_2, respectively.
- **Galati area, Romania**: Plans include the Port of Galati and 42 major industrial installations along the Danube River. Storage options include EOR and depleted hydrocarbon reservoirs, as well as onshore and offshore deep saline aquifers. River and canal links to the Black Sea offer the potential for CO_2 transport by shipping combined with pipelines.
- **Upper Silesia, Poland:** The industrial areas of Katowice, Rybnik and Bedzin are being considered, with 16 coal mines, ten large power plants, coking plants and metallurgical industry. Potential CO_2 storage sites have already been identified and capacities estimated, and these comprise one aquifer site and three coal seam sites. Three potential research areas have been identified in the Upper Silesia Coal Basin.

GeoERA "Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe"[10] is an ERA-NET Co-Fund Action run by the national and regional Geological Survey Organisations of Europe (GSOs). It receives funding through H2020 (2018–2022). The overall goal of this ERA NET is to integrate information and knowledge held by the GSOs on subsurface energy, water and raw material resources. Together with the EC, the GeoERA consortium organises and co-funds transnational research projects, including for example:

[10] Although GeoERA does not directly address CO_2 storage, we include it here because of its relevance to geological storage and trans-national cooperation.

1) The GeoConnect³d project that is developing and testing a new methodological approach to prepare and disclose geological information for policy support and subsurface management. The project includes regional case studies of the Roer-to-Rhine region and the Pannonian basin. Applicability of the regional results at pan-European level is being tested by applying the methodologies in two smaller pilot areas in southern Germany and Ireland.
2) The "3DGEO-EU (3D geomodelling for Europe)" project aims to harmonise geological data and 3D geological models across national boundaries to create a basis for trans-European assessments of resource potential and eventual consideration of conflicts of use.

For an overview of participating countries, see Table 6.

6.3 National research related to CCS

Note: The information provided by the questionnaires about national projects varied substantially with respect to detail, which made statistical handling of this information unfeasible. The information about national projects should therefore be considered qualitatively rather than quantitatively.

A total of 18 countries reported to have conducted or are in the process of carrying out > 90 nationally funded projects related to CO_2 storage since 2012, ranging from development of test sites and dedicated laboratories to PhD projects (Tab. 7). Few budget numbers are readily available for these projects, making it difficult to compare the scale of the national efforts beyond a qualitative assessment of number of projects and the topics addressed. The focus of national research projects on CO_2 storage in Europe appears to be focused on storage capacity assessment (addressed by 16 out of 18 countries) and modelling of subsurface storage processes (14 countries), with less attention given to well technology, social acceptance, and complex management (addressed by 8, 8 and 9 countries, respectively).

Considering research activities on the different parts of the CCS chain, it can be stated that in some countries, such as Sweden, Denmark, Germany, Poland and Spain, the research focus has been on advancing CO_2 capture technologies rather than on storage in recent years. Also, CO_2 utilisation research is prioritised in comparison to CO_2 storage in some countries such as Germany and Finland. For example, Finland focuses its research activities on CCU and clean H_2 production, including capture on bioenergy production and conversion to sustainable chemicals and materials, and direct air capture powered by solar photovoltaic systems.

Thirteen countries reported that they host large-scale CCS research facilities (Tab. 7). These range from specialist laboratory facilities to entire test sites. An abbreviated list is given below. Detailed information is found in the country reports (see Annex). For information on pilot and demonstration projects on CO_2 capture, transport and storage, see Chapter 5.

Table 7: Key statistics for CCS-related research activities in European countries based on country reports, in some cases supplemented by on-line sources. Countries marked in grey are not covered in detail in the report but are included here for completeness. Countries participating only in GeoERA projects are indicated with an asterisk in the column "Number of research institutions involved in CO_2 storage research". The column "Number of country-country links" indicates the engagement with other European countries as the sum of other participating countries in all projects a given country is involved in (calculated from Tables 4 and 6).

	National statistics				Multinational statistics		
Countries	Dedicated national funding instruments for CCS research	Number of research institutions involved in CO_2 storage research	Number of nationally funded CO_2 storage research projects	Large scale CCS research infrastructure	Number of projects each country participates in	Number of projects coordinated by each country	Number of country-country links
Albania		1*			1		31
Austria		2			5		74
Belgium		2		Yes	8	1	91
Bosnia and Herzegovina		1			2		46
Bulgaria		1			1		21
Croatia		2	2		5		89
Cyprus		1*			1		31
Czech Republic		3	3		6		90
Denmark	Yes	4	1		11	1	78
Estonia		1	1		5		54
Finland		1		Yes	6	1	80
France	Yes	9	19	Yes	25	10	196
Germany	Yes	5	6	Yes	33	1	233
Greece		4			10	1	98
Hungary		3	1		3		67
Iceland		3			8	2	71
Ireland		3	3		3		49
Italy	Yes	13	3	Yes	15	2	121
Latvia		1			4		66
Lithuania		1	1		5		80
Luxemburg		1*			2		46
Malta		1*			1		31
Netherlands	Yes	6	20+	Yes	28	3	183
North Macedonia		1			1		31
Norway	Yes	15	20+	Yes	27	16	169
Poland	Yes	18	1	Yes	14		128
Portugal		6	2	Yes	4		66
Romania		2	2		12		126
Serbia		2			3		50
Slovakia		3			4		81
Slovenia		5			4		81
Spain		6			17	1	142
Sweden	Yes	4		Yes	9	1	93
Switzerland	Yes	4	1	Yes	12		65
Turkey		3		Yes	5		44
Ukraine		4	2		3		52
United Kingdom	Yes	17	3	Yes	33	9	189

ECCSEL CCUS infrastructure network: Five countries, France, Italy, the Netherlands, Norway and the UK, coordinate a large part of their CO_2 research infrastructure through the EU-funded ECCSEL network and the ECCSEL European Research Infrastructure Consortium (ERIC). ECCSEL lists over 80 facilities operated by 23 different universities, institutes etc. The facilities range from a single instrument to a full laboratory or pilot plant or field test site. Each of the five countries has institutes active in CO_2 research who are not ECCSEL members. ECCSEL offers open access to their CCUS research facilities to address the following aspects of CO_2 capture and transport: Membranes, integrated CCUS systems, pressure/injection, migration, security/ troubleshooting, CO_2 pipeline transport and integrity, shipping of CO_2, smart integration with carbon capture and re-use into valuable products.

In terms of CO_2 storage, field laboratories and pilots related to CO_2 storage and monitoring (facilities that are part of ECCSEL are indicated) include:

- the **Sotacarbo Fault Laboratory** (Italy, Sardinia, injection and monitoring to 250 m depth along a fault in rhyolite, ECCSEL),
- the **GeoEnergy Test Bed (**UK, injection and monitoring to 280 m depth in strata equivalent to North Sea storage targets, ECCSEL),
- the **Svelvik CO_2 field laboratory** (Norway, four 100 m deep instrumented monitoring wells around a central injection well in glaciomarine sediments, ECCSEL),
- the **Andra underground research laboratory** (France, tunnel system at ca. 500 m depth in Jurassic clay, boreholes and test facilities, ECCSEL),
- the **Flair soil station** (France, a mobile laboratory for tracking CO_2 in the shallow vadose zone, ECCSEL),
- the **Mont Terri underground rock laboratory** (Switzerland, operated by the Swiss Geological Survey, used by a number of national and international consortia),
- **CATLAB** (Oise, France, CATenoy experimental site and gas-water-rock interactions LABoratory, CO_2 injection and tracking in a chalk aquifer to 25 m depth, ECCSEL),
- the **Panarea Natural Laboratory** (Italy, seafloor leakage of CO_2, ECCSEL),
- the **Latera Natural Laboratory** (Italy, onshore leakage of CO_2, ECCSEL),
- the Rijswijk Center for Sustainable Geo-energy (**RCSG) Test RIG and Large Well** (Netherlands, drilling rig and existing borehole for testing, ECCSEL).

In addition, noteworthy, smaller-scale research facilities on CO_2 capture, transport or storage reported in the questionnaires, include the following:

- CO_2 capture from naturally carbonated waters in the area of Spa, Belgium.
- In Germany, capture technology research facilities are operated by TU Darmstadt, the University of Stuttgart, Research Centre Jülich, etc. on, for example, carbonate-looping and membrane technologies.
- A clinker cooler pilot plant was built and tested at the Heidelberg Cement plant in Hannover, Germany (EU project CEMCAP).
- The FALCON CO_2 Flow Loop Laboratory operated by the Norwegian Institute for Energy Research (IFE) in Kjeller, near Oslo, Norway.
- DeFACTO CO_2 flow loop facility, operated by SINTEF in Trondheim, Norway. 139 m horizontal and up to 90 m (depth) vertical loops for the Demonstration of Flow Assurance for CO_2 Transport Operations.
- Equinor maintains a pipeline transport test facility for natural gas and CO_2 at their research premises in Porsgrunn, Norway.
- CO_2 Transport research facility and safety platform: Mont la Ville experimental site in Oise (France, ECCSEL).
- In Portugal, the academia-industry collaborative "NET4CO_2" maintains laboratory facilities for testing CO_2 capture through the continuous formation of gas hydrates using the patented NETMIX technology.
- Turkey lists the TUPRAS Izmit Refinery Capture pilot site, where the MOF4AIR project is ongoing.
- CO_2 injection pilot tests at the Umurlu Geothermal Field, and the Kizildere Geothermal Field, Turkey, in the SUCCEED project.
- Pilot-scale Advanced-Capture-Technology (PACT) facilities, UK.
- A UK initiative scoping the opportunity for a CO_2 storage testbed.

6.4 Global collaboration

Companies and research institutions from non-European countries are involved in several European CO_2 storage-related research projects (Tab. 8).

Table 8: Non-European involvement in European CO_2 storage-related research projects.

	H2020 projects active as of 30th June 2021				Regional networks		ACT projects granted 2019								ACT projects granted 2017	
Countries	C4U	CHEERS	ConsenCUS		NCCS		ACTOM	DIGIMON	LAuNCH	MemCCSea	PrISMa	REX-CO2	SENSE		ALIGN CCUS	Pre-ACT
AUSTRALIA																
CANADA																
CHINA																
JAPAN																
U.A.E.																
USA																

Mission Innovation (MI), launched in 2015, is a global intergovernmental platform comprising representatives from 22 countries and the European Commission (on behalf of the European Union) for clean energy innovation through action-oriented cooperation. The follow-up initiative, Mission Innovation 2.0, was launched on 2nd June 2021 to continue catalysing action and investment in research, development and demonstration to make clean energy affordable, attractive and accessible for all, this decade. The following European countries are members in the Mission Innovation initiative: Austria, Denmark, Finland, France, Germany, Italy, The Netherlands, Norway, Sweden and UK (EU MS also effectively contribute under part the EU umbrella).

The **North Sea Basin Task Force** (NSBTF) was established in 2005 by the Governments of the UK and Norway. Today the Task Force is composed of government and industry members from Norway, the UK, the Netherlands, Germany and Flanders. The task force aims to develop common principles for managing and regulating the transport, injection and permanent storage of CO_2 in the North Sea sub-seabed ensuring cost-effective and environmentally responsible operations. Furthermore, it aims to share knowledge between the governments and industries of represented countries as regulation and projects develop.

Chapter 7: National actors driving CCS forward, public awareness and engagement

Note: The information presented in this chapter is largely based on the personal perceptions and experiences of the individual authors, scientific surveys are not available in the literature for all countries or projects. Thus, no clear statistics and rating could be given and only tendencies and trends will be reported on a more general level with specific examples.

In many of the studied European countries, awareness of and knowledge about CCS technology within the general public is still low to very low (Fig. 9) and CCS is often perceived as a risky technology largely due to its unfamiliarity. Striking exceptions are Iceland and Norway (see below). For industrial and political stakeholders, a somewhat higher awareness and knowledge together with a more positive perception is reported for many countries. The topic of climate change has a higher awareness level than CCS technology in the general public in many countries – however, the drivers and the potential consequences of climate change, and the magnitude of changes required to meet climate targets, are often also quite poorly understood by the general public.

For Norway and Iceland, high and very high awareness levels, respectively, and neutral to positive attitudes towards CCS, are reported (cf. Fig. 9):

- Norway: In Norway there is a broad political consensus in favour of CCS among all political parties and main political players including, for example, trade unions and the Confederation of Norwegian Enterprises. The relatively high public awareness and knowledge about CCS can, in part, be a result to the Government's investment in high-profile projects such as the Technology Centre Mongstad (capture test centre) and the Norwegian full-scale CCS Longship demonstration project (including the Northern Lights project). The fact that CO_2 storage in Norway will continue to be carried out offshore presumably facilitates public acceptance.
- Iceland: CCS technology in general and in particular the "Carbfix technology" involving CO_2 mineralisation in basalt is widely known and its public acceptance is very high due to numerous public information and engagement activities by the Carbfix partners and other national advocates. Additional likely reasons for the high knowledge and acceptance level in Iceland include, amongst others, the following:
  i) the "Carbfix technology" is based on processes that also occur in nature,
  ii) the rapid mineralisation significantly reduces the risk of CO_2 leakage,
  iii) the "Carbfix technology" has been developed at a geothermal plant, i.e. in the renewable energy sector, rather than the oil and gas sector,
  iv) the "Carbfix technology" is perceived as an Icelandic brand within the energy and utility sector.

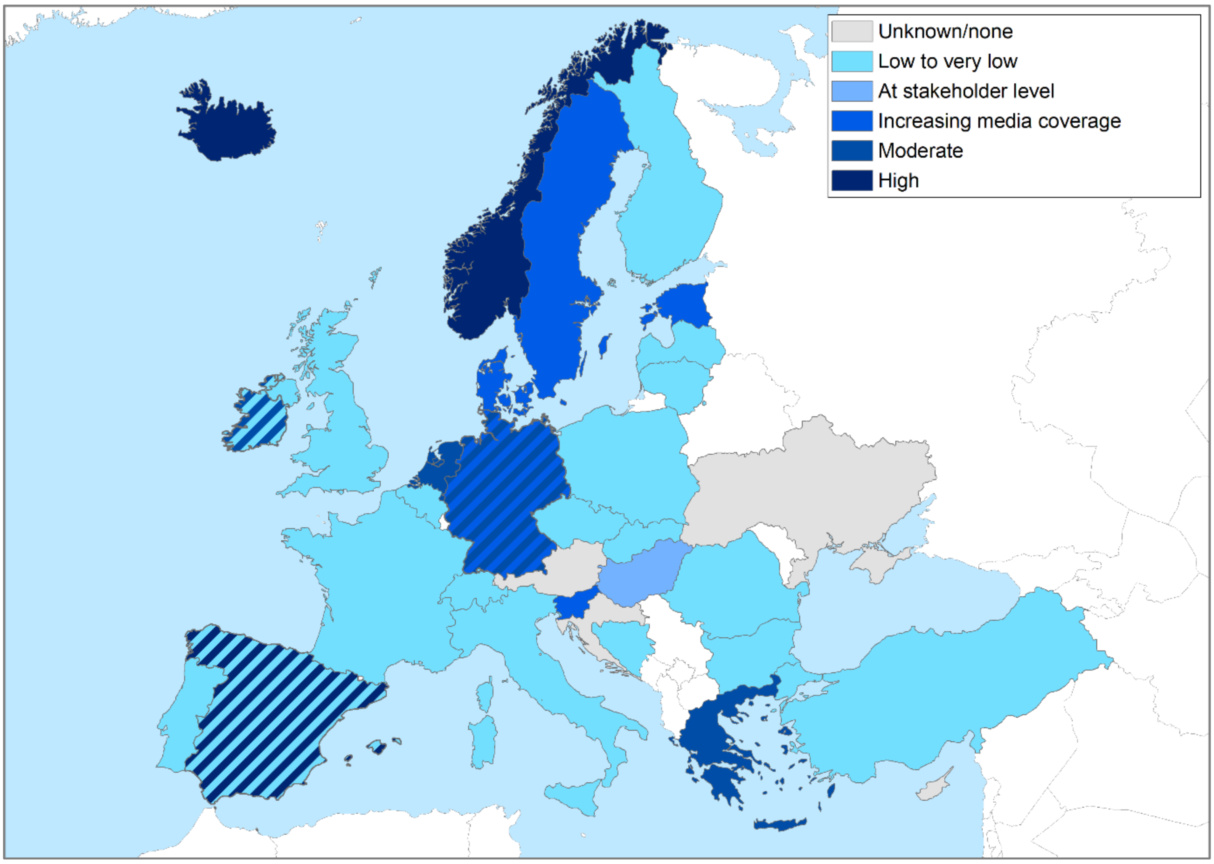

Figure 9: Public awareness and knowledge of CCS in European countries as perceived by this report's national contributors during 2020. In countries with hatched infill, awareness and acceptance was locally higher in the areas surrounding pilot projects than in the rest of the country.

At various pilot sites, informing and engaging the local public living around the respective projects has been successful, for example, in Hontomín (Spain), Ketzin (Germany), Cork (Ireland) and Hellisheidi (Iceland). At all these sites, it was found that the better the knowledge about the technology, the more the project (and CCS technology in general) was accepted by the local population. Accompanying social scientific studies also revealed that the characteristics of the relational context in which the people came to learn about CCS technology or the pilot project were an important factor for how the technology or project was perceived: An open interactive format, which allowed for rich exchange and discussion, favoured acceptance. In contrast, a more frontal approach and imposition of projects appeared to stimulate reactions of rejection.

In several European countries (e.g. Slovenia, Sweden, Denmark, Estonia, Germany), the interest in and the media coverage of CCS technology has slightly to moderately increased in recent years – in particular during the negotiations on national CO_2 emission-reduction targets and measures to reach these targets. In some countries, the perception of CCS technology is more positive for capture from industrial facilities (e.g. Germany), on bioenergy plants (BECCS) or in combination with direct capture of CO_2 from the air (DACCS) (e.g. Belgium, Sweden, Switzerland) as compared to capture from fossil-fuelled power generation. In industrial facilities, non-energy related CO_2 emissions are inherent to some of the industrial processes, for example, the calcination process during cement production. Thus, applying CCS for such industrial facilities is perceived as a (potentially) acceptable emission-reduction measure, whereas CCS on power is considered an obstacle to advancing the transition from a fossil based towards a renewable energy-based system in some countries. Combining geological CO_2 storage with energy generation from biomass or with direct air capture potentially allows "negative" CO_2 emissions that may be required for compensating hard-to-abate GHG emissions, for example, from agricultural soils. In many countries, this additional benefit leads to a more positive perception of these technologies in comparison to CCS on power. Storage offshore is often perceived as less risky than onshore storage and therefore has a (somewhat) higher acceptance (e.g. in Germany, Sweden and the Netherlands).

In some countries (e.g. Estonia, Finland, Belgium, Germany, Portugal), carbon capture and utilisation (CCU) receives more attention from the public and politicians than CO_2 storage. Likely reasons for this include the economic benefits of CCU, capturing/removing CO_2 being more straightforward to regulate and having a higher public acceptance of CCU as compared to CCS. In some of these countries, in particular where there is no suitable geology in-country or where legislation forbids CO_2 storage, the stated intention is to store the CO_2 that cannot be utilised elsewhere through projects such as Longship.

There are various national advocates of the CCS technology in some of the studied European countries that have stipulated the discussion on the pros and cons of the CCS technology in comparison to other (technological) options for reducing CO_2 emissions:

- **National CO_2 Clubs and Networks**: In France, Italy, Romania, Spain and the UK, national "CO_2 clubs" have been established by universities/research institutes and/or companies covering, for example, the oil and gas industry, equipment manufacturing/ distribution, as well as a wide range of support services that promote CCS as one technological measure for CO_2 emission reduction:

- PTECO$_2$: Plataforma Tecnológica Española del CO$_2$,
- Romanian CO$_2$Club,
- CO$_2$ Club Italia,
- French Club CO$_2$,
- CATO, The Netherlands,
- UKCCSRC – UK Carbon Capture and Storage Research Centre,
- SCCS – Scottish Carbon Capture and Storage,
- CCSA – UK Carbon Capture and Storage Association,
- Norwegian Petroleum Directorate CO$_2$ Storage Forum.

- **National scientific or engineering academies, think tanks or governmental fora** such as the Danish Council on Climate Change (Klimarådet), Denmark, National Academy of Science and Engineering (acatech) and Energy Systems of the Future (ESYS) Initiative of the German Academies of Sciences, Germany, Irish Academy of Engineering, Ireland, and Fossil Free Sweden Initiative and FORES think tank, Sweden, have considered CCS. Also, the Norwegian non-governmental organisation Bellona is strongly advocating the need for CCS implementation in Europe.
- **Individual institutions** such as the geological surveys or a specific research institution.
- **The national representatives of European regional networks** such as BASRECCS, ENeRG or representatives of emission-intensive industries.

Chapter 8: Summary and conclusions

The 2021 update of the state-of-play on CO_2 geological storage in Europe demonstrates clear progress in the roll-out of CO_2 storage since the first assessment in 2012 (Rütters et al. 2013). After a decrease in the number of CCS projects and initiatives between 2010 and 2017, there is a continuing steady increase in the number of projects in Europe, a trend which is also observed worldwide (GCCSI 2020). The decline in the number of CCS projects from 2013 to 2017 was mainly related to the difficulty in setting up robust economic business models and to the lack of recognition of the role of CCS in the climate change mitigation toolbox. The notable progress in CCS implementation has been stimulated by recent developments in European and national climate-protection targets and policies that are being implemented to meet the climate protection targets set by the Paris Agreement in 2015, as well as the European Green Deal and the European Climate Law, which enshrines in law the objective of the EU to reach climate neutrality by 2050.

The focus of CCS-related activities has shifted from research and pilot-scale testing to the planning and implementation of larger-scale CCS projects and clusters. Progress is particularly tangible in Norway, the Netherlands, and the UK where large-scale CCS projects involving more than one emitter or emission clusters are currently being implemented. These projects use both national and European funding, for example, the EU support of transport infrastructure projects (Projects of Common Interest). Simultaneously, companies and sites offering a “CO_2 transport and storage service” are emerging such as the Longship project. In Iceland, after pioneering CO_2 storage by mineral storage in basalt formations, larger-scale follow-up projects on CO_2 mineral storage are currently evolving.

In most European countries, the focus for applying CCS is now on emissions from the industrial sector that are hard to abate, such as chemical, steel, cement and waste-to-energy plants, whereas emphasis was placed on capture from fossil-fuel-fired power plants at the time of the previous assessment. Recently, capture on other CO_2 emitters/sources such as geothermal plants, low-carbon “blue” H_2 production (i.e. hydrogen production from natural gas with CCS) or directly from the air has received increased attention with several projects currently in the advanced planning stage. In addition, bioenergy generation with CCS is being discussed and advanced in several countries as a promising option for potentially achieving negative CO_2 emissions.

In some countries, CO_2 capture and utilisation (CCU) is currently favoured over CO_2 storage by the public and politicians, being considered a (value-creating) technological option for CO_2 emission reduction and an essential building block for an envisaged circular economy. The potential for emission reduction of CCU strongly depends on the envisaged types of utilisation, the permanence of CO_2 “storage” in the final product, the scale of application and the overall lifetime carbon footprint of the technology. The use of CO_2 for enhanced oil recovery from depleting reservoirs is being considered in Austria, Croatia, the Czech Republic, Latvia, Lithuania, Poland, Croatia and Turkey with projects in different stages of assessment and planning. Operating CO_2-EOR projects have been reported from Croatia, Hungary and Turkey. Implementation of CO_2-EOR projects may represent a good opportunity to kick-start broader CCUS activities in several countries, for example, in Central and Eastern Europe. In some other European countries, the continued oil production by CO_2-EOR is regarded with some scepticism in terms of its climate benefits, by the public and politicians.

Research activities on CCS have focused on capture and storage with comparatively few projects investigating aspects of CO_2 transport. CO_2 capture involves a range of different technologies that are being optimised through R&D. Capture from industrial emissions and alternative CO_2 sources (e.g. cement, steel or geothermal plants, H_2 production or direct air capture) is now under investigation and specific challenges for the different settings are being researched. CO_2 storage research is largely focused on refining aspects of the technology to improve efficiency and reduce costs.

Apart from the two operational large-scale, commercial CCS projects at Sleipner and Snøhvit in Norway and the two smaller-scale Icelandic CO_2 mineral storage operations, no other CO_2 injection and storage sites are currently in operation in Europe. CO_2 injection operations at the pilot sites at Ketzin (Germany), K12B (The Netherlands), and Lacq (France), have finished as planned and the development of the onshore pilot site at Hontomín, Spain, has stalled. As a result, there is still limited experience with licencing and regulating CO_2 storage operations in Europe.

Updates of national storage capacity assessments have been reported by the majority of countries assessed, reinforcing the need for an up-to-date, consolidated and harmonised European CO_2 storage atlas. In most European countries, saline aquifers and depleted/depleting hydrocarbon fields are considered for storage of dense-phase CO_2 with offshore locations being preferred over onshore locations in most coastal countries.

Public interest in CCS and related media coverage has increased in many European countries over recent years. One aspect that helped to bring CCS back onto national emission-reduction agendas in some countries is the potential of CCS to deliver negative CO_2 emissions when combined with bioenergy use or direct air capture. From reported local experiences and scientific investigations, it can be concluded that where local stakeholders are informed and understand CCS technology, a higher level of acceptance is observed. An early, open and transparent stakeholder dialogue and engagement generally led to a reported higher level of acceptance of CCS technology and/or specific projects.

Overall, a wide range of activity and knowledge levels on CCS across Europe is evident from our survey, which underpins the continued need for pan-European knowledge exchange, technology transfer and cooperation on CCS to roll-out CO_2 capture, transport and storage at the scale required to achieve significant CO_2 emission reductions in Europe.

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Note: This reference lists includes references from the report and from the Annex.

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ANNEX

This Annex contains specific information on the state-of-play on CO_2 geological storage in 32 European countries provided by CO_2GeoNet members and contributors from countries outside the Association as responses to a questionnaire survey. Respondents were asked to answer questions on the following topics:

1) national storage options, potential and capacity;
2) large-scale and demonstration CCS projects, pilot and test sites for CO_2 capture, injection and storage;
3) national policies and climate-protection strategies, national legislation and regulations;
4) research activities with respect to CO_2 storage;
5) national actors driving CCS forward, public awareness and engagement.

The information contained in this Annex is as recent as of 30th June 2021.

Country-specific information was provided by the authors listed in the following:

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*: Country represented in the CO_2GeoNet Association and covered by member(s).

Note that the references cited in the Annex are included in the overall reference list.

Summarising the state-of-play on geological CO_2 storage in AUSTRIA (AT; as of 30th June 2021)

AT1. National storage assessment, storage options, potential and capacity

Since the State of Play report on geological CO_2 storage in 2013 (Rütters et al. 2013), no major changes occurred, neither in the Austrian storage assessment nor the estimated CO_2 storage capacities. Potential CO_2 storage sites in Austria have been presented at the 68th SPE Annual conference in Vienna (Scharf & Clemens 2006) and only focused on hydrocarbon fields. All mentioned storage sites are located in the Vienna Basin or the Molasse Basin. The storage capacities were estimated by simple assumptions and lead to a cumulative capacity of 465 Mt CO_2. This number does not account for economic feasibility and hence actual storage volumes will be smaller.

Recent results from the ENOS project led to an estimated storage potential of 121 Mt CO_2 in the biggest oil reservoirs of the Austrian Vienna Basin. This study focused on combined CCS with CO_2-EOR and used production data, initial oil in place and some additional reservoir parameters for the storage evaluation.

So far, no research has been performed on CO_2 storage in saline aquifers or salt domes. There is no national CO_2 storage atlas available for Austria. The main reason for the rather limited progress in storage assessment is a Federal Law that entered into force in 2011 and bans both, the underground CO_2 storage as well as the exploration for geological CO_2 storage sites.

AT2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

AT2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

Capture on…

…**biomass power plants:** "ViennaGreenCO_2" project, CO_2 post-combustion capture with solid sorbents, capture volume of 0.7 t/day (in operation until 2019).

…**cement plants**: In June 2020, the Lafarge cement plant in Mannersdorf co-signed a memorandum of understanding for a full-scale CCU project and presented its plan to capture almost 100% of its CO_2 emission by 2030, (700,000 t CO_2 per year). No further details are currently known.

AT2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

AT2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

Castor Project (2004–2008): The Atzbach-Schwanenstadt gas field was considered to be transformed into a CO_2 storage. Suitable CO_2 sources were evaluated and the distribution of the injected CO_2 was calculated in a reservoir model.

AT2.4 Past and current full-chain CCS projects & projects/sites in preparation

None.

AT2.5 Plans for CCUS cluster development

Lafarge Zementwerke, Verbund, OMV and Borealis signed a memorandum of understanding in June 2020. The aim of the "Carbon2ProductAustria" (C2PAT) project is to develop a full-scale CCU plant with CO_2 capture in Austria's biggest cement plant (Lafarge cement plant in Mannersdorf). Austria's biggest electricity provider (Verbund) will create green hydrogen that will be used, together with the CO_2, to create synthetic fuels, plastics and chemicals (OMV and Borealis). The plant should be finished by 2030. No further details are currently known.

AT3. National policies, legislation and regulations

AT3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

In May 2018, Austria presented a climate and energy strategy up to 2030. It comprises 12 flagship projects that should represent a first step towards meeting the country's climate obligations:

1. Efficient goods transport logistics
2. Strengthening public rail transport
3. E-mobility plan
4. Thermal renovation of buildings
5. Renewable heating
6. 100,000 rooftops solar panel and small-scale storage programme

7. Renewable hydrogen and biomethane
8. Green finance
9. Energy research initiative 1 – Energy systems of the future
10. Energy research initiative 2 – "Mission innovation Austria" programme
11. Communication – education and awareness-raising for a sustainable future
12. Bio-Economy strategy

It is not mentioned how much emissions are expected to be saved by the individual projects. The potential role of CCS was also not mentioned.

In December 2019, Austria presented its long-term strategy on how to reach its climate goals up to 2050, following up to EU regulation 2018/1999). The strategy comprises several future scenarios, where CCS and CCU play an important role to meet Austria's climate obligations. Additionally, the possibility was mentioned to transport the captured CO_2 into a different country and store it in e.g. large-scale offshore storage sites. The NECP for the period 2021–2030 does not mention CCS.

AT3.2 National legislation and regulations

3 years after implementation of the EU CCS Directive (2009/31/EC) Austria has made use of its right to ban CO_2 storage according to article 4 §1. Since then, as stated by Federal Law Act No 144/2011 §2, the underground storage of CO_2 as well as the exploration for geological CO_2 storage sites are forbidden throughout the country. The only exceptions are research projects with a maximum storage capacity of 100,000 tonnes CO_2 and the exploration of storage sites for development or testing of new products or processes. This prohibition needs to be revaluated every 5 years. The last evaluation was in 2018 where the continuation of the prohibition was decided.

In general, landowners in Austria have a claim on the property down to the earth's centre. However, hydrocarbons and geological structures bearing hydrocarbons are deemed as national resources in Austria, meaning they are exclusive property of Austria regardless of any claims. The responsible governmental body is the Federal Ministry of Agriculture, Regions and Tourism and its "Montanbehörde" is the competent mining authority.

AT4. Research

AT4.1 National funding for research related to CCS and research priorities

Research related to CO_2 capture, transport and storage is funded in Austria by Klima- und Energiefonds.

There is no exclusive research programme for CCS. Nevertheless, the following research programmes addressed/address CO_2 capture and usage:

- Energieforschung (e!MISSION),
- Energieforschungsprogramm.

AT4.2 Research institutions involved in research related to CO_2 storage

CCS was hardly a research topic during the last couple of years. Austria is rather focusing on mitigation of CO_2 emissions and CCU projects. All major CCS research projects took place before the ban in 2011. Examples for CCS research institutions are:

- Geologische Bundesanstalt, GBA
- Montanuniversität Leoben, Chair of Reservoir Engineering

AT4.3 Existing larger scale research infrastructure

None.

AT4.4 Involvement in EU-funded and other regional/international research projects related to CCS

GBA is currently involved in the following EU-funded research projects addressing aspects relevant to CCS: Enabling onshore CO_2 storage in Europe (ENOS).

AT5. National actors driving CCS forward and public engagement

AT5.1 Awareness of CCS technology

To our knowledge, there has been no exclusive study about the public awareness of CCS technology in Austria. Before introducing the legal ban of CO_2 storage, the public opinion on CCS was very critical. However, since then topics linked to CCS have disappeared from the public discourse and lost the interest of journalists. The raised public awareness concerning the climate crisis might lead to a turn of public perception and to an, at least, slightly higher public acceptance.

AT5.2 National advocates for CCS

None.

AT5.3 Public engagement

None.

Summarising the state-of-play on geological CO_2 storage in BELGIUM (BE; as of 30th June 2021)

BE1. National storage assessment, storage options, potential and capacity

Although there is no true CO_2 storage atlas available for Belgium, capacity assessments on national and reservoir level have been made. A first national capacity assessment has been performed by the RBINS-GSB (Geological Survey of Belgium), starting in the GESTCO project (Christensen & Holloway 2004). Laenen et al. (2004) also published an overview of the storage options in the north-eastern Campine Basin and Roer Valley Graben. Baele et al. (2007) and Dupont & Baele (2009) have investigated the storage potential in coal sequences in the Walloon Region. Piessens & Dusar (2004) have looked into the storage of CO_2 in abandoned coal mines.

During the national PSS-CCS projects (2005–2011), funded by the Belgian Science Policy Office, a more detailed national assessment was made, adding uncertainties (Piessens et al. 2012). The capacity assessments were combined with a techno-economic assessment to quantify the effect of uncertainties on theoretical, practical and matched capacity numbers. These assessments were updated and published in a partly internally funded PhD research project at the RBINS-GSB (Welkenhuysen et al. 2013). These numbers were reported and compiled with other EU data in the EU FP7 CO_2StoP project (Poulsen et al. 2014).

Because of a historical lack of commercial interest in the deep subsurface in Belgium, potential storage targets, caprocks, their properties and capacities have large uncertainties. At the time of writing, no exploration licences or storage permits for CO_2 have been filed or granted. Potential storage capacity in the northern Flemish region is situated in the north-eastern Campine Basin, with saline aquifer targets from Upper Cretaceous to Devonian age. Additionally, storage could be possible in Carboniferous coal sequences and abandoned mines. In the southern Walloon Region, potential storage options are mainly located in an east-west band stretching from the cities of Liège to Mons, with saline aquifer targets from Lower Carboniferous to Devonian age. Storage could also be possible in Carboniferous coal sequences and abandoned mines. There is no (historical) hydrocarbon production, thus no storage potential in depleted hydrocarbon fields.

The theoretical total CO_2 storage capacity of Belgium is assessed to be around 1 Gt (1,000 Mt). A more realistic simulation provides an average practical capacity of 620 Mt, and a matched capacity of 109 Mt based on techno-economic source-sink matching. These numbers represent averages, with uncertainty ranges that span about one order of magnitude (Welkenhuysen et al. 2013).

BE2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

BE2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

Capture on cement: LEILAC project at the HeidelbergCement cement plant in Lixhe, Belgium. This EU H2020 funded pilot project (2016–2020) uses a direct separation process, developed by Calix, to capture process emissions from the calciner. The pilot plant was installed successfully, is operational and has a capacity to capture about 25 kt CO_2/year.

Direct air capture: At the deep geothermal plant site of Balmatt in Mol, owned by VITO, a pilot project started in 2018 to install a direct air capture installation on the air-cooling units of the geothermal plant.

BE2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

BE2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

None.

BE2.4 Past and current full-chain CCS projects & projects/sites in preparation

None.

BE2.5 Plans for CCUS cluster development

The development of a CCS network in Belgium, connecting to neighbouring countries, was studied and simulated in the PSS-CCS projects (Piessens et al. 2012).

In the Port of Antwerp, several companies have signed an agreement to investigate the feasibility of CCUS. In 2020, a PCI (Project of Common Interest) has been approved by the EC (CO_2TransPorts) to investigate connecting the Ports of Rotterdam and Antwerp and the North Sea Port (Ghent, Terneuzen, Borsele, Vlissingen). This project includes cross-border transport with a connection to the PORTHOS project in Rotterdam. Regarding the timeline, the port connections are planned by 2026 for amounts up to 10 Mt CO_2/year. Upscaling is planned after 2030.

BE3. National policies, legislation and regulations

BE3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

Belgium is a federal state, and the competences on energy and climate are distributed over the federal and regional level. At regional level, the Flemish government approved their energy and climate plan 2021–2030 on 18/12/2018. The Walloon government approved their air-climate-energy plan 2021–2030 on 04/04/2019. The Brussels government is working towards an air-climate-energy plan for 2030, planned for 2023. In their 2019–2024 policy statement the Brussels government announced a goal of 40% GHG emission reduction by 2030.

Combining the regional efforts, a national energy and climate plan 2021–2030 was approved on 18/12/2019, with a commitment for the whole of Belgium of 35% GHG emission reduction compared to 2005 for the non-ETS sectors.

Policy strategies and measures are mainly targeted towards an increase in renewables (17.5% in 2030, mainly wind and bioenergy), energy efficiency (-15% of primary consumption in 2030) and a circular economy. Additionally, a nuclear phase-out is scheduled by 2025, for a total capacity of 6 GW. Hydrogen is recognised as an essential element in the energy transition.

Belgium forms an important fuel and chemistry cluster in Europe, thus the potential for CO_2 capture and use is recognised. CO_2 storage is only mentioned as an option abroad. The R&D programme "Moonshot Vlaanderen CO_2 neutraal" provides support for CCS networks and CCU installations in Flanders, but currently only supports one capture project and no storage.

BE3.2 National legislation and regulations

Belgium is a federal state, and CO_2 storage is a competence of the regional authorities.

In both the Brussels Region and the North Sea area (the latter is governed by the federal government) storage is evaluated to be infeasible due to geological conditions. Hence, here, the CCS Directive was not transposed into regional/national legislation and storage is de facto prohibited.

In the Flemish Region, the EU CCS Directive was transposed into the decree of 08/05/2009 on the deep subsurface, which went into effect on 15/07/2011. This decree regulates activities below the level of -500 m, and received minor updates over the following years. There are no a priori restrictions on geological storage of CO_2, and a procedure for exploration and exploitation licences is available. Next to an exploration/storage permit, an environmental permit is needed.

In the Walloon Region, the EU CCS Directive was transposed into a regional decree M.B. 03/09/2013. This decree was revised in 2019 with updated environmental regulations which will become applicable in 2021. There are no a priori restrictions on geological storage of CO_2, and a procedure for exploration and exploitation licences is available. Next to an exploration/storage permit, an environmental permit is needed.

BE4. Research

BE4.1 National funding for research related to CCS and research priorities

Since the PSS-CCS projects (2005–2011), funded by the Belgian Science Policy Office, ended there is and has been no research programme in Belgium specifically targeting or funding CO_2 storage. The RBINS-GSB has co-funded two project with own funds:

- **PhD project** (Welkenhuysen 2017): For Belgium, focussing on capacity assessment, techno-economic source-sink matching, and network/infrastructure development.
- **GeoConnect³d project**: Project in the frame of the EU H2020 GeoERA. This project focusses on compiling and presenting geological information through a structural framework in a way that is accessible and usable to stakeholders. One research topic is the interaction of subsurface activities, another are unusual geological expressions, geomanifestations, for which the CO_2-rich spring waters in Spa are monitored.

The Moonshot "Vlaanderen CO_2 neutraal" funding programme partly targets CCS networks and CCU installations in Flanders. The direct air capture project by VITO is related to the CAPTIN project (Intensification of CO_2 Capture Processes), funded by this programme.

Table BE: Overview of research topics addressed by recent nationally funded research projects on CO_2 storage.

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	X	X	X	-	-	-	X	X	-
Project examples	PhD	PhD, GeoConnect³d	GeoConnect³d				PhD	GeoConnect³d	

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

BE4.2 Research institutions involved in research related to CO_2 storage

CO_2 storage is a very uncommon research subject. A limited number of institutes are currently involved in CO_2 storage research, and are cooperating in this field.

- The **RBINS-GSB** is a member of CO_2GeoNet and is regularly involved in CCS-related research.
- At the **Antwerp University**, and more specifically the Environmental Economics research group, CCS has been and still is a research subject for nearly 10 years.

Since 09/2020 there is a strong and structural cooperation between RBINS-GSB and Antwerp University on this topic.

BE4.3 Existing larger scale research infrastructure

Lixhe: pilot capture plant for process emissions at the HeidelbergCement plant in Lixhe, built as part of the EU H2020 LEILAC project.

Spa: In the area of Spa, in the south-east of Belgium, naturally carbonated waters are coming to the surface. Monitoring equipment and strategies are being developed by the Geological Survey of Belgium.

BE4.4 Involvement in EU-funded and other regional/international research projects related to CCS

- Enabling onshore CO_2 storage in Europe (ENOS)
- Low Emissions Intensity Lime And Cement 2 (LEILAC2)
- Cross-border, cross-thematic multiscale framework for combining geological models and data for resource appraisal and policy support (GeoConnect³d)

BE5. National actors driving CCS forward and public engagement

BE5.1 Awareness of CCS technology

General knowledge and awareness of CCS technologies is low in Belgium. There have been no scientific surveys or published studies on public awareness. In 2013, VITO has conducted a survey among a number of CCUS stakeholders, and generally CCU is preferred over CCS (Laenen et al. 2013).

BE5.2 National advocates for CCS

RBINS-GSB, limited to scientific advice or reporting only.

BE5.3 Public engagement

As communication activities at the end of research projects, a number of interviews and press releases have been made by the RBINS-GSB and Antwerp University. As there is low awareness about the deep subsurface and CCS in particular, general interest and feedback was low. The following public communications were made or contributed to:

- Online news item: Starckx, S. 2013. Toekomst CO2-opslag hangt aan een zijden draadje. Argus Actueel, 13/05/2013.
- Online opinion: Piessens K. & Welkenhuysen K. 2013. De waagschaal van energie en klimaat: beter in balans met steenkool. EOS wetenschap (online opiniestuk).
- Science magazine paper: Welkenhuysen, K. & Piessens, K. 2016. Het belang van geologische opslag van CO_2 voor België. Science Connection (Federaal Wetenschapsbeleid), maart-april 2016, 50, "Het klimaatonderzoek in België", 32-33.
- Radio interview: Welkenhuysen, K., 2017. 10 minute radio interview on CO_2 storage in Belgium. Radio 1, Nieuwe Feiten (12u-13u), 02/11/2017.

- Press release: Welkenhuysen, K. 2017. CO2-opslag in aardlagen kan tot twee derde van industriële uitstoot neutraliseren. Belga, 26/10/2017. Published online by Het Laatste Nieuws and De Morgen.
- Online news article: Schepens, W. 2018. We kunnen het klimaat manipuleren om de opwarming van de aarde tegen te gaan: maar is dat wel verstandig? VRT Nieuws, online persartikel op vrtnws.be, 08/07/2017
- Newspaper article: Martin, M., 2019. Is het klimaat geholpen met de opslag van CO_2? De Morgen, 07/05/2019, p. 9.
- Online news item: Martin, M., 2019. CO_2 opslaan onder de Noordzee: een ambitieuze zet in het klimaatverhaal? De Morgen, online persartikel op demorgen.be, 07/05/2019.

Summarising the state-of-play on geological CO_2 storage in BOSNIA AND HERZEGOVINA (BA; as of 30th June 2021)

BA1. National storage assessment, storage options, potential and capacity

Primarily, potential areas for gas storage (including CO_2) in Bosnia and Herzegovina had been mapped within an internal case study (Tomić et al. 2007). That case study contains nationwide thematic maps of 15 locations of Paleozoic and Mesozoic age assessed for their potential suitability according to the criteria: lithology, geomechanical and technical conditions, environment and safety, locations and investment. Some of these areas were military facilities, some of them were insufficiently researched and some were in exploitation. The case study showed that salt mine ”Tetima” (NE part of Bosnia and Herzegovina, near to Tuzla) is the best location for gas (including CO_2) storage in Bosnia and Herzegovina. This location had 23/25 points according to the considered criteria. During the ESTMAP project (2015–2016), this location was more precisely defined.

In the EU GeoCapacity project, CO_2 storage capacities of Bosnia-Herzegovina were assessed for the first time. It was concluded that Bosnia and Herzegovina lacks substantial geological storage capacity due to a “predominance of carbonate sedimentary formations with a high level of carstification and tectonic disturbance of their brittle layers” (Vangkilde-Pedersen 2009). Storage capacity in saline aquifers was estimated as 197 Mt CO_2.

There is no national CO_2 storage atlas available.

Today, there are about 30 empty salt caverns (filled by salt water) with capacity about 200,000 m^3 per cavern. A total of 100 such caverns are expected. Their storage space as estimated to be roughly 20-25 million m^3.

There has not been any application for a CO_2 storage exploration licence or storage permit filed or granted.

All values given above represent volumetric capacities that do not consider any geotechnical or socio-economic constraints that will reduce the volume of realistically usable storage capacity.

Our City Government is against geological CO_2 storage by their proclaimed politics but not by law.

BA2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

BA2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

None. There is an idea for CO_2 capture from the coal power plant Tuzla but it is currently "on hold".

BA2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None. Connected with BA2.1.

BA2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

None. There is an idea for demo/pilot project at salt mine "Tetima" but we are still waiting for a suitable project and help from EU.

BA2.4 Past and current full-chain CCS projects & projects/sites in preparation

None.

BA2.5 Plans for CCUS cluster development

None. It can be realised through linking a coal power plant (capture) – transport – "Tetima" (storage).

BA3. National policies, legislation and regulations

BA3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

Back in 2013, Bosnia and Herzegovina adopted the Climate Change Adaptation and Low Emission Development Strategy and ratified the Paris Agreement in March 2017. However, our country has yet to begin implementing the Paris Agreement in a systematic manner.

Bosnia and Herzegovina is also committed under the Energy Community Treaty to achieving a target of 40% renewable energy in its energy mix by 2020. However, the reform of the renewable energy framework regarding net metering and development of incentive mechanisms has yet to be conducted. It is crucial that both Entities, i.e. the Federation of Bosnia and Herzegovina and Republika Srpska, and the central government of Bosnia and Herzegovina, find a compromise solution under the Energy Community rules in order to implement the provisions of the Third Energy Package throughout the country.

Concerning emissions of greenhouse gases, Bosnia and Herzegovina has an opportunity to set up a functional system in this regard and to integrate relevant parts of that system with already established systems in the country, such as environmental permitting system in order to utilise its limited resources. All EU Member States, regardless of the fact if they are Annex I or non-Annex I countries to the Kyoto Protocol, are requested to participate in the EU Emission Trading System. This also applies to Bosnia and Herzegovina, which is a non-Annex I country. Bosnia and Herzegovina will need to transpose the EU legal instruments on greenhouse gases. As concerns this document, the EU CCS Directive is included in the text of the most important national planning document – Environmental Approximation Strategy of Bosnia and Herzegovina from May 2017 on pages 70-71 and with some details about storage permits on page 110, but no further documents regarding the transposition are available (see also BA3.2).

The most valuable progress related to CO_2 emissions reduction has been achieved in the public buildings sector - by actors such as the Ministry of Foreign Trade and Economic Relations of Bosnia and Herzegovina (MoFTER), the Federation of Bosnia and Herzegovina's environmental funds and spatial planning ministries as well as some cantonal ministries - by growing implementation of the energy efficiency infrastructure measures from just a few public sector buildings annually in 2014 and 2015 to retrofitting at least 50 public sector buildings a year for the past three years and with the ambition to continue achieving the same or a greater number.

The outcome of two projects will reduce CO_2 emissions total for public sector buildings by approximately 8%. Speaking about adaptation to climate change, the greatest progress in Bosnia and Herzegovina is achieved at the municipal level. Several projects the UN Development Programme implements directly support Bosnia and Herzegovina's preparation for the Energy Climate Plan 2020–2030. In practical terms this means increased energy efficiency, greater usage of renewable energy and improvement of the energy and transport infrastructure and services. The intention is to lead to international investment, job creation and the growth of business in a resource efficient economy.

Primary targets are: (1) enforce the concept of low carbon urban development in cities across the country; (2) increase the use of public transportation in urban areas and develop a national e-transportation strategy; (3) increase the utilisation of renewable energy in district heating systems across the country; (4) introduce a carbon tax for heavy polluting industries; (5) continue to increase the country's ability to prevent and respond to climate disasters.

Bosnia's National Energy and Climate Plan (NECP) has not been finalised yet.

BA3.2 National legislation and regulations

At the level of Bosnia and Herzegovina, no legislation transposing the EU legislation on ambient air quality or air emissions have been adopted, because this sector falls under exclusive competence of the administrative Entities. In Bosnia and Herzegovina, CO_2 has not been defined or regulated by legislation. Traditionally, CO_2 has not been considered a pollutant, nor is it listed among the pollutants in any of the legislation in Bosnia and Herzegovina.

There is currently no legislation setting out the proprietary rights of stored CO_2. The existing legal frameworks of the energy sector, geological exploration and mining, and environmental protection may be a basis for introduction of a legal regime of CCS in the country (see also Kulichenko & Ereira 2012). The legislation on production, transportation, distribution, and storage of gas is perhaps the most likely to correspond to the requirements of CCS. The legislation on geological exploration and mining is also pertinent, since the focus of Directive 2009/31/EC is geological storage of CO_2.

In Bosnia and Herzegovina, the national legislation does not yet explicitly regulate transportation of CO_2 in pipelines. Also, there is no specific licensing system in place yet for CCS projects. However, the existing permitting system from the gas sector might be applicable. There is also no CCS legislation at present in Bosnia and Herzegovina on third party access rights to transportation networks. The gas sector legislation vis-à-vis third party access rights may be relevant.

In Bosnia and Herzegovina, public participation is one of the principles of environmental protection under the law of both administrative Entities that acceded to the Aarhus Convention in 2008.

The "owner" of the subsurface in Bosnia and Herzegovina is the State (Bosnia and Herzegovina, Entities and Cantons or Municipalities). Currently, there are no CCS sites and facilities in Bosnia and Herzegovina. The administrative Entities' laws only regulate the gas sectors within their own territories. Gas sector installations in Bosnia and Herzegovina are public property and owned by the Entities.

BA4. Research

BA4.1 National funding for research related to CCS and research priorities

We have no funding for any research related to CCS in Bosnia and Herzegovina.

BA4.2 Research institutions involved in research related to CO_2 storage

A first assessment of CCS opportunities including storage potential and capacities in Bosnia and Herzegovina were performed within the EU GeoCapacity project. Also, the Faculty of Mining, Geology and Civil Engineering, University of Tuzla, participated in the ESTMAP project as a further attempt to activate the issue of use and storage CO_2 through the project work.

BA4.3 Existing larger scale research infrastructure

None.

BA4.4 Involvement in EU-funded and other regional/international research projects related to CCS

None.

BA5. National actors driving CCS forward and public engagement

BA5.1 Awareness of CCS technology

The public acceptance of CCS in Bosnia and Herzegovina is very low. Our State government (not Entities' governments) does some things to activate this theme and they are ready to help other institutions (primarily universities, but also others) in everything but financial.

BA5.2 National advocates for CCS

None.

BA5.3 Public engagement

The State government has raised the issue of CCS in line with Bosnia's desire to join the EU, but in our country progress is very slow.

Summarising the state-of-play on geological CO_2 storage in BULGARIA (BG; as of 30th June 2021)

BG1. National storage assessment, storage options, potential and capacity

CO_2 geological storage studies and capacity estimations in Bulgaria have been performed in the frame of European projects: Castor WP-2 (2005), EU GeoCapacity (2006–2008), CGS Europe (2011–2013) and CO_2StoP (2012) as well as within two business projects supported by Bulgarian Government (namely by Ministry of Economy, Energy and Tourism):

1. Project “Assess the Bulgarian capacity for storage of CO_2” (2010), funded by EBRD and accomplished by Worley Parsons Resources & Energy, INYPSA and Sofia University.

2. Project "CO_2 Storage feasibility study in Bulgaria (Pavlikeni region)" (2011–2012), a programme sponsored by Japan's New Energy and Industrial Technology Development Organisation (NEDO). The feasibility study has been conducted by Toshiba Corporation with support from other parties, including Schlumberger Carbon Services and Sofia University.

The Bulgarian CO_2 storage capacity estimate is based on a large data base including mainly original seismic and borehole results integrated with knowledge on the subsurface. It was calculated in a unified way accepted in the frame of the EU GeoCapacity project.

The largest capacity of potential CO_2 storage options in Bulgaria is related to saline aquifers (2,560 Mt), coal fields have considerably less opportunities (27 Mt), while possibilities to use depleted hydrocarbon fields are practically absent.

The CO_2 storage capacity in deep saline aquifers in Bulgaria is based on the assessment of 10 sites. Six of the recognised aquifers are located in Northern Bulgaria, the other four in Southern Bulgaria.

Most of unmined coal reserves in Bulgaria occur at shallow depths, not favourable for safe injection of CO_2. Deeper occurrence of coal-bearing formations (>800 m), potentially suitable for CO_2 storage, exists only in two fields, in which the total estimated CO_2 storage capacity is about 27 Mt.

The majority of discovered hydrocarbon fields in Bulgaria lie outside the depth interval for effective CO_2 storage, i.e. 800-2500 m. Only two gas fields (1 onshore and 1 offshore) have productive reservoirs at favourable depths. However, the onshore field was converted into sub-surface gas storage in 1974. Thus, only the gas field located offshore was considered for CO_2 storage. Assessment of this field suggests good opportunities for CO_2 storage with a capacity of about 6 Mt. However, there is considerable interest in converting this field into a sub-surface gas storage facility.

There is no publicly available CO_2 storage atlas of Bulgaria.

BG2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

BG2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

None.

BG2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

BG2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

None.

BG2.4 Past and current full-chain CCS projects & projects/sites in preparation

None.

BG2.5 Plans for CCUS cluster development

None.

BG3. National policies, legislation and regulations

BG3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

There is no integrated strategy of CCS deployment in Bulgaria. The "Integrated Energy and Climate plan of Bulgaria for the period 2021–2030", developed in accordance with EU requirements, was accepted by the Bulgarian Government in the beginning of 2020.

BG3.2 National legislation and regulations

The EU CCS Directive has been transposed into the Bulgarian environmental legislation during 2011. Along with the adopted changes to the Bulgarian Environmental Protection Act (mid 2011), the transposition of CCS Directive was completed with the adoption of the Carbon Dioxide Storage in Depths of Earth Act in February 2012 (see also, e.g. Nikolova et al. 2012).

BG4. Research

BG4.1 National funding for research related to CCS and research priorities

There have not been any special funding instruments to support CCS-related research in Bulgaria paid by national resources.

BG4.2 Research institutions involved in research related to CO_2 storage

The Sofia University "St. Kliment Ohridski", Department of Geology, through team of Prof. Dr. Georgi Georgiev, is the only Bulgarian institution, which up to now has performed assessments of CO_2 storage potential in Bulgaria in the frame of EU projects Castor WP2 (2005), EU GeoCapacity (2006–2008) and CO_2StoP (2012), as well as within the two above mentioned business projects supported by the Bulgarian Ministry of Economy, Energy and Tourism.

BG4.3 Existing larger scale research infrastructure

None.

BG4.4 Involvement in EU-funded and other regional/international research projects related to CCS

None.

BG5. National actors driving CCS forward and public engagement

BG5.1 Awareness of CCS technology

Two brochures on CCS published into the Bulgarian language have been accepted positively by the public – 1) "ГЕОЛОЖКО РЕШЕНИЕ – ЗА КЛИМАТИЧНИТЕ ПРОМЕНИ" prepared in 2007 in the frame of the project CO_2NetEast, 2) translation of the CO_2GeoNet brochure "What does CO_2 geological storage really mean?" into Bulgarian language published during 2012 in the frame of the project CGS Europe, i.e.

BG5.2 National advocates for CCS

There is no national club or lobby group in the country, but some industry units and representatives have showed cursory interest to geological options for CO_2 storage around their location.

BG5.3 Public engagement

None.

Summarising the state-of-play on geological CO_2 storage in CROATIA (HR; as of 30th June 2021)

HR1. National storage assessment, storage options, potential and capacity

There is no national atlas of CO_2 storage in Croatia, and there have not been any exploration licence applications so far. The only data regarding the regional storage potential comes from the results of the FP6 project EU GeoCapacity (Vangkilde-Pedersen 2009) which were later refined in the FP7 project CO_2StoP resulting in the publicly available European CO_2 Storage Database. In the ongoing STRATEGY CCUS project, some new estimates are given and a map is made available at that covers the continental part of the country.

Compared to its needs, Croatia has ample theoretical storage potential, mainly in its northern, continental part (Kolenković et al. 2013). It is not excluded that additional capacity will be defined in the Adriatic offshore, after targeted exploration (Saftić et al. 2019). There are no national regulatory barriers for CO_2 storage, but also there is no large (immediate) political need to make use of CCS technology because the current decarbonisation targets have already been met on a national level (see also HR3).

HR2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

HR2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

There are no specifically built capture facilities in Croatia. There is one natural gas processing plant (NGPP Molve) and one fertilizer plant (Petrokemija Kutina) that are able to give almost clean stream of CO_2.

HR2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

Connected to HR2.3 below, Ivanić project is being prepared for Phase 2 which will include recirculation of produced CO_2 partly in the same reservoirs and maybe partly in the neighbouring small fields.

HR2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

There is only the CO_2-EOR project carried out by the INA Oil Company and followed by development of the same site (Ivanić project) where the two depleted oil reservoirs of the Ivanić and Žutica fields 45 km E of Zagreb are being brought on to the tertiary production phase. This is an ongoing commercial project, and all is within the company. CO_2 is brought by a pipeline from the gas condensate field Molve located close to Hungarian border (70 km distance approx.), recompressed and injected through several wells in Miocene sandstones with intergranular porosity. The project is working well and is currently on increasing the oil production.

AAT GEOTHERMAE is a pilot project in northern Croatia, being started and developed in cooperation with CLEAG from Switzerland. The location is named Draškovec and it lies in the Međimurje county, in a lowland area just north of the Drava River. The project includes building of a geothermal power plant (18.6 MW_e) with co-generation (75 MW_{th}) and a heat distribution system to the small town of Prelog (industrial zone and residential areas). This should all be combined with a wellness and spa resort close to the site ("Hortus Croatiae") and agricultural production. Altogether four production wells and four injection wells are planned. The natural gas separated from the water will be used for "green power" by capturing the CO_2 from the flue gases, mixing it with the CO_2 that was also separated from the water and injecting it back into the subsurface. The project had significant political support and gained substantial EU funding. It is under development and applies for the second phase.

HR2.4 Past and current full-chain CCS projects & projects/sites in preparation

None.

HR2.5 Plans for CCUS cluster development

From the STRATEGY CCUS project, the most current plans are given in Figure HR. This shows concentration of sources, depleted HC fields and regional saline aquifers in continental Croatia. Two hubs are envisaged – Eastern cluster (EC) and Central cluster (CC), with CO_2 in EC to be transported to the Beničanci oil field and Bokšić gas field in eastern part of the Drava depression, while in the CC a timely shift of direction of transport is now planned – firstly CO_2 is going to be brought in the western part of the Sava depression (with number of oil and gas reservoirs) and later the direction of transport would be changed using the same pipeline system to store CO_2 in the western part of the Drava depression where the reservoirs are not depleted yet. This altogether means that CO_2-EOR and CCUS in Croatia will initially be developed onshore although half of emission sources are located on the Adriatic coastline.

To deal with this part would require development of storage sites in the (northern) Adriatic offshore, or to use the regional pipeline corridor and build there another line specifically for CO_2 (oil and LNG already exist). There are many environmental considerations that can either stop this second phase of development or make it uneconomical.

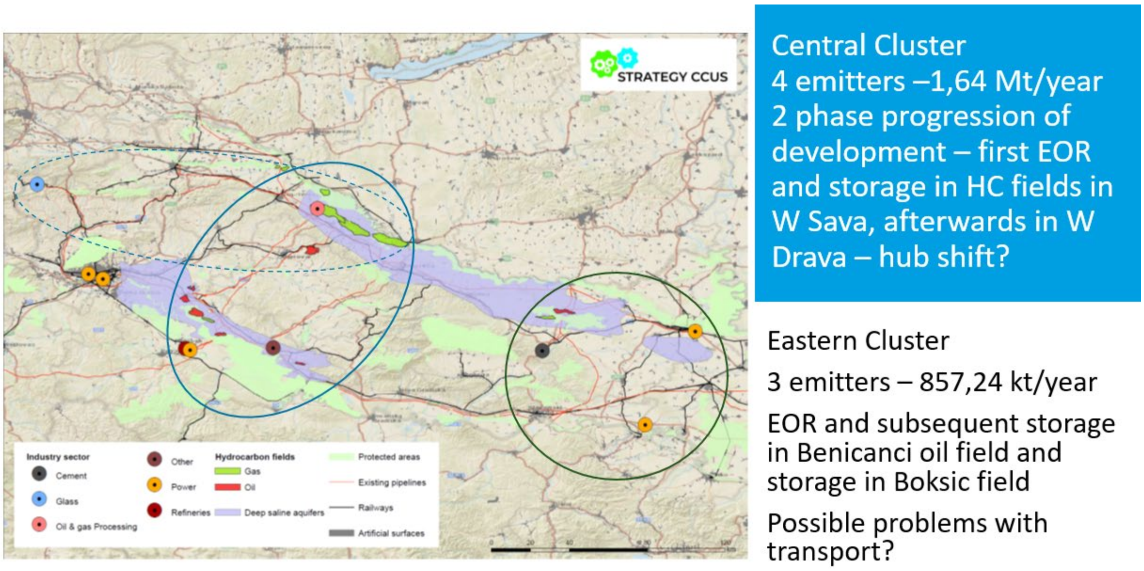

Figure HR: Web map for the Northern Croatia promising region – STRATEGY CCUS.

HR3. National policies, legislation and regulations

HR3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

Relatively low emissions per capita result in a perceived lack of incentives for ambitious immediate action (see emission reduction status described per ETS/non-ETS below). A large proportion of hydroelectric power installed causes variable total emissions depending on rainfall. Current increase in energy import (mostly oil/gas and petroleum products), especially after 2015 significantly influences the carbon budget and it should also be noted that general decline in industrial activity in the past decades resulted firstly in sharp decrease in energy imports 1990–1992 and then a gradual one in 2008–2014 period. In total, this means that Croatia has no urgent problem with CO_2 emissions but this is only temporary, i.e. until 2030, because a strong increase of RES implementation is planned.

ETS sector emissions: 10 649 kt $CO_{2\,eq}$ which is a reduction of -21.4% during 2005–2017. This means that the EU target for 2020 (-21%) has already been achieved. However, to reach the EU target for 2030 (-43%) a strong transition will be needed. This is only 9 years away! It is currently planned to achieve this with strong increase of renewables in electricity production.

Non-ETS emissions: 17 404 kt $CO_{2\,eq}$ which is a reduction of -4.2% during 2005–2017, which is below the EU target (-20%) but Croatia was given a specific target for 2020 (+11%) so this is presently significantly exceeded with a good perspective that a specific target of -7% by 2030 might be reached if the trend is kept up. One must be careful here, as non-ETS emissions are harder to decarbonise in comparison to large sources and the presently achieved reduction is not only the result of active measures, as explained above.

ETS sector emissions locations: There are only a few large (exceeding 100,000 t/year) stationary sources of CO_2 – 1 natural gas processing plant (NGPP), 1 thermal power plant (TPP), 3 cement plants and 1 fertilizer plant. Half of these are in the continental part of the country and half are located on the coastline. There is potential to decarbonise them by using CCS technology because there are approximately 15 depleted oil and gas fields that can be used for geological storage of CO_2. The CO_2-EOR technology is being tested through the ongoing CO_2-EOR project Ivanić (with alternating injection of CO_2 and brine) but this is still strictly a mining project.

HR3.2 National legislation and regulations

Low-Carbon Development Strategy of the Republic of Croatia until 2030 with an outlook to 2050 (long prepared but formally accepted in the end only in 2020) – includes CCS but only in the most ambitious of the three emission reduction scenarios.

Energy Development Strategy of the Republic of Croatia up to 2030 with an outlook to 2050 (accepted in parallel with National Energy and Climate Plan (NECP) – recognises CCS as one of the viable options and includes continuation of domestic oil and gas exploration and production.

National Energy and Climate Plan (NECP), draft assessment was received, 2nd version was prepared and upon public consultation accepted in 2020.

The Ministry of Environmental Protection was responsible for this activity until 2016. Restructuring the government "moved" this to the Ministry of Environmental Protection and Energy during the 2016–2020 period. The competent authority in terms of the EU CCS Directive is the Croatian Hydrocarbon Agency (CHA) that deals with permitting and all subsurface exploration. The Environmental Protection and Energy Efficiency Fund (EPEEF) is the state funding agency for covering all sectors but they seldom have a specific call that would be oriented to CCS. The most recent reorganisation of the government after the 2020 elections resulted in the establishment of the large Ministry of Economy and Sustainable Development that is supposed to govern this sector among many others.

The EU CCS Directive was transposed in national regulations within the Law on Exploration and Exploitation of Hydrocarbons in 2014 (Zakon o istraživanju i eksploataciji ugljikovodika, Narodne novine, 94/13 and 14/14), which was replaced by the new one - Law on Exploration and Exploitation of Hydrocarbons in 2018 (Zakon o istraživanju i eksploataciji ugljikovodika, Narodne novine, 52/18). One of the main changes here is that the Directive was only partly contained within the original Law in the first arrangement and most of it was in the respective By-law, whereas now it is almost all in the Law itself, although the By-law still defines the details, as stipulated in Article 103. The Republic of Croatia has therewith prepared the legal framework for geological storage of CO_2 with the only exception that the state is firstly responsible to define the prospective areas wherein exploration licences can be issued, also meaning that the state can actually exclude some areas from this purpose if it decides so, but in advance. All other stipulations are strictly in accordance with the Directive, including the fact that pilot projects (under 100 kt/year) are exempted from these procedures because they are aimed at research.

HR4. Research

HR4.1 National funding for research related to CCS and research priorities

There was only one research project specifically oriented to CCS field and it was funded by the only national science agency – Croatian Science Foundation: Evaluation System for CO_2 Mitigation (ESCOM). Exemplary references of the published results are Vulin et al. (2018) and Vulin et al. (2020).

Table HR: Overview of research topics addressed by the ESCOM project.

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	(X)		X	X	X	X	X		(X)

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

There is another project from the same funding, oriented at the geological characterisation of the subsurface in the eastern part of the Drava depression aimed to estimate the Energy Potential (GEODEP). It also considers the CO_2 storage potential among other possible subsurface uses, but only in the part of continental Croatia.

HR4.2 Research institutions involved in research related to CO_2 storage

This is not a common research topic, but there is a constant activity of a small group of researchers at University of Zagreb – Faculty of Mining, Geology and Petroleum Engineering and also at the Energy Institute Hrvoje Požar. This is almost exclusive list.

HR4.3 Existing larger scale research infrastructure

None.

HR4.4 Involvement in EU-funded and other regional/international research projects related to CCS

University of Zagreb – Faculty of Mining, Geology and Petroleum Engineering recently participated/ currently participates in two Horizon 2020 projects:

1. ENOS – Enabling Onshore CO_2 Storage in Europe as a CO_2GeoNet associated third party.
2. STRATEGY CCUS – A viable solution to sustainable future as a partner.

HR5. National actors driving CCS forward and public engagement

HR5.1 Awareness of CCS technology

There is no scientific survey available and a public debate on this topic in Croatia is still non-existent. The focus of any carbon emission reduction policies is on renewable energy sources, energy efficiency and land use, land-use change and forestry activities. Since Croatia is recently fulfilling its European goals in the short term (5 years), this is not regarded urgent in comparison with developing economy as a whole.

HR5.2 National advocates for CCS

CCS can still be advocated only by a small group of researches in the mentioned institutes and by the state regulatory body (Croatian Hydrocarbon Agency – CHA) that is supposed to work on the implementation of this technology when the time comes. Current developments in the national oil industry (INA) prevent the management from expanding the investment, but there is still the ongoing CO_2-EOR project Ivanić and there are plans for its second phase which would include reinjection of the produced CO_2.

There are, though large emitters from the energy sector, cement industry, fertilizer plant and others that are looking forward to reducing their present and future expenditures connected to CO_2 emissions but they lack the funds and lobbying strength. Moreover, the continuation of domestic oil and gas production is planned in the Energy strategy, meaning that government has not officially backed down from this sector and this has implication of the possibilities for the future developments of CCUS in addition to CO_2-EOR.

HR5.3 Public engagement

Current public engagement campaign is only within the STRATEGY CCUS project.

Summarising the state-of-play on geological CO_2 storage in CYPRUS (CY; as of 30th June 2021)

CY1. National storage assessment, storage options, potential and capacity

There is no information available on storage capacity. The tentative storage capacity is unavoidably limited by the geological layer formation of Cyprus, which has not yet been exploited in this respect. There is no national CO_2 storage Atlas available for Cyprus.

So far there have not been any applications for CO_2 storage exploration licences nor for storage permits.

CY2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

CY2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

No demonstration or pilot projects or sites for CO_2 capture have existed, exist or are in preparation.

CY2.2 Past and current demonstration/pilot projects for CO_2 transport & projects/sites in preparation

No demonstration or pilot projects or sites for CO_2 transport have existed, exist or are in preparation.

CY2.3 Past and current demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

No demonstration or pilot projects or sites for CO_2 geological storage have existed, exist or are in preparation.

CY2.4 Past and current full-chain CCS projects & projects/sites in preparation

No demonstration or pilot full-chain CCS projects or sites have existed, exist or are in preparation.

CY2.5 Plans for CCUS cluster development

No plans for CCUS cluster development exist.

CY3. National policies, legislation and regulations

CY3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

The Department of Environment of the Republic simply states the key points of the EU CCS Directive.

CY3.2 National legislation and regulations

The transposition of the EU CCS Directive was completed and the national "CO_2 Storage in Geological Formations Law" was voted by the parliament and came into force on 8th June 2012. There was also a small amendment of the Law on 2nd December 2015. The main clauses of the Law are as follows:

This Law establishes the legal framework for the environmentally safe storage of CO_2 in geological formations as a contribution to the fight against climate change. The purpose of environmentally safe storage of CO_2 in geological formations is the permanent isolation of CO_2 in such a way as to eliminate as much as possible the negative consequences and any risks to the environment and human health. The Law applies to the storage of CO_2 in geological formations in the territory of the Republic of Cyprus, in its Exclusive Economic Zone, and on its continental shelf.

The Law does not apply to the storage of CO_2 in geological formations with a total estimated storage of less than 100 kt, which is carried out for research, development or testing of new products and processes.

CO_2 storage is prohibited for (a) a storage site with a storage complex extending beyond the area referred to above, and (b) in a water column.

The Minister may, by decree published in the Official Gazette of the Republic, designate, after consulting an Advisory Committee, the areas from which CO_2 storage sites may be selected in accordance with the requirements of this Law. The evaluation of the exploration permit applications is done by the Advisory Committee, which prepares an opinion in the form of a draft decision for exploration permit, based on guidelines issued by the competent authority and submits it to the competent authority, within two months from the date of receipt of the respective application.

The competent authority ensures that: (a) any storage site is not operated without first obtaining a storage permit, there is only one operator for each storage site and conflicting uses of that site are not permitted; (b) storage licensing procedures are open to all entities that have the technical and financial capacity as well as reliability for the operation and control of the storage site and to maintain impartiality and transparency at all stages of the licensing process. The competent authority ensures that conflicting uses of the storage complex are not permitted during the licensing process.

Each operator must obtain a storage permit before starting any activity. The storage license is approved and is valid for a specific period and with specific conditions and is subject to renewal, if requested by the operator at least six months before its expiration.

The law also states that a CO_2 stream should consist primarily of CO_2. To this end, no waste or other materials may be added for the purpose of disposing of such waste or other materials. A CO_2 stream may contain traces of related substances from the source, binding or injection process and traces of substances added to assist in the monitoring and verification of CO_2 migration. The concentrations of these substances are determined by a relevant decree and must be lower than certain levels. The competent authority ensures that the operator keeps a record of the quantities and characteristics of the delivered and injected CO_2 streams, including their composition. The operator should submit to the competent authority at least one annual report by 31st March of the following year for monitoring carried out during the year in question. The competent authority plans and carries out regular and extraordinary inspections of all storage complexes. The competent authority takes the necessary measures to ensure that potential users have access to CO_2 transmission networks and storage sites for the purpose of storing the generated and bound CO_2 in geological formations. The competent authority ensures that, in the event of leaks or significant irregularities, the operator notifies it immediately and that it takes the necessary and appropriate corrective measures without delay.

In cases of cross-border transport of CO_2, cross-border storage sites or cross-border storage complexes, the competent authority ensures that, in cooperation with the respective competent authorities of the other Member States of the European Union, the requirements of this Law and the rest of the relevant European Union legislation are met.

A CO_2 storage site closes: (a) if the relevant conditions laid down in the storage permit have been complied with; (b) at the substantiated request of the operator and with the authorisation of the competent authority; or (c) if the competent authority so decides after the storage permit has been revoked.

The competent authority establishes and maintains: (a) a register of applications for exploration permits; (b) a register of exploration permits issued; (c) a register of applications for storage permit; (d) a register of the storage permits granted; (e) a permanent record of all closed storage sites and surrounding storage facilities, including maps and parts of their spatial extensions, as well as available information useful for assessing the complete and permanent isolation of stored CO_2.

The competent authority makes available to the public the data and environmental information relating to the storage of CO_2 in geological formations in accordance with applicable law.

CY4. Research

CY4.1 National funding for research related to CCS and research priorities

There has not been specific funding for research related to CCS (other than the general research funding for any kind of research provided by the Research Promotion Foundation of Cyprus).

CY4.2 Research institutions involved in research related to CO_2 storage

There are no research institutions involved in research related to CO_2 storage.

CY4.3 Existing larger scale research infrastructure

There is no existing larger scale related research infrastructure.

CY4.4 Involvement in EU-funded and other regional/international research projects related to CCS

There are no EU-funded and other regional/international research projects related to CCS with participation of Cypriot partners.

CY5. National actors driving CCS forward and public engagement

CY5.1 Awareness of CCS technology

There does not seem to exist any awareness of CCS technology.

CY5.2 National advocates for CCS

There does not seem to exist any national advocates for CCS other than the Department of Environment.

CY5.3 Public engagement

There does not seem to exist any public engagement other than that of the Department of Environment as the official authority.

Summarising the state-of-play on geological CO_2 storage in the CZECH REPUBLIC (CZ; as of 30th June 2021)

CZ1. National storage assessment, storage options, potential and capacity

The CO_2 storage potential of the Czech Republic has been mapped in the EU GeoCapacity project (2006–2008), showing the largest capacity in aquifers (conservative capacity estimate 766 Mt), followed by coal seams (54 Mt) and hydrocarbon fields (33 Mt). The CO_2StoP update of 2014, based on the stochastic computations of capacities using the StoreFit tool revealed storage capacity intervals of 134-990 Mt in aquifers for 2% storage efficiency and 17.8-21.1 Mt in hydrocarbon fields.

A re-assessment of the storage capacity of the eastern part of the country (the Carpathians) has been performed within the REPP-CO_2 project in 2015–2016, bringing more precise information on some prospective storage sites, but without any major change in the overall storage capacity figures. In general, the country might lack sufficient storage capacity if CCS is to be deployed at larger scale.

There is no publicly available CO_2 storage atlas of Czechia.

Five CO_2 storage exploration licences were awarded in early 2010s but have never been used and were relinquished after several years. No storage permit applications have been filed yet.

There is a regulation-related factor limiting CO_2 storage in Czechia – the Czech national law (Act No. 85/2012) limits the amount of CO_2 that can be stored in one storage site to 1 Mt/year.

CZ2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

CZ2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

None.

CZ2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

CZ2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

No CO_2 storage project has been realised yet. A CO_2 storage pilot project in the LBr-1 depleted HC field has been prepared by the REPP-CO_2 and ENOS projects in 2015–2019, but put on hold due to issues related to legacy wells and expected high cost of their re-abandonment.

Zar-3 – a depleting HC field is now being studied as a new possible target of a CO_2 storage pilot within the project “CO_2 Storage Pilot in a Carbonate Reservoir” (CO_2-SPICER; 2020–2024), a Czech-Norwegian research project supported from Norway Grants and the Technology Agency of the Czech Republic.

CZ2.4 Past and current full-chain CCS projects & projects/sites in preparation

A couple of full-chain CCS projects are in early phases of preparation with the vision to apply for Innovation Fund funding. Details are still confidential and cannot be revealed.

CZ2.5 Plans for CCUS cluster development

None.

CZ3. National policies, legislation and regulations

CZ3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

There is no integrated strategy of CCS deployment in Czechia. The Czech Republic's NECP of November 2019 mentions possible use of CCS in combination with natural gas, without closer specification. The National Energy Policy (latest update in 2014) acknowledges possible role of CCS after 2040 and recommends support of research related to CO_2 storage.

The National Climate Policy of 2017 presents several scenarios targeting the original 80-95% emission reduction goal for 2050. One of the scenarios includes massive deployment of CCS applied to power production; this scenario is, however, unrealistic in view of the planned abandonment of coal mining and closure of coal-fired power plants (time plan for this now under discussion).

CZ3.2 National legislation and regulations

The EU CCS Directive was transposed into the Czech legislation in 2012 (Act No. 85/2012). In 2016 a brief technical amendment was passed (Act 193/2016). The time limit prohibiting CO_2 storage projects exceeding 100 kt until 1st January 2020 has expired and CO_2 storage is now generally allowed.

The competent authority defined in the law is the Regional Mining Authority.

The subsurface is owned by the state.

CZ4. Research

CZ4.1 National funding for research related to CCS and research priorities

There have not been any special funding instruments to support CCS-related research in Czechia paid by national resources. Research funding opportunities, especially the programmes of the Technology Agency of the Czech Republic (TACR) have been common with other types of energy-related research.

The only focused funding was provided by Norway Grants. A special programme – CZ08 – Carbon Capture and Storage was implemented in 2015–2017, supporting 4 research projects and numerous supporting bilateral Czech-Norwegian activities by CZK 118 million (ca. EUR 4.7 million). The only CO_2-storage-related project was REPP-CO_2 (Preparation of a Research Pilot Project on CO_2 Geological Storage in the Czech Republic). The other projects of the CZ08 programme dealt with CO_2 capture, transport, integration in value chain and awareness raising.

Table CZ: Overview of research topics addressed by the REPP-CO_2 project

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	x	(x)	-	x	x	x	x	x	-

The new round of Norway Grants (currently running) includes a special CCS-devoted part (budget ca. CZK 125 million, combining funding from Norway Grants, the Czech national budget and own resources of project participants) in the Programme for applied research, experimental development and innovation, administered by TACR (KAPPA programme). Two projects were selected for funding – one dedicated to CO_2 capture (hybrid nanofiber membranes) and one focusing on storage (CO_2-SPICER – see above).

A large national research centre for low-carbon energy technologies – Bio-CCS/U (2018–2022) – is currently financed by the Czech Operational Programme "Research, Development and Education" that uses EU money from the European Social Fund (ESF) and the European Regional Development Fund (ERDF). The centre deals with oxy-fuel combustion of biomass and various aspects of CCU related to production of 3rd and 4th generation biofuels.

CZ4.2 Research institutions involved in research related to CO_2 storage

Czech Geological Survey (CGS) is the major player in CO_2 storage-related research in Czechia. Other actors are:

- VSB – Technical University of Ostrava
- ÚJV Řež, a.s.

CZ4.3 Existing larger scale research infrastructure

None.

CZ4.4 Involvement in EU-funded and other regional/international research projects related to CCS

CGS was involved in the ENOS project (Enabling onshore CO_2 storage in Europe, H2020, 2016–2020).

The consultancy company EUROPEUM is involved in the project "Building momentum for the long-term CCS deployment in the CEE region" that is supported by the Fund for Regional Cooperation of EEA and Norway Grants.

CZ5. National actors driving CCS forward and public engagement

CZ5.1 Awareness of CCS technology

In general, knowledge of the general public about the CCS technology is very limited because of the lack of any visible activity up to now. No scientific survey has been performed regarding public opinion on CCS.

CZ5.2 National advocates for CCS

There is not any national club or lobby group in the country, but industry representatives of emission-intensive industries and the national oil & gas company have become active in supporting CCS as a measure of CO_2 emission reduction.

CZ5.3 Public engagement

None.

Summarising the state-of-play on geological CO_2 storage in DENMARK (DK; as of 30th June 2021)

DK1. National storage assessment, storage options, potential and capacity

The first assessment of CO_2 storage capacity for Denmark was published in the EU Joule II report (Holloway 1996) and estimated to 5,597 Mt CO_2 in onshore aquifers and 592 Mt CO_2 in hydrocarbon fields in the North Sea. It was assumed that the storage was in traps onshore and that the total trap volume was 4% of the aquifers and that 6% of the trap pore volume could be filled with CO_2.

In 2004 the GESTCO project estimated a storage capacity in saline aquifers as 16,867 Mt CO_2 and 629 Mt in hydrocarbon fields (Larsen et al. 2003, Shuppers et al. 2003). The aquifer capacity was based on storage in 11 mapped geological structures (4 way-closures). These estimates were updated in the EU GeoCapacity project (Vangkilde-Pedersen 2009) to 16,672 Mt in aquifers and 810 Mt in hydrocarbon fields.

In 2013 the CO_2StoP project created a GIS database and calculated a storage capacity for aquifers between 263-275,000 Mt CO_2, with a mean value of 51,900 Mt. This calculation was based on total estimate for four aquifer storage units (Poulsen et al. 2014). No calculations for the Danish hydrocarbon fields were made in CO_2StoP.

No national CO_2 storage atlas has been published, but Danish storage data is included in both the CO_2StoP database (available at the EGDI platform) and in the NORDICCS atlas. An update of the Danish CO_2 storage capacity was finalised in 2020. The update revisited the geological structures mapped in GESTCO, EU GeoCapacity, NORDICCS and CO_2StoP, and the updated storage capacity were estimated to be between 12.3 Gt and 24.6 Gt. The updated storage capacity estimates are published in “Evaluation of the CO_2 storage potential in Denmark” (Hjelm et al. 2020).

A pre-application from the Swedish company Vattenfall for large-scale CO_2 storage in northern Jutland was stopped in 2011 by the Minister of Climate and Energy. This was followed by a moratorium for CO_2 storage in Denmark. Only CO_2 storage used in connection to EOR in the Danish hydrocarbon fields in the North Sea was excluded.

DK2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

DK2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

A carbon capture pilot was built at the Esbjerg power plant as part of the European CASTOR project. The capture tests were conducted in 2006–2007 and was followed by the CESAR project which carried out tests in 2009–2010. The capture pilot facility was decommissioned in 2011.

The waste incineration facility in Copenhagen, ARC (Amager Resource Center), is in the process of constructing a CO_2 capture pilot (EUDP 2020-I Net Zero Carbon Capture på ARC). The test pilot facility is expected to be ready in 2022/2023 and plans for a total capture rate of 500 kt/year. The pilot is supported by the Danish Energy Technology Development and Demonstration Program (EUDP).

Another carbon capture project supported by EUDP is GreenCem. The cement producer Aalborg Portland has received funding to develop an integrated a CO_2 capture facility. The project will use the CO_2 for synthetic fuel production.

DK2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

No project on CO_2 transport has been carried out in Denmark, except as part of the full-chain Vedsted project (section DK2.3) in which CO_2 transport by a 30 km pipeline was considered, but the project was closed in 2011 due to the moratorium for CO_2 storage in Denmark.

DK2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

The Greensand project (2020) is analysing the possibility to store CO_2 in depleting oil fields in the Danish North Sea. The consortium includes Ineos, Maersk Drilling, Wintershall Dea and GEUS and is funded by the Danish Energy Technology Development and Demonstration Program (EUDP).

DK2.4 Past and current full-chain CCS projects & projects/sites in preparation

- **The Vedsted-Nordjyllandsværket project** (2009–2011) initiated by Swedish energy company Vattenfall, who planned to store CO_2 captured from the heat and power plant Nordjyllandsværket in the city of Aalborg, transportation by pipeline and injection into a geological structure (aquifer) 30 km vest of Aalborg. The exploration phase included new seismic survey and reuse of data from the Vedsted-1 well. The application for CO_2 injection was stopped in 2011 due to the moratorium for CO_2 storage in Denmark and the project was closed shortly afterwards.
- **Capture, storage and use of CO_2 (CCUS2020)** is an ongoing research project covering the entire CCS value chain including use of carbon (Capture, storage and use of CO_2). The project is analysing the technological barriers for implementing CCUS in Denmark. The project was a cooperation between several Danish state institutions and included the Geological Survey of Denmark and Greenland, the Danish Energy Agency, Gas Storage Denmark, Energinet and The Ministry of Climate, Energy and Utilities and it is funded by the Danish Research reserve (part of the Danish finance act for 2020).

DK2.5 Plans for CCUS cluster development

The C4 cluster is formed by a number of major utility companies in the Copenhagen metropolitan area that plan to make carbon capture a crucial element in the green transition in Denmark. Planned CO_2 emission reductions totals at around 3 million tonnes per year. The C4 consortium consists at present of ARC, Argo, BIOFOS, Copenhagen Malmö Port (CMP), CTR, HOFOR, Vestforbrænding, VEKS and Ørsted.

DK3. National policies, legislation and regulations

DK3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

In June 2020, the Danish parliament passed a new Climate Act. The Climate Act will act as the new framework for Danish climate policy in the years to come, for example through establishing an ambition mechanism with a five-year cycle, designed to ensure both early action and to revise the reduction targets.

Basic facts

- The Climate Act aims at reducing Denmark's carbon emissions by 70% by 2030 compared to 1990 levels and towards net-zero by 2050.
- The Climate Act is legally binding.
- The emissions are calculated in accordance with the UN accounting rules.

Milestone targets

- The Climate Act contains a mechanism for setting milestone targets. Every five years the government must set a legally binding target with a ten-year perspective.
- During the government's forthcoming Climate Action Plan in 2020, an indicative milestone target will be set for 2025.
- The milestone targets will be implemented in Danish law.

Annual Climate Action Programmes

- The Danish Government will develop annual Climate Action Plans that will outline concrete policies to reduce emissions for all sectors: energy, housing, industry, transportation, energy efficiency, agriculture, and land use change and forestry.

The Danish Council on Climate Change ("Klimarådet")

- The Danish Council on Climate Change will present their professional assessment of whether the initiatives in the Climate Action Plan is sufficient to reduce emissions.
- The Danish Council on Climate Change provides recommendations on climate initiatives. The council's budget will be more than doubled with the Annual budget and more experts are added to the council. Furthermore, the council's political independence is strengthened as it can now elect its own chairperson and members.

Global reporting and strategy

- The Climate Act commits the Government to separately report on Denmark's impact on international emissions, including those pertaining to international shipping and aviation. Furthermore, reductions from electricity produced from renewable sources and the effects of Denmark's bilateral energy cooperation with 15 countries can be taken into account. Finally, it will shed light on the impacts of consumption.
- Furthermore, the Climate Act commits the Government to form a yearly global climate strategy to ensure that Denmark keeps on its ambitious work at the global scene.

DK3.2 National legislation and regulations

The EU CCS Directive was implemented in the Danish subsurface act in spring 2011, but a moratorium for CO_2 storage in Denmark has existed since autumn 2011. Only CO_2 storage used for EOR in the Danish hydrocarbon fields in the North Sea was permitted. Permission to store CO_2 offshore and onshore Denmark was postponed to 2020 pending on discussions in the Danish parliament. The permission to store CO_2 was accepted by a majority of the parliament members in spring 2021, but legislation is to be finalised in 2022. Opposite to the moratorium in 2011, CO_2 EOR is no longer permitted following the decision for settlement of Danish oil and gas production by 2050.

DK4. Research

DK4.1 National funding for research related to CCS and research priorities

- **The Danish Energy Technology Development and Demonstration Program (EUDP)**. The programme is funding technology development and demonstration projects covering the entire CCS chain. EUDP also administrates the Danish part of the ERA-Net ACT (Accelerating CCS Technologies).
- **Innovation Fund Denmark (IFD)** invests in projects at all stages of the research and innovation value chain. Thus, IFD invests in the early strategic research project, where targeted efforts and cooperation with the most competent international and/or Danish partners from relevant scientific and professional disciplines are crucial, as well as a promising project that lacks the final steps towards implementation and a successful introduction into market/society.
- **Independent Research Fund Denmark (DFF)** funds specific research activities within all scientific areas that are based on the researchers' own initiatives and that improve the quality and internationalisation of Danish research.

Between 2011 and 2020 only one storage related CCS-project has received national funding. The project "CO_2 neutral energy system utilising the subsurface (CONvert)" was a techno-economic feasibility study of an integrated energy system, combining geothermal, CCS and energy storage by power-to-gas. The project was funded by the Danish Energy Technology Development and Demonstration Program (EUDP).

In 2020 a research project covering the entire CCS value chain including use of carbon (Capture, storage and use of CO_2 – CCUS2020) and funded by the Research reserve (part of the finance act 2020) was launched. The project is analysing the technological barriers for implementing CCUS in Denmark.

Table DK: Overview of research topics addressed by the CCUS2020 project.

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	(x)	(x)	-	-	-	(x)	(x)	(x)	-

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

DK4.2 Research institutions involved in research related to CO_2 storage

GEUS – The Geological Survey of Denmark and Greenland was for many years the only research institute involved in CO_2 storage research projects. With the increased national focus on CCS as a tool to mitigate CO_2 emissions several Danish universities are conducting research in CCS, e.g. the Technical University of Denmark (DTU) is conducting research in both CO_2 storage and capture, the universities in Copenhagen (KU) and Aarhus (AU) are conducting research for CO_2 storage.

DK4.3 Existing larger scale research infrastructure

At present, no large-scale research infrastructure exists in Denmark.

DK4.4 Involvement in EU-funded and other regional/international research projects related to CCS

GEUS has contributed to a vast number of EU funded projects such as SACS, GESTCO, EU GeoCapacity, CASTOR, CO_2Store, COACH, Dynamis, CO_2ReMoVe, CO_2SINK, ECCO, CO_2Care, SiteChar, ENOS, SECURe. Examples of other international projects in which GEUS was involved are Weyburn, CGS Europe, BIGCCS and NORDICCS.

DK5. National actors driving CCS forward and public engagement

DK5.1 Awareness of CCS technology

Both the Danish Climate Act and the Climate Agreement for Energy and Industry from 22nd June 2020 mention CCS as one of the future technology solutions to reduce CO_2 emissions in Denmark). Public discussions in the press prior to the Climate Act agreement have caused increased interest in CCUS from owners of large emission point sources, such as waste incineration facilities and CO_2 intense industry (cement) and is reflected in the number of research, pilot and demonstration projects planned and applied for in 2020.

DK5.2 National advocates for CCS

The Danish Council on Climate Change (Klimarådet) is an independent body of experts that advises on the transition to a low-carbon society and considers CCUS as a necessary technology to reduce CO_2 emissions. The political and commercial independent green think tank **CONCITO**, who convey new and proven climate solutions to politicians, companies and citizens, is in general positive towards CCS.

Denmark has established a total of 14 “climate partnerships”, each partnership covering a specific business sector. The purpose is to give advice on how to reduce CO_2 emissions and identify any barriers for a green transition. Two of these partnerships, the energy consuming industry and energy supply partnerships, point to CCS as a solution for CO_2 reductions within their sectors.

DK5.3 Public engagement

At present theirs no public engagement in CCS projects. The only experience with public engagement is related to the Vedsted project in 2009–2011 where the local population near the injection site formed a protest group against CO_2 storage. The group created a lot of press attention and organised a demonstration in front of the Danish Parliament in 2011, at the time where the subsurface act was discussed related to implementation of the EU CCS directive. The EU CCS Directive was implemented in the Danish subsurface law, but shortly after a moratorium against CO_2 storage was decided by the parliament.

Summarising the state-of-play on geological CO_2 storage in ESTONIA (EE; as of 30th June 2021)

EE1. National storage assessment, storage options, potential and capacity

CO_2 storage capacity of Estonia was estimated until now as zero, explained by its shallow sedimentary basins and the presence of potable water in the local aquifers (Shogenova et al. 2009a, b). However, the Cambrian Series 3 Deimena Stage sandstones, the most prospective storage reservoir in the Baltic States, could be re-estimated for CO_2 storage in the south west of Estonia based on the recent research results (Pärn 2018), giving prospects for good isolation of the Cambrian saline aquifer by upper aquitards. Salinity about 20g/l, the low reservoir temperature (9˚C) and overall pressure-temperature (P-T) conditions are positive factors supporting storage of CO_2as a dense-phase fluid (density about 900 kg/m^3). Additional exploration data and storage site modelling are needed to estimate its storage capacity and safety.

EE2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

EE2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

A project on mineral carbonation of CO_2 using annually at least one megaton of oil shale ash and producing high-quality carbonate materials for various uses is under development now by environmental company Ragn-Sells AS. Ragn-Sells established a subsidiary, R-S OSA Service, to administer the oil shale ash valorisation project launched five years ago. The company has led the creation of a scientific consortium in which, among others, researchers from the University of Tartu and the Tallinn University of Technology are involved in fundamental and applied research. The company submitted an application to the Estonian Patent Office to request patents for its innovative oil shale ash valorisation process, which makes it possible to reprocess the majority of the ash waste created in energy generation in Estonia into materials.

EE2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

EE2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

None.

EE2.4 Past and current full-chain CCS projects & projects/sites in preparation

None.

EE2.5 Plans for CCUS cluster development

Economic modelling of the Estonian–Latvian transboundary capture–transport–sink scenario of industrial CO_2 emissions was first made in EU GeoCapacity project using a GIS-based Decision Support System (Shogenova et al. 2011). Considering these research results, a new study of the cross-border transport, utilisation and storage of CO_2 emissions produced by cement industry and power sector in Estonia are made in the frame of the Horizon 2020 project CLEANKER (Simmer 2018, Shogenova et al. 2021a). The considered cluster of emission sources includes the four largest Estonian power plants, Kunda Nordic Cement plant in Estonia and Latvenergo, TEC2 power plant in Latvia. The developed CCUS scenario includes mineral carbonation of CO_2 with oil shale ash produced in Estonia. Captured CO_2 will be transported via pipelines to onshore CO_2 storage sites in Latvia (Blidene and North-Blidene).

Another proposed cluster includes in addition to Estonian and Latvian sources mentioned above, a cement plant from Lithuania and a storage site offshore Latvia (E6 structure) (Shogenov & Shogenova 2021). The methodology elaborated by the CLEANKER project, including database development, is applied for techno-economic modelling (Shogenova & Shogenov 2018).

At the moment all these cluster scenarios are developed only at the research level.

EE3. National policies, legislation and regulations

EE3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

Estonia has ratified the Paris Climate Agreement on 4th November 2016. The long-term target of Estonia is to reduce the emission of greenhouse gases by 2050 by 80% in comparison with the emission levels of 1990. As the country moves towards this target, emissions will be reduced by about 70% by 2030 and by 72% by 2040 in comparison with the 1990 emission levels. If the policies are implemented, then by 2050, GHG emissions will have decreased the most in the energy sector and industry (by 67%).

Estonia has ratified the London Protocol, and in 2019 has ratified the 2009 amendment to article 6, enabling the export of CO_2 streams for the purpose of storage in trans-boundary sub-seabed geological formations. Now Estonia is among the seven countries which ratified this amendment.

Estonia is a party of the OSPAR Convention under the European Union sign. Estonia is a contracting party to the Helsinki Convention (HELCOM).

In 2019 increase of CO_2 emission allowance price up to EUR 25-30 per tonne in EU ETS led to an increase of the oil-shale based energy price and made it not competitive to the cheaper Russian energy (as Russia is not paying any carbon taxes). As a result, the largest Estonian national energy company Eesti Energia decreased energy production by about a factor of 2 and decreased production of CO_2 by 5 Mt in 2019, compared to 2018. In addition, Eesti Energia is planning to apply CCUS in 2030 to 2035 for shale oil and chemicals produced from Estonian oil shales. To reach carbon neutrality in the power sector, Eesti Energia has started to replace oil shales by biofuel (wood waste) for energy production.

In addition, Estonia has future plans to produce H_2. Producing H_2 with CCS could be one of the future options to implement CCS technology. National financial support is targeted now on CO_2 capture and use.

As reported by Eesti Energia, Estonia's total CO_2 emissions decreased by about a quarter over the year. The European Union is setting a target of reducing carbon emissions by 50-55% by 2030 compared to 1990, but Estonia is ahead of that ambition and has already reduced its emissions by nearly 65%.

EE3.2 National legislation and regulations

Estonia has banned commercial-scale CCS in its territories (both onshore and offshore) and therefore, the transposition of the EU CCS Directive was focused primarily on CO_2 transport networks.

The Ministry of Environment of Estonia is the only competent authority responsible for fulfilling duties established under Article 23 of the Directive, except in the case of construction of a transboundary transport pipeline, which requires a permit from the Government.

Although there are no specific CO_2 storage capacity studies ordered by the legal authorities, published studies of Estonian researchers indicate that geological conditions are very unfavourable for onshore storage (Shogenova et al. 2009a, b, 2011). According to these research results, the territory of Estonia, the exclusive economic zone and continental shelf of Estonia are unsuitable for CO_2 storage within the meaning of UNCLOS and the EU CCS Directive. Therefore, the Earth's Crust Act and the draft Act amending the Water Act prohibit the geological storage of CO_2 in both the earth's crust or in sea areas. Exploration permits stipulated in Article 5 of the EU CCS Directive are not used in Estonia.

CO_2 injection for research purposes (up to 100 kt CO_2) is permitted in Estonia according to Estonian regulations.

Monitoring. Commission Decision 2010/345/EU amending Commission Decision 2007/589/EC is a basis for regulation determining the emissions from CO_2 storage and transport in Estonia, including provisions for reporting. Operators must submit an annual report to the Ministry of Environment of Estonia on the monitoring technology used and the quantities of CO_2 transported for storage during the reporting period. Operators must keep a record of the quantities and chemical content of the CO_2 transported, which should be sent to the Ministry of Environment once a year.

Transport networks and transboundary issues. According to the Water Act a permit is required for the construction of CO_2 transport pipelines underwater and this permit is issued by the Minister of Environment. Also, the requirement for submerging a cable line under water and consent for this is granted by the Government.

According to Planning Act, a CO_2 transport pipeline that runs underground through several local government areas is considered to be a linear structure, the corridor of which is established under country plans.

According to the Act amending the Ambient Air Protection Act (RT I 31.12.2010, 31) "the owner or operator of the existing transport pipeline has an obligation to connect to the existing CO_2 transport pipeline by pipeline of another entity who has requested that ('accessing entity') if the technical conditions allow for it and it does not pose a risk to the existing transport capacity, people's health or environment". Any refusals must be explained in writing within 30 days of receiving the access application.

EE4. Research

EE4.1 National funding for research related to CCS and research priorities

CO_2 storage group of Department of Isotope Geology of Institute of Geology (now Department of Geology-TalTechDG) of Tallinn University of Technology made research focused on storage site characterisation and capacity assessment in the regional scale (Shogenov et al. 2013 a, b, 2017a, Sliaupa et al. 2013, Nordbäck et al. 2017), petrophysical and numerical seismic modelling (Shogenov et al. 2013a, 2016), classification of reservoir quality (Shogenov et al. 2015a), experimental modelling of CO_2-fluid-rock interaction (Shogenov et al. 2015b), synergy of CO_2 storage and CO_2 use for recovery of resources (Shogenov et al. 2017b, 2019, Shogenova and Shogenov 2017), CCS regulations in Europe and Baltic Region (Shogenova et al. 2011, 2013, 2018).

The PhD research of K. Shogenov "Petrophysical models of the CO_2 plume at prospective storage sites in the Baltic Basin" defended in 2015 in Tallinn University of Technology (TTU) was partially funded by Estonian targeted funding programme of the Estonian Ministry of Education and Research, Archimedes Foundation programme DoRa, Estonian Doctoral School of Earth Sciences and Ecology, and project "ERMAS" of the Estonian national R&D Programme KESTA. It was also partly funded by EU FP7 project CGS Europe and Marie Curie Research Training Network QUEST.

The project "Climate change mitigation using CCS and CCU technologies (ClimMIT)" targeted on CO_2 capture and use options in Estonia was completed in 2021 with participation of Tartu University and coordinated by Tallinn University of Technology. The project was funded for 2 years by Estonian and European Regional Funds.

There is no national research funding in Estonia for CO_2 storage in 2020–2021. National research funding was used for CO_2 mineral carbonation studies in TalTech-DG (Veetil & Hitch 2020, Li et al. 2019, Wang et al. 2019).

Research on CO_2 mineral carbonation and CO_2 capture is ongoing in TalTech, Department of Materials and Environmental Technology (Usta 2019, Sanna et al. 2014, Uibu & Kuusik 2014, Berber et al. 2020, Yörük et al. 2020). PhD research by M. C. Usta on CO_2 mineral carbonation is funded now by national funding and by the Horizon 2020 project CLEANKER.

Table EE: Overview of research topics addressed in PhD thesis K. Shogenov (2015).

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	X	-	-	-	-	-	X	X	-

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

EE4.2 Research institutions involved in research related to CO_2 storage

Department of Geology (former Institute of Geology), Tallinn University of Technology (TalTech-DG), is the only research group in Estonia involved in research related to CO_2 storage since 2006, including FP6 EU GeoCapacity and CO_2NetEast projects, FP7 CGS Europe and CO_2StoP projects and the ongoing Horizon 2020 ENOS and CLEANKER project.

EE4.3 Existing larger scale research infrastructure

None.

EE4.4 Involvement in EU-funded and other regional/international research projects related to CCS

TalTechDG is currently involved in the following EU-funded research projects addressing aspects relevant for/related to CCS:

- Enabling onshore CO_2 storage in Europe (ENOS), as a linked third party to CO_2GeoNet participating as a partner and, as a partner, in the Horizon 2020 project CLEANKER – CLEAN clinKER production by calcium looping process (TalTech is coordinator of CO_2 transport, use and storage WP7). Two TalTech departments take part – Department of Geology (coordinator of WP7 and research on CO_2 transport and storage) and Department of Materials and Environmental Technology (research on CO_2 mineral carbonation of waste materials).
- TalTechDG researchers are members of the regional Baltic CCS network BASRECCS, being presented in BASRECCS Board and organising annual Baltic Carbon Forum.
- In 2016–2017 TalTechDG (TTUGI) participated in the CGS Baltic Seed Money project (Nordbäck et al. 2017).
- From September 2020 - October 2021 TalTechDG will take part in the seed money project RouteCCS (Routing Deployment of Carbon Capture, Use and Storage CCUS in the Baltic Sea Region), coordinated by Uppsala University, organised by BASRECCS and funded by Swedish Institute.

EE5. National actors driving CCS forward and public engagement

EE5.1 Awareness of CCS technology

The project ClimMIT targeted on CO_2 capture and use (described in EE4.1) was ordered by Estonian ministries (Ministry of Environment, Ministry of Economic Affairs and Communication and Ministry of Finance) and the Estonian Research Council.

Interest in CCS increased after decision of Estonia to become climate-neutral by 2050. A presentation on CCS was made to the Estonian Prime minister during a Conference at the Estonian Academy of Sciences (2019) by the Rector of Tallinn University of Technology.

The annual Baltic Carbon Forum (BCF) in Tallinn organised by BASRECCS network has been attracting attention from Estonian media since 2018. Before, during and after the BCF 2019, Estonian BASRECCS members from TalTechDG gave a series of interviews on carbon capture, use and storage technologies in TV channels, radio and newsletters available in Russian and Estonian languages. Some of these interviews you can see, hear and read here: interview 1, interview 2, interview 3, interview 4, and interview 5.

Additionally, some news presented at the BCF 2019 were reported by Estonian journalists – see here.

EE5.2 National advocates for CCS

As Estonia does not have national CCS club, the main advocate is regional BASRECCS NGO (registered in Finland). There is yet no political decision to include CCS into the priority fields. A decision will be taken after results of CLIMMIT project (cf. EE4.1 and EE5.1) will be reported in 2021.

EE5.3 Public engagement

None.

Summarising the state-of-play on geological CO_2 storage in FINLAND (FI; as of 30th June 2021)

FI1. National storage assessment, storage options, potential and capacity

The bedrock in Finland is mainly composed of crystalline and low porosity rock types, while sedimentary basins suitable for geological storage of CO_2 are lacking. Thus, there is no identified geological CO_2 storage potential in Finland (CCSP Carbon Capture and Storage Programme – Final report). One considered option for storing CO_2 is mineral carbonation, i.e. the reaction of CO_2 with calcium and magnesium-bearing silicate minerals to form carbonates. The large amounts of material involved and the low reaction rates have been a major hold-up for this technology. Alternatively, Finland may store captured CO_2 on an interim basis and transport it abroad for storage. Currently, the nearest identified and demonstrated geological storage sites are located in the North Sea and Baltic Sea.

FI2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

FI2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

None.

FI2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

FI2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

None.

FI2.4 Past and current full-chain CCS projects & projects/sites in preparation

The FINNCAP-Meripori CCS project was an initiative by the Finnish power companies Fortum and Teollisuuden Voima (TVO) to develop and implement a CCS solution for the Meri-Pori power plant by 2015. The project had planned to capture and store more than 1.2 Mt CO_2/year. In 2010, TVO withdrew from the project, which was cancelled later that year by Fortum due to changes in the company strategy and the outcome of various studies.

FI2.5 Plans for CCUS cluster development

None.

FI3. National policies, legislation and regulations

FI3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

CCS has been identified in the national energy and climate scenarios as one of the technical potential options in certain scenarios. Also potential for negative emissions is identified in relation to bioenergy with CCS and forestry operations in general. Lately the political and high level discussion has been around CCU, H_2 production and use and indirect electrification. The context has mainly been energy intensive industry, and to a lesser extent transportation. However, there is no consensus yet about what the role of CCS could be in national climate mitigation. Currently priorities for Finland's decarbonisation seem to be on other technologies than CCS (renewables + nuclear) with very strong links to circular economy.

CCS does not have a role in the NECP of Finland, nor does CCU.

FI3.2 National legislation and regulations

Latest revisions implemented in 2013, Finnish Act on Carbon Capture and Storage 416/2012 as amended by Act 127/2013. According to this Act CO_2 storage is forbidden in Finland except for small scale projects with a total intended storage below 100 000 t undertaken for research, development or testing of new products or processes.

FI4. Research

FI4.1 National funding for research related to CCS and research priorities

No significant CCS projects ongoing with only minor activities regarding bioenergy-CCS. However, there is major focus on CCU and H_2 with several research projects and programmes. Few examples of projects:

- **BECCU**: The BECCU project is developing a new value chain from bioenergy production to sustainable materials by utilising carbon dioxide emissions and clean hydrogen. EUR 2 million funding by Business Finland, started 2020.
- **SOLETAIR**: The Soletair direct air capture pilot plant developed by VTT Technical Research Centre of Finland and Lappeenranta University of Technology (LUT) uses CO_2 to produce renewable fuels and chemicals. The pilot plant is coupled to LUT's solar power plant in Lappeenranta. The aim of the project is to demonstrate the technical performance of the overall process and produce 200 litres of fuels and other hydrocarbons for research purposes. This concerns a one-of-a-kind demonstration plant in which the entire process chain, from solar power generation to hydrocarbon production, is in the same place. 2017–2018 funding by Business Finland.
- **GreenE2**, an open innovation "ecosystem" for all companies and organisations which are interested in developing knowhow and business opportunities related to power-to-X-to-power and products. 2020–2022, funding by Business Finland.

FI4.2 Research institutions involved in research related to CO_2 storage

Geological survey of Finland, GTK.

FI4.3 Existing larger scale research infrastructure

VVT Bioruukki Pilot Centre is a centre for piloting new bio-based products and circular economy solutions.

FI4.4 Involvement in EU-funded and other regional/international research projects related to CCS

In 2016–2017, the Geological Survey of Finland, GTK, coordinated the CGS Baltic Seed Money project (Nordbäck et al. 2017).

From September 2020–March 2022 BASRECCS (NGO registered in Finland, see below) takes part in another seed money project RouteCCS (Routing Deployment of Carbon Capture, Use and Storage CCUS in the Baltic Sea Region), coordinated by Uppsala University, organised by BASRECCS and funded by the Swedish Institute.

The BASRECCS network (a network of experts and stakeholders operated as an association, registered in Finland with secretariat based in Finland), is organising annually the Baltic Carbon Forum supported by Nordic Energy Research and/or Nordic Council of Ministries (2018–2020). Since 2013 several members from Finland have been registered and participated in the network (GTK, VTT, University of Helsinki, Aland University of Applied Sciences).

LUT University is an active partner in CO_2 capture research, participating in the Horizon 2020 CLEANKER project. LUT Energy Systems School is working on the project "P2X Joutseno industrial scale pilot plant – feasibility study and development of e-fuels production". The purpose of the project is to make a thorough feasibility study of an industrial-scale production plant for carbon neutral fuel production.

FI5. National actors driving CCS forward and public engagement

FI5.1 Awareness of CCS technology

There is low general awareness of the CCS technology and its possibilities. The general opinion is that CCS is not a feasible option in Finland and in general the failure of the technology to be widely implemented a decade ago showed that it is not a "winning" technology.

FI5.2 National advocates for CCS

BASRECCS is a main advocate for CCS in Finland. As it is registered in Finland, Finnish representatives are always taking part in the BASRECCS board. Peter Molander is one of the founders and has been the BASRECCS's secretary network since its foundation.

Among regional advocates are Nordic Energy Research and the Nordic Council of Ministries.

FI5.3 Public engagement

The annual Baltic Carbon Forum supported by Nordic Energy Research and the Nordic Council of Ministries is the main platform for engagement of industry, policy makers and academia in CCS activities in the Baltic Sea area including Finland.

Summarising the state-of-play on geological CO_2 storage in FRANCE (FR; as of 30th June 2021)

FR1. National storage assessment, storage options, potential and capacity

Three sedimentary basins are considered for geological CO_2 storage: Paris Basin, Rhone Valley (mainly the southern part near Marseille) and Aquitaine Basin.

- The Aquitaine Basin has not been thoroughly assessed for storage capacity. Deep aquifers were mapped but their possible storage volume has not been evaluated. Depleted reservoirs can be an option for CO_2 geological storage with a storage potential onshore of 560 Mt CO_2.
- Storage capacity of the Paris Basin has been assessed globally and through several regional projects. Most of the evaluated capacities have been estimated by volumetric calculations with a storage efficiency factor. Injection simulations were performed for the Lower Triassic sandstone aquifer (East Paris Basin) and for the Keuper aquifer in two areas: north and south of Paris. A total of 222 Mt CO_2 of storage capacity was estimated for these two areas. There are also onshore depleted hydrocarbon fields that could provide a CO_2 storage capacity estimated at 111 Mt CO_2.
- The Rhône Valley has been assessed only in its southern part (Fos-Marseille area). Four geological structures, mainly onshore, could be suitable to CO_2 storage, with a potential storage capacity of 57 Mt CO_2 in total according to initial estimates based on volumetric calculations. No injection simulation has been performed.

Offshore France has potential for CO_2 storage (offshore Aquitaine and offshore Mediterranean), but these possibilities have not been studied yet.

Ongoing projects are focussed on the two most promising regions: Rhone Valley and South Paris Basin. One storage pilot was developed in the Aquitaine Basin with injection of more than 51,000 t CO_2 in an onshore depleted gas field from January 2010 to March 2013 (see details in "Past and current demonstration/pilot projects"). This research project is now closed and there is currently no operational storage in France.

There is no national CO_2 storage atlas available for France.

An exclusive research permit "Ouest Lorraine" for CO_2 storage was awarded In October 2011 by the French government to the ArcelorMittal Geo Lorraine (AMGL) as part of the preparation of a CCS demonstration project at the Florange steel factory in Lorraine (the ULCOS-BF CCS demonstration project). The permit, valid for a period of 5 years, covered the northern part of the Meuse and Meurthe-et-Moselle departments, as well as the western part of the Moselle department. The exploration phase aimed at the acquisition of geological data in the field in order to confirm that the potential areas under consideration are indeed suitable for CO_2 storage (as per European directive 2009/31/EC). However, the project was stopped due to ArcelorMittal's decision to close the steel plant end 2012.

Earlier, at the time of the preparation of the Lacq Integrated CCS pilot project, there was no specific legislation for the storage of CO_2 as it was being drawn up at European and French levels. Therefore, a circular from the Ministry of Ecology dated 14 February 2008 specified the regulatory framework applicable to the CO_2 injection and storage in the Rousse depleted gas field. It was decided that the project should apply under the Mining Code, within the scope of Article 3-1 applicable to the search for geological formations suitable for storage of "chemicals for industrial use", and must comply with the provisions relating to injection and underground storage. The project captured and stored 51 kt CO_2 from an oxyfuel industrial boiler in the Lacq industrial complex from 2010 to 2013.

FR2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

FR2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

Below is a summary of past and current pilot and demonstration projects for CO_2 capture in France.

CO_2 capture on power plant:

- EDF coal power plant in Le Havre (Normandy region): Post-combustion CO_2 capture pilot in an operational 600 MW coal-fired power plant, inaugurated on 11th October 2013, in operation until 2014. The CO_2 contained in the flue gas was 12% (vol) and the facility could capture up to 25 t CO_2/day. The capture technology implemented was developed by Alstom and DOW Chemical and was called Advanced Amines Process (AAP).

CO_2 capture on H_2 production plant:

- Air Liquide H_2 production plant in Port-Jérôme (Normandy region; see Pichot et al. 2017): Air Liquide has developed a solution specifically tailored for CO_2 capture from an H_2 production plant from natural gas, through Steam Methane Reforming. This technology, which is called CRYOCAP™H_2, uses cryogenic purification to separate the CO_2. The technology was demonstrated at industrial scale at Port Jérôme in 2015. Air Liquide is capturing 100 kt CO_2/year, which is sold for various CO_2 uses.

CO_2 capture on an industrial boiler:

- TOTAL boiler in Lacq (New Aquitaine region): An existing air-fired boiler was converted from air-combustion into oxy-combustion. The continuous operation, from 2010 to 2013, of the 30 MW_{th} retrofitted boiler was a success. The captured CO_2 was then transported via an existing pipeline and injected into a nearby depleted gas reservoir.

CO_2 capture on steel plants:

- ArcelorMittal steel plant in Florange (Great East region): A demonstration plant of post-combustion capture, with subsequent transport and storage in a nearby deep saline aquifer, was planned as part of the **ULCOS II** programme and submitted to the NER 300 European funding programme supporting the demonstration of a wide range of innovative low-carbon technologies. However, the demonstration project was withdrawn at the end of 2012 as a decision was made to close the steel plant. ULCOS (Ultra-Low CO_2 Steelmaking) was a consortium of 48 European companies and organisations that launched a cooperative R&D initiative to enable drastic reductions in CO_2 emissions from steel production.

- ArcelorMittal steel plant in Dunkirk (Upper France region):
  3D – DMX Demonstration project (Funding: H2020)
  Launched in 2019, the 3D project has three main objectives in the medium to long term:
  1. Demonstrate the effectiveness of the DMX™ process on an industrial pilot that will capture 0.5 t CO_2/hour from steel mill gas by 2021.
  2. Prepare the implementation of a first industrial unit at the ArcelorMittal site in Dunkirk, which could be operational starting in 2025 and that will capture more than 1 Mt CO_2 per year (125 t CO_2/hour) to be stored in North Sea geological storage.
  3. Explore the future European Dunkirk North Sea Cluster that should be operational by the year 2035 with more than 10 Mt CO_2 per year captured with geological storage in the North Sea.

  DINAMX – DémonstratIoN et Applications innovantes du DMX (Funding: Investissements d'Avenir, a national tool promoting investments for the future)
  Launched in 2020, the main objective of the DINAMX project is to complete the demonstration of the DMX process on blast furnace gas and to extend the applicability of the CO_2 capture to other national emitters in order to reduce industrial CO_2 emissions in France.

FR2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

There was only one CO_2 transport pilot project in operation in France, from 2010 to 2013, associated with TOTAL integrated CCS pilot in Lacq (New Aquitaine region). The CO_2 captured at the 30 MWth retrofitted boiler in Lacq was compressed (to 27 barg), dried and transported in a gaseous phase via an existing pipeline to the Rousse depleted gas field, 29 km away, where it was injected for permanent storage.

FR2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

The only CO_2 injection and storage project that has come into operation in France, from 2010 to 2013, was associated with TOTAL integrated CCS pilot in Lacq (New Aquitaine region). The CO_2 captured at the 30 MWth retrofitted boiler in Lacq was transported 29 km away via an existing pipeline to the Rousse depleted gas field, where it was injected at a depth of 4500 m for permanent storage. More than 51,000 t CO_2 were injected.

Currently, a few areas in France are being studied, e.g. through the following projects, with the intention of preparing CO_2 storage pilots at a later stage:

- **STRATEGY CCUS** (Funding: H2020): The two areas studied for France are 1) the Paris basin down to the Orléans area, 2) the Rhône valley, from Fos-Berre/Marseille to Lyon metropole.
- **PilotSTRATEGY** (Funding: H2020): The project will advance the geological characterisation of deep saline aquifers in the Paris basin and propose the construction of a CO_2 storage pilot, in line with the scenarios being elaborated in STRATEGY CCUS.
- **CO_2SERRE** (Funding: Centre-Val de Loire region): This project is studying the feasibility of capturing CO_2 from a biomass energy plant close to Orléans, use it in nearby greenhouses and storing the excess amount in a nearby deep saline aquifer (2019–2023).
- **CO_2-Dissolved** projects (Funding: ANR, Centre-Val de Loire region): This suite of projects is studying the feasibility of a novel CO_2 injection strategy in deep saline aquifers, combining injection of dissolved CO_2 (instead of supercritical CO_2) and recovery of the geothermal heat from extracted brine. The search is currently on to find an appropriate site to validate co-injection (CO_2 dissolved in brine), probably in the Paris Basin, and the intention is to then move to full-scale demonstration of the technology.

Previously, the following projects were started (Funding: ADEME), but were discontinued in 2012. They both intended to prepare research demonstration projects for CO_2 storage in deep saline aquifers:

- **France Nord**: This was a Joint Industry Project that grouped four public research institutes (BRGM, IFPEN, INERIS and Eifer) with seven industrial partners (Total, GDF SUEZ, Storengy, EDF, Air Liquide, Lafarge and Vallourec). The first step of the France Nord project was to identify a geological site in the deep saline aquifers of the Paris Basin providing a storage capacity of at least 200 Mt CO_2 during 40 years of injection. This level of capacity was considered appropriate for a project of industrial size. In parallel, a review of CO_2 emitters in Northern France was performed, and potential CO_2 transportation solutions were reviewed. The second step was to implement a CCS pilot in a CO_2 storage target identified previously. An R&D programme was also implemented, reviewing key elements of the CCS chain. Five potential CO_2 storage targets were analysed in detail, following a regional geological assessment, geological modelling and dynamic flow simulations (Bader et al. 2014). However, on the basis of available data, it was not possible during the project to identify a CO_2 storage site with the target capacity of 200 Mt of CO_2. As a consequence, the pilot was not implemented.
- **TGR-BF** (top gas recycling blast furnace): This project aimed to establish an integrated demonstrator of CO_2 capture, transport and storage on an industrial scale. The project investigated how to capture the CO_2 at the ArcelorMittal's Florange steel factory in Lorraine, and the feasibility of onshore storage nearby in a deep saline aquifer. In October 2011, the French government awarded the research permit, which was aimed at acquiring locally a new dataset in order to finalise the characterisation (as per European directive 2009/31/EC) of the storage part of the ULCOS-BF CCS demonstration project. However, the project was stopped due to ArcelorMittal's decision to close the steel plant end 2012.

FR2.4 Past and current full-chain CCS projects & projects/sites in preparation

- **Lacq Integrated CCS pilot project** (New Aquitaine region): This was an intermediate-scale project that demonstrated an entire integrated CCS process, from emissions source to underground storage in a depleted gas field. The project captured and stored 51 kt CO_2 from an oxyfuel industrial boiler in the Lacq industrial complex, from 2010 to 2013. See details in the above sections.
- **ULCOS-BF CCS demonstration project in Florange** (Great East region): Studies to prepare an integrated capture, transport and storage demonstration project at Florange, in order to reduce emissions from ArcelorMittal's steel plant. See details in

the above sections. ULCOS-BF was candidate to European NER300 funding, but was abandoned end 2012 due to ArcelorMittal's decision to close the steel plant.

- **H2020 3D – DMX demonstration project in Dunkirk** (Upper France region): Launched in 2019, the H2020 3D project has three main objectives in the medium to long term as detailed in FR2.1.

FR2.5 Plans for CCUS cluster development

Plans for CCUS cluster development in France are presently being prepared as part of the H2020 STRATEGY CCUS project (2019–2022), coordinated by BRGM. STRATEGY CCUS aims at supporting the development of low-carbon energy and industry in Southern and Eastern Europe. The project is focusing on eight regions considered promising for carbon capture, utilisation and storage (CCUS). Two of them are in France: 1) the Paris basin, from Paris to Orléans, 2) the Rhône valley, from Fos-Berre/Marseille to Lyon metropole. The aim is to encourage and support initiatives within each region by producing local development plans and business models tailored to industry's needs.

Other recent initiatives for the development of CCUS clusters include the Dunkirk North Sea CCUS initiative, the Axe-Seine CCUS initiative (from Le Havre to Rouen), and the PYCASSO initiative in south-west France to develop a cross-border (Spain and France) CCUS industrial project with CO_2 storage in the depleted gas fields around Lacq.

FR3. National policies, legislation and regulations

FR3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

The National Low-Carbon Strategy (SNBC, Stratégie Nationale Bas-Carbone) is France's roadmap for climate change mitigation policy. It was released in 2015 by the French Government to steer policy to meet the commitment to reduce national GHG emissions by 75% by 2050 compared to 1990 (Factor 4). The need to develop and deploy CCS was mentioned.

This strategy was revised in 2020 (SNBC2) to set out the path to carbon neutrality in 2050. The revised strategy outlines ways to compensate for irreducible anthropogenic emissions of greenhouse gases with carbon sinks including natural sinks (forest, soils) and anthropogenic sinks (CCUS). CCUS is anticipated to contribute 15 Mt CO_2/year by 2050. It is recommended to initiate today the development and adoption of disruptive technologies to reduce and if possible eliminate residual emissions, such as supporting the development of pilot and possibly commercial units in carbon capture and storage (CCS) and carbon capture and use (CCU) with the use of CO_2 as a raw material for the manufacture of fuels or chemicals.

France's National Energy and Climate Plan (NECP) for the period from 2021 to 2030 was published in 2020. It does mention CCUS, in coherence with the SNBC2.

By 2050, France expects to reach a level of emissions of around 80 Mt $CO_{2\,eq}$ considered as unavoidable, in particular in non-energy sectors (agriculture and industry). It is anticipated that in 2050, CCS would avoid 5 Mt CO_2/year in industry and about 10 Mt CO_2/year of negative emissions from biomass energy production plants (BECCS), i.e. a carbon sink of 15 Mt CO_2/year.

In conclusion, France is pursuing its efforts to develop the CCUS carbon sink and is gradually preparing to deploy it on its territory (for more details, see Czernichowski-Lauriol et al. 2021).

FR3.2 National legislation and regulations

In France, the Mining Code, the general regulation of the extractive industries, and the Environment Code define the regulatory framework for the subsurface industry.

The Directorate for Energy within the DGEC (General Directorate for Energy and Climate) implements and enforces regulations relating to exploration and exploitation of CO_2 storage, supports experiments in the field of CO_2 storage, collects and stores information relating to the monitored activity, and ensures its dissemination.

The Directive 2009/31/EC of the European Parliament and of the Council on the geological storage of carbon dioxide was transposed into French law in 2010/2011. Guidelines for the safety of a CO_2 geological storage site were published in 2012.

According to the current legislation and regulations, CO_2 storage is allowed onshore and offshore without specific limitations.

FR4. Research

FR4.1 National funding for research related to CCS and research priorities

In France, two national agencies are funding CCS and CCU projects:

- Agence Nationale de la Recherche - ANR (National Agency for Research),
- Agence de l'Environnement et de la Maitrise de l'Energie - ADEME (Environment and Energy Management Agency).

Both provide funding through calls for proposals. ANR is the main agency, providing funding for low TRL research in all scientific fields including CCUS. ADEME focuses on energy and environmental topics, has a more restricted budget for low TRL research projects, but can provide significant funding for higher TRL projects, such as CCS pilot and demonstration projects.

The region “Centre-Val de Loire” in central France, around Orléans, is currently funding two CCUS research projects following calls for research projects mentioning the geological storage of CO_2 from 2018. Industry funding can also support research activities through specific contracts.

The following table summarises the main national research projects since 2012. Note that other research activities targeting France are also underway through European projects – see section FR4.4.

Table FR: Overview of research topics addressed by recent nationally funded research projects on CO_2 storage.

Topic / Funding source	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	(x)	X	X	X	X	X	X	X	X
ANR		CO2-Dissolved PILOTE CO2-Dissolved CO2-Diss INJECTION	CO2-Dissolved	CO2-Dissolved	CIPRES	CIPRES	CGSμLab CO2-Dissolved FISIC H-CUBE SIGARRR	COPTIK EM-HONTOMIN MISS CO2	GEFISS
ADEME			SENSE	REX CO2	Aquifer-CO2Leak IMPACTCO2	Aquifer-CO2Leak IMPACTCO2	Aquifer-CO2Leak	Aquifer-CO2Leak GeCO SampA	
Region Centre-Val-de Loire	CO2SERRE	GEOCO2	GEOCO2				CO2SERRE		CO2SERRE GEOCO2

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

FR4.2 Research institutions involved in research related to CO_2 storage

Major research institutes:

- BRGM
- IFPEN
- Institut National de l'EnviRonnement industriel et des rISques, INERIS
- Institut National des Sciences de l'Univers, Centre National de la Recherche scientifique, INSU-CNRS
- Mines de Paris
- Institut de Physique du Globe de Paris, IPGP

Other research institutions

- Université de Lorraine
- Université de Pau
- Laboratoire Navier, École des Ponts ParisTech, etc.

FR4.3 Existing larger scale research infrastructure

France is one of the five founding member countries of the ECCSEL ERIC European Research Infrastructure on CO_2 capture and storage. The current research facilities available for access by worldwide scientists are listed below. See website for more details:

ECCSEL storage facilities in France:

- BRGM BIOREP reactor, Orléans
- ANDRA Underground Research Laboratory, Bure
- INERIS CATLAB shallow CO_2 Injection Site, Catenoy
- IFPEN GasGeochem Laboratory, Rueil-Malmaison
- IFPEN ESCORT mobile Equipment for Soil CO_2 ORigin Tracking

ECCSEL transport facilities in France:

- INERIS CO_2 Transport Platform, Mont La Ville

ECCSEL capture facilities in France:

- EDF's CO_2 Capture Pilot in Le Havre (currently unavailable)

Note that CNRS is joining ECCSEL in 2021, bringing additional innovative research facilities.

FR4.4 Involvement in EU-funded and other regional/international research projects related to CCS

Active and recently completed projects include:

- **3D** (2019–2023) – DMX Demonstration in Dunkirk (Funding: H2020)
- **CHEERS** (2017–2023) – Chinese-European emission-reducing solutions
- **DISCO2 STORE** (2021–2025) – Discontinuities in CO_2 storage reservoirs
- **ECCSELERATE** (2020–2022) – Ensuring the long-term sustainability of the ECCSEL ERIC Research Infrastructure
- **ENOS** (2016–2020) – Enabling onshore CO_2 storage in Europe
- **LEILAC2** (2020–2025) – Low emissions intensity lime and cement 2: demonstration scale
- **PilotSTRATEGY** (2021–2026) - CO_2 geological pilots in strategic territories
- **SECURe** (2018–2021) – Subsurface Evaluation of Carbon capture and storage and Unconventional Risk
- **STRATEGY CCUS** (2019–2022) – Strategic planning of regions and territories in Europe for low-carbon energy and industry through CCUS
- **SUN2CHEM** (2020–2023) – Novel photo-assisted systems for direct Solar-driven redUctioN of CO_2 to energy rich CHEMicals

FR5. National actors driving CCS forward and public engagement

FR5.1 Awareness of CCS technology

Awareness of CCS is low in France. Currently there is no intense public debate, probably due to the absence of concrete storage projects in the country. Some local resistance around the first pilot in Lacq occurred, but this was managed successfully by TOTAL. More interest on CCS may arise due to the new objective of carbon neutrality and the necessity to compensate irreducible CO_2 emissions by carbon sinks (SNBC2 2020).

FR5.2 National advocates for CCS

The French Club CO_2 stimulates the exchange of CCUS information and initiatives between industry, research organisations and public authorities, since its creation in 2002.

FR5.3 Public engagement

None since 2012.

The GEFISS research project (Extended governance for sub-soil engineering), funded by ANR from 2018 to 2022, has the objective to build knowledge about governance in the field of subsurface engineering (geothermal energy, energy storage, CO_2 storage...). The project brings together a multidisciplinary team made up of experts from the human and social sciences, earth sciences, public debate, as well as industry representatives.

Summarising the state-of-play on geological CO_2 storage in GERMANY (DE; as of 30th June 2021)

DE1. National storage assessment, storage options, potential and capacity

Depleted natural gas fields and saline aquifers are the most favourable options for the geological storage of CO_2 in Germany (May et al. 2002). Potential areas for CO_2 storage in saline aquifers had been mapped for the German mainland (onshore) in 2008–2011 within the project “Storage Catalogue of Germany” as a joint effort of BGR and the state geological surveys of Germany (Reinhold & Müller 2011). The catalogue contains nationwide thematic maps of 18 reservoir and barrier rock units of Paleozoic and Mesozoic age assessed for their potential suitability according to the criteria depth, (net) thickness and lithology, integrated in a GIS-based map-application. Further, BGR had performed several regional CO_2 storage capacity assessments in Germany, based on the evaluation of the volumetric storage potential of formations or individual trap structures. In addition, BGR estimated the CO_2 storage capacity of hydrocarbon fields in Germany. In summary, due to their large extent, deep saline aquifers have the largest potential for CO_2 storage in Germany (especially in the North German Basin). Their storage potential was estimated to be in the range of 20-115 Gt (Knopf & May 2017; see below for details). The storage capacity of depleted gas fields in Germany was estimated to be about 2.75 Gt (May 2007). The storage potential of depleted oil reservoirs is about 0.13 Gt.

Recent research activities have mainly focussed on the German North Sea region including the mapping of evaluated reservoir and barrier rock units (Bense & Jähne-Klingberg 2017), following the approach used in the “Storage Catalogue of Germany” project: In most areas of the German North Sea prospective reservoir rock units are overlain by prospective barrier rock units.

For the purpose of method comparison, a nationwide capacity assessment based on the results of Reinhold & Müller (2011) and Bense & Jähne-Klingberg (2017) was performed using a regional aquifer based approach to estimate storage capacity (Knopf & May 2017). This approach did not consider individual trap structures. Instead, it was based on the regional extent of potentially suitable reservoir rock units considering the accessible pore space of aquifers. This assessment yielded a total CO_2 storage capacity for Germany (on- and offshore) in the range given above.

All values given above represent volumetric capacities that do not consider any geotechnical or socioeconomic constraints that will reduce the volume of realistically usable storage capacity. Especially in the North of Germany, some German federal states have prohibited geological CO_2 storage by law, thus significantly reducing the currently usable storage potential in Germany. No application for site exploration or storage permit has been filed since the implementation of the national CO_2 Storage Act. The time for submission of storage application according to the federal CO_2 storage law has expired at the end of 2016 so that the socioeconomic storage capacity is currently zero in German territory (see also DE3.2).

DE2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

DE2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

Capture on…

…**power plants**: Capture pilot plants were built and operated on the following power plants:

- Schwarze Pumpe (Vattenfall/Linde; oxyfuel, lignite-fired; in operation until 2014),
- Wilhelmshaven (Uniper/FLUOR; PCC , hard coal-fired; in operation until 2014),
- Staudinger (Uniper/Siemens; PCC, hard coal-fired; in operation until 2013),
- Heilbronn (EnBW/atea Anlagentechnik GmbH; PCC, hard coal-fired; in operation until 2014),
- Niederaußem (RWE/Linde; PCC, lignite-fired; in operation since 2009): At a 1,000 MW unit of the Niederaußem power plant an amine scrubbing pilot plant was built on for solvent testing and process optimisation (maximum capture rate: 300 kg CO_2/h). In addition to solvent and capture process optimisation, various utilisation options for the captured CO_2 have been investigated including e.g. production of algal biomass (RWE-Algenprojekt), syn gas (project CO_2RRECT), polyurethane (project Dream Production), methanol/power-to-gas (project MefCO_2) and dimethyl ether (project ALIGN-CCUS).

…**steel mills**: Duisburg, North Rhine Westphalia (Thyssen Krupp/project Carbon2Chem): A steel mill gas separation and purification pilot for CCU application such as syngas production is operated at the Thyssen Krupp integrated iron and steel mill.

…**cement plants**: Mergelstetten, Baden-Württemberg (Buzzi Unicem – Dyckerhoff/ HeidelbergCement AG/ SCHWENK Zement KG/Vicat; project Catch4Climate): An oxyfuel pilot plant (semi-industrial scale) for clinker production is currently under construction at the SCHWENK Zement KG cement plant.

Within the LEILAC 2 project (2020–2025), a demonstrator for CALIX's direct separation technology will be built at the HeidelbergCement plant in Hannover, foreseen to capture about 100,000 t CO_2/year.

...**ammonia plant**: Dormagen, North Rhine Westphalia (Ineos/Covestro): CO_2 from an ammonia plant is used for polyol production (initiated in project DreamProduction, commercial polyol plant in operation since 2016).

DE2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

DE2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

The only CO_2 injection and storage project that has come into operation in Germany is the pilot project at Ketzin, Brandenburg, operated by Deutsches GeoForschungsZentrum GFZ. From June 2008 until August 2013 about 67 kt CO_2 were injected in a saline aquifer at a depth of 630 to 650 m. CO_2 injection at Ketzin was funded and investigated by various national and international research projects (e.g. CO_2SINK, CO_2ReMoVe, CO_2CARE, CO_2MAN, COMPLETE), that focussed on predicting, monitoring and modelling the subsurface processes and the migration of the CO_2 plume. Well abandonment and dismantling was completed and on-site research activities were finished in December 2017. In May and June 2011 1,515 t CO_2 captured at the lignite-fired power plant Schwarze Pumpe (CO_2 purity >99.7%) were injected, during other times food-grade CO_2 was used for injection. In autumn 2014 CO_2 back-production of about 240 t CO_2 from the storage reservoir was successfully demonstrated. The Ketzin pilot site was operated under the supervision of the Landesamtes für Bergbau, Geologie und Rohstoffe Brandenburg (LBGR) according to the Federal Mining Act.

CO_2 injection facilities were built at Maxdorf, in the Altmark gas field. There the combination of CO_2 storage and enhanced gas recovery was planned to be tested in a pilot project. The accompanying research project CLEAN (Kühn & Münch 2013) starting in 2008 and the entire initiative were terminated in 2010, as the mining authority of Saxony-Anhalt did not decide about the application for an injection permit.

No pilot or demonstration projects are currently in operation or in preparation.

DE2.4 Past and current full-chain CCS projects & projects/sites in preparation

In October 2009 an exploration permit (for the natural resource brine) had been granted to Vattenfall Europe for the site Birkholz-Beeskow (as part of the EEPR Jänschwalde demonstration project), but exploration never started. The Jänschwalde demonstration project was stopped in December 2011 and Vattenfall returned the exploration licence for brine to the mining authority.

RWE DEA planned to build an IGCC plant near Cologne and to transport CO_2 captured at this plant by pipeline to North Frisia for injection and storage. An exploration permit for brine was granted for the foreseen storage area. In autumn 2009 the initiative was dismissed due to public opposition before exploration of the area started.

At present no full-chain CCS project are in operation or in preparation.

DE2.5 Plans for CCUS cluster development

The feasibility for clustering CO_2 from different emitters in various parts of Germany was studied, for example, within the EU-funded projects CO_2EuroPipe (2009–2011), COCATE (2010–2012) and ALIGN CCUS (2017–2020). In the CO_2EuroPipe project, CO_2 transport by dedicated CO_2 pipelines/pipeline networks or by barge on inland waterways from the Rhine/Ruhr area and the area around Hamburg to harbour cities at the North Sea was detailed for different amounts of captured CO_2.

In view of preparing the 5th PCI list, to be adopted in October 2021, the CO_2 liquefaction and buffer storage in Wilhelmshaven is a candidate PCI project for cross-border CO_2 transport networks.

DE3. National policies, legislation and regulations

DE3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

The national Climate Action Plan 2050 was adopted by the Federal Government in 2016 stating Germany's long-term goal to become greenhouse gas-neutral by 2050. Also, emission reduction targets for 2030 for the individual sectors energy supply, buildings, transport, industry and business, agriculture and forestry are given in the plan. One key aspect of the plan is the restructuring of the energy sector, in particular the further expansion of renewable energy supply and the gradual phasing out of electricity generation from fossil fuels. As about 38% of the industrial emissions directly result from production processes in the basic materials industry, it will be necessary to lower these emissions, which cannot be avoided, by other measures such as implementation of new technologies, a carbon circular economy, or by CCS.

In October 2019, the Climate Action Programme 2030 was adopted comprising the four components: 1) carbon pricing, 2) burden reduction for citizens and industry, 3) sector-specific measures (e.g. increasing energy efficiency and optimising or substituting production processes in industry sector), 4) non-sector-related measures such as increasing the production and use of H_2 as well as carbon storage and use: A national H_2 strategy has been approved on 10th June 2020 in which production and use of green H_2 is the key element while the use of "CO_2-neutral" (i.e. blue or turquoise) H_2 is seen as an interim solution until green H_2 is available in sufficient amounts. CO_2 storage and/or use are considered as measures to reduce otherwise unavoidable industrial emissions. For emissions that cannot be used, offshore storage is suggested. To support the implementation of these technologies, the federal government intends to support R&D in CCU (and CCS) technologies and initiate a dialogue process with stakeholder groups.

Germany's National Energy and Climate Plan (NECP) adopted on 10th June 2020 lists the further development of opportunities to use CO_2 within the framework of CCU/CCS as part of the measures to promote innovation and competitiveness.

DE3.2 National legislation and regulations

The transposition of EU Directive was completed and the national CO_2 storage law (Kohlendioxid-Speicherungsgesetz – KSpG) has been approved by the parliament on 17th August 2012 and came into force on 24th August 2012. According to this demonstration law geological storage of CO_2 was allowed in Germany for projects involving storage of up to 1.3 Mt CO_2 per year. Overall, the annual amount of CO_2 stored in Germany should not exceed 4 Mt CO_2. A simplified permitting procedure is possible for research storage sites with an overall amount of injected CO_2 up to 100 kt/site. In addition to limiting amounts of CO_2 stored, the KSpG set a deadline according to which applications for site exploration and storage permits could only be filed until 31st December 2016. Competent authorities according to the EU Directive are the state authorities as well as BGR and the German Environment Agency (UBA). The state authorities are the permitting bodies while UBA and BGR are given a reviewer's role in the permitting process. BGR is also responsible for providing geological information for capacity assessments, in consultation with the state geological surveys, and for keeping a registry.

The KSpG allows the individual states to prohibit geological storage of CO_2 within certain regions of their territory (so-called "Länderklausel"). As a result, CO_2 storage is at present prohibited in Mecklenburg-Vorpommern, Niedersachsen and Schleswig-Holstein. In their evaluation report (according to § 44 KSpG), that was presented and discussed in the parliament in December 2018, the German federal government stated that they see currently no need for modifying the KSpG. In consequence, CO_2 storage is currently not permissible in Germany due to the expired application deadline.

The KSpG also provides the legal basis for planning assessment procedures for CO_2 pipeline installations as well as for third-party access to transport and storage infrastructure.

In the German Federal Mining Law, a differentiation is made between "freely mineable" and "freehold" subsurface resources. The latter are the landowner's possession, whereas "freely mineable" resources are not part of his freehold. Concessions for the use/mining of "freely mineable" resources are currently filed for a specific location for an unlimited time period. A storey-wise use of the subsurface is not foreseen. CO_2-based EGR or EOR operations might be permitted and regulated under the Federal Mining Law.

DE4. Research

DE4.1 National funding for research related to CCS and research priorities

Research related to CO_2 capture, transport and storage is funded in Germany by:
i) Bundesministerium für Bildung und Forschung – BMBF (Federal Ministry of Education and Research) and
ii) Bundesministerium für Wirtschaft und Energie – BMWi (Federal Ministry for Economic Affairs and Energy).

Main research programmes were/are:

- 7th Energieforschungsprogramm (BMWi; 09/2018 - present): Research topics include CO_2 technologies for the energy transition focussing on CO_2 capture and use.
- Programme "CO_2 avoidance und use in basic industries" (BMWi; since 2021): Advancing and upscaling CO_2 capture is addressed together with CCU and CO_2 cycling technologies and CO_2 transport options on a regional, national and European scale.
- Programme CO_2-Reduktionstechnologien (COORETEC) (BMWi; 2004 -11/2016): Predominately research on technologies for improving power plant efficiency and on technologies for the separation and transport of CO_2 were funded.
- Framework programme FONA (Forschung für Nachhaltige Entwicklung/Research for Sustainable Development; BMBF) that started in 2015: Regarding CO_2 technologies, FONA measures concentrate on CO_2 capture and use, e.g. a) measure CO_2Plus (2016–2019), b) measure Carbon$_2$Chem (2016–2026), c) measure CO_2-WIN (2020–2023). The following FONA measures included aspects related to CO_2 storage:
  i) Programme "Geotechnologien" (BMBF/DFG): From 2005 to 2014 33 projects were funded dealing with different aspects of CO_2 storage, the results of which were collated and assessed in the project AUGE (2012–2016).
  ii) Programme "GEO:N – Geoforschung für Nachhaltigkeit", subprogramme „Nutzung unterirdischer Geosysteme" (2017–2020) addressing specific research gaps with high relevance for various subsurface technologies.

- The Deutsche Allianz für Meeresforschung/German Marine Research Alliance (DAM) founded in 2019 will fund research on "Marine Carbon Sinks in Decarbonisation Pathways" in one of their missions. Complementary to that, BMBF recently launched a call on terrestrial methods for CO_2 removal from the atmosphere including BECCS and DACCS.

Table DE: Overview of research topics addressed by recent nationally funded research projects on CO_2 storage.

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	(x)	(x)	x	x	x	x	x	x	x
Project examples	TUNB (2014-2021)	CLUSTER (2015-2018)	CLUSTER (2015-2018)	COMPLETE (2014-2017)	MONACO (2011-2014)	CO2MAN (2010-2013), COMPLETE (2014-2017)	CLUSTER (2015-2018)	MONACO (2011-2014), COMPLETE (2014-2017)	CCS Chancen (2012-2014)

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

Projektträger Jülich (PtJ), the German national funding agency, is a partner in the ERA NET Co-fund "Accelerating CCS Technologies (ACT)" (2016–2021), a tool established under the Horizon 2020 programme. The ACT initiative aims to facilitate RD&D and innovation within CO_2 capture, transport, utilisation and storage by funding research projects for specific topics. Currently, the funding agencies of 16 countries, regions and provinces are partners in ACT.

DE4.2 Research institutions involved in research related to CO_2 storage

As research funding in Germany has been focussed very much on CO_2 capture and use rather than storage, relatively few research institutions are currently investigating aspects related to CO_2 storage. Examples are

- Deutsches GeoForschungszentrum Potsdam (GFZ),
- Bundesanstalt für Geowissenschaften und Rohstoffe (BGR),
- Helmholtz Centre for Ocean Research Kiel (GEOMAR),
- Forschungszentrum Jülich/Institute of Energy and Climate Research Systems Analysis and Technology Evaluation (IEK-STE)
- Fraunhofer ISI – Fraunhofer Institute for Systems and Innovation.

DE4.3 Existing larger scale research infrastructure

CO_2 storage:

- None. The pilot injection site at Ketzin has been the only research site in Germany for CO_2 injection and storage (see DE2.3).
- For studying CO_2 migration through the subsurface and soil and assessing potential environmental impacts as well as for testing near-surface monitoring methods, various sites in Germany have been used where CO_2 naturally emanates from the ground, e.g. at Laacher See.

CO_2 capture:

- Post-combustion: Niederaußem capture test centre for amine scrubbing (see also DE2.1).
- Alternative capture technologies such as carbon or chemical looping or membrane technologies have been investigated at small to medium scale test sites, e.g. at the Technical University of Darmstadt and at Stuttgart University.
- A clinker cooler pilot plant, a building block for implementing CO_2 capture in cement plants with oxyfuel firing, was built and tested at the Heidelberg Cement plant in Hannover (project CEMCAP).
- Carbon2Chem project: CO_2 separation and purification for CO_2 use is tested and optimised at the Thyssen Krupp integrated iron and steel mill in Duisburg (see also DE2.1).
- A demonstrator for the “direct separation technology” will be built at the HeidelbergCement plant in Hannover as part of the LEILAC2 project (see also DE2.1).

DE4.4 Involvement in EU-funded and other regional/international research projects related to CCS

BGR has been/is currently involved in the following EU-funded research projects addressing aspects relevant for/related to CCS:

- Enabling onshore CO_2 storage in Europe (ENOS),
- 3D geomodelling for Europe (3DGEO-EU),
- Low emissions intensity lime and cement 2: demonstration scale (LEILAC2),
- Advanced carbon capture for steel industries integrated in CCUS (C4U).

GFZ is currently involved in the following EU-funded research projects addressing aspects relevant for/related to CCS:

- Subsurface evaluation of CCS and unconventional risks (SECURe),
- Pressure control and conformance management for safe and efficient CO_2 storage - Accelerating CCS technologies (Pre-ACT).

DE5. National actors driving CCS forward and public engagement

DE5.1 Awareness of CCS technology

In general, knowledge in the general public about the CCS technology is limited (e.g. Schumann et al. 2014, Dütschke et al. 2016). CCS is often perceived as a risk technology with a risk potential similar to nuclear waste storage (Dütschke et al. 2015). In consequence, the public acceptance of CCS in Germany is low. Discussions on the potential roles and benefits of CCS and CO_2 storage have been resumed to some degree in the public in the last few years, e.g. by the National Academy of Science and Engineering (acatech 2018). Also, the German Chancellor Angela Merkel stated in May 2019 at the Petersberger Klimadialog that (geological) storage of CO_2 is one option to be considered to compensate future CO_2 emissions that cannot be avoided easily otherwise (Merkel 2019). For industry, the increasing price of CO_2 emission allowances is becoming a game changer turning CCS/CCU into a considered technological option for CO_2 emission reduction.

DE5.2 National advocates for CCS

The liberal democrats (FDP) are the only party is the German parliament proposing CO_2 storage for climate protection. Further, CCS/CCU has been included recently in the discussed portfolio of CO_2 emission reduction technologies necessary for achieving Germany's climate protection targets by several initiatives e.g. by the National Academy of Science and Engineering ("acatech") (e.g. acatech 2018) and the Energy Systems of the Future (ESYS) Initiative of the German Academies of Sciences (e.g. ESYS 2019).

DE5.3 Public engagement

Analysing the public acceptance of different CCS chain scenarios, Dütschke et al. (2016) identified a strong impact of the considered emitters on the scenario perception: Scenarios with capture on industrial processes or biomass power plants received a significantly higher acceptance in their studies than capture on coal-fired power plants. Whereas the three former initiatives for large-scale CO_2 storage (Beeskow/Neutrebbin by Vattenfall, North Frisia by RWE, Altmark by GDF Suez) provoked strong public opposition, operation of the injection pilot site at Ketzin by GFZ was well accepted by the local stakeholders. The reasons for these differences are seen in the smaller scale and limited duration of CO_2 injection, the credibility of the operator and an early, open, transparent and continued engagement of local stakeholders at Ketzin (Dütschke et al. 2015).

After the closure and abandonment of the Ketzin site, stakeholder engagement occurs currently on a more general level, e.g. in stakeholder discussion fora organised by acatech or the ESYS initiative (see DE5.2) or by providing information on webpages and answering to journalist enquiries.

According to the Climate Action Programme 2030, the German government will promote research and development into the storage and use of CO_2 and will launch a dialogue on these technologies with all stakeholder groups.

Summarising the state-of-play on geological CO_2 storage in GREECE (GR; as of 30th June 2021)

GR1. National storage assessment, storage options, potential and capacity

At the current stage, there is no national CO_2 storage atlas or CO_2 storage license/permit granted in Greece. Research studies that investigate potential sites for CO_2 storage remain at a theoretical level providing estimations based on model calculations. The major regions for CO_2 storage include the Mesohellenic Trough (Western Macedonia, Greece) and Western Thessaloniki Basin (North Greece), as well as the offshore Prinos oil and South Kavala gas field (North Greece).

The Mesohellenic Trough is an Oligocene to M. Miocene mollasic basin in North Greece. Research estimations indicate that there are two saline formations (Eptachori and Pentalofos), which can serve as potential sites for CO_2 storage (Koukouzas et al. 2009). The Eptachori formation (U. Eocene- L. Oligocene) is composed mostly by clastic sedimentary rocks (conglomerates, sandstones; Koukouzas et al. 2019) and presents 1 to 1.2 km thickness (Ferrière et al. 2004, Kilias et al. 2015), whereas the Tsotylli formation (L.-M. Miocene) presents ~ 1500 m thickness (Zelilidis et al. 2002) composed mainly by marls accompanied by conglomerates and sandstones (Koukouzas et al. 2019). Research estimations indicate total storage capacity of ~ 216 Mt CO_2 (RWE 2006). Based upon the research results of the GESTCO (2004) project (Christensen & Holloway 2004), the saline reservoir rocks of Prinos oil field (North Greece) provide the potential for storing an additional amount of 1,350 Mt CO_2. The West Thessaloniki basin is an on-shore basin located in North Greece composed by Tertiary sedimentary saline aquifers that can store up to 605 Mt CO_2 (Koukouzas et al. 2011, Christensen and Holloway 2004). The Alexandria basin is located in the North Aegean and has a CO_2 storage capacity of ~ 35 Mt CO_2 in saline aquifers (RWE 2006).

There are six well studied oil and gas fields in Greece which may serve as CO_2-storage sites (Tasianas & Koukouzas 2016, Hatziyannis 2009, Rütters et al. 2013). These include the Prinos (producing field; North Greece), South Kavala (exhausted field; North Greece), Katakolo-East Katakolo (non-producing field; South Greece), Kalirachi (non-producing field; North Greece) and Epanomi (non-producing field; North Greece) fields. The Prinos oil field (~ 260 m thickness) exhibits the appropriate geological properties (porosity, permeability, mineralogical composition and cap-rock formation) that can justify the implementation of CO_2-storage technologies (RWE 2006, Koukouzas et al. 2019). Theoretical estimations indicate that the Prinos oil field can store up to 19 Mt of CO_2 (IEAGHG 2005). The total of CO_2 storage potential of the six hydrocarbon fields is 70 Mt (Tasianas & Koukouzas 2016, Hatziyannis 2009, Rütters et al. 2013).

Several Greek sites have been proposed for CO_2 storage through carbon mineralisation. These include ultramafic rocks, basaltic rocks and sandstones (Kelektsoglou 2018). However, only few studies provide significant estimations on the amount of the potentially stored CO_2. Basaltic outcrops from the Volos region (Microthives and Porphyrio localities; Central Greece) exhibit the appropriate physicochemical properties (porosity, SiO_2-saturation, mineralogical composition) for CO_2 mineralisation (Koukouzas et al. 2019). Theoretical calculations indicate 82,800 and 27,600 tons of maximum CO_2 storage potential (Koukouzas et al. 2019). These calculations take into consideration the volume of the basaltic outcrop, the average porosity, as well as the specific gravity of the CO_2. Based on similar calculation models Petrounias et al. (2020) suggest storage capacity of ~ 18×10^5 tons of CO_2 within the Klepa-Nafpaktia sandstones (Central-Western Greece) through mineral carbonation processes.

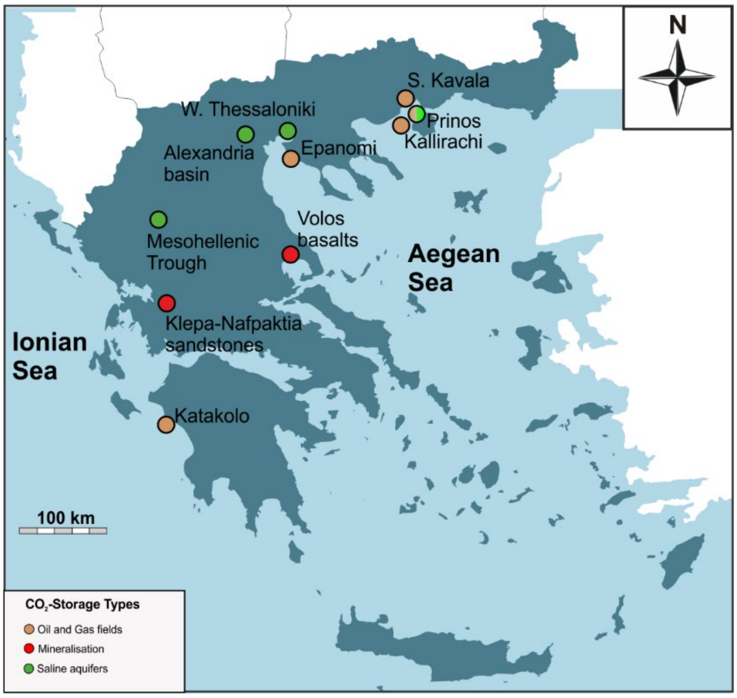

Figure GR: Potential sites for CO_2 storage in Greece (Oil and gas fields: Prinos: 17 Mt CO_2; South Kavala: 4 Mt CO_2; Kataklolo-East Katakolo: 3.2 Mt CO_2; Kallirachi: 35 Mt CO_2; Epanomi: 2 Mt; Saline aquifers: Mesohellenic Trough: 216 Mt CO_2; W. Thessaloniki basin: 605 Mt CO_2; Prinos: 1,350 Mt CO_2; Alexandria: 35 Mt CO_2; CO_2 mineralisation: Microthives: 82.8 kt CO_2; Porphyrio basalts: 27.6 kt CO_2; Klepa-Nafpaktia sandstones: 1.8 Mt CO_2).

GR2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

GR2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

Ptolemais V is a project in preparation stage that includes a new power plant, which is constructed on CCS ready technology. This power plant will be prepared to have all the necessary premises and essential equipment for effective CO_2 capture and storage (Vatalis et al. 2014).

GR2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

GR2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

None.

GR2.4 Past and current full-chain CCS projects & projects/sites in preparation

None.

GR2.5 Plans for CCUS cluster development

None.

GR3. National policies, legislation and regulations

GR3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

In Greece, the Ministry of Environment and Energy has set strategic targets on the National Energy and Climate Plan (NECP) until 2030. These targets include:
a) 55% reduction of the GHG emissions compared to those of 2005, which will further contribute to the transition towards a climate neutral economy until 2050,

b) at least 35% of the gross final energy consumption will correspond to renewable energy resources (exceeding the European target for 32%); the Greek strategic plan aims to incorporate renewable energy resources into the means of transport (1/3 of cars will be electric),
c) lower energy consumption in 2030 compared to that of 2017,
d) strategy for the full decarbonisation of the electricity production by 2028, providing support to specific regions during the post-lignite period,
e) design of a Master Plan within 2020 that will provide a complete development roadmap for the post-lignite period,
f) promotion of circular economy that will contribute to mitigation of climate change. Supplementary actions include the target of the Athens Municipality for 40% reduction of the GHG emissions (2.03 Mt CO_2) until 2030 according to the Climate Action Plan of 2017 (Skoula 2017).

GR3.2 National legislation and regulations

Greece has adopted the EU Directive on CCS in 2011 (FEK 2011, 2013, Shogenova et al. 2013). The Official Gazette No B 2516/7-11-2011 permits the implementation of CO_2 storage processes in geological formations. It applies to CO_2 storage in geological formations including the sea borders. It also includes geological formations with an estimated storage capacity of more than 100 kt for research and development or testing of new products and processes. According to the Official Gazette (FEK 2011) CO_2 storage is not allowed in the water column and underground aquifers. The Ministry of Environment, Energy and Climate Change is the competent authority in Greece providing to the Minister the right to designate the areas that are acceptable for CO_2 storage.

GR4. Research

GR4.1 National funding for research related to CCS and research priorities

None.

GR4.2 Research institutions involved in research related to CO_2 storage

In recent years, there is increasing interest and involvement of some Greek research and academic institutes in CO_2 capture, storage and utilisation through several EU-funded research projects. Research institutions, involved in CO_2 storage research in Greece, are the following:

- Centre of Research and Technology Hellas (CERTH)
- Chemical Process and Energy Resources Institute (CPERI)
- Center for Renewable Energy Resources and Saving (CRES)
- Hellenic Survey of Geology & Mineral Exploration (HSGME)

GR4.3 Existing larger scale research infrastructure

None.

GR4.4 Involvement in EU-funded and other regional/international research projects related to CCS

CERTH is currently involved in the following CCS-related EU-funded research projects:

- CO_2 Geological Pilots in Strategic Territories – PilotSTRATEGY,
- Strategic Planning of regions and territories in Europe for low-carbon energy and industry through CCUS – STRATEGY CCUS,
- Low Emissions Intensity Lime and Cement 2: Demonstration Scale – LEILAC2,
- Innovative management of COAL BY-PROducts leading also to CO_2 emissions reduction – COALBYPRO,
- Accelerating CCS technologies as a new low-carbon energy vector – ACT.

GR5. National actors driving CCS forward and public engagement

GR5.1 Awareness of CCS technology

In Greece, there is limited knowledge in the general public on CCS topics. The first research that aimed to record public awareness was conducted by Pietzner et al. (2011). The outcomes of this research indicate that 76.5% of the public had never heard about CCS, whereas only 23.5% had heard a little or quite a bit about CCS.

GR5.2 National advocates for CCS

None.

GR5.3 Public engagement

Results of the study conducted by Pietzner et al. (2011) on public engagement indicate that the public perception was slightly supportive on implementing CCS technologies as measures to mitigate climate change (Pietzner et al. 2011). In addition, perceptions of Greek society on CCS technologies were strongly associated with their attitudes to natural gas production and storage. Detailed investigation on CCS public awareness was conducted in the framework of EU-funded project STRATEGY CCUS (Oltra et al. 2020). The perceptions were measured using questionnaires as tools to select and assess data. The stakeholders participating in the research comprised politicians, researchers and educators, people from the industrial sector and influencers. Most of the interviewees were quite supportive on CCUS. However, a part of interviewees was quite sceptic regarding the readiness level and the effectiveness of CCUS.

Summarising the state-of-play on geological CO_2 storage in HUNGARY (HU; as of 30th June 2021)

HU1. National storage assessment, storage options, potential and capacity

Storage Capacity assessment has been going on since the mid 2000s. The target structures are depleted hydrocarbon reservoirs and deep saline aquifers. Coal storage is not anymore on the agenda. There has been no significant progress in the aquifer storage assessment since 2013. The level of knowledge concerning these aquifers is still quite low, with only low resolution regional data available. The estimated storage capacity in 11 sub-basins of the Pannonian Basin is 700-800 Mt CO_2.

Depleted hydrocarbon reservoirs have been thoroughly studied. The selected reservoirs are similar to those reported in 2013, however the level of knowledge has increased considerably. Assessment is carried out by the Mining and Geological Survey of Hungary.

At all potential sites well logs reaching or crosscutting the reservoirs have been reprocessed and reinterpreted focusing on the reservoir and seal. Based on the reinterpreted well logs petrophysical parameters (i.e. effective porosity, permeability) have been re-estimated using Monte Carlo simulation. The estimate storage capacity in 12 selected potential sites is approximately 100 Mt CO_2.

Furthermore, geochemical reactivity modelling as well as worst case leakage scenario modelling has been carried out for the potential sites in order to support future risk assessment. Some of these scenarios and modelling have been published and presented (e.g. Szabó et al. 2018). Cap rocks of potential storage formations have been subjected to detailed mineralogical analysis and laboratory experiments (e.g. Szabó et al. 2016). The reactivity of old well cements in the presence of CO_2 at reservoir conditions has also been modelled (e.g. Szabó-Krausz et al. 2020).

Results have not been presented in National Storage Atlas. No exploration has been licenced for CO_2 storage so far.

HU2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

HU2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

None.

HU2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

HU2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

CO_2 injection in hydrocarbon fields with the purpose to increase the production of oil and gas (CO_2-driven enhanced oil recovery or CO_2-EOR) has been going on in Hungary since the 1970s. Several projects including Nagylengyel, Budafa, Lovászi, Szank DK, Kiskundorozsma and Pusztaföldvár have successfully demonstrated the operability of these activities in sandstone, carbonate and metamorphic reservoirs resulting in 6-13% increase in cumulative production (see also Szelényi 2015).

HU2.4 Past and current full-chain CCS projects & projects/sites in preparation

None.

HU2.5 Plans for CCUS cluster development

None.

HU3. National policies, legislation and regulations

HU3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

National Energy and Climate Plan is a technology-neutral approach, does not refer to specific technologies. It sets emission reduction targets as well as desired share of renewables. CCS is included in the planning. However, the deployment of CCS/CCUS technology is expected after 2030.

National Energy Strategy includes CCS as a possible option to decarbonise energy industries as well as emission intensive industries (i.e. chemical industry, cement industry, bioethanol). There are several scenarios modelled with and without CCS. The strategy states that decarbonisation scenarios without CCS are extremely expensive. The strategy estimates that the technology will only be mature and ready for wide deployment after 2030.

National Action Plan for Utilisation and Reserve Management of Energy-Related Mineral Resources provides an insight in the available storage capacities concerning depleted hydrocarbon and aquifer storage (numbers similar to 2013 report; Rütters et al. 2013). Additionally, the potential availability of recently actively producing reservoirs is also considered. Certain storage-related risk assessment priorities are also discussed.

National Clean Development Strategy, finally accepted on 5th September 2021, includes CCS/CCU as one of the so far immature but potential technologies that can massively contribute to GHG emission reduction.

2nd National Climate Change Strategy explicitly refers to CCS/CCUS as one of the potential tools of decarbonisation. The strategy points out four main activities that should be carried out in relation with CCS/CCUS, which are the following:

1) Geological assessment should be continued to find suitable structures for storage.

2) Detailed cost-benefit analysis should be made for the national application possibilities for CCS/CCUS.

3) Potential industrial applications of captured CO_2 should be studied.

4) The potential of combining biomass with CCS (negative emissions) should be assessed.

HU3.2 National legislation and regulations

The implementation of the EU CCS Directive took place in May 2012 coming into force in July. The Directive is integrated in the National Mining Act and there is a Governmental Decree controlling its enforcement. There have not been major revisions of the national legislation. Some minor amendments are regularly made. There are no restrictions except for the general ones that are valid for other type of sub-surface activities. The competent authority is the Mining and Geological Survey of Hungary.

HU4. Research

HU4.1 National funding for research related to CCS and research priorities

Currently the storage capacity assessment project carried out by the Mining and Geological Survey is the only research project related to CCS in Hungary. It includes some modelling activity mostly related to geochemical models. The topic is not excluded from energy/ emission reduction related programmes, but currently there is no other known activity going on.

Table HU: Overview of research topics addressed by recent nationally funded research projects on CO_2 storage.

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	X	-	-	-	-	-	(x)	-	-

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

HU4.2 Research institutions involved in research related to CO_2 storage

There has been only one CCS-related research topic going on 2015–2020 in Hungary which was focusing geological storage of CO_2. Major universities (Eötvös University, Budapest, Technical University of Budapest), and research institutes were involved in the research.

HU4.3 Existing larger scale research infrastructure

None.

HU4.4 Involvement in EU-funded and other regional/international research projects related to CCS

None.

HU5. National actors driving CCS forward and public engagement

HU5.1 Awareness of CCS technology

There is no scientific survey dealing with the public awareness of CCS technology available in Hungary. General knowledge of CCS is present only at stakeholder level. General public is well aware of climate change but not of CCS.

HU5.2 National advocates for CCS

None.

HU5.3 Public engagement

None.

Summarising the state-of-play on geological CO_2 storage in ICELAND (IS; as of 30th June 2021)

IS1. National storage assessment, storage options, potential and capacity

Iceland lacks the geology required for storage of CO_2 as a supercritical fluid in sedimentary basins. An alternative method relies on in-situ mineral storage of CO_2 via its injection into reactive rocks such as mafic or ultra-mafic rocks for rapid mineralisation (e.g. Snæbjörnsdóttir et al. 2020). Mineral carbonation can be promoted by the dissolution of CO_2 into water before or during its injection. No cap rock is required when injecting water charged with CO_2, as it is denser than CO_2-free water. As such, it does not have the tendency to migrate upward to the surface. By dissolving CO_2 into water before or during its injection, solubility trapping is achieved immediately (Sigfússon et al. 2015), and the bulk of the carbon is trapped in carbonate minerals within two years of injection at 20-50°C (Matter et al. 2016, Pogge von Strandman et al. 2019).

By provoking the mineralisation of the injected CO_2 into carbonate minerals such as calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$) or magnesite ($MgCO_3$) via its injection into reactive host-rocks, the injected carbon is permanently fixed and there is a negligible risk of it returning to the atmosphere.

Approximately 90% of the bedrock in Iceland is basalt indicating that theoretically much of Iceland could be used for injecting CO_2, fully dissolved in water, into basaltic rocks. The most feasible formations are the youngest basaltic formations, found in the active rift zone. These basalt formations consist of lavas, hyaloclastic (glassy) formations and associated sediments younger than 0.8 million years covering about one third of Iceland. Thus, CO_2 storage in basalts is now considered to be a promising option and the feasibility of CO_2 storage in basaltic rocks is currently investigated in Iceland and demonstrated as part of the Carbfix project.

The storage potential of such systems located onshore in Iceland, the largest landmass above sea-level at the mid-oceanic ridges, has been estimated by direct measurements of CO_2 bound in carbonates in drill-cuttings from three basalt hosted geothermal fields. Although these carbonates are precipitated over large timescales (10,000-300,000 years), the results provide insights into the permeability and active porosity of natural systems and indicate that young and fresh basalts can naturally store over 100 kg CO_2/m^3 (Wiese et al. 2008). Applying these estimates to the most feasible formations in Iceland reveals a theoretical storage potential estimate of up to 2,500 Gt CO_2 or $2.5 \cdot 10^6$ Mt CO_2 (Snæbjörnsdóttir et al. 2014).

Carbfix has recently launched its Mineral Storage Atlas that highlights suitable geological formations for mineral storage worldwide. Altogether the global storage potential has been estimated at >100,000 Gt CO_2.

The licensing procedure for mineral storage projects in Iceland is still being formed. Despite this, two commercial carbon storage projects have been implemented under geothermal exploration licenses and are subject to environmental impact assessment.

IS2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

The development of the Carbfix technology, i.e. injection of CO_2 dissolved in water into the subsurface where it reacts with basaltic rocks to form solid carbonate minerals, has been ongoing since 2007 with first field testing occurring in 2011. Initially, the concept was proven with commercially bought CO_2 which could be supplied to the system in a controlled manner. As the Carbfix capture technology was further developed, a stream of CO_2 from the Hellisheidi geothermal power plant was available providing opportunities for more long-term testing of surface equipment. In 2012, an integrated approach of capturing, injecting, and monitoring the fate of injected CO_2 was demonstrated (Carbfix1) enabling decisions to scale up the injection of separated CO_2 from the Hellisheidi geothermal power plant (Carbfix2) in two steps in the years 2014 and 2016. Carbfix joined forces with the Swiss clean tech company Climeworks in 2017 with a pilot injection of CO_2 captured directly from the atmosphere with the capacity of about 50 t CO_2/year (project Arctic Fox). Demonstrations of 4 kt/year injection of CO_2 from the atmosphere will commence in 2021 (ORCA).

IS2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

None.

IS2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

IS2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

Carbfix 1 pilot injections (TRL3 to 7): Following the study of natural analogous, extensive laboratory testing and modelling of all components of the Carbfix value chain between 2007 and 2012 (e.g. Stockmann et al. 2008, Gudbrandsson et al. 2008, Flaathen et al. 2009, Gysi & Stefansson 2011, Aradóttir et al. 2012), a series of experiments was carried out in the vicinity of the Hellisheidi power plant. After a successful verification of the injection system in late 2011 (beta testing TRL 3-5), the pilot injection was commenced in January 2012 with the injection of 175 tonnes of CO_2 (e.g. Snæbjörnsdóttir et al. 2017; Figure IS). The CO_2 was stored in a 30 m^3 reservoir tank and co-injected with locally sourced groundwater. The injected gas was mixed with the down flowing water via a sparger at a depth of 340 m ensuring complete dissolution of the CO_2 in the down flowing water as the mixture was carried down the well via a mixing pipe to a depth of 540 m.

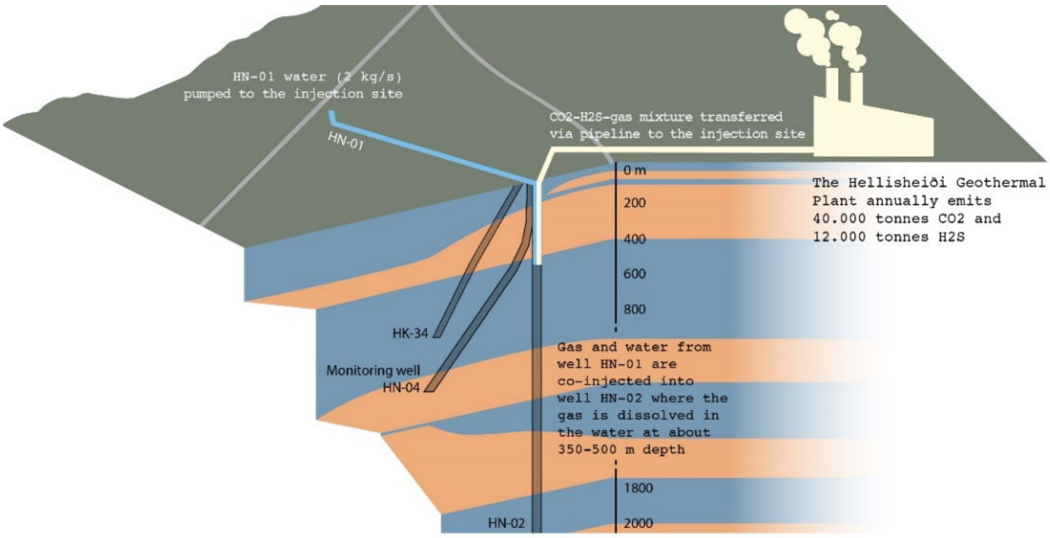

Figure IS1: Geological cross section of the Carbfix injection site. Blue indicates lava flows and orange indicates hyaloclastic (glassy) formations. The CO_2-H_2S gas mixture used in the second injection was separated from other geothermal gases at the power plant and transported via a gas pipe to the injection site where it was dissolved in water from well HN-01 within the injection well HN-02 (modified from Snæbjörnsdóttir et al. 2017).

At 540 m depth the CO_2 charged fluid was released into the subsurface rocks in the 20-50°C hot reservoir. The carbonation process was quantified using reactive and non-reactive tracers, and isotopes, which revealed the rapid mineralisation of the injected CO_2 with over 95% of the injected gas mineralised within two years (Matter et al. 2016, Pogge von Strandman et al. 2019).

Following the CO_2 injection, a mixture of 75% CO_2 and 25% H_2S from the Hellisheidi power plant were successfully injected under the same conditions, demonstrating for the first time the whole carbon capture, transport, injection, and permanent storage chain for the injected gases (Snæbjörnsdóttir et al. 2017). Furthermore, this injection experiment demonstrated that the Carbfix method can be used for injection of gas-mixtures and impure gas mixtures, adding to the applicability of the method.

Carbfix seawater pilot (TRL3-5): Carbfix has developed the scientific basis for using seawater to dissolve CO_2 prior to injection, significantly expanding the applicability of the technology in coastal areas, areas where fresh water availability is limited, and for offshore injection. An onshore pilot injection of 1000 t CO_2 dissolved in seawater will be carried out in Q2 in 2022.

IS2.4 Past and current full-chain CCS projects & projects/sites in preparation

Carbfix 2 – industrial operations (TRL7 to 9): Following the success of the initial Carbfix project in Hellisheidi, the project was upscaled starting in 2014 in a hotter reservoir, with a stepwise increase in the amount of gases injected (Gunnarsson et al. 2018, Sigfússon et al. 2018, Gíslason et al. 2018). The acid gases (CO_2 and H_2S) are captured directly from the geothermal power plant exhaust stream by its dissolution into pure water (condensed steam from the power plant turbines), in a scrubbing tower. The resulting gas-charged water is injected to about ~800 m depth into the basaltic reservoir at temperatures of ~250°C. Since the injected gas-charged fluid is acidic, it is strongly undersaturated with respect to the primary and secondary minerals of the basaltic reservoir (Clark et al. 2018).

The dissolution gradually increases the pH of the gas-charged fluid to a range suitable for CO_2 mineralisation, provoking mineralisation of the injected gases some distance away from the injection. Therefore, to date there is no sign of decreasing system injectivity since the initiation of the CO_2 injection in 2014. The injection has been monitored via sampling of nearby monitoring wells (Figure IS2).

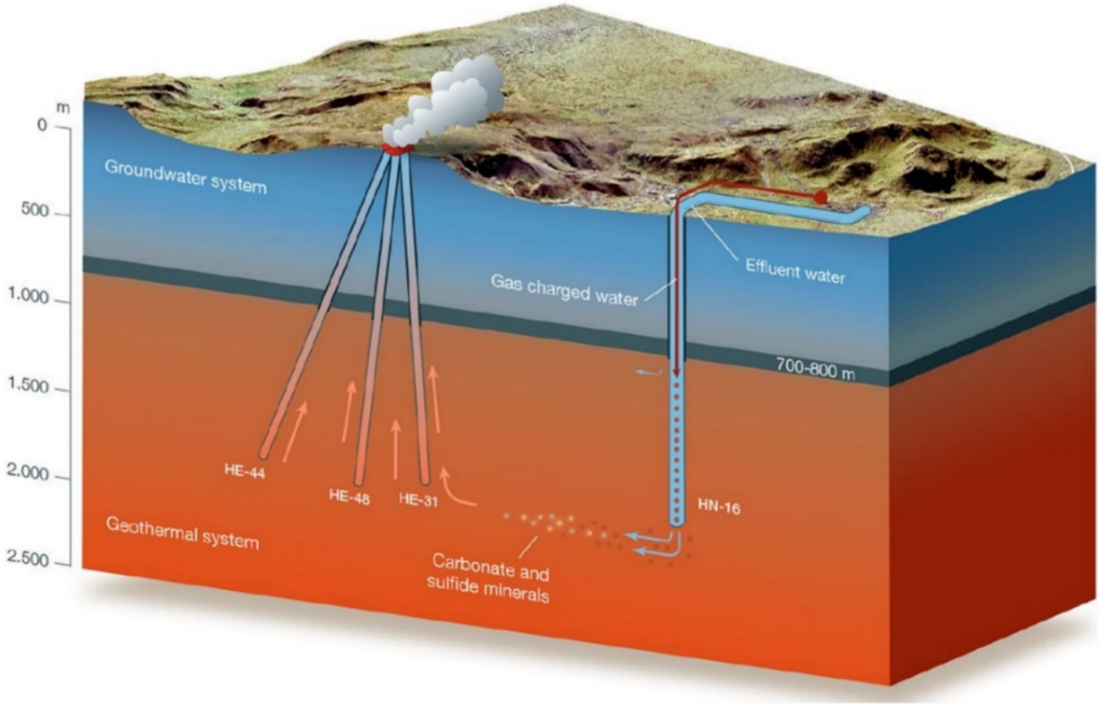

Figure IS2. Schematic cross section of the Carbfix2 injection site. Gas-charged and effluent water are injected separately to a depth of 750m, then allowed to mix until they enter the reservoir at a depth of 1900-2200 m. This combined fluid flows down a hydraulic pressure gradient to three monitoring wells located 984, 1356, and 1482 m from the injection well at the reservoir depth.

The system captures and stores ~1/3rd of the CO_2 emissions from the Hellisheidi power plant at present, or about 15,000 t annually, aiming for injection of over 90% of the CO_2 from the plant in the near future (Sigfússon et al. 2018). To date, over 65,000 t CO_2 have been captured and injected from the Hellisheidi power plant. At present, >50% of the injected CO_2 is fixed as carbonate minerals within months of its injection in this upscaled system. (Clark et al. 2020). Furthermore, full economic analysis of the current ongoing Carbfix injections at Hellisheidi shows the overall cost of carbon capture and storage to be ~$25 US/t CO_2, far lower than alternatives (Gunnarsson et al. 2018).

Carbfix Nesjavellir Pilot Injection (TRL5 to 7): Building on the experience of the successful CO_2 and H_2S capture and storage at the Hellisheidi geothermal power plant, the same approach is planned to be implemented at a second plant, the Nesjavellir geothermal plant. A pilot capture and injection of ~1000 tons CO_2/year will start early 2022 as part of the H2020 backed GECO project.

Carbfix-Climeworks Cooperation (TRL5 to 7 and TRL7 to 9): Carbfix joined forces with the Swiss clean-tech company Climeworks (CW) in 2017 as a part of the H2020 funded Carbfix2 project to explore the option of combining direct air capture (DAC) technology with injection and mineralisation of CO_2. At that time, the two technologies had already been demonstrated in their operational environment, CW had demonstrated its technology at TRL 5, and Carbfix was already being demonstrated as a complete system at TRL 7. The integrated Carbfix-CW demonstration moved the CW technology from TRL 5 to TRL 7. The collaboration has resulted in the first commercial DACCS chain with the Orca plant and on-site injection in a dedicated injection well.

The Arctic Fox: In October 2017, a single DAC capture unit, the Arctic Fox, with capture capacity of 50 t CO_2/year was installed at the Hellisheidi site where the current Carbfix injection is taking place. The DAC technology developed by CW is based on an alkaline-functionalised adsorbent using heat energy through a temperature-vacuum-swing process and developed by Climeworks, has been installed at the Hellisheidi site, where current Carbfix injection is taking place. Figure IS3 provides an overview of the Climeworks DAC cycle. The air-derived CO_2 stream is then transferred to the Carbfix injection system where it is injected and mineralised, achieving a negative emission pathway (Gutknecht et al. 2018). Two modes of operation were tested. First, the CO_2 was transported at near atmospheric pressure to the suction end of the Carbfix capture plant where it was dissolved alongside non-condensable gases from the power plant prior to re-injection. Secondly, the DAC-derived CO_2 was compressed to a pressure of 12 bar-g and introduced to the CO_2-loaded injection water exiting the Carbfix capture plant. This ensured total injection of CO_2 since the Carbfix Capture plant at Hellisheidi has less capture efficiency.

The ORCA: The up scaling of the Climeworks DAC technology in combination with the Carbfix re-injection technology, the ORCA project, is currently ongoing, with injection capacity of about 4,000 t CO_2/year bringing the TRL level of a combined system of the two technologies to TRL 9 (Figure IS3). The capture and storage systems were commissioned in Q3 2021. For the ORCA project, the injection system from Carbfix1 was updated and additional pressure sensors installed at selected depths in the mixing pipe to enable better monitoring of the injection system. Monitoring pressure in the mixing pipe enables early detection of incomplete gas dissolution enabling rapid response by either adjusting the mixing depth or water to gas ratio. Additionally, the wellhead from Carbfix2 was amended to enable up to 10 bar-g pressure in the well head annulus. This was done to ensure CO_2 injection into injection wells with low injectivity.

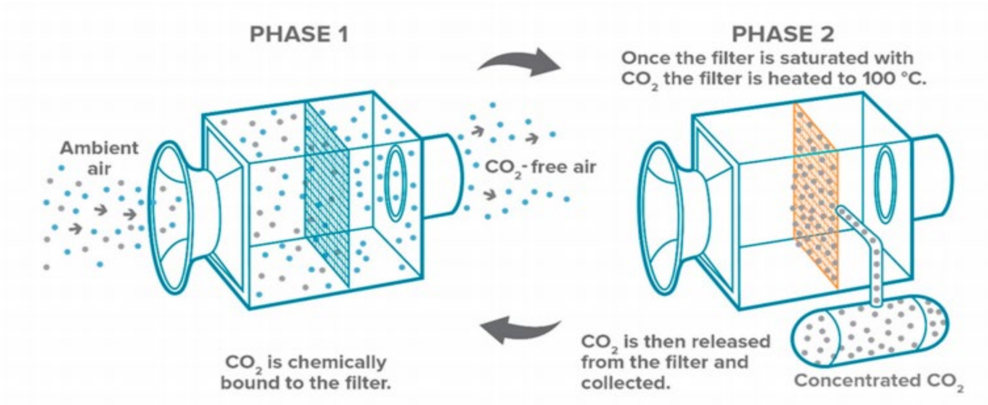

Figure IS3: Schematics of the CO_2 adsorption/desorption process.

Carbfix SORPA pilot (TRL3-7): An injection experiment is being carried out to assess the feasibility of CO_2 mineralisation in older and less permeable basalts using the Carbfix technology. The basalts are located outside of the active rift zone. The CO_2 dissolved in water is being captured from a methane plant at a landfill near Reykjavík. The pilot involves injection of about 3500 t of dissolved CO_2/year and started in Q3 2021, with planned upscaling to 3,700 t/year.

CO_2SeaStone pilot (TRL4-7): The first field scale demonstration of Carbfix using seawater, instead of fresh water, as CO_2 solvent and carrier. The pilot demonstration will be carried out in Reykjanes, onshore SW-Iceland in a saline system. The validation of mineralisation using seawater will unlock large coastal and offshore regions where fresh water is a scarce resource. The CO_2 for the pilot will be transported from Switzerland in a Swiss-funded project called DemoUpCarma, in which CO_2 will be capture at biogenic sources and transported in 40 ft containers to Iceland.

Silverstone CCMS (TRL9): Full-scale carbon capture and mineral storage (CCMS) project at the Hellisheidi geothermal power plant. A new capture plant will be designed and constructed which is optimised for CO_2 dissolution under ~10 bar pressure. The project is funded by the EU Innovation Fund small scale projects.

IS2.5 Plans for CCUS cluster development

The Coda Terminal will be a highly scalable onshore carbon mineral storage hub in SW-Iceland with an estimated overall storage capacity of 500 Mt CO_2. The port will be equipped to receive large quantities of CO_2 transported by ship from industries in Northern Europe. The Coda Terminal will enrich and de-risk geological CO_2 storage, in particular by dramatically reducing the capital investments and the liabilities associated with conventional storage projects, which rely on injection of CO_2 into depleted hydrocarbon sites or deep saline aquifers.

The Coda Terminal project builds on established industrial-scale operations of the Carbfix technology in Iceland involving injection of CO_2 dissolved in water into basalt formations. Significantly lower storage costs make CO_2 transportation by ships economically viable over large distances. The Coda Terminal will cooperate with experienced maritime operators using innovative solutions in tank design. The Coda Terminal is expected to be able start commercial operations in 2025. The project has strong support from the government and local authorities.

IS3. National policies, legislation and regulations

IS3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

The Icelandic government has announced plans to reduce emissions by 55% by 2030 with respect to 1990 levels. The target will be met with transition to renewables in the transport sector, recovery of wetlands and notably, increased carbon storage in biomass and geologic storage in basalts. For emissions that fall under direct government responsibility (not ETS), Iceland has pledged to reach carbon neutrality by 2040.

Carbfix features prominently both in the climate action plan and roadmap to carbon neutrality. In June 2019, the government of Iceland, OR - the mother company of Carbfix, and the heavy industry (Alcoa, Elkem, Century Aluminum, Rio Tinto and PCC) signed a trilateral Declaration of Intent to explore whether the Carbfix process is technologically and economically viable to reduce CO_2 emissions from industrial facilities in Iceland, which notably account for 40% of the country's greenhouse gas emissions.

IS3.2 National legislation and regulations

The Icelandic government is in the process of transposing the EU CCS Directive into national law (see draft legislation on Government Consultation Portal). As the directive mainly focuses on methodology for storage of CO_2 rather than injection of CO_2 leading to mineralisation, guidance documents on monitoring etc. are not well suited for the Carbfix technology. To ensure the compatibility of the Carbfix method with the EU CCS Directive, DG Clima was consulted before the bill transposing the EU CCS directive into national law was prepared. The bill clearly stipulates that avoided CO_2 emissions that are injected into the subsurface for permanent mineral storage on the basis of the Carbfix method are deductible within the ETS system.

The bill was adopted on 11th March 2021 with a bi-partisan support from all Parties in the Parliament. With the bill the geological storage of CO_2 in Icelandic territory is permitted, whether it being permanent storage under the CCS method or mineralisation of CO_2 under the Carbfix method. The monitoring and financial requirements for the method are currently being elaborated.

National laws and regulations	Corresponding international laws and regulations
Planning Act and Planning Regulation: Planning Act no. 123/2010 and Planning Regulation no. 90/2013 as amended no. 578/2013 and no. 903/2016	Directive 2009/31/EC on the geological storage of CO_2 (CCS Directive)
Laws and regulations on Environmental Impact Assessment: Assessment Act no. 106/2000 and Evaluation Regulation no. 660/2015 as amended no. 713/2015 and no. 1069/2019	Directive 2014/52/EU on Environmental Impact Assessment amending the EIA Directive 2011/92/EIA
Laws and regulations on buildings and structures: Civil Engineering Act no. 160/2010, Building Regulation no. 112/2012 together with the amendments no. 1173/2012, 350/2013, 280/2014, 360/2016, 666/2016, 722/2017, 669/2018 and 1278/2018, Regulation on construction permits no. 772/2012 as amended no. 1068/2019 and no. 378/2020	London protocol on marine pollution, adopted in 1996 to modernise and eventually replace its forerunner, the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (London Convention)
Laws and regulations on hygiene and pollution prevention Act no. 7/1998 on hygiene and pollution prevention, Regulation no. 550/2018 on emissions from business operations and pollution control, Draft bill on CO_2 injection as an addition to laws and regulations on hygiene and pollution prevention	Directive 2003/87/EC of the European Parliament and of the Council establishing a scheme for greenhouse gas emission allowance trading

IS4. Research

IS4.1 National funding for research related to CCS and research priorities

The Icelandic Research Fund is the main national body that supports research & development in CCS. Funding opportunities offered by the IRF include the Technology Development Fund, the Climate Fund and The Strategic Research and Development Programme 2020–2023 Societal Challenges. Subsurface mineralisation and capture from the local aluminium- and silicon production industry comprises the majority of CCS-related research in Iceland.

Table IS: Overview of research topics addressed by recent nationally funded research projects on CO_2 storage.

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	(x)	-	-	X	X	X	X	(x)	X
Project examples	CO2SeaStone Elfstone			CO2SeaStone		CO2SeaStone	CO2SeaStone Elfstone	CO2SeaStone Elfstone	

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

IS4.2 Research institutions involved in research related to CO_2 storage

Research on carbon capture and storage via carbon mineralisation is a growing research topic in Iceland. The topic has been studied at the two largest universities in Iceland; the University of Iceland and Reykjavík University, and ISOR (Iceland GeoSurvey) has been largely involved with research projects on the topic. Furthermore, Iceland University of Arts has annually featured Carbfix in lectures.

IS4.3 Existing larger scale research infrastructure

None.

IS4.4 Involvement in EU-funded and other regional/international research projects related to CCS

- Carbfix2
- NORDICCS
- CO2REACT
- Carbfix2
- S4CE
- GECO
- SUCCEED
- Silverstone

IS5. National actors driving CCS forward and public engagement

IS5.1 Awareness of CCS technology

In contrast to many places across Europe, the level of awareness and public acceptance in Iceland of carbon capture and storage is high. Likely reasons for its wide acceptance are that the Carbfix method is based on processes that already occur in nature, the rapid mineralisation, the elimination of the risk of CO_2 leakage, and the technology being born from the renewable geothermal energy sector rather than the oil and gas sector. The results of a Gallup survey conducted in 2019 confirmed that two out of three were in favour of Carbfix whereas less than 4% were opposed. These results show that once the public is informed, public acceptance of the technological advances proposed within the project is expected to be high. Surveys on Icelandic brands within the energy and utility sector carried out quarterly by MMR, market and media research, further support the high level of public acceptance of the Carbfix CO_2 mineral storage technology. Measurement of the Carbfix brand, recently added to the survey, shows a significant rise in positivity towards the brand in Q3 of 2020 compared to Q2 with rating rising from 5.6 to 6. Executives, directors, managers and senior officials are the most positive towards Carbfix. Key stakeholders in Iceland have expressed similar attitudes towards CO_2 mineral storage as shown by the aforementioned polls and surveys. The Carbfix technology plays an important role in reducing CO_2 emissions from the energy and industry sector's in Iceland's Climate Action Plan.

IS5.2 National advocates for CCS

Carbon mineral storage has no shortage of individual advocates. However, when it comes to organised groups or advocacy networks, Carbfix relies on foreign entities via membership in the Global CCS Institute, the CCUS Projects Network and the Negative Emissions Platform.

IS5.3 Public engagement

The following highlights a few activities in the recent past but is not a complete list:

- The European Researcher's Night (Vísindavaka), a large science and technology fair, took place in Reykjavik on 30th September 2019. Carbfix had a dedicated booth which featured samples of calcite, pyrite, a drill core, a microscope to look more closely at the samples, VR glasses that showed the injection well and a video for more detailed information. In addition to the dedicated Carbfix booth, Sandra Ósk Snæbjörnsdóttir also gave a 20 min presentation to the visitors on the potential of carbon mineral storage. The evening was a great success with over 5600 visitors attending.
- Carbfix has received immense support and attention in Iceland and abroad, receiving numerous prestigious international awards and attracting large media attention from the likes of BBC, in Sir David Attenborough's documentary *Climate Change: The Facts*, Netflix in Zac Efron's *Down to Earth* series, and HBO in the documentary *Ice on Fire*, produced and narrated by Leonardo DiCaprio, ZDF (Germany), AFP (France), National Geographic (US), Weather Channel (US) and the China Global Television Network.
- A Geothermal Exhibition is located at the Carbfix demonstration site in Iceland. It provides an interactive educational experience for school groups and the general public. Visitors are offered guided tours of the facility to learn about geothermal energy and the Carbfix mineral storage technology. The Geothermal Exhibition has recently been ranked among the most visited destinations in Iceland, receiving around 100,000 visitors annually. A showroom dedicated to Carbfix was recently opened at the exhibition.
- German Chancellor Angela Merkel and various political and economic advisors to the Chancellor visited the Hellisheidi Geothermal Power Plant on 20th August 2019. Brynhildur Davíðsdóttir, Chairman of the Board of Directors of Reykjavík Energy, and Bjarni Bjarnason, CEO of Reykjavík Energy, welcomed the chancellor, followed by a long-table discussion. Edda Sif Pind Aradóttir, coordinator of CarbFix2, introduced the CarbFix process and its link to Germany through the H2020 funded GECO project. The chancellor showed great interest in CarbFix and the opportunity to apply the process in different locations throughout the world.

Summarising the state-of-play on geological CO_2 storage in IRELAND (IE; as of 30th June 2021)

IE1. National storage assessment, storage options, potential and capacity

An all-island Ireland assessment completed in 2008 (SEI/EPA 2008) identified storage potential in the almost-depleted Kinsale Head natural gas field in the Celtic Sea Basin, with a calculated practical capacity of 330 Mt CO_2. Permo-Triassic basins in the Irish Sea with similar geology to the East Irish Sea gas and oil field (UK) have theoretical capacity, and large but unquantified storage potential exists in the Mesozoic basins on the western shelf. A joint Geological Survey Ireland –British Geological Survey project (Bentham 2015) sought suitable closures and practical capacities for the Permo-Triassic basins in the Irish Sea as well as potential sites with similar Cretaceous geology to the Kinsale Head gas field.

PSE Kinsale Energy Limited, the previous operator of the Kinsale Head gas field, conducted an assessment of CO_2 storage potential of the depleted "A" sand reservoir. A capacity of 286 Mt CO_2 was calculated to fill the main field structures, considering Kinsale Head and Ballycotton as a single storage complex, over a 60-year injection phase to return the field to its original pressure.

Ervia, the commercial semi-state utility company, is currently conducting a feasibility study into potential for CO_2 storage at the depleted Kinsale Head gas field, including reservoir studies, reprocessing seismic and assessing legacy wells.

There has been no application for a CO_2 storage licence.

IE2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

IE2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

Ervia is a partner of the REALISE project consortium (REALISE – Demonstrating a Refinery-Adapted Cluster-Integrated Strategy to Enable Full-Chain CCUS Implementation, which aims to demonstrate CO_2 capture at oil refineries.

IE2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

Ervia has signed a Memorandum of Understanding with Equinor, to jointly explore the potential to export CO_2 from Ireland to the Northern Lights CO_2 storage project in Norway.

IE2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

Ervia is conducting a feasibility study into potential for CO_2 storage at the depleted Kinsale Head gas field, including reservoir studies, reprocessing seismic and assessing legacy wells.

IE2.4 Past and current full-chain CCS projects & projects/sites in preparation

See IE2.5.

IE2.5 Plans for CCUS cluster development

Ervia has obtained a Project of Common Interest status for the potential of a CO_2 capture cluster of two CCGT power stations and an oil refinery in the Cork region, combined with pipeline transport and storage at the depleted Kinsale Head gas field.

IE3. National policies, legislation and regulations

IE3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

The Government's 2015 Energy Policy (White) Paper and National Mitigation Plan (2017) recognised CCS as a potential bridging technology that could support the transition to a low carbon economy while allowing an appropriate level of gas fired power generation to balance intermittent renewable generation.

The Climate Action Plan (2019) refers to the need to support further research into the feasibility of CCS deployment in Ireland, and specifically, Action 33 of the Plan mandates the establishment of a CCS Steering Group. This inter-departmental group has been convened and will oversee the development of CCS policy, monitor the progress of CCS research and proposals for projects, evaluate investment requirements, where applicable (including for Ervia's Kinsale Head project) and make recommendations on developing statutory and regulatory provisions, if required.

IE3.2 National legislation and regulations

Statutory Instrument No. 575 of 2011, European Communities (Geological Storage of Carbon Dioxide) Regulations 2011, transposes Directive 2009/31/EC by prohibiting storage of CO_2 in amounts greater than 100 000 t in the territory of the State, its exclusive economic zone and on its continental shelf.

The CCS Policy and Project Feasibility Steering Group is mandated to make recommendations to Minister for the Environment, Climate and Communications on what policy considerations would be appropriate with respect to implementation of CCS in Ireland.

IE4. Research

IE4.1 National funding for research related to CCS and research priorities

Geological Survey Ireland and Science Foundation Ireland have funded national research in CCS. These are generally through open calls rather than specific targeted calls. GSI has conducted general storage capacity research in the past.

Table IE: Overview of research topics addressed by recent nationally funded research projects on CO_2 storage.

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	X	-	-	-	(x)	-	X	-	-
Project examples	GSI-BGS Irish Sea iCRAG offshore basins				Sequestration in crushed basalt soil		Ervia Kinsale reservoir		

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

IE4.2 Research institutions involved in research related to CO_2 storage

Geological Survey Ireland GSI has funded a capacity assessment of saline aquifers in the Irish Sea (jointly with BGS; Bentham 2015), and a "short call" project on crushed rock/soil sequestration at University College Dublin (McDermott 2018). The Irish Centre for Research in Applied Geosciences (iCRAG) has recently hosted two research projects, funded by Science Foundation Ireland, re-using hydrocarbon exploration data from the offshore North Celtic Sea and Slyne basins to identify potential storage sites. Ervia (commercial semi-state body) is funding its own investigations at Kinsale gas field.

IE4.3 Existing larger scale research infrastructure

None.

IE4.4 Involvement in EU-funded and other regional/international research projects related to CCS

Ervia is a partner of the H2020 REALISE project consortium, which aims to demonstrate CO_2 capture at oil refineries.

IE5. National actors driving CCS forward and public engagement

IE5.1 Awareness of CCS technology

Public awareness of CCS in Ireland is low, reflecting the lack of any major developments.

IE5.2 National advocates for CCS

There is no national body or lobby group for CCS, although, for example, bodies such as the Irish Academy of Engineering have supported its potential for Ireland (IAE 2016).

IE5.3 Public engagement

Local public engagement by Ervia around their project area in Cork – reported as favourable but results not published.

Summarising the state-of-play on geological CO_2 storage in ITALY (IT; as of 30th June 2021)

IT1. National storage assessment, storage options, potential and capacity

Saline aquifers: Up to now evaluation of storage capacity has been performed only in the context of research projects. Since the role of CCS in the Italian energy strategy is still quite marginal, there has been no substantial national public investment in capacity assessment. Capacity estimations in both siliciclastic and carbonate formations have been performed mainly by OGS within the EU GeoCapacity project (Donda et al. 2011, Civile et al. 2013). Some other authors published also some studies (Buttinelli et al. 2011, Amorino et al. 2005, Catelletto et al. 2013, Colucci et al. 2016). All the results are based mainly on public data, available from the Ministry of the Economic Development in the framework of the project "Visibility of Petroleum Exploration Data in Italy (ViDEPI)" and on additional databases available from different authors and institutions. This dataset includes about 1650 well data and 55,000 km of 2D multichannel seismic profiles acquired since 1957 by several oil companies for hydrocarbon exploration.

The main Italian sedimentary basins, i.e. the Apennine foredeep and the Adriatic foreland, host the best potential sites, which are characterised by thick accumulations of siliciclastic sediments and carbonates. The potential reservoirs comprise deep saline aquifers hosted in both carbonate and sandstone formations. The latter reveal a theoretical storage capacity ranging from 30 to more than 1,300 Mt CO_2 (Donda et al. 2011). Based on the assessment performed and considering data quality and uncertainty, these areas could potentially contain the entire volume of CO_2 emitted in Italy for at least the next fifty years.

Additional potentially suitable areas have been identified by Civile et al. (2013) in carbonate successions. These areas consist of deep saline aquifers, except in the Malossa–San Bartolomeo area, where depleted oil and gas fields reveal suitable conditions for CO_2 storage. The potential reservoirs were generally recognised within the fractured shallow marine carbonate platform successions. Among them, the most suitable formations are those composed of dolostones and represented by the Late Triassic–Lower Liassic carbonate platform succession, recognised in the Po Plain, along the Adriatic Sea and in the Sicily Channel. These studies provide an overview of the main characteristics of potential sites suitable for CO_2 geological storage in Italy; more detailed analyses are needed to characterise the storage systems at regional and site scale. This is particularly relevant in the case of carbonate rocks, where the permeability and porosity are strongly related to diagenetic processes, dolomitisation and tectonic fracturing.

Hydrocarbon fields: Hydrocarbon production in Italy is associated with the three main tectono- stratigraphic systems: 1. biogenic gas in the terrigenous Pliocene-Quaternary foredeep wedges; 2. thermogenic gas in the thrusted terrigenous Tertiary foredeep wedges; 3. oil and thermogenic gas in the carbonate Mesozoic substratum. The potential storage capacity of 14 depleted fields, which represent only a small proportion of the total number of Italian hydrocarbon fields, has been estimated as: in gas reservoirs: 1.6 Gt - 3.2 Gt; in oil reservoirs: 210 Mt - 226.5 Mt (see the final report of the EU GeoCapacity project).

CO_2 storage in hydrocarbon fields has always been hampered by the public acceptance, especially after the May 2012 Emilia earthquake, when rumours began to circulate that the earthquake was somehow related to hydrocarbon exploitation. This idea was based on the levels of extraction and re-injection from an oil field located proximal to the earthquake epicentre and on the conclusions of a study that stated that a relationship could not be ruled out (ICHESE 2014). Lively debates, especially following the May 2012 earthquake, highlight that separating natural earthquakes from induced seismicity is crucial for the public acceptance of any subsurface usage in Italy.

Coal fields: The main coal basin in Italy is the so called "Sulcis Coal Basin"; it is Eocene in age and located in SW Sardinia. At present it hosts the last active Italian coal mine, the "Monte Sinni u/g" mine, now in a definitive closure phase. Preliminary studies on coals extracted from the mine showed promising developments for ECBM technologies here. Storage capacity of CO_2 by ECBM was estimated in the EU GeoCapacity project as 42 Mt CO_2 for the onshore area and 29 Mt for the offshore area giving a total estimated storage capacity of 71 Mt.

Despite the studies performed so far, a comprehensive atlas as those developed for CO_2 storage in other European countries and, for example, Australia and the US does not exist yet.

CO_2 storage exploration licenses or storage permits have not been awarded until now by the competent Ministry. ENI, the more important company in Italy for energy, has recently announced the project of a national hub in Ravenna province, in the Northern Adriatic Sea, so giving a new impulse to CCS concept and technologies in Italy.

IT2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

IT2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

ENEL launched in 2011 an innovative CO_2 capture plant at the Federico II coal power plant located in Cerano, Municipality of Brindisi. It consisted of four units with a capacity of 660 MW_e each (total capacity 2640 MW_e). The pilot plant was designed for a nominal gas flow rate of 15,000 Nm^3/h and to treat 10,000 m^3 of fumes per hour from the Federico II coal plant, separating out 2.5 t CO_2 hourly and up to 8,000 t/year, equivalent to the CO_2 absorbed by around 800,000 trees. The capture plant costs EUR 20 million to complete. The European Union provided a grant of EUR 100 million from its European Recovery Programme for Energy towards the Brindisi pilot project and for preliminary work on the Porto Tolle plant. The capture plant was closed after two years for investments issues.

In June 2020, ENEL announced that starting from January 2021, the Federico II power plant will undergo to a conversion process to a highly efficient gas plant, reaffirming the commitment to the energy transition towards a power plant free from fossil fuels.

Within the CLEANKER project, supported by the EC H2020 programme, several cement industries in collaboration with research centres in Italy and other European countries, are developing a calcium-looping technology to capture CO_2 in the cement production process. The same project considers how to develop a full chain CCS application in Northern Italy.

IT2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

There are neither demonstration nor pilot projects for CO_2 transport in Italy.

IT2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

In Italy up to now, no demonstration or pilot projects have been carried out with CO_2 injection into geological formations. Presently the ENI initiative to develop a storage hub in the Ravenna areas is expected to lead to one or more pilot projects. In the past, there have been some significant initiatives:

The **Zero Emission Porto Tolle (ZEPT) Project** covered the design, procurement and construction of a demonstration CO_2 capture plant as well as the detailed site characterisation, to verify the feasibility of the injection and storage of CO_2 in a safe and verifiable manner. The project was funded by the European Energy Programme for Recovery (EEPR) during the period 2009–2013. The plan was to install the CO_2 capture demonstration plant on an ultra-supercritical 660 MW_e unit of the Porto Tolle power plant, which will be co-firing coal and biomass. The post-combustion capture unit was designed to treat a flue gas flow rate of 0.8 million Nm^3/h, equivalent to a net electrical output of 250 MW_e. The demonstration plant would separate about 1 Mt/year CO_2 (capture efficiency >90%) to be transported by offshore pipeline to a deep saline aquifer located about 100 km SE of the power unit. The ZEPT Project (Porto Tolle) has been suspended due to the decision of the Italian

State Council to annul the environmental permit for the Porto Tolle power plant. Given this, and notwithstanding all the efforts put in place, the project promoter reported to the EC that it was not possible to mitigate the permitting and financial risks and decided to start termination of the contract. The request for termination was accepted by the EC (effective on 11th August 2013).

ENI – Feasibility study and pilot project of injection into a depleted hydrocarbon field in cooperation with Enel, which was testing a variety of different chemical solutions to capture CO_2 at Brindisi power plant with the aim of finding the most effective one. Brindisi's project was expected to use a post-combustion method, in which liquid solvents such as ammonia would have washed the exhaust gases after the coal is burned, so as to remove the CO_2. Operational capture tests started at Brindisi in June 2010. In mid 2011 the CO_2 was liquefied and briefly stored in tanks to be transported to the ENI/ Stogit storage site. The CO_2 pipeline to the Stogit field was planned to be in operation from 2012. After an initial testing period in March 2011, the project was expected to be operational by 2012. However, the project didn't proceed to the operational phase.

IT2.4 Past and current full-chain CCS projects & projects/sites in preparation

ENI recently announced the new "Ravenna hub" that will create one of the largest CCS centres in the world. The depleted offshore gas fields of the middle Adriatic will be used for CO_2 storage and the existing infrastructures still operational at present will be employed, together with new CO_2 capture systems at onshore ENI power plants and other industrial plants in the vicinity.

IT2.5 Plans for CCUS cluster development

Apart from the "Ravenna hub" project mentioned above there are no industrial initiatives in Italy regarding clusters of emitters connected to single or multiple storage sites.

IT3. National policies, legislation and regulations

IT3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

In the past, the role of CCS in the Italian mitigation strategy has been scarcely considered and the relevant ministries have only supported a limited number of research activities on the technology. In 2019, the Italian Government approved the Integrated National Energy and Climate Plan. Within this framework, CCS is viewed as a measure needed to be drawn up to accompany the transformation of the energy system towards the 2050 zero emission target, both in the electricity and industrial sectors, to bring the energy system in line with the pathway to a complete decarbonisation by 2050.

IT3.2 National legislation and regulations

The EU CCS Directive has been transposed in Italy in 2011 (legislative decree 162/2011), however the implementation regulation is still underway.

Competent authority for providing permits for exploration and exploitation of CO_2 storage resources is the Italian Ministry of Economic Development (MISE). According to Italian law, the subsurface is owned by the Italian State.

IT4. Research

IT4.1 National funding for research related to CCS and research priorities

MIUR (Ministry of University and Research): Since 2014 OGS has been granted an important funding to develop research and infrastructures on CCUS by **MIUR**: The **ECCSEL NatLab Italy** project has allowed the setting up of two important natural laboratories, in Panarea (offshore) and in Latera (onshore). Both laboratories play a key role in the study of CO_2 migration, leakage and impacts on ecosystems, offering the possibility to test and calibrate new sensors and to develop innovative monitoring techniques. The ECCSEL Natlab Italy has been recently supported by two other important projects, again funded by MIUR: IPANEMA and IPANEMA HR. The first one aims at implementing the technological potential of the Panarea laboratory to perform advanced studies on CO_2 monitoring. The second one is aimed at reinforcing the human capital and performing high-level research on CCUS.

Autonomous Region of Sardinia: The **Center of Excellence on Clean Energy** is funded by the Autonomous Region of Sardinia, which aims at strengthening a research infrastructure on low carbon energy, with particular reference to the development of CCUS technologies. Research is being carried out in the Sulcis area (with the participation of Sotacarbo, OGS, INGV, University of Cagliari and University of Rome "La Sapienza"), with focus on the study of possible CO_2 leaks along the faults.

Ministry of Economic Development (MISE): As part of the Research Programme for Electric System funded by the MISE, Enea and Sotacarbo are carrying out studies for the production of liquid and gaseous fuels through the catalytic hydrogenation of CO_2.

Table IT: Overview of research topics addressed by recent nationally funded research projects on CO_2 storage.

Topic	Storage capacity assessment	Land planning & infra-structure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed		X			X			X	
Project examples		ECCSEL NatLab-Italy IPANEMA IPANEMA HR			ECCSEL NatLab-Italy IPANEMA IPANEMA HR			ECCSEL NatLab-Italy IPANEMA IPANEMA HR	

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

IT4.2 Research institutions involved in research related to CO_2 storage

The interest in the field of research regarding CO_2 geological storage has been increasing in these last years thanks to the development of research activities, but also by the increment of teaching activities dedicated to different targets (activation of university courses on CCS, professional masters, etc.).

The main universities and research organisations active in the field of CO_2 storage research are:

- OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale),
- Sapienza University of Rome,
- CNR-ITAE (National Research Council - The Advanced Energy Technology Institute),
- CRS4 (Center for advanced studies, research and development in Sardinia),
- ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development),
- INGV (National Institute of Geophysics and Volcanology),
- LEAP(Laboratorio Energia & Ambiente Piacenza),
- Politecnico di Milano,
- Politecnico di Torino,
- RSE-Ricerca sul Sistema Energetico,
- Sotacarbo S.p.A.,
- University of Bologna,
- University of Cagliari.

IT4.3 Existing larger scale research infrastructure

Italy is part of ECCSEL European Research Infrastructure Consortium (ERIC), which constitutes an important reference point for technology and research. ECCSEL groups a network of excellent facilities, accessible to the national and international community, and facilitates the development of joint research projects on CCUS. ECCSEL is linked to the major national players on CCUS and to the running projects. Italy participates in ECCSEL with a total of 17 facilities and 5 facility owners:

OGS owns 8 facilities all dedicated to storage: the natural laboratories of Panarea and Latera, the Biomarine lab, PITOP geophysical test site, the calibration and metrology test site (CTMO), an aircraft for remote sensing surveys, OGS Explora research vessel and the DeepLab.

- Sotacarbo offers 6 facilities, dedicated to capture, utilisation and storage: Advantest Rock laboratory, PEC lab, COHYGEN, MEfCO_2 laboratory, Fault Lab and XtL pilot.
- ENEA, the University of Bologna and LEAP offer one facility each on capture ZECOMIX, MEMLAB and CO2Box, respectively.

The ECCSEL membership is planned to be expanded in the future, both in terms of facility owners and of new facilities.

IT4.4 Involvement in EU-funded and other regional/international research projects related to CCS

- ENOS (ENabling Onshore CO_2 Storage in Europe)
- ECCSELERATE (ECCSEL ERIC – accelerating user access, growing the membership and positioning internationally to ensure long- term sustainability)
- SUCCEED (Synergetic Utilisation of CO_2 storage Coupled with geothermal Energy Deployment)
- CLEANKER (CLEAN clinKER production by calcium looping process)
- Store&Go (Innovative Large Scale Energy STORagE Technologies & Power-to-Gas Concepts after Optimisation)
- MefCO_2 (Synthesis of methanol from captured carbon dioxide using surplus electricity)

IT5. National actors driving CCS forward and public engagement

IT5.1 Awareness of CCS technology

Awareness of the CCS technology is generally low in Italy, as in many other European countries (Eurobarometer 2011). Although there are no recent surveys, the situation has probably only slightly improved, given the low policy and media interest.

IT5.2 National advocates for CCS

CO_2 Club Italia was initiated in 2007 by a group of universities and research institutes and, since then, has been active to encourage collaboration between public and private research groups, promote contacts and information exchanges among all stakeholders, transfer and disseminate information through websites, organise conferences and seminars, formulate recommendations to research funding bodies regarding the organisation and start-up of interdisciplinary activities, and promote the Italian technological portfolio at European and international level. The interest in CCUS is also demonstrated by the Italian participation in international initiatives as SET Plan, CSLF, Innovation Fund.

IT5.3 Public engagement

In Italy, due to the absence of CCS projects, we can only refer to public engagement research experiences on hypothetical CO_2 storage installations. Interviews and focus groups have been performed in Rome and other parts of Italy by Sapienza University of Rome (Vercelli et al. 2015, Mabon et al. 2013). Participants, for the most part, had an open attitude towards the technology. However, the perception was easily influenced by the characteristics of the relational context in which the participants came to learn about it. An open and interactive format, which allowed for rich exchange and discussion, favoured collective reflection processes on the different aspects of the technology. A more frontal and directive approach appeared to stimulate more defensive reactions such as “not in my backyard”. Input from the participants has provided a rich set of recommendations for a practical approach to public perception issues.

Summarising the state-of-play on geological CO_2 storage in LATVIA (LV; as of 30th June 2021)

LV1. National storage assessment, storage options, potential and capacity

The largest estimated CO_2 storage capacity in Latvia is in the Cambrian Series 3 Deimena Formation estimated as 400 Mt onshore and more than 300 Mt CO_2 offshore (Sliaupa et al. 2013, Shogenov et al. 2013a, b, Shogenova et al. 2019). Since 2013 onshore storage capacity has been re-estimated for four Latvian onshore structures (Dobele, South-Kandava, Blidene and North Blidene) and for the E6 offshore structure (Shogenov et al. 2013a, b, Shogenov 2015, Simmer 2018, Shogenova et al. 2019).

The following common methodology was applied: Three-dimensional (3-D) structural models were constructed using structure maps of the top reservoir and wells cross sections. Static capacities were estimated using the formula reported in Bachu et al. (2007, 2008) and recommendations made by US DOE (2008). Optimistic and conservative estimations were based on various storage efficiency factors (10-20% for optimistic and 4% for conservative estimates). The average conservative-optimistic (C-O) storage capacity of E6 structure is about 150-380 Mt CO_2 (Shogenov et al. 2013b).

The capacity of the largest offshore structure E6 was additionally re-estimated recently for two different formations (Upper Ordovician Saldus F. and Cambrian Deimena F.) at the end of CO_2-EOR cycle in Upper Ordovician Saldus Formation. As a result average C-O storage capacity of the Latvian offshore E6 structure is about 265-490 Mt CO_2 (Shogenov and Shogenova 2017, 2021).

Overall, Latvia has very good geological options for CO_2 storage and could store CO_2 emissions captured in the Baltic Sea Region (BSR) countries without CO_2 storage potential. The largest Latvian emissions could be also stored together.

There is no national storage atlas available. Also, there has been no application for a CO_2 storage exploration permit.

LV2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

LV2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

None.

LV2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

LV2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

None.

LV2.4 Past and current full-chain CCS projects & projects/sites in preparation

None.

LV2.5 Plans for CCUS cluster development

The cement company SCHWENK Latvia (SCHWENK building material group) is planning to develop a CCUS project for its Broceni Cement Plant in Latvia. CO_2 will be captured by one of the CO_2 capture technologies recently developed for cement industry. Captured CO_2 could be transported to one of the prospective storage sites in Latvia (Dobele, or North-Blidene/Blidene). SCHWENK Latvia is planning to work on regulatory issues with the Latvian ministries and parliament and on public acceptance with local population. Currently storage is legally prohibited but the climate law is under review. Akmenes Cement Plant in Lithuania, recently acquired by SCHWENK Building materials group, could be considered as well to join the CO_2 capture and storage project (Source of information: Reinhold Schneider, SCHWENK Latvia, presentation on 7/10/21).

LV3. National policies, legislation and regulations

LV3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

Latvia has ratified the Paris Climate Agreement on 16th March 2017. In order for Latvia to achieve its objectives to progress towards climate neutrality and climate resilience, several key national level planning documents have been adopted. In July 2019, the Cabinet of Ministers endorsed the Latvian climate change adaptation plan for the period up to 2030, in order to help Latvian citizens and the economy to better adapt to climate change already happening and thereby mitigate the damage caused by climate change. In January 2020, the Cabinet of Ministers approved the Latvian strategy for the achievement of climate neutrality by 2050, a long-term vision document to ensure a single country's direction, as well as to justify the incorporation of a carbon low-capacity development framework into all sector planning documents. In January 2020, the Cabinet of Ministers also endorsed the Latvian national Energy and climate Plan 2021–2030, which provides for concrete measures to reduce GHG emissions and increase CO_2 uptake, to improve energy efficiency and promote renewables in the sectors of energy, agriculture, transport, etc. and to promote research and innovation in their respective fields.

Latvia submitted its 2050 climate and energy strategic targets to EC in January 2020, planning to decrease its emissions to 65% by 2030 and to 85% by 2040 compared to 1990 and to become climate neutral in 2050 (without Land use, land-use change, and forestry (LULUCF)). For LULUCF, it is planned to decrease Latvians emissions to 38% by 2030 and to 76% by 2040 compared to 1990 and to become climate neutral in 2050. The CCUS technology is also introduced in the Latvian strategy: “Introduction of technologies for storage and use of CO_2 emissions. Towards full decarbonisation, in addition to natural carbon sinks and storage systems, carbon capture and storage (CCS) and carbon capture and use (CCU) technologies could be introduced. Until now, when identifying potential geological storage sites in Latvia and performing cost modelling, it was concluded that the efficiency of CO_2 storage (CCS) construction sites is too low and such a solution would not be economically justified at present. However, further research is needed on the suitability and economic viability of CCS technologies in various industrial processes. CCU technologies, on the other hand, involve the processing of captured carbon for future use, for example in the production of plastics, concrete or fuel. The carbon reduction potential of a CCU needs to be estimated throughout its life cycle assessment”.

Latvia is not a party of London Conventions and London Protocol.

Latvia is a party of the OSPAR Convention under the European Union sign.

Latvia is a contracting party to the Helsinki Convention, 1992 (HELCOM).

LV3.2 National legislation and regulations

Latvia has made amendments to its national legislation to transpose the EU CCS Directive. A framework has been established for obtaining permits for CO_2 capture installations, requirements have been set to regulate CO_2 transportation and a purity criterion has been established. The Saeima (Latvian Parliament) has adopted legislative amendments prohibiting the storage of CO_2 within Latvia's borders, its exclusive economic zone, and on its continental shelf except for research purposes in amounts of up to 100 kt CO_2 (100,000 t). The duration of the ban is dependent on information to be provided by the Ministry of Environmental Protection and Regional Development to the Parliament. The Latvian Parliament will then use this information to determine whether to lift or maintain the ban. Latvia explained the ban by: i) lack of experience in using CCS technology on an industrial scale and dealing with its environmental impacts; ii) opposition from experts in the environmental authorities and from environmental organisations; iii) the absence of demand for CCS from Latvia's energy and industrial operators, as natural gas is used as a fuel almost exclusively and the capacity of combustion plants is small compared to the rest of the EU. Latvia's geological structures were intended to be used primarily for natural gas storage and for geothermal energy recovery (none of these plans are implemented up to now and there are no new developments).

Latvia approved the law "Arrangements for transporting carbon dioxide streams" in October 2011, which includes issues on transport networks, pipelines, transboundary transport. In more detail, the law (consisting of four paragraphs) defines the procedure for the transport of CO_2 streams through pipelines to storage sites in geological structures, the purity criteria for CO_2 streams ($\geq$ 96% CO_2) and the procedures for giving access to transport networks and storage sites. The law is mainly dedicated to regulating "third-party access", and only very shortly addresses transboundary transport by requiring a cooperation of competent authorities of both bordering Member States. It states that "The transport network operator shall provide a potential user of the transport network with access to the transport network for the transport of carbon dioxide streams through pipelines to areas where carbon dioxide storage is permitted. The operator of the transport network may deny access to the transport network, as a result of lack of capacity or connection". Also, cooperation between Member States is envisaged for the case when the transport network or the storage site is under the jurisdiction of two or more than two Member States.

Latvia has experience in transboundary transport of natural gas (from Russia), and its underground storage and supply when necessary to Estonia and Lithuania.

In Latvia the land including the subsurface belongs to the landlords. For onshore CO_2 storage in Latvian structures the permits from many small landlords will be required.

Table LV: Public authorities in Latvia responsible for the national transposition of the EU CCS Directive.

Competent Authority	Role
Ministry of Environmental Protection and Regional Development	Coordinates the transposition of the EU CCS Directive and cooperates with the Ministry of Justice in matters concerning the determination of jurisdiction and transboundary transport.
State Office of Environmental Monitoring	Ensures that the capture and storage for plants greater than 300 MW are evaluated.
State Environmental Service	Incorporates “capture readiness” requirements for combustion plants in their permits and is responsible for setting the requirements for CO_2 stream composition.

LV4. Research

LV4.1 National funding for research related to CCS and research priorities

There is no national funding for CCS research in Latvia. The CO_2 storage research for Latvia is done since 2013 by Estonian TalTech-DG researchers.

LV4.2 Research institutions involved in research related to CO_2 storage

LEGMA (now LEGMC - Latvian Environment, Geology and Meteorology Centre) participated in FP6 EU GeoCapacity and FP7 CGS Europe project. No ongoing research activities on CCS in Latvia. Department of Geology (former Institute of Geology) of Tallinn University of Technology has been involved in research related to CO_2 storage in Latvia since 2006, including FP6 EU GeoCapacity and CO_2NetEast projects, FP7 CGS Europe and CO_2StoP projects and ongoing Horizon 2020 ENOS and CLEANKER projects. Several Master and PhD theses on CO_2 storage have been defended. Estonian-Latvian CCUS scenarios are under development now in the CLEANKER project (Shogenova et al. 2021a, Shogenov & Shogenova 2019, 2021).

LV4.3 Existing larger scale research infrastructure

None.

LV4.4 Involvement in EU-funded and other regional/international research projects related to CCS

None for Latvian partners.

LV5. National actors driving CCS forward and public engagement

LV5.1 Awareness of CCS technology

Low awareness in Latvia.

LV5.2 National advocates for CCS

Odin Energi Latvia is a company owning hydrocarbon licences for Latvian offshore structures. This company and the governmental institution State Construction Control Bureau which is the supervising institution for Odin Energi Latvia, for its hydrocarbon exploration and production licence in Latvian offshore, could be considered as possible supporters of CCS in Latvia.

The cement company SCHWENK Latvia is a new advocate for CCUS in Latvia.

LV5.3 Public engagement

None.

Summarising the state-of-play on geological CO_2 storage in LITHUANIA (LT; as of 30th June 2021)

LT1. National storage assessment, storage options, potential and capacity

Šliaupa et al. (2013) evaluated Lithuania's CO_2 storage capacity in depleted oil fields as 5.7 Mt CO_2. Later work has shown the potential in the residual oil zone of the Cambrian Deimena Formation to be much greater (Haselton 2019, Shogenova et al. 2021b). A study of the capacity of 116 structures in the Lithuanian Cambrian aquifer showed that the two largest structures have a storage capacity of 8 Mt and 21 Mt CO_2, respectively. Storage capacity is also available in several structures offshore Lithuania. However, detailed estimation of their storage capacity have not been done yet, except for the small E7 structure, which was considered earlier as located in the Latvian economic zone. The average conservative-optimistic storage capacity of the E7 structure is about 7-34 Mt CO_2 (Shogenov et al. 2013b).

Potentially greater storage potential is available through CO_2-EOR in the Baltic Basin hydrocarbon province. The Danish-Lithuanian oil company Minijos Nafta investigated CO_2-EOR to exploit the residual oil zone (not otherwise exploitable) in the Cambrian sandstones in 2013 and 2015 based on CO_2 injection tests in three oil exploitation wells. The CO_2 was purchased from an Achema fertilizer plant in Lithuania. Obtained results showed about 250 Mt CO_2 storage potential in the west Lithuanian Gargzdai zone. Also, the study indicated that CO_2-EOR can increase recoverable oil reserves by up to 145 million barrels (Nordbäck et al. 2017, Haselton 2019).

LT2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

LT2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

According to a presentation made by Thomassen (2019), Fortum Oslo Varme AS (FOV) is planning a CO_2 capture pilot plant in Klaipeda at its combined heat and power plant. Annual volume of CO_2 generated is about 275,000 t/year. With a capture rate 95%, about 260,000 t CO_2 are planned to be captured annually (870 t daily). Captured CO_2 will include 50% of biogenic CO_2. Two capture technologies are evaluated based on Stockholm Exergi and FOV experience (amine scrubbing and hot potassium carbonate). Pilot plant testing was planned for 2020.

A memorandum of understanding (MoU) for NET Power emission-free, gas fired electric plants was signed for the CleanEnergy Project in Lithuania with NET Power, 8 Rivers and the Lithuanian Ministry of Energy in March 2019 (Haselton 2019). Talks have been initiated with the Northern Lights project regarding transport and storage of the captured CO_2 (Thomassen 2019). However, no progress or news are reported about this Fortum project at the present time.

LT2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

LT2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

CO_2-EOR was tested by Minijos Nafta in the Cambrian sandstones in 2013 and 2015 in the west Lithuanian Gargzdai zone in three oil exploitation wells (Nordbäck et al. 2017, Haselton 2019). The area of the Gargzdai uplift zone is 380 km^2, seven oil fields had been identified and commercially exploited in the zone. CO_2 injection experiments for EOR were performed in the Diegliai, the Pociai and the South Siupariai field. From the total amount of 1300 t CO_2 injected in the three wells, only 330 t CO_2 were recovered together with the oil while the rest stayed underground (Haselton 2019).

LT2.4 Past and current full-chain CCS projects & projects/sites in preparation

In 2019, plans for the Minijos Nafta “Clean Energy Project” were reported, which included building an Allam cycle power plant in western Lithuania with CO_2 capture, use of CO_2 for EOR, recycling and permanent CO_2 storage and to provide a storage site for other major GHG emitters in Lithuania (Haselton 2019).

LT2.5 Plans for CCUS cluster development

There is no concrete national initiative. Until recently, all possible activities were initiated by the Minijos Nafta company (for further details see Haselton 2019), but CO_2 injection activities had to cease after 1st July 2020 when the Lithuanian CO_2 injection ban of October 2019 came into force.

On 30th June 2021, the SCHWENK Building Materials Group acquired additional shares of the Akmenės Cementas AB cement plant in Lithuania, now holding a total of 97% of the company shares. SCHWENK reported recently that the Akmenės Cementas AB cement plant could be considered for CO_2 capture and storage project together with the Broceni cement plant in Latvia.

LT3. National policies, legislation and regulations

LT3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

Lithuania has ratified the Paris Climate Agreement on 2nd February 2017.

Lithuania's strategic objective of climate change mitigation is to ensure sustainable development, to achieve rapid economic growth and reduce GHG emissions. Together with the EU and the other Member States Lithuania aims to pursue long-term climate stabilisation-related objectives of the Paris Agreement by implementing a socially fair, competitive, innovative and cost-effective transformation of all sectors of the economy and achieve GHG emission neutrality by 2050. The strategic objective of climate change mitigation shall pursue the following objectives: to decrease GHG emissions by 20% in 2020, not less than for 40% in 2030, for 70% in 2040 and 80% in 2050 compared to 1990. GHG reduction targets for the non-EU-ETS participating sectors are set at the level of a maximum increase of 15% in 2020 compared to 2005 and a decrease for at least 9% by 2030 (Lietuvos Respublikos Seimas 2019). Reducing CO_2 levels through environmentally safe carbon capture and use technologies (CCU) are mentioned in the Lithuanian climate strategy, which is interpreted as "… projected growth in the number of green jobs for Lithuania in relevant areas: agriculture and forestry, energy production from RES, bioeconomy, green infrastructure, the circular economy, etc. […] An important role in promoting the transition to less polluting technologies should be carried out by charges for environmental pollution, CO_2 pricing system and the waiver of applicable subsidies for fossil fuels." CO_2 geological storage is not introduced in the Lithuanian strategy.

Lithuania is not a party of London Conventions and London Protocol.

Lithuania is a party of the OSPAR Convention under the European Union sign.

Lithuania is a contracting party to Helsinki Convention of 1992 (HELCOM).

LT3.2 National legislation and regulations

In 2011, two new legal acts were adopted in Lithuania to regulate the geological storage of CO_2 including licensing systems and implementation of the EU CCS Directive: 1) Law of the Republic of Lithuania on Geological Storage of Carbon Dioxide (Official Gazette, 2011, No 91-4325), referred to as "the Law"; and 2) Resolution No 1166 of the Government of the Republic of Lithuania of 5th October 2011 on the approval of the description of the procedure for exploration of carbon dioxide geological complexes, use and closure of carbon dioxide storage sites (Official Gazette, 2011, No 5833-123), referred to as "the Description". Also, in 28 legal acts, Lithuania transposed the specific provisions of the EU CCS Directive into national law.

Among the Baltic States, Lithuania was the only country allowing CO_2 geological storage both onshore and offshore up to October 2019. In October 2019, the new government of Lithuania with a large lobby from the agricultural party adopted a new Subsurface Law in Lithuania, by which the injection and/or storage of CO_2 in natural and / or artificial underground cavities and/or aquifers is prohibited. This ban for any injection of the CO_2 into the subsurface came into force on 1st July 2020.

LT4. Research

LT4.1 National funding for research related to CCS and research priorities

There is no national funding for CCS-related research in Lithuania at present.

LT4.2 Research institutions involved in research related to CO_2 storage

Institute of Geology and Geography of Nature Research Centre has been involved in research related to CO_2 storage since 2005, including the projects FP6 EU GeoCapacity and CO_2NetEast, FP7 CGS Europe and CO_2StoP and a subcontract to the Horizon 2020 project ENOS.

The PhD thesis "Prospects of CO_2 geological storage in the Baltic Sedimentary Basin", which included research on risk factors, was defended in 2014 by Rasa Šliaupienė (Šliaupienė & Sliaupa 2012, Šliaupienė 2014).

LT4.3 Existing larger scale research infrastructure

None.

LT4.4 Involvement in EU-funded and other regional/international research projects related to CCS

Institute of Geology and Geography of Nature Research Centre had a subcontract with the ENOS project for WP6.3 (pilots). Vilkyciai pilot project study for CO_2-EOR was prepared in the frame of this subcontract.

LT5. National actors driving CCS forward and public engagement

LT5.1 Awareness of CCS technology

Public awareness is low. There are no special surveys.

LT5.2 National advocates for CCS

Minijos Nafta company and Fortum are the most longstanding interested stakeholders in CCS. More recently, however, SCHWENK Building Materials Group can be also considered an industrial advocate for CCUS in Lithuania.

LT5.3 Public engagement

None.

Summarising the state-of-play on geological CO_2 storage in THE NETHERLANDS (NL; as of 30th June 2021)

NL1. National storage assessment, storage options, potential and capacity

The focus for CO_2 storage in the Netherlands is on depleted hydrocarbon (predominantly gas) fields where currently only offshore possibilities are being developed. The total theoretical storage capacity in Dutch offshore gas fields lies around 1.6 Gt spread over 150 fields. The effective capacity (minus unsuitable fields) of all offshore fields is around 900 Mt (NLOG 2020). The most extensive research conducted to establish the total storage capacities in the Netherlands can be found in the following reports:

- EBN-Gasunie report entitled "Transport en opslag van CO_2 in Nederland (in Dutch; EBN & Gasunie 2017),
- TNO-GCCSI report entitled "Independent assessment of high-capacity offshore CO_2 storage options (Neele et al. 2012).

Table NL1: Summary and breakdown of storage capacity and number of fields in the Netherlands (theoretical storage capacity, practical storage capacity; from EBN & Gasunie 2017). Note that the storage capacity of the giant Groningen gas field has not been included in the numbers for the onshore.

	Offshore		Onshore	
Theoretical storage capacity	2,246 Mt	222	1,392 Mt	172
Practical storage capacity	1,678 Mt (75%)	104 (47%)	1,060 Mt (76%)	54 (31%)

There is more than enough storage capacity in the Dutch offshore gas fields to store all CO_2 for the coming decades that can be realistically captured in the Netherlands. This estimation is based on three scenarios analysed by EBN and Gasunie, with a maximum potential of 30 Mt CO_2 to be stored per year (EBN & Gasunie 2017).

The option of EOR is not considered to have much potential for the Netherlands, TNO estimated a capacity of only 7 Mt CO_2, excluding the larger Schoonebeek field. The application of CO_2-EOR would require further site-specific studies and is not a current focus in the Netherlands.

Knowledge regarding deep saline aquifers is currently limited in the Netherlands with locations and potential not currently mapped in detail. The extent of the storage potential of deep saline aquifers is therefore not systematically determined. Neele et al. (2012) provided an estimate of the storage capacity for selected aquifers in the Dutch offshore of 1,370 to 1,485 Mt CO_2.

Finally, the option of salt caverns has also been considered. These caverns are mostly used for salt production or temporary gas storage (peak shavers). A theoretical capacity of 40 Mt CO_2 is estimated, but this would be spread over more than 100 caverns. Overall, the use of salt caverns for CO_2 storage in the Netherlands is not currently considered a practical option.

The P18-4 gas reservoir had an irrevocable permit for permanent storage in 2013, which was part of the ROAD CCS Project cancelled in 2017. A draft decision on the amendment of the P18-4 permit was made so that it fits to the requirements in the Porthos project. Recently applications for permanent storage permits have been prepared for the P18-2 and P18-6 gas reservoirs, which are planned to be used in the Porthos project together with the P18-4 reservoir (see Section NL2.4).

NL2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

NL2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

Since August 2019, CO_2 is captured from an AVR (Afvalverbranding Rijnmond) waste incineration stack in Duiven. A post-combustion capture installation with a capacity of 100 kt CO_2/year was installed which is sufficient for 25 to 30% of the CO_2 emission of the AVR plant. The captured CO_2 is sold to horticultural greenhouses for fertilisation purposes.

NL2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

Already since 2005, pure CO_2 is being transported via a pipeline operated by OCAP to end users in greenhouse farming. The CO_2 is produced at a refinery operated by Shell and since 2011 also from bioethanol production by Alco. Several hundred kilotons of CO_2 per year are delivered to more than 600 greenhouse farmers. In the future, the OCAP infrastructure may be connected with the Porthos network which is now being developed (see Section NL2.4).

NL2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

A CO_2 storage pilot in the offshore K12-B gas reservoir was in operation from 2004 to 2017 (Vandeweijer et al. 2018). In total, a little more than 100 kt CO_2 were injected.

NL2.4 Past and current full-chain CCS projects & projects/sites in preparation

Porthos is currently the most developed full-chain CCUS project in the Netherlands. The Porthos consortium will provide the transport and storage facilities and the emitters will be responsible for the capture processes. Porthos will transport the CO_2 from suppliers (suppliers are not yet formalised) via an onshore pipeline to a compressor station from where it will travel offshore by pipeline 20-25 km to economically depleted natural gas fields for storage. The Porthos Project concept is based on a collective pipeline of approximately 30-33 km that runs through Rotterdam's port area. This pipeline will serve as a basic infrastructure that a variety of industrial parties can connect to in order to dispose of the CO_2 captured at their facilities. Alongside storage, the Porthos infrastructure is also suitable for transporting CO_2 for use in industries. A share of this CO_2 will be used for greenhouse farming in the province of South Holland. By 2030, it is expected to be able to store between 2 and 5 Mt CO_2 every year. The project has been awarded PCI Status. Recently the Dutch government has made a reservation of EUR 2.2 billion for four CO_2 suppliers to be connected to the Porthos infrastructure (see also Section NL3.1).

Three offshore storage sites are planned: the P18-2, P18-4 and P18-6 depleted gas fields. All lie in the North Sea, all are accessible from the P18-A platform. TAQA is the operator and EBN is a co-shareholder in the natural gas extraction. TAQA already has a CO_2 storage permit for P18-4.

Previous projects include the **ROAD project** which was developed by Maasvlakte CCS Project C.V., a joint venture of E.ON Benelux and ENGIE Energie Nederland (known as GDF SUEZ Energie Nederland N.V. prior to April 2015). ROAD aimed to capture CO_2 from the flue gases of Maasvlakte Power Plant 3 (MPP3) using post-combustion capture technology. The captured CO_2 was then to be transported through a pipeline and injected into a depleted gas field under the North Sea. Due to financial uncertainty the project was cancelled in 2017.

A number of **onshore demonstration projects** have previously been prepared in the Netherlands, including storage in the depleted gas field of Barendrecht by Shell, storage below coal layers in the Limburg area (on the DSM industrial terrain Chemelot) by DSM and storage in the depleted gas fields Boerakker, Eleveld and Sebaldeburen in the Northern part of the Netherlands. However, mainly due to the lack of public support, onshore storage is not being developed further, since sufficient offshore storage capacity is available.

NL2.5 Plans for CCUS cluster development

The Porthos project will form part of an industrial cluster, with numerous CO_2 sources in the Port of Rotterdam planned to utilise one transport and storage system offshore. Currently, the Port of Rotterdam area has an existing system that delivers CO_2 from industrial emitters to greenhouses; the surplus CO_2 is currently being emitted. Porthos would form the first phase of a hub-and-cluster style development. Operations are planned to start in 2024. Many other hypothetical developments have been envisaged for The Port of Rotterdam. The Port of Rotterdam and Port of Antwerp attained PCI status for the cross-boundary transport infrastructure project CO_2TransPorts, which received CEF funding.

There is the potential to expand the industrial cluster even further by including other emitters in the Port of Rotterdam as well as the rest of the Netherlands, and potential connections with other nearby industrial clusters including Le Havre, Antwerp and the Ruhr area. This phase would include new transport and storage infrastructure including development of nearby aquifers, a pipeline between Antwerp and Rotterdam utilising existing pipeline corridors, CO_2 shipping connecting Le Havre, and inland shipping of CO_2 on the Rhine (Element Energy 2017).

The H (H_2)-Vision concept developed by The Port of Rotterdam involves the large-scale production of hydrogen using both natural gas and refinery fuel-gas as feedstock. The overall goal of the H-Vision concept is to enable significant CO_2 emissions reductions in the power and industrial sector in Rotterdam, while developing the infrastructure for "green hydrogen". The additional hydrogen produced can be used for high-temperature heating processes in the large refinery sector of the port, and also for power generation either through the use of gas turbines (able to run on hydrogen rich fuels), or through the conversion of existing coal-fired power plants. It is understood that the H-Vision concept could reduce CO_2 emissions from the processes in the port area by between 2 to 6 Mt per annum.

Other initiatives for CCS cluster development are centred around the Amsterdam harbour area (Athos), Eemshaven (H2M) and Den Helder (Aramis). A public-private consortium in the Athos project is studying the feasibility of capturing CCS from industrial sources in the Amsterdam region and to transport and store the CO_2 in the North Sea region. Start of operations is expected in 2027.

NL3. National policies, legislation and regulations

NL3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

The Dutch Climate Act calls for a 49% reduction in greenhouse gas emissions by 2030, compared to 1990 levels, and a 95% reduction by 2050. The National Climate Agreement contains agreements with the sectors on what they will do to help achieve these climate goals. The participating sectors are: electricity, industry, built environment, traffic and transport, and agriculture and land use. For full details, see:

- **Climate Act** in Dutch,
- **Climate Accord** in Dutch; Section C.3 treats measures for industry including CCS,
- **Joint fact finding document on CCS** supporting Climate Accord in Dutch,
- Background document with **CCS roadmap** for the Netherlands in Dutch.

Generally, CCS is recognised in the Netherlands as part of the suite of technologies required to reach the Paris Agreement targets. The coalition agreement of the Rutte III cabinet endorses the importance of CCS.

In 2019, the Dutch subsidy scheme for Demonstrating Energy Innovation (Demonstratie Energie-Innovatie, DEI) was altered significantly. More emphasis is now placed on the condition for achieving CO_2 reductions in pilot and demonstration projects, and new types of projects have become applicable. The subsidy scheme is now open and the Netherlands Enterprise Agency (RVO.nl), is assessing proposals on a first-come-first-served basis.

The scheme was previously intended to showcase Dutch energy innovations, particularly for the export of new technologies. From 2019, there is more emphasis on technologies that can contribute to achieving the national climate agreement "het Klimaatakkoord". CO_2 reduction technologies for industry, including CO_2 capture, storage and use (CCUS) are now applicable for funding.

Recently (February 2020) the SDE ++ subsidy was released. In 2020, the SDE ++ was opened to various categories of CCS. The SDE ++ offers subsidies for the use of renewable energy technologies and other CO_2 reducing technologies. The "unprofitable top" is subsidised for each technique. This is the difference between the cost price of the technology that reduces the CO_2 (the "base amount") and the market value of the product that the technology produces (the "correction amount"). The base amount is determined for the entire duration of the subsidy, while the correction amount is determined annually. If the market value rises, the unprofitable top will decrease and so will the subsidy (RVO 2020). The SDE ++ subsidy for CCS has a cap of 7.2 Mt CO_2. From 2035 onwards CCS will only be subsidised if it results in negative emissions (Climate Plan 2020).

NL3.2 National legislation and regulations

The Netherlands has strict regulations and permitting requirements regarding mining activities. The regulations for offshore mining activities are built around the already existing hydrocarbon production industry. Amendments have been made to the Dutch Mining Act to allow for the storage of CO_2, as a result of the implementation of the EU CCS Directive into national law in 2011 (Directive 2009/31/EC). The Netherlands is also a contracting party to both the 1996 London Protocol and the 1992 OSPAR Convention. Both the London Protocol and OSPAR Convention are recognised in the legal text of the Dutch Mining Decree, and although the contents of their associated guidelines have not been transposed into the Decree, they are applicable to all mining activities covered by the Mining Act. A majority of the regulatory framework regarding wells is based on use with hydrocarbons although use with CO_2 is permitted. None of the current standards or best practice documents contain reference to the re-use of offshore wells for CO_2 injection. In 2021 the Mining Act was amended so that operators can obtain an exemption of decommissioning gas production infrastructure, e.g. for the purpose of re-using wells.

Currently there are no fully integrated commercial CCS projects operational in the Netherlands and the re-use of a well for permanent CO_2 storage has not been undertaken since the European CCS Directive was implemented in 2011. Permits have been issued for the re-use of wells though, and CO_2 was injected at the K12-B field from 2004–2017 for enhanced gas recovery purposes. The K12-B project re-used a gas production well for the injection of CO_2. A CO_2 storage permit has also been issued in the Netherlands, to the ROAD project, for the storage of CO_2 in the P18-4 gas field although this project never entered into operation. Due to the lack of commercial CCS operations, the Dutch National Framework is currently lacking CO_2 specific legislation and standards for wells and for the reuse of wells. Such legislation would greatly aid the commercial development of CCS projects. To date the State Authority of Mines considers the current law and rules to be adequate for CO_2 related wells.

Across the full CCS chain different elements are covered by different permitting requirements. The legislative requirements for a CO_2 storage permit, which would include well requirements, are given by The Dutch Mining Act (Mijnbouwwet). The competent authority regarding the Mining Act and therefore CO_2 storage is the Ministry of Economic Affairs and Climate Policy.

NL4. Research

NL4.1 National funding for research related to CCS and research priorities

CATO is the Dutch national R&D programme for CO_2 capture, transport and storage in which a consortium of nearly 40 partners contributes. Building on the success of the first two funding programmes CATO-1 and CATO-2 which finished in 2014 the Dutch CATO programme is still underway today. Besides the financial contributions of industrial partners, the third phase of CATO will be funded by government sources, such as TKI, CLIMIT, and EU ERA-NET.

The CATO programme office coordinates all the programmes under the CATO umbrella to strengthen the CSS network and knowledge transfer. Participants in the CATO programme are or have been involved in many projects and networks regarding CCS, such as those funded by the 6. and 7. EU Framework Programmes, as well as H2020 activities. This helps to ensure coordination with ongoing and envisaged research efforts. For those projects that do not include any CATO participants, CATO seeks to maintain close contact and learn from their findings. Members of the CATO programme are also involved in international boards such as IEAGHG and ETP-ZEP.

Alongside CATO, individual research institutes, universities and companies take part in various EU projects with partners from industry, SMEs, and NGOs.

Table NL2: Overview of research topics addressed by the nationally-funded research programme CATO.

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	(x)	X	X	X	X	X	X	X	X

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

NL4.2 Research institutions involved in research related to CO_2 storage

Research institutes involved in CO_2 storage research include:

- TNO Energy Transition;
- Universities: Delft University of Technology, Utrecht University, VU University Amsterdam, University of Groningen.

Furthermore, large industrial partners involved in CATO subproject 3 on CO_2 storage and monitoring, include: Shell, E.ON, RWE, Electrabel GDF-Suez, TAQA, EBN, Wintershall, and Schlumberger.

Smaller partners include: Panterra, IF, DAP and the Rotterdam Climate Initiative.

A full list of participants to CATO can be found at the CATO website.

NL4.3 Existing larger scale research infrastructure

The Netherlands (TNO) has capture test facilities for post-combustion capture (solvent and membranes) and chemical looping:

- Mini Plant for solvent preparation & testing, Delft
- QSCAN solvent test street, Delft
- Chemical looping combustion fixed bed facility, Delft
- High pressure absorption and desorption pilot, Delft
- Aerosol Test and Counter Measure, Delft

For storage technology, TNO has the following facilities:

- Mobile Seismic Array (MobSeis), Utrecht
- Test Rig and Large Well (RCSG), Rijswijk

Details can be found on the ECCSEL website.

NL4.4 Involvement in EU-funded and other regional/international research projects related to CCS

TNO is currently or has been involved in the following EU-funded research projects addressing aspects relevant for/related to CCS:

- Enabling onshore CO_2 storage in Europe, ENOS (H2020 project)
- Accelerating Low carbon Industrial Growth through CCUS, ALIGN CCUS (ACT project)
- Reusing existing wells for CO_2 storage operations, REX-CO2 (ACT project)
- CCUS Knowledge Sharing Network
- Establishing CO_2 enhanced Oil recovery Business Advantages in South Eastern Europe, ECOBASE (ACT project)
- Demonstrating a Refinery-Adapted Cluster-Integrated Strategy to Enable Full-Chain CCUS Implementation, REALISE (H2020 project)
- Pressure control and conformance management for safe and efficient CO_2 storage - Accelerating CCS Technologies, Pre-ACT (ACT project)

- Digital Monitoring of CO_2 storage projects, DIGIMON (ACT project)
- The Norwegian CCS Research Centre, NCCS (public-private funding)
- Subsurface Evaluation of CCS and Unconventional Risks, SECURe (H2020 project)
- European Research Infrastructure for CO_2 Capture, Utilisation, Transport and Storage (CCUS), ECCSEL (European Research Infrastructure Consortium) and project ECCSELARATE

NL5. National actors driving CCS forward and public engagement

NL5.1 Awareness of CCS technology

The extensive review of the Dutch public opinion and awareness of CCS undertaken over 12 years ago as part of the CATO project (Paukovic et al. 2011) determined that overall awareness of CCS is low, and the understanding of the drivers and intricacy of climate change science is also relatively poorly understood by the general public. More recent investigations in the ALIGN-CCUS project (ALIGN-CCUS 2021) revealed that the awareness of the Dutch public of CCS is moderate. Opinions of informed citizens were found to be neutral to slightly positive.

NL5.2 National advocates for CCS

None.

NL5.3 Public engagement

Probably, Barendrecht is the most well-known case study currently available for its issues around public acceptance. Public acceptance was a key challenge for the project given its location in a densely populated area and in-depth reviews have been undertaken (Kuijper 2011). One of the key lesson from the Barendrecht project is that in the case of publicly co-funded projects it is essential that the authorities and the companies involved work together very closely from the start in developing a public engagement strategy. In the Netherlands opinions on the need for CCS are still hotly debated within and between different organisations including political parties, knowledge institutes and NGOs. As a result, there are many stakeholders with an interest in the success or failure of demonstration projects.

Summarising the state-of-play on geological CO_2 storage in NORWAY (NO; as of 30th June 2021)

NO1. National storage assessment, storage options, potential and capacity

Apart from the not-fully-explored storage potential on Svalbard (Braathen et al. 2012), there are no on-shore sedimentary basins suited for CO_2 storage in Norway. Capacity assessments are therefore at present exclusively based on saline aquifers and depleted petroleum reservoirs in offshore areas. The Norwegian Petroleum Directorate (NPD) has compiled an online CO_2 Atlas for the Norwegian Continental Shelf. The Atlas includes interactive maps providing an overview of potential storage sites in the Norwegian North Sea, the Norwegian Sea and the southern Barents Sea.

Assessments of individual aquifers and structures with respect to capacity, injectivity and safe storage of CO_2, were carried out using a standardised checklist based on petroleum industry experience. The assessments include estimates of reservoir thickness and permeability, seal quality, the quality of data coverage, technical maturity, the presence of old wells penetrating the seal, and dense-phase CO_2 storage as the safest and most efficient storage option. For some areas, poor seismic data coverage and absence of well data constrain the precision of the estimates. The assessment of storage capacity does not address economic aspects. The most recently-updated total for offshore storage capacity - most of it defined as exploration phase (Halland 2019) - is around 70 Gt, which represents a substantial increase over previous estimates of 29 Gt by Vangkilde-Pedersen (2009) and 48.4 Gt by Halland et al. (2014). Due to the presence of aquifers suitable for storage at several stratigraphic levels, where the Jurassic forms the main potential target for CO_2 injection, the total capacity of the North Sea aquifers is much larger than for the other regions.

The first permit by the authorities to exploit an area for injection and storage of CO_2 was awarded in January 2019 to the Northern Lights project. The project is a collaboration between Equinor, Shell and Total, involving capture of up to 1.5 million tons of CO_2 per year from industrial sources on land, subsequent transport by ship and pipeline and sub-surface sequestration in the Johansen and Cook Formations at 2700 m depth, southeast of the Troll field in the North Sea. Northern Lights supports the ambition of the Norwegian government to develop a full-scale CCS value chain by 2024. A plan for development and operation of the site was submitted to the Ministry of Petroleum and Energy on 15th May 2020. An investment decision by the Norwegian Parliament is expected in 2020/2021. The facility will become operational early in 2025, with a planned lifetime of 25 years and a storage capacity close to 40 Gt in phase one. Phase two envisages an expansion to an injection capacity of 5 Mt CO_2/year.

NO2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

NO2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

Carbon capture at Fortum Varme's waste-incineration plant at Klemetsrud, Oslo. Initiative aiming to capture 400,000 tons/year (or 90%) of CO_2 emissions from the plant, employing Shell's CANSOLV CO_2 carbon capture technology, which was approved by DNV GL as qualified for a full-scale demonstration project in July 2020 following more than 5000 hours of testing during the FEED-phase in 2019. Full-scale capture is expected to be operational by 2023/2024. The facility is part of the Northern Lights CCS value chain.

Carbon capture at NORCEM's cement factory in Brevik aims to capture 400,000 tons/year (or 50%) of CO_2 emission from the plant. The facility is part of the Northern Lights CCS value chain. DNV-GL awarded a "Statement of Qualified Technology" for the capture technology supplied by Aker Solution in April 2020. In June, the company owners approved and recommended full-scale development of the capture facility, pending a final decision on government financial support expected in autumn 2020.

SINTEF AS CO_2 capture pilot plant at Tiller. Test facility for development of post-combustion CO_2 capture. Active Since 2010, it consists of a complete absorption and desorption plant with a CO_2 capacity of 50 kg CO_2/h. The facility is part of ECCSEL.

Technology Centre Mongstad, TCM, was established with the aim of capturing CO_2 emissions from the petroleum refinery plant at Mongstad in 2012. Plans for full-scale capture were cancelled by the government in 2017, but the facility is now the world's largest a test centre for CO_2 capture technologies (see also NO4.3).

NO2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

The Snøhvit facility on Melkeøya. Up to 700,000 tons of CO_2 from the natural gas production at the Snøhvit field in the Barents Sea is separated out of the natural gas using amines at the onshore pipeline terminus at Melkeøya near Hammerfest, and transported back to the field by a second, 145 km long, pipeline for re-injection (see NO2.3 for details).

The **CCB Kollsnes** storage terminal and pumping station near Bergen is part of the Northern Lights CCS value chain. CO_2 captured from industrial plants in Eastern Norway will be shipped to Kollsnes for interim storage before being transported offshore by a pipeline and injected for permanent storage 1000-2000 m below the seabed.

NO2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

At the **Sleipner field**, operated by Equinor, close to 1 Mt CO_2 are annually separated from production of natural gas and re-injected into the Utsira Formation (Baklid et al. 1996, Furre et al. 2017, Ringrose 2018). The operation has been active and closely monitored since 1996 providing a good case study for long-term reservoir response to CO_2 injection.

The **Snøhvit field** is a gas field in the Barents Sea operated by Equinor. Since 2008, 700,000 t CO_2 from the gas production from the Early and Middle Jurassic Nordmela and Stø Formations has annually been separated out at the onshore pipeline terminus and piped back to the field for re-injection into the Stø Formation below the actual gas field. Initially, CO_2 was re-injected into the Early Jurassic Tubåen Formation where the storage capacity was discovered to be less than expected (Grude et al. 2014).

The **UNIS CO_2 lab** located near Longyearbyen was initiated in 2011 building on CO_2 research conducted at the University Centre in Svalbard (UNIS), the laboratory has carried out studies aimed at implementing a full CCS chain involving the capture of CO_2 from Norway's only coal-fuelled power plant and injection into the Triassic aquifer below Longyearbyen. A comprehensive evaluation of the storage site was carried out, including extensive outcrop and seismic studies, and drilling, logging and sampling of a number of wells (Braathen et al. 2012, Ogata et al. 2012, Bohloli et al. 2014; Olaussen et al. 2019). All data and publications from the project can be accessed for research purposes through the UNIS CO_2 website. The initiative was funded through a combination of governmental grants through the CLIMIT programme of the Norwegian Research Council and industry partners, and involved a number of Norwegian universities and research Institutes.

NO2.4 Past and current full-chain CCS projects & projects/sites in preparation

Northern Lights (see above).

NO2.5 Plans for CCUS cluster development

Northern Lights (see above).

NO3. National policies, legislation and regulations

NO3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

As of February 2020, Norway's updated climate target under the Paris agreement (NDCs), is to reduce emissions by at least 50%, and towards 55% by 2030 compared to 1990 levels. This is in line with the emissions pathways towards 2050 and onwards, as described by the IPCC special report on the impacts of global warming as necessary to limit global warming to 1.5 °C, and corresponds to the global long-term goal of the Paris Agreement. The Norwegian authorities' choice of measures is based on the principle that emitters should bear the cost of emissions. More than 80% of GHG emissions in Norway are subject to tariffs or part of the common European quota system (EU-ETS) limiting emissions from industry, power generation, petroleum industry and air transport. Quotas assigned to emitters are reduced annually to achieve a 43% emission reduction by 2030 compared to 2005. In addition to tariffs and quotas, the government employs law, regulations, and incentives. Oil heating of buildings is to be prohibited as of 2020. The 2017 law of Public Acquisition includes an environmental clause encouraging the use of climate-friendly options, and development of urban areas is to include comprehensive solutions for collective transport and extensive, bicycle paths and pedestrian areas. The governmentally-supported electrification of the transport sector is already well established, with Norway currently sporting the highest number of electric cars per capita of any country. There are several governmental support measures to encourage development of reduced or zero-emission solutions. These include Enova and Klimasats, organised under the Ministry of Climate and Environment and contributing to a national change in energy production and usage. There are also several dedicated programmes funded through the Norwegian Research Council supporting basic and applied research and development of environmental friendly energy and handling of greenhouse gases. About 50% of the financial portfolio of Innovasjon Norge, the Norwegian government's instrument for innovation and development of national enterprises and industries, has an environmentally-focussed profile.

The Norwegian government concurs with statements by the IPCC and the IEA that achieving climate goals will be difficult and significantly more costly to reach without CCS. Norway's national strategy for CCS includes research, development and demonstration of CCS technology and realising a full-scale project with international dissemination potential. The latter has come into fruition through the Northern Lights project currently being assessed by the government for implementation.

NO3.2 National legislation and regulations

The EU CCS Directive entered into force for Norway in 2014 (Vold 2020). Responsibility for implementation of the Directive in Norway is delegated to the Ministry for Petroleum and Energy (resource management) and the Ministry for Climate and Environment (environmental issues). The Ministry of Petroleum and Energy has the main responsibility for enacting governmental strategies regarding CO_2 handling. The interests of the Norwegian State in relation to CCS are managed by Gassnova, a state enterprise responsible for maturing full-scale CCS projects in Norway to the investment decision stage.

A dedicated legal regulatory framework for transport and sub-sea CO_2 storage on the Norwegian continental shelf was introduced in 2014. This includes regulations on the utilisation of subsea reservoirs on the continental shelf for the storage of CO_2 and on the transport of CO_2 on the continental shelf. These supplement the 1963 Act on Research, Exploration and Exploitation of Other Natural Resources than Petroleum on the Ocean Floor (the Continental Shelf Act), the 1981 Pollution and Waste Act, and the 1996 Petroleum Activities Act.

NO4. Research

NO4.1 National funding for research related to CCS and research priorities

For 2020, the Norwegian government allocated NOK 628 million for CCS research. The funds are managed by the CLIMIT programme – which covers both the support scheme for research and development (CLIMIT R&D) administered by the Norwegian Research Council (NRC), and Gassnova's support scheme for development and demonstration of technology for CO_2 capture and storage (CLIMIT Demo) including the Mongstad TCM facility. CO_2 storage-related research on site characterisation, storage capacities, well technology and modelling has also been funded through the PETROMAKS2 programme. NRC funding schemes range from research projects solely funded by the NRC to projects involving 20-50% industry sponsorship. The NRC also provides multi-year funding for several time-limited centres for environmentally-friendly energy (FME), including the former SUCCESS (2010–2018), and BIGCCS (2008–2016), and the present NCCS (Norwegian CCS Centre, 2016–2024). Industry involvement in CCS-related research in Norway is substantial (e.g. by Equinor, Aker Solutions), with companies contributing to CCS research related to their commercial activities either through in-house research, acting as sponsors for research projects proposed by the universities and institute sector, or providing financial and in-kind support for research centres.

Table NO: Overview of research topics addressed by recent nationally funded research projects on CO_2 storage (if no project acronyms are available, shortened project titles are used in the table with full names and links given below). For a comprehensive overview of nationally funded research projects in Norway visit the CLIMIT website.

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	X	X	X	X	X		X	X	X
Project examples	Injection well management ...	PREEM CCS CO2-Hub Nordland	Injection well management… . EDDiCCUT	REX-CO2 O2 limits	ECO2 TrykkCO2	Protection of Caprock Integrity … CO2SafeArrest	CONQUER MatMoRA-II Real-Time Monitoring…	DigiMon Passive sampler for monitoring Prediction of CO_2 leakage … ACT4storage	PERCCSEPTIONS

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

Full project names and links:

- Subsurface storage of CO_2 – Injection well management during the operational phase
- Techno-Economic Feasibility Study of the Implementation of Carbon Capture from Major Emission Sources at Preemraff Lysekil" (PREEM CCS)
- CO_2-Hub Nordland
- EDDiCCUT (Environmental Due Diligence of CO_2 Capture and Utilization Technologies)
- Reusing existing wells for CO_2 storage operations (REX-CO_2)
- Materials selection for CO_2 transport and injection wells - O_2 limits
- Sub-seabed CO_2 Storage: Impact on Marine Ecosystems (ECO2)
- Environmental impacts of leakage from sub-seabed CO_2 storage (TrykkCO_2)
- Protection of Caprock Integrity for Large-Scale CO_2 Storage
- Improving safety and efficiency of CO_2 pipelines by developing and validating predictive models for CO_2 pipeline design (CO_2SafeArrest)
- CO_2 Storage in the North Sea: Quantification of Uncertainties and Error Reduction (CONQUER)
- Geological Storage of CO_2, Mathematical Modeling and Risk Assessment (MatMoRA-II)
- Real-Time Monitoring for Safe Geological CO_2 Storage (DigiMon)
- Passive sampler for monitoring of CO_2 leakage
- Prediction of CO_2 leakage from reservoirs during large scale storage
- Acoustic and Chemical Technologies for environmental monitoring of geological carbon storage (ACT4storage)
- Public perceptions of carbon capture and storage (PERCCSEPTIONS)

NO4.2 Research institutions involved in research related to CO_2 storage

Major:

- SINTEF Energy Research AS
- SINTEF Tel-tek
- NTNU Norwegian University of Science and Technology
- NORCE Norwegian Research Centre AS
- NIVA Norwegian Institute for Water Research
- IFE Institute for Energy Technology
- NGI Norwegian Geotechnical Institute
- NPD Norwegian Petroleum Directorate
- DNV-GL Det Norske Veritas-Germanischer Lloyd

Minor:

- University of Bergen
- University of Oslo
- University of Tromsø
- University Centre in Svalbard
- NGU Geological Survey of Norway
- USN University of South-Eastern Norway

NO4.3 Existing larger scale research infrastructure

The **Technology Center at Mongstad (TCM)**. Established in 2012, TCM is a test centre for developing CO_2 capture technologies operated by Equinor and owned by the Norwegian State through Gassnova with Equinor, Shell and Total as industrial partners. The main objective of TCM is to test, verify and demonstrate different technologies related to cost-efficient and industrial scale CO_2-capture. Since the operational start-up in 2012, Aker Solutions (Norway), Alstom SA (France), Cansolv Technologies Inc. (Canada), Carbon Clean Solutions (UK/India), ION Engineering (USA) and Fluor Corporation (USA) have tested their technologies at TCM. The centre collaborates with a number of international and national research institutes and universities.

Svelvik CO_2 Field Lab: Initiated in 2009, the Svelvik Field Lab is part of the ECCSEL infrastructure. Four 100 m deep wells spaced 10 to 20 metres from a central injection well are used to study CO_2 migration in the shallow subsurface, identify possible leakage pathways and assess the suitability of different monitoring techniques. The field laboratory is operated by SINTEF in collaboration with partners from the institute and academic sector as well as industry.

NTNU, the Norwegian University of Science and Technology, and the research institute SINTEF in Trondheim host a 8,000 square metre, EUR 40 million research facility, where 750 people work at mitigating emissions like CO_2, NO_x, SO_x and other greenhouse gases. The facility is part of ECCSEL with laboratories for fabrication of polymer-based membranes, testing of membrane gas permeation performance, absorption kinetics, solvent degradation and thermodynamic studies.

NCCS, the Norwegian CCS Research Centre is a national Centre for Environment-friendly Energy Research (FME) funded by the Norwegian Research Council and industry for eight years (2016–2024). It is part of the Norwegian government objective for realisation of a full-scale CCS chain by 2022. The NCCS vision is to address the major obstacles within demonstration and industry projects worldwide.

The FALCON **CO_2 Flow Loop Laboratory** operated by the Norwegian Institute for Energy Research (IFE), operational since 2011, consists of a tiltable rig to test long distance pipeline transport of pure CO_2 or CO_2 mixtures ranging from low pressure vapour flow to supercritical flow.

DeFACTO CO_2 flow loop facility is operated by SINTEF in Trondheim, Norway, and comprises a 139 m horizontal and up to 90 m (depth) vertical loops for the Demonstration of Flow Assurance for CO_2 Transport Operations.

Equinor operates a **CO_2 multiphase test rig** at their Porsgrunn refinery R&D facilities, in partnership with Total, Gassnova and Gassco (Andersen et al. 2021). The flow loop is the world's largest test facility for CO_2 transport, has a 200 m pipe line with an 80 mm inside diameter and a section that can be inclined to 10°. It is a modification, completed in 2020, to the gas-oil-water multiphase pipeline transport test rig built in 1997. The modification allows study of simultaneous pipeline transport of CO_2 in gas and liquid phases. Research results are considered important for determining pipeline routes and which reservoirs can be utilised, especially for the CO_2 transport and storage project Northern Lights.

NO4.4 Involvement in EU-funded and other regional/international research projects related to CCS

Norwegian participation in recent (post 2013) and current EU-funded, regional and international research projects:

- Accelerating Carbon Capture using Oxyfuel Technology in Cement Production (AC^2OCEM)
- Act on Offshore Monitoring (ACTOM)
- Digital Monitoring of CO_2 storage projects (DIGIMON)

- Lowering absorption process uncertainty, risks and costs by predicting and controlling amine degradation (LAUNCH)
- Innovative membrane systems for CO_2 capture and storage at sea (MemCCSea)
- Negative Emissions in the Waste-to-Energy Sector: Technologies for Carbon Capture, Utilisation & Storage (NEWEST-CCUS)
- Process-Informed design of tailor-made Sorbent Materials for energy efficient carbon capture (PrISMa)
- Reusing existing wells for CO_2 storage operations (REX-CO_2)
- Assuring integrity of CO_2 storage sites through ground surface monitoring (SENSE)
- Accelerating Low carbon Industrial Growth through CCUS (ALIGN CCUS)
- Enabling a Low-Carbon Economy via Hydrogen and CCS (ELEGANCY)
- Pressure control and conformance management for safe and efficient CO_2 storage - Accelerating CCS Technologies (Pre-ACT)
- ACORN
- Establishing CO_2 enhanced Oil recovery Business Advantages in South Eastern Europe (ECOBASE)
- Demonstration of Gas Switching Technology for Accelerated Scale-up of Pressurised Chemical Looping Applications (GASTECH)
- Three Dimensional Printed Capture Materials for Productivity Step-Change (3D-CAPS)
- Strategies for Environmental Monitoring of Marine Carbon Capture and Storage (STEMM-CCS)
- Towards a transport infrastructure for large-scale CCS in Europe (CO_2Europipe)
- NordiCCS – Nordic CCS Competence Centre

NO5. National actors driving CCS forward and public engagement

NO5.1 Awareness of CCS technology

Awareness about CCS in Norway is relatively high (Whitmarsh et al. 2019, Coombes 2019). CCS is a very visible topic in public discussions in Norway, partly due to increased media and public attention to climate issues, but also governmental investment in high-profile projects such as Mongstad and Northern Lights have contributed to raise awareness of and knowledge about CCS technology, although Bryhn et al. (2018) suggest that CCS is too technical in the manner it is presented to the public, which creates a barrier for the public in understanding CCS.

NO5.2 National advocates for CCS

There is a broad consensus in favour of CCS among all political parties. This commitment is evident and visible in their political programmes and part of public discourse.

Environmental NGOs such as Bellona and Norges Naturvernforbund (Friends of the Earth Norway), and ZERO are strong and visible supporters of CCS.

Development of CCS technology in Norway is also jointly supported by the Confederation of Norwegian Enterprise (NHO) and the trade unions.

NO5.3 Public engagement

Given the general awareness of climate change and the visibility of high profile, mainly publically funded CCS projects, public engagement is very visible. Similar to what is seen in public discussions on climate change, the discourse on CCS in social media and public press and popular science journals is often polarised. Critics express doubts about the necessity of CCS, the global effect of Norway investing in carbon storage, the cost to the public and, to some extent, safety concerns. Supporters emphasise the need for mitigating GHG national emission, taking our share of global responsibility, and striving to set an example for other countries to follow. In general the public supports the government's efforts toward CCS.

According to Karlstrøm and Ryghaug (2014), public attitudes to CCS in Norway (related to production of natural gas) was "neither positive nor negative", reflecting discussions over the environmental merits of CCS. The same study also suggests that public and broad political support for CCS in Norway could be due to it being associated with industrial development. As suggested by Leiss and Larkin (2019) and Coombes (2019) the fact that storage in Norway will be carried out offshore, away from populated areas make it easier for the public to accept.

Summarising the state-of-play on geological CO_2 storage in POLAND (PL; as of 30th June 2021)

PL1. National storage assessment, storage options, potential and capacity

The national programme "Assessment of formations and structures for safe CO_2 geological storage, including monitoring plans" (2008–2012) included an itemisation and pre-characterisation of formations and structures suitable for CO_2 storage, provided that further surveys under exploration permits for storage sites are carried out. These results are the basis for the preparation of work-plans for detailed geological characterisation of a potential storage site and baseline monitoring, including drilling of new exploratory wells (or CO_2 test injection wells), new seismic and other geophysical surveys.

As part of the regional studies an estimate of the CO_2 storage potential for the considered geological formations and structures has been provided. These estimates relate to the static, effective storage capacity. The (very roughly) estimated potential for storage in saline aquifers is 11.66 Gt CO_2 for 45 structures in the formations of Paleozoic, Mesozoic (the greatest potential, especially for the Jurassic) and Cenozoic (Miocene). If we omit the Cretaceous structures, an estimated storage potential of 9.17 Gt for the 35 structures remains. Additionally, for regional Cambrian and Carboniferous aquifers the potential was estimated as 2.84 Gt. Hence, the saline aquifers have a total storage potential of approximately 12-14.5 Gt (Wójcicki et al. 2014).

The potential for storage in the hydrocarbon structures is 784-1,021 Mt. These are mostly depleted gas fields; the share of the selected oil fields, of various degree of depletion, is less than 10% of the above values.

The potential for storage in coal beds can be estimated as 20-100 Mt CO_2 (the first value is for the considered possible exploration permit areas within the Upper Silesian Coal Basin (USCB), the second for the entire considered area of USCB - coal seams at depths of 1-2 km; Wójcicki et al. 2014).

Research works related to CO_2 storage assessment, storage options, potentials and capacities are currently conducted in the framework of the STRATEGY CCUS project which will provide each of the promising regions in Southern and Eastern Europe (including Silesia region in Poland) with CCUS scenarios for short, medium and long-term delivery, and based on results from various completed and current European projects. The scenarios will consider a wide range of issues, including CO_2 storage capacity.

The "Interactive Atlas of presenting the possibility of geological sequestration of CO_2 in Poland" has been created based on the results of the national programme "Assessment of formations and structures for safe CO_2 geological storage, including monitoring plans" (Wójcicki et al. 2008, Wójcicki et al. 2014).

No application for a CO_2-storage exploration license has been submitted, nor has a license for CO_2 storage in Poland been granted to date.

PL2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

PL2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

- TAURON Wytwarzanie SA Łagisza Power Plant – adsorption DR-VPSA (Dual-Reflux Vacuum-Pressure Swing Adsorption), hard coal, fluidised bed boiler for supercritical parameters 460 MWe, 100 m^3n/h of flue gas, 13% CO_2, capture rate 90%, years 2013–2014. Funding from National Centre for Research and Development, Research Task no 2 of the strategic programme "Advanced energy technologies" realised in years 2010–2015 by Częstochowa University of Technology, Eurol Innovative Technology Solutions Sp. z o.o., TAURON Wytwarzanie S.A.
- TAURON Wytwarzanie SA Łaziska Power Plant – a pilot amine-based CO_2 capture plant. Funding from industry: TAURON Polska Energia and TAURON Wytwarzanie S.A. Two directions of research: 1) CO_2 capture, with funding from the National Centre for Research and Development, Research Task no 1 of the strategic programme "Advanced energy technologies", from a power plant with the parameters hard coal, a pulverised bed boiler (200 MW), 200 m^3n/h of the flue gas, 13.5% CO_2, and a capture rate of 90%. 2) CO_2 conversion: The KicInnoEnergy CO_2-SNG project demonstrating the conversion of CO_2 captured from the flue gas plus hydrogen produced by an electrolyser to synthetic natural gas (SNG).
- Jaworzno III – the mobile installation created in the Łaziska Power Plant was utilised in the Jaworzno power plant for the investigation of capture processes on fluidised bed boiler (2018–2019).

PL2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

There were no projects oriented only to transport. CO_2 transport was always part of other projects.

PL2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

Studies for establishing a future CO_2 test injection at a site close to the TAURON power plants (Southern Poland region) were conducted before 2014.

A pilot test for enhanced coal-bed methane (ECBM) recovery named RECOPOL (Reduction of CO_2 Emissions by Means of CO_2 Storage in the Silesian coal basin of Poland) started in November 2001 in Poland. The RECOPOL project was the first European field demonstration of ECBM. The Polish partner in this undertaking was the Central Mining Institute. The RECOPOL site was located in the west central Upper Silesian basin in the South of Poland near the Czech border. Liquid CO_2 from an industrial source was first injected in August 2004. Continuous injection started in April 2005 after reservoir stimulation. The total amount of CO_2 injected was 760 t between August 2004 and the end of June 2005 with 68 t CO_2 produced back (van Bergen et al. 2006).

No further pilot or demonstration projects on CO_2 geological storage are currently in operation or in preparation.

PL2.4 Past and current full-chain CCS projects & projects/sites in preparation

In 2008, the Polish Government formally submitted information to the European Commission on two CCS demonstration projects possibly to be developed: 1) at Bełchatów Power Plant and 2) in Kędzierzyn (polygeneration project). However, both projects were abandoned due to financial problems (Wróblewska 2014).

The **Bełchatów project** was significantly advanced before abandonment. The plan was to construct a full-scale capture plant (1.8 Mt/year) using Alstom's advanced amines technology at the new 858 MW_e lignite-fired unit. The EU EEPR grant was awarded by the European Commission to the project. The project was also submitted to the EU NER 300 programme. However, due to difficulties with closing a financial plan the project was stopped in 2013. The lignite-fired unit is built as CO_2 capture-ready. CO_2 transportation was foreseen in the form of a pipeline and associated infrastructure to transport compressed CO_2 from the capture plant to the storage site. CO_2 storage was included in the project in the form of injection of pressurised CO_2 into deep saline aquifers for permanent storage.

The **Polygeneration project** with CO_2 capture on the Kedzierzyn Chemical Plant aimed at the establishment of a zero-emission facility combining power engineering with chemical production. The project consisted of a coal gasification plant for synthesis gas production for chemicals (methanol and hydrogen) as well as the production of high-pressure steam for co-generation of electricity and heat, and a second plant integrated with gas and steam turbines in an IGCC (integrated gasification combined cycle) configuration, including CO_2 removal before combustion of the syngas in the gas turbine of the IGCC system. Captured CO_2 was to be transported and stored in selected geological structures of the Mesozoic basin. The Kędzierzyn polygeneration project was abandoned in 2011.

PL2.5 Plans for CCUS cluster development

The STRATEGY CCUS project funded by the European Union aims to produce local development plans and business models tailored to industry's needs in eight regions identified as promising for CCUS. The development plans will also define CO_2 transport corridors between local CCUS clusters of industry, and connecting with North Sea CCUS infrastructure, in order to reduce costs and contribute to a Europe-wide CCUS infrastructure. One of the promising start-up regions was selected in Poland, i.e. the Upper Silesia in Poland (including the industrial areas of Katowice, Rybnik and Będzin).

PL3. National policies, legislation and regulations

PL3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

Poland's National Energy and Climate Plan for the years 2021–2030 (NECP PL) sets the following climate and energy goals for 2030:

- -7% in sectors not covered by the ETS system compared to the level in 2005 by reducing emissions in transport, construction and agriculture, taking into account the beneficial effects of CO_2 absorption by ecosystems and the flexibility associated with land use, land use change and forestry (LULUCF);
- 21-23% of RES share in gross final energy consumption by 2030 (total consumption in electricity, heating and cooling as well as for transport purposes) including yearly increases in the share of RES in heating and cooling by an average of 1.1 percentage point per year; 14% share of renewable energy in transport; 32% RES share in electricity production in 2030. Achievement of the targets is by support and promotion mechanisms, use of advanced biofuels, introducing offshore wind energy and increasing the dynamics of development of renewable energy micro installations;
- improving energy efficiency – 23% reduction of primary energy consumption comparing to the PRIMES 2007 forecast (the development of ecological and effective heating systems, the production of heat in cogeneration, intelligent networks and the functioning of mechanisms that stimulate the saving of energy end-use and pro-saving behaviour; in terms of energy efficiency and the improvement of housing conditions developing a long-term strategy for the renovation of domestic stocks of residential and non-residential buildings, public and private);

- the share of coal in electricity generation will be systematically reduced – in 2030 it will reach the level of 56-60% and in 2040 the downward trend will be maintained;
- implementation of nuclear energy in Poland; commissioning of the first nuclear power unit 1-1.5 GW in 2033 and another five units in the next years up to 6-9 GW.

The Ministry of Energy is working on the project "Polish Energy Policy" (PEP), which will determine the government's long-term vision for the energy sector. The project, which begun in November 2019, provides for an evolutionary transformation of the electricity production sector towards fewer emissions, at a pace that guarantees energy security and is not threatening the competitiveness of the economy. The goals of the state energy policy also include energy efficiency, reducing the impact of the energy sector on the environment, and the optimal use of Polish energy resources. The objectives of PEP2040 are consistent with Poland's NECP and assume a reduction of CO_2 emissions by 30% by 2030 (in relation to 1990).

The 2030 National Environmental Policy defines the development strategy in the areas of environment and water management. No reference is made to CCS, assumed biomass sequestration, or wooden construction.

The Strategy for Responsible Development – Programme for Silesia 2017 assumes that innovations in the energy sector will primarily concern the reduction of negative impact on the environment by the mining industry. The subject of initiatives reported under the European Commission Programme will be research and development in the field of clean coal technologies, alternative forms of coal mining, and CO_2 capture, use and storage.

PL3.2 National legislation and regulations

The implementation of Directive 2009/31/EC took place in 2014 in the announcement of the uniform text of the Act of 9th June 2011 of the Geological and Mining Law allowing underground storage of CO_2 in order to conduct a demonstration project[11] on carbon capture and storage (currently applicable Act of the Geological and Mining Law: Journal of Laws 2019 item 868):

- For new installations of combustion of fuels in order to generate electricity with a capacity of ≥300 MW, it is necessary to draw up and submit to the marshal of the province an ecological review, including assessment of readiness to adapt carbon dioxide capture installations on the basis of an analysis of the availability of underground CO_2 storage facilities, technical feasibility and economic efficiency of the CO_2 transport network, technical feasibility and economic modernisation of installations for adaptation to carbon capture.

[11] As defined in Commission Decision 2010/670/EC.

- Activities in the field of underground storage of CO_2 require a license, which is granted by the minister for the environment. The concession will be granted only for demonstration projects.

Regulation of the Minister of the Environment of 8th December 2017 on mining plant operation plans (Journal of Laws of 11th December 2017, item 2293) specifies the detailed requirements for mining plant operational plans for underground storage of CO_2. The operational plan should specify, among other items, the quantity, composition and characteristics of the injected CO_2, the characteristics of the underground CO_2 storage site, geological, hydrogeological and geological and engineering conditions of the underground carbon storage complex, description of the "mining area" (here: for CO_2 storage), natural, technical and environmental hazards, anticipated organisational and technical measures necessary for ensuring occupational safety and universal safety as well as protection of mineral deposits, groundwater and other elements of the environment, as well as envisaged undertakings aimed at preventing carbon leakage.

The Act of 10th April 1997 Energy Law (Journal of Laws 2019, item 755) regulates the issue of CO_2 transport.

The Regulation of the Minister of the Environment of 3rd September 2014 on areas in which the localisation of geological CO_2 storage sites is allowed, OJ 2014, item 1272, defines areas that may be considered for storage site exploration: the only available place in this respect is Cambrian reservoir within exclusive economic zone of the Republic of Poland.

PL4. Research

PL4.1 National funding for research related to CCS and research priorities

In the years 2014–2017 research activities were mainly done in research projects funded from Norway Grants within the Polish-Norwegian Research Programme operated by the National Centre for Research and Development in Poland. Works have mainly focussed on potential and development of CO_2-EOR technology and CCUS clusters. In October 2020, six research projects started that are related to several parts of the CCUS chain including CO_2 storage with funding from the POLNOR CCS 2019 Call of the Programme "Applied Research" implemented under The Norwegian Financial Mechanism 2014–2021. The objective of the Programme "Applied Research" is to enhance performance of applied research in Poland through improved research cooperation between Poland and Norway. The cooperation is to be based on equal partnerships between Norwegian and Polish research institutions and enterprises. The POLNOR CCS 2019 aims to support international, Polish-Norwegian research projects in the area of carbon capture and storage including: Storage pilots, full value chain analysis, new knowledge that facilitates large-scale CO_2 storage, social science related to deployment of CCS, development of CO_2 capture solutions integrated in power and industry processes.

The Polish Ministry of Environment was funding the national programme "Assessment of formations and structures suitable for safe CO_2 storage including monitoring plans" in the years 2008–2012.

Also research institutions (e.g. Central Mining Institute, PGI-NRI, MEERI, AGH-UST) use funding provided by Ministry of Science and Higher Education in their statutory activities or research grants related to geological storage of CO_2.

Table PL: Overview of research topics addressed by recent nationally funded research projects on CO_2 storage.

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	(x)	(x)	(x)	(x)	(x)	(-)	(x)	(x)	(x)
Project examples	National programme, STRATEGY CCUS	Technological Initiative I	Technological Initiative I	National programme	Technological Initiative I		National programme, RECOPOL	National programme, RECOPOL	National programme

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

PL4.2 Research institutions involved in research related to CO_2 storage

The following research institutes are involved in research related to several parts of CCUS chain including CO_2 storage:

- AGH University of Science and Technology (AGH UST)
- Central Mining Institute (CMI)
- Polish Geological Institute – National Research Institute (PGI-NRI)
- Mineral Economy and Energy Research Institute of the Polish Academy of Sciences (MEERI PAS)
- Oil and Gas Institute - National Research Institute (OGI)
- PBG Geophysical Exploration, Company Ltd. (PBG)
- Silesian University of Technology
- Warsaw University of Technology
- West Pomeranian University of Technology
- Gdańsk University of Technology

- Institute of Fluid Flow Machinery Polish Academy of Sciences
- Wrocław University of Science and Technology
- Cracow University of Technology CUT
- University of Warsaw
- Institute of Chemical Engineering - Polish Academy of Sciences
- Institute for Chemical Processing of Coal
- Institute of Low Temperature and Structure Research - Polish Academy of Sciences
- Czestochowa University of Technology

PL4.3 Existing larger scale research infrastructure

In Poland the following key research infrastructures devoted to the advanced research studies on CO_2 storage, capture and transport were included in ECCSEL within the H2020 Infradev-3 activities:

1. High pressure thermogravimetric analyser (HP-TGA, Główny Instytut Górnictwa)
2. Fixed bed reactor (FBR, Główny Instytut Górnictwa)
3. Pilot-scale moving bed reactor (MBR, Główny Instytut Górnictwa)
4. Facilities to assess lithology, mineralogy and elemental as well isotopic composition of rock samples (PGI-NRI PETRO-LAB, Polish Geological Institute – National Research Institute)
5. Tools for monitoring of shallow subsurface as well as groundwater-soil system (PGI-NRI GEOPH-LAB, Polish Geological Institute – National Research Institute)

PL4.4 Involvement in EU-funded and other regional/international research projects related to CCS

The project "Strategic planning of Regions and Territories in Europe for low-carbon energy and industry through CCUS Coordination and Support Action (CSA) (STRATEGY CCUS)" funded in the frame of Horizon 2020 (May 2019 to April 2022) aims at the preparation of strategic plans for the development of carbon capture, utilisation and storage (CCUS) technologies in Eastern and Central Europe within the following time horizons: short (up to 3 years), medium (3-10 years) and long (over 10 years); development of a pan-European CCUS infrastructure and plans for carbon dioxide corridors between local industrial CCUS clusters (see also PL2.5).

PL5. National actors driving CCS forward and public engagement

PL5.1 Awareness of CCS technology

CCS has been a concern for the public from the very beginning. In addition to financial issues, there is also public uncertainty about the safety of CO_2 storage as well as on its impact on the environment.

In summary, in most cases CCS installations are criticised for issues such as (Jankowski et al. 2014):

- high investment and operating costs,
- high energy consumption of capture,
- interference with geological structures during CO_2 injection,
- uncertainty of CO_2 binding underground,
- risk related to possible failures - escaping carbon dioxide can be a lethal threat to people and animals.

In recent years, public awareness surveys for CCS have been conducted, the results of which were published in two articles. The first article found positive acceptance of CCS, however, to a large extent there is a problem of ignorance of this technology and a lack of decisiveness. Analysis of the results of the study showed the need to update school curricula in the field of environmental protection (Weiss & Lutyński 2018). The other article presents the issue of social acceptance for CCS as a potential means of reducing CO_2 emissions in Poland. This problem is essential for the implementation of large CCS projects. Organising relevant information campaigns related to new techniques of reducing CO_2 emissions into the atmosphere may help in the implementation of CCS projects. The most important thing in such campaigns is to present information to the laypersons in a proper way (Weiss & Lutyński 2017).

Therefore, in recent years, due to the lack of financing for the development of CO_2 capture technology and the lack of social acceptance for the geological storage of CO_2, particular attention has been paid to the possibility of CO_2 use in industrial processes (the so-called utilisation).

PL5.2 National advocates for CCS

None.

PL5.3 Public engagement

None.

Summarising the state-of-play on geological CO_2 storage in PORTUGAL (PT; as of 30th June 2021)

PT1. National storage assessment, storage options, potential and capacity

The interesting areas for CO_2 storage in Portugal are in the sedimentary basins along the coastal Atlantic margin of the country (more than two thirds of Portugal's mainland are underlain by basement (Variscan) igneous and metamorphic rocks rendering geological CO_2 storage infeasible). Although less-common options for CO_2 storage, such as ultramafic and mafic rocks for mineral carbonation (Moita et al. 2020, Romão et al. 2016) and CO_2 hydrates (Bernardes et al. 2015), may have potential to be applied in Portugal, the main opportunities are in deep saline aquifers since there are no exploited oil and gas fields. Coal seams in a carboniferous basin in the north of the country were in the past the subject of some research (Lemos de Sousa et al. 2007), but the potential seems limited. Due to the large Portuguese continental shelf, composed mainly of sedimentary rocks, offshore opportunities play a major role (Carneiro et al. 2015).

GIS mapping (e.g. stratigraphy, seismicity, neotectonics, location of CO_2 industrial sources, etc.) and geological/ geophysical characterisation studies have been conducted to screen potential areas in the scope of nationally funded projects – KTEJO (Pereira et al. 2014) – and international research projects – EU-FP7 COMET (Boavida et al. 2013) and CCS-PT (Seixas et al. 2015). The promising areas are located in the following sedimentary basins:

a) Porto Basin with a total area of 2,150 km^2. It is located entirely offshore in the Northwest of Portugal. It has an estimated storage capacity of approximately 1.73Gt CO_2 (central value P50), with an uncertainty interval ranging between 0.87 Gt CO_2 (P90) and 3.46 Gt CO_2 (P10);
b) Lusitanian Basin with a total area of 22 000 km^2. The basin occurs both onshore and offshore, along most of the western coast of the country. It has an estimated storage capacity of approximately 3.19 Gt CO_2 (central value P50), with an uncertainty interval ranging between 1.59 Gt CO_2 (P90) and 6.34 Gt CO_2 (P10);
c) Algarve Basin with a total area of 8500 km^2, which occurs both onshore and offshore along the Southern coast of Portugal. This basin extends into Spanish territory where it is called the Cadiz basin. The estimated storage capacity of this basin is approximately 2.17 Gt CO_2, with an uncertainty interval ranging between 1.09 Gt CO_2 (P90) and 4.34 Gt CO_2 (P10).

The theoretical storage capacity of the deep saline aquifers in Portugal is approximately 7.09 Gt CO_2 (central value P50), with an uncertainty interval ranging between 3.54 Gt CO_2 (P90) and 14.1 Gt CO_2 (P10) (Pereira et al. 2021a). Figure PT1 illustrates the geographic distribution of the four sedimentary basins with the potential thirty-six storage units of three different reservoirs (Upper Triassic, Lower Cretaceous and Miocene) and the storage capacity estimates (P50) of each unit.

The identified storage units present promising geological indicators (e.g. suitable reservoir properties at desired depths for CO_2 injection in the dense phase, relevant storage capacities, etc.), although several factors (such as the lack of data from direct measurements, the presence of productive freshwater aquifers overlying the potential reservoirs, relevant active seismicity, etc.) clearly require more detailed assessment. Future data acquisition and information gathering may lead to a revision of the storage capacities and feasibilities of potential storage units in each basin.

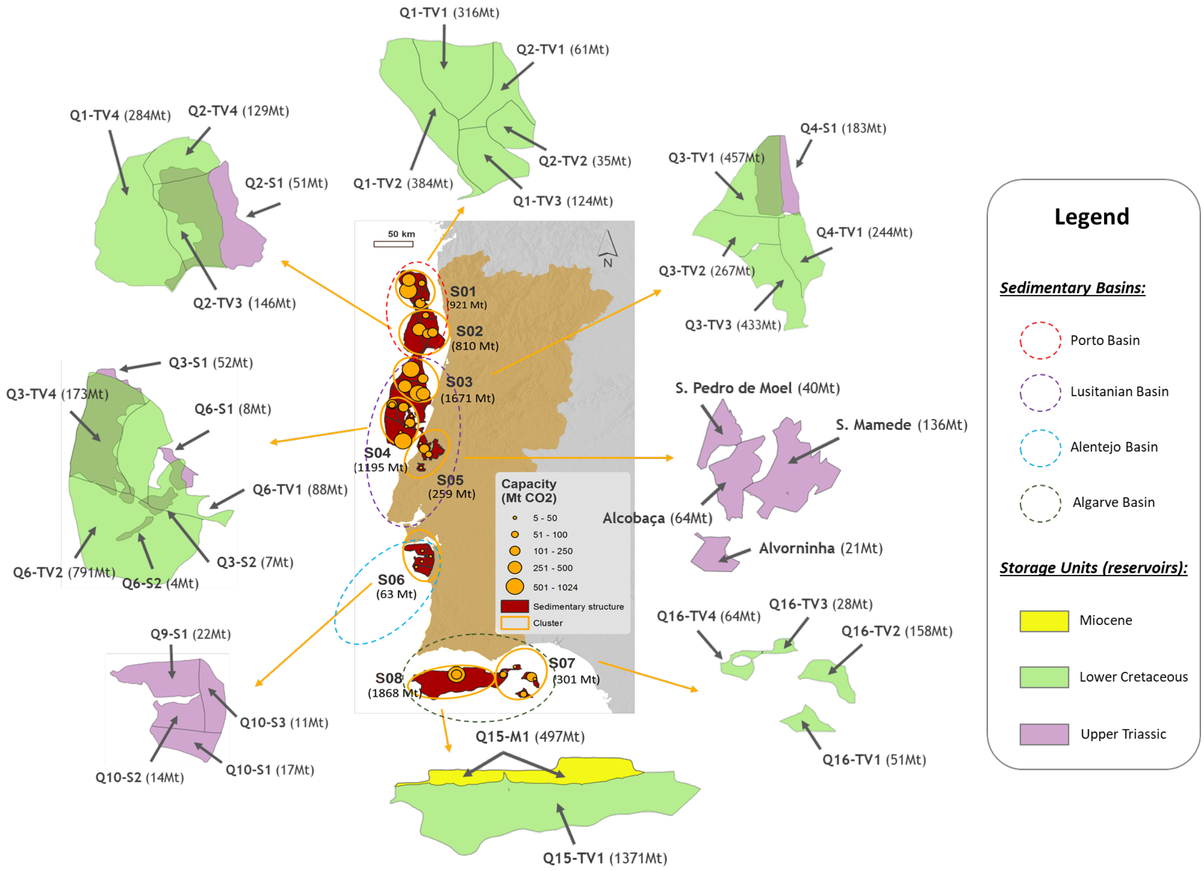

Figure PT1:Location of the thirty-six storage units in Portugal and respective clusters. The individual polygons refer to the storage units in each cluster (yellow circles/ ellipses).

The most promising region in mainland Portugal, being studied under the ongoing European project STRATEGY CCUS, is the Lusitanian Basin (both offshore and onshore) with 17 potential storage units that have been identified (storage clusters S03, S04 and S05 of Fig. PT1). In general, this region is reasonably well understood due to the hydrocarbon exploration activities, providing a large amount of geophysical surveys (2D seismic reflection data) and some deep wells spatially distributed in both onshore and offshore zones. In addition, the central and northern sectors of the Lusitanian Basin are the only regions in Portugal where recent 3D seismic surveys were acquired, one offshore and the other onshore, along with new boreholes. The interpretation and analysis of these new direct and indirect geophysical measurements will reduce the uncertainty about reservoir properties and will provide further information to estimate the storage capacities more accurately, but the work is still ongoing as the data only recently became publicly available. The potential reservoirs in the Lusitanian basin are the siliciclastic layers of the Torres Vedras Group (Lower Cretaceous) and the Grés de Silves Fm. (Upper Triassic).

Geologically, the Torres Vedras Group reservoirs, located offshore, are composed of sandstones and conglomerates characterised by high permeabilities (and therefore good injectivity is expected). However, the quality of the seal (the Cacém Fm.) is the parameter with the higher uncertainty. On the other hand, the Silves Group potential reservoirs, extending both onshore and offshore, have an excellent caprock in the Dagorda Fm., well-known from onshore outcrops, although low injectivity is expected due to the high uncertainty about the heterogeneity and permeability of the reservoir layers.

The confidence of the storage resource (i.e. the deep saline aquifers) of each potential reservoir was evaluated using the Boston Square Analysis method to assess the attribute suitability and data quality of several parameters (Pereira et al. 2021b). From this assessment, the main knowledge gaps regarding these potential storage units are injectivity and fracture parameters, for onshore sites, and seal quality for offshore sites. Besides these sources of uncertainty, the lack of hydraulic tests at desired depths is also an important knowledge gap to be filled for more reliable local estimations of the permeability values of both reservoir types.

In addition to the storage resource confidence, the classification of the deep saline aquifer maturity has been conducted for the seventeen potential storage units in the Lusitanian Basin. Based on the four-tier maturity pyramid, the offshore units (Lower Cretaceous and Upper Triassic reservoirs) were classified as Tier 1 (Pereira et al. 2021a), corresponding to the regional assessment for the estimates of geologic formation and storage unit capacities. The onshore units (Upper Triassic reservoirs) were classified as Tier 2, consisting in the discovery assessment for the estimation of storage capacity of each daughter unit (i.e. suitable reservoir) – Castelo Viegas Fm. and Penela Fm. belonging to the Silves Group (Pereira et al. 2021b).

The total storage capacity of the offshore storage units is approximately 2.9 Gt CO_2 (central value P50), with an uncertainty interval ranging between 1.4 Gt CO_2 (P90) and 5.4 Gt CO_2 (P10). The four onshore storage units have lower geological storage capacities than those offshore, with an estimated central value (P50) of approximately 0.3 Gt CO_2, within an uncertainty interval ranging between 0.1 Gt CO_2 (P90) and 0.5 Gt CO_2 (P10). Thus, the total storage capacity of potential storage units in the Lusitanian Basin is approximately 5.9 Gt CO_2 considering an optimistic scenario (i.e. P10). The storage costs for the onshore and offshore operations are about EUR 3-4/ton and EUR 12-17/ton, respectively. Compared to the onshore costs, higher offshore storage costs are expected despite the lower environmental and health risks, and a better social acceptance for CCUS deployment.

It is relevant to mention the existence of the PilotSTRATEGY project funded by the European Union, recently approved, focusing on the characterisation of an adequate location for an injection pilot in the onshore or offshore setting of the Lusitanian Basin. This multi-disciplinary project integrates the collaboration between Portuguese local teams from institutions/ industry partners, and the local teams of institutions/ industry partners from Spain and France.

Currently there is no specific CO_2 storage Atlas available, but a CCS Roadmap for Portugal with potential storage areas/ sites exists from previous studies.

PT2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

PT2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

None.

PT2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

PT2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

The ongoing EU funded project PilotSTRATEGY (2021–2026) aims to characterise two areas (one onshore and one offshore) for the implementation of a pilot storage site. PilotSTRATEGY work includes detailed geo-characterisation, feasibility studies and preliminary design or prefront end engineering and design studies. Regional stakeholders and the local public will be involved in developing recommendations and concepts as part of the pilot conceptualisation and design. Also, they will be involved in the decision about the onshore or offshore location of the pilot.

PT2.4 Past and current full-chain CCS projects & projects/sites in preparation

None.

PT2.5 Plans for CCUS cluster development

In the ongoing EU-funded project STRATEGY CCUS (2019–2022), a cluster development is being analysed for potential future development in the Lusitanian basin. The cluster encompasses emission facilities that spread from the Lisbon-Setúbal industrial area to the Figueira da Foz region. The main industrial sectors included in the cluster are the cement, lime and glass sectors, with the pulp-and-paper sector having a possible business case related to BECCS and negative emissions.

PT3. National policies, legislation and regulations

PT3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

Portugal is in line with the objectives outlined in terms of the European Green Deal from the European Commission of converging to carbon neutrality by 2050. Portugal's international commitment led the government to implement the Roadmap for Carbon Neutrality 2050 (APA 2019), which was published through Council of Ministers Resolution 107/2019 of 1st July 2019. This aims essentially at identifying and analysing the alternative trajectories, technically feasible, economically viable and socially accepted, to achieve the goal of a neutral carbon economy by 2050.

Thus, Portugal aims to reduce emissions between 45% - 55% by 2030, between 65% - 75% by 2040 and between 85% - 90%, compared to 2005. The remaining emissions would be offset through land use and forests. Despite these ambitious targets, where in general all national sectors (e.g. energy industry, industry, buildings, transport, etc.) play a key role for carbon neutrality, it is expected that by 2050, and in particular in the industry sector, it will have a less significant emission reduction of around 72% - 88% when compared to 2005 (APA 2019). It would be in this sector, and specifically in the cement sector, that the application of CCS/CCUS technologies could play an essentially decisive role, not only for the commitment of national carbon neutrality in 2050 but also for the contribution of achieving the so-called negative CO_2 emissions.

The Carbon Neutrality Roadmap is under revision, in part motivated by the National Hydrogen Strategy, a framework document under public discussion, and a much larger role for CCUS will probably result, since the National Hydrogen Strategy includes the utilisation of CO_2 for production of methane and methanol.

PT3.2 National legislation and regulations

According to the Portuguese Republic Diary (i.e. "Diário da República") (1st serie, nº 53), the Decree-law (no. 60/2012), established on 14th March 2012, transposes directive no. 2009/31/EC of the European Parliament and of the Council, of 23th April 2009, and establishes the legal regime for the geological storage activity of CO_2. Article 2º (Decree-law) states that the deployment of CO_2 geological storage can be applied to: a) national territory, including the territorial sea and contiguous zone; b) Economic and Exclusive Zone (Portuguese ZEE); and c) continental shelf.

Relevant aspects regarding the national legislation for the activities of capture, transport and geological storage of CO_2 are the following:

1) An environmental license is required, under the Legal Regime for Integrated Pollution Prevention and Control (PCIP).
2) An environmental impact study must be conducted, under the Legal Evaluation Regime Environmental Impact Assessment (EIA).
3) The provision of a financial guarantee is required, under the legal regime of liability for environmental damage.
4) DGEG is the licensing authority (but offshore activities must also go through a permitting procedure with the Marine Authority).
5) No licensing necessary for pilot injection < 100 kt of CO_2 (for scientific research purposes, not commercial).

PT4. Research

PT4.1 National funding for research related to CCS and research priorities

Research on CCUS in Portugal can be funded by two mechanisms that include partial or entirely national funds:

- The Foundation for Science and Technology (Fundação para a Ciência e Tecnologia - FCT), which is the national institution that funds research at an academic level. Calls are not specifically made about CCUS or even parts of the chain, but rather for "all

scientific subjects". It is the primary funding institution to which R&D institutions have applied for research on CCUS.
- ANI, Agência National da Inovação, which promotes innovation in SME and large companies, often together with R&D institutions, including programme Portugal 2020.

The research topics in CO_2 storage associated with international cooperation and EU-funding are presented in section PT4.4.

Table PT: Overview of research topics addressed by recent nationally funded research projects on CO_2 storage.

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	X	X	-	-	-	-	-	-	-
Project examples	KTEJO, INCARBON	KTEJO							

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

PT4.2 Research institutions involved in research related to CO_2 storage

Several national institutions and universities have been involved in research and development related to capture and geological storage of CO_2:

- University of Évora – Earth Sciences Institute (ICT);
- University Fernando Pessoa – Department of Energy, Environment and Health Research Unit (FP-ENAS);
- University of Lisbon (NOVA) – Research Center for Environmental and Sustainability (CENSE);
- National Laboratory of Energy and Geology (LNEG);
- Directorate General for Energy and Geology (DGEG);
- Collaborative laboratory NET4CO2.

PT4.3 Existing larger scale research infrastructure

The academia-industry collaborative laboratory NET4CO2 maintains laboratory facilities for testing CO_2 capture through the continuous formation of gas hydrates using a patented NETMIX technology.

PT4.4 Involvement in EU-funded and other regional/international research projects related to CCS

- **FP7 COMET**: Integrated infrastructure for CO_2 transport and storage in the west Mediterranean, joint research Project co-financed by the European Seventh Framework Programme (FP7). This project assessed CO_2 transport and storage in West Mediterranean area, specifically, the Iberian Peninsula (Portugal and Spain) and Morocco. Coordinator: Portugal. 1/2010 through 12/2012.
- **CSS Roadmap for Portugal**: CO_2 capture and storage in Portugal: a bridge to a low carbon economy (2015), co-funded by Global CCS Institute. This project evaluated the role the CCS technology could play in the Portuguese energy and industry system as a mitigation option to achieve deep GHG emissions reductions. The cost effectiveness of its deployment, and the risks and additional benefits it may provide for economic development are also analysed.
- **STRATEGY CCUS** (ongoing): an ambitious three-year project (2019–2022) funded by the European Union to support the development of low-carbon energy and industry in Southern and Eastern Europe. This project aims to encourage and support initiatives within each region by producing local development plans and business models tailored to industry's needs.
- **PilotSTRATEGY** (ongoing): a five-year project (2021–2026) to characterise sites for implementation of CO_2 storage pilots. PilotSTRATEGY will investigate deep saline aquifers in detail in three regions of Southern Europe: Paris Basin (France), Lusitanian Basin (Portugal) and Ebro Basin (Spain). At the end of the project, the level of site characterisation in these three regions will be sufficient to allow a final investment decision to be made and for storage permitting and project approval to be obtained. In two further regions of Eastern Europe, West Macedonia (Greece) and Upper Silesia (Poland), PilotSTRATEGY will increase the maturity and confidence level of understanding of deep saline aquifer storage resources.

PT5. National actors driving CCS forward and public engagement

PT5.1 Awareness of CCS technology

Although CCS technology is a relatively new concept for the general public in Portugal, the national partners involved in the development of CCS in Portugal have held workshops/webinars in the past two years under the scope of project STRATEGY CCUS. Activities included implementing a Regional Stakeholder Committee (RSC) that involved representatives of several sectors that could be interested by deployment of CO_2 storage in the Lusitanian basin. The main goal is to raise awareness in the RSC members about the importance of CCS and its potential to mitigate CO_2 emissions.

Although the view of most stakeholders is positive towards the need to consider CCUS in CO_2 emissions reduction scenarios for the regional industry, not all participants are convinced of the relevance of geological storage of CO_2 to achieve carbon neutrality, suggesting the need for more utilisation instead.

PT5.2 National advocates for CCS

None.

PT5.3 Public engagement

Workshop "Industry Challenges in the Transition towards a Low Carbon Economy - The role of CCS technology". Green Business Week, 5th March 2015, Lisbon. The event occurred during a business week about renewable and green technologies and engaged with SME and industrial players for presentation of the national roadmap for CO_2 capture and storage, project CCS-PT.

Seminar "Perspectives for capture, transport and sequestration of CO_2 in Portugal", 4th and 5th June 2014, Lisbon. The event addressed mostly academia and university students and intended mostly to spread knowledge about the technology and present the state of development of technology worldwide.

Seminar "CO_2 storage in the Clean Development Mechanism: Opportunities in the Community of Portuguese Speaking Countries", 19-20th September 2013, Lisbon. An event through invitation with representatives of the policy makers from all countries in the Community of Portuguese Speaking Countries, aiming essentially to identify grounds of cooperation on CCS research.

Summarising the state-of-play on geological CO_2 storage in ROMANIA (RO; as of 30th June 2021)

RO1. National storage assessment, storage options, potential and capacity

For Romania only saline aquifers and depleted oil and gas fields have been found to offer suitable storage options. The storage capacity is considered sufficient to store emissions for many years and was estimated to be 18.6 Gt in saline aquifers and 4 Gt in depleted hydrocarbon fields (Rütters et al. 2013).

There is no existing national CO_2 Storage Atlas in Romania.

RO2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

GETICA CCS was a government-initiated demonstration project, officially supported by the Prime Minister and coordinated by the Ministry of Economy, Trade and the Business Environment and endorsed by the Global CCS Institute. Within the project, CO_2 capture (1.5 Mt/year CO_2) was foreseen at the TURCENI Energy Complex in the Oltenia region, the most energy intensive region at national level, responsible for about 40% (24.5 Mt CO_2 per year) of the total amount of CO_2 emissions. Different parts of this project are presented in the subsections on capture, transport and storage and on full-chain projects (RO2.1 to 2.4).

RO2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

As a part of the GETICA CCS demonstration project, a capture plant was to be fitted to one of the existing six units in CE Turceni SA, namely to Unit no. 6 of 330 MW. Unit no. 6 is an existing, rehabilitated power unit, fuelled by local lignite, equipped with a wet flue gas desulfurisation plant and a dense slurry installation for ash and slag discharge.

The optimum technology choice of post-combustion carbon capture technologies should be tailored to the specifics of the individual projects. Considering the time schedule of the GETICA CCS demonstration project, the selection concentrated on Chilled Ammonia Process (CAP) and the Advanced Amine Process (AAP), as they were the technologies furthest in development and closest to commercialisation.

RO2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

The GETICA CCS demonstration project included CO_2 transportation from the capture facility in Turceni to a geological storage site. Transportation was planned to be performed by an onshore pipeline. Dense phase CO_2 has been selected as being the most cost effective solution for long-distance pipeline transportation.

The Feasibility Study analysed two CO_2 transport pipeline routes to the first-choice and alternate storage sites described below, Zone no. 5 and Zone no. 1, respectively. A pipeline route to the primary storage choice, Zone no. 5, was developed. As a backup, Zone no. 1 could still be a possible storage site following an assessment based on further investigation. A 40 km long pipeline was considered to transport the CO_2 from the carbon capture plant both to Zone no. 5 and to Zone no.1. Due to the fact that the pipeline will pass nearby populated areas, a minimum clearance of 500 m from the existing villages and building has been considered. The pipeline will be installed in a hilly area, and some sections of the pipe route are subject to landslides. The pipeline design pressure-temperature envelope is: 0-140 bar, 0-50ºC. The foreseen operating range is 80-120 bar, 0-40ºC.

RO2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

The GETICA CCS demonstration project included geological storage. The selection of potential CO_2 storage sites was made based on all the data that were made available by oil and gas companies, comprising 241 2D seismic lines and 141 well information packages, geological cross-sections, geological and geophysical maps and data from literature. The selection was made by considering an investigation area of 50 km radius around Turceni. The analysis of the available data concluded that the best solution for storage would be the Sarmatian formation. Based mainly on data made available to GeoEcoMar for the Feasibility Study, 11 possible storage sites were selected. Acquisition of additional data from oil and gas companies allowed this list to be reduced to 7 potential storage sites. A final selection of the two most suitable sites for CO_2 storage named Zone 1 and Zone 5 was made on the basis of storage capacity, structural framework, reservoir properties and seal.

The design of the surface and injection facilities will be made at the beginning of the Development Phase (Phase 3) and will be based on the characterisation made in Phase 2. The preliminary dynamic simulations show that up to 9 injectors could be needed for Zone 1 and 5 injectors for Zone 5, with a large distance between them.

The finalised definition of the storage site (proposed during FEED & Detailed Engineering) will include the validated locations of the injection wells and associated surface facilities, including the compression/pumping station.

RO2.4 Past and current full-chain CCS projects & projects/sites in preparation

There are no CCS projects operating currently in Romania. The only project proposed for this country was the demonstration project GETICA CCS, for which the feasibility study was completed in 2011. The project competed for NER 300 programme, was selected on the waiting list, but was stalled due to the lack of funding and government support. The designated storage operator for one of the two deep saline aquifers identified as suitable storage sites was the partially state-owned company ROMGAZ (operator for gas reservoirs and seasonal storage of natural gas). For GETICA CCS project, new injection and monitoring wells were planned to be drilled. The feasibility study also included a section addressing the problem of old legacy wells (well integrity study), present on the proposed storage complex and intercepting the storage reservoir. The study revealed the presence of many legacy wells and pointed out the need for additional investigations in order to assure that these wells will not become preferential leakage pathways for the injected CO_2.

RO2.5 Plans for CCUS cluster development

Danube CCUS cluster.

RO3. National policies, legislation and regulations

RO3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

Taking into account the dramatic decrease of power production during the period 1989–2000 due to the severe recession caused by the transition to the market economy, Romania will meet without any problems the national target set by Kyoto Protocol (8% reduction of GHGs during 2008–2012) compared with 1989. After the restructuring process of the Romanian economy, in the last years the Gross Domestic Product (GDP) has increased, so it is expected that CO_2 emissions will continue to increase in the future, but to a lower level than in 1989. In the Romanian energy sector it is both necessary and possible to i) increase energy efficiency in energy production, distribution and end-use; ii) reduce carbon intensity of power sector by switching from coal and fuel oil to natural gas; iii) promote policies aiming to cut down subsidies which encourage market imperfections; iv) research, develop and increase the use of renewable energy sources, (i.e. solar, wind, micro-hydro and biomass).

RO3.2 National legislation and regulations

Following the request of the European Commission to transpose Directive 31/2009 into Member States' national legislations, Romanian government issued the Emergency Ordinance 64/2011 on the CO_2 geological storage. This ordinance was approved by Romanian Parliament with some modifications in the form of the Law 114/2013. This law, together with specific procedures for granting exploration and storage permits for CO_2 geological storage sites issued by National Agency for Mineral Resources (NAMR, Competent Authority both for CO_2 geological storage and for hydrocarbon operations), provides the legal framework for safe geological storage of carbon dioxide. For CO_2 geological storage, a dedicated service within the agency was established in 2013. This service for CO_2 geological storage coordinated the elaboration of specific procedures for granting exploration and storage permits. No solicitation was made so far.

NAMR also regulates hydrocarbon operations in Romania, including well operations and transfer of assets between hydrocarbon licence holders. The agency establishes also hydrocarbon concession perimeters and granting hydrocarbon licences. Regarding the hydrocarbon wells and operations, these are regulated through Petroleum Law and specific Orders of NAMR (procedures for application of Petroleum Law). These regulatory acts establish the conditions for temporary and permanent abandonment of wells, lifting of abandonment and the transfer of assets between hydrocarbon license holders. The transfer is permitted so far only for hydrocarbon operations. It is not clear if the abandoned wells, transferred to the state by petroleum license holders can be used for CO_2 operations. There is no regulatory act clearly specifying this.

For the safety of petroleum offshore operations, a governmental agency (Competent Authority for Regulating Offshore Petroleum Operations to the Black Sea - ACROPO) was created in 2016, its attributions being stated within Law 165/2016. ACROPO must provide advises to NAMR in granting petroleum licences within Black Sea and must ensure that the operators fulfil their obligation in ensuring the safety of petroleum operations offshore according with national and international legislation.

Other authorities involved in the process of permitting for CO_2 geological storage, according to OUG 64/2011 are:
i) National Agency for Environmental Protection, for approving the initial and updated (at least once in 5 years) the monitoring plan, for imposing the restitution of greenhouse gas allowances according to Governmental Decision 780/2006 in case of leakages.
ii) Local Agencies for Environmental Protection for granting the environmental permit.
iii) National Environmental Guard for organising and implementing a system of announced (at least one per year during the operation period and once in five years till the transfer of responsibility to the state) and unannounced inspections to the storage sites.
iv) Local authorities for approving the plans for site construction.

RO4. Research

RO4.1 National funding for research related to CCS and research priorities

Work related to the CO_2 geological storage began in Romania with the affiliation of the GeoEcoMar to ENeRG in 2002 and continued with participation of the institute in international projects related to CCS: as subcontractor in “CASTOR” project, as partner in “EU GeoCapacity”, “CO_2Net East”, “Impact of communication”, “CGS Europe”, “CO_2StoP” projects as well as in similar national projects: “The National Programme of Carbon Capture and Storage for 2011–2020 period” and “Geological storage” section of the Feasibility Study for the “Getica CCS Demonstration Project”.

RO4.2 Research institutions involved in research related to CO_2 storage

GeoEcoMar, CO_2 Club Association.

RO4.3 Existing larger scale research infrastructure

None.

RO4.4 Involvement in EU-funded and other regional/international research projects related to CCS

Apart from the current CCUS projects ENOS (ENabling ONshore CO_2 storage in Europe), ALIGN CCUS (Accelerating Low Carbon INdustrial Growth through CCUS) and ECO-BASE (Establishing CO_2 enhanced Oil recovery Business Advantages in South Eastern Europe), GeoEcoMar is involved in the project STRATEGY CCUS (STrategic planning of Regions And Territories in Europe for low-carbon enerGy and industrY through CCUS).The STRATEGY CCUS project team, including GeoEcoMar specialists, is elaborating detailed plans for comprehensive European CO_2 gathering networks and industrial clusters linked to CO_2 storage sites via hubs, pipeline networks and shipping routes.

RO5. National actors driving CCS forward and public engagement

RO5.1 Awareness of CCS technology

The most frequently identified issue linked to CCUS implementation mentioned by companies in Romania was the lack of funding for supporting the development of CCUS projects. Therefore, industrial companies (and energy companies as well) postpone the implementation of CCUS projects, even though the CO_2 emitters are obliged to buy emission certificates to compensate for the CO_2 emission, and the price of these emission certificates has increased several times in the last years. Thus, the industrial sector that emits CO_2 is aware of CCS/CCUS technology, but does not see the business case.

In contrary, research institutes and university research centres in Romania show interest and involvement in CCUS development, due to their participation in recent research projects.

The members of mass-media and the local public interviewed in Romania demonstrate little knowledge or awareness about CCUS, but at the same time they expect the public to form a positive attitude about CCUS, if CCUS would be developed in connection with local economic interests. Regarding public acceptance, the respondents in Romania considered the level of awareness about CCUS among the public to be very low (both for local and general publics), and most respondents believed that public information campaigns should be launched in order to build an informed opinion about CCUS and to prevent a negative attitude which could be long-lasting.

RO5.2 National advocates for CCS

CO_2Club is the NGO funded in 2007. Its main objective is to promote CCUS technology in Romania. Over the years, the CO_2Club has organised workshops, seminars and round tables in order to inform the public and the stakeholders from various fields. The CO_2Club takes part in several international CCUS projects. Its involvement in international CCUS projects in recent years is very important for the future of national CCUS projects in Romania.

RO5.3 Public engagement

Public engagement includes measures ranging from providing information, education, and consultation to deliberation. Several studies have been conducted in the last 3 years. The aim of one of the studies, made by the ALIGN CCUS project, was to understand success factors and pitfalls in community engagement and community compensation for CCUS projects, and to identify and close relevant knowledge gaps. The conclusions were that there is substantial overlap in relative preferences for community compensation measures among citizens of Romania, the UK, and Netherland, but there are also relevant differences between countries when it comes to CCS acceptability and the evaluation of compensation measures. These findings can provide a useful tool for researchers in this field looking to close knowledge gaps as well as for stakeholders (e.g. project developers, authorities, community engagement managers) wanting to understand how to effectively make use of community engagement and community compensation in the CCUS context.

An example of public engagement is the international event: "ECO-BASE Seminar on Legal and Regulatory Framework of CO_2 Utilisation (EOR) and Geological Storage - South East Europe" that was organised by the ECO-BASE project team in Bucharest on 17-18th September 2019. The aim of this workshop was to facilitate direct contacts between representatives of the important companies from oil and gas domain and companies with major CO_2 emissions (>100,000 t/year) from the whole industrial domain (energy, steel, cement etc.) as well as with important representatives of the Romanian administrative and political structures.

Summarising the state-of-play on geological CO_2 storage in the SLOVAK REPUBLIC (SK; as of 30th June 2021)

SK1. National storage assessment, storage options, potential and capacity

The Slovak Republic has been a member of consortia of European projects, which elaborated initial information, estimating the theoretical storage capacities. The projects were CASTOR (Christensen et al. 2006) and EU Geo Capacity (Vangkilde-Pedersen et al. 2009), coordinated by the Geological Survey of Denmark.

In 2011 a national project was finished in Slovakia (Kucharič et al. 2011 - Quantitative parameters of geological structures suitable for CO_2 storage – in Slovak) with main goal to identify and assess suitable geological structures for CO_2 storage in Slovakia.

There is no existing national CO_2 Storage Atlas in the Slovak Republic. Available and public is the map of areas in which it is allowed to carry out geological exploration for establishing a CO_2 storage site (by the Ministry of Environment of the Slovak Republic).

There is no evidence of any filed or granted CO_2 storage exploration license or storage permit given by Ministry of Economy of the Slovak Republic and Ministry of Environment of the Slovak Republic.

SK2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

SK2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

None.

SK2.2 Past and current demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

SK2.3 Past and current demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

None.

SK2.4 Past and current full-chain CCS projects & projects/sites in preparation

None.

SK2.5 Plans for CCUS cluster development

None.

SK3. National policies, legislation and regulations

SK3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

According to EU Directive 2016/2284 on the reduction of national emissions of certain atmospheric pollutant (National Emission Ceilings Directive – NECD), the Slovak Republic submitted the National Air Pollution Control Programme (NAPCP), which is an act by Ministry of Environment of the Slovak Republic to reduce air pollution and its associated risks to the environment and human health by reducing of emissions of NO_X, SO_2, NH_3, non-methane volatile compounds (NMVOC), fine particular matter ($PM_{2.5}$) and greenhouse gases (CO_2 etc.) for the years 2020–2030. NAPCP has to be updated at least every four years and contributes to achieving of goals of air quality according EU Directive 2008/50/ES.

SK3.2 National legislation and regulations

The EU CCS Directive has been transposed to the national legislation by the CO_2 Storage Act No. 258/2011 Zb. that also includes an amendment of the Mining Act No. 44/1988 Zb. and the Geological Act No. 569/2007 Zb. CO_2 storage is generally enabled by legislation. The storage site operator has first to obtain an exploration permit awarded by the Ministry of Environment, and then, based on the assessment of the storage complex and its verified geological model, get an Attestation of suitability of the natural geological structure for CO_2 storage. This Attestation is issued by the Ministry of Economy of the Slovak Republic. Only after that attestation, the operator can ask for a storage permit that is issued by the Main Mining Office of the Slovak Republic. The operator is required to pay fees for exploration and mining activities. The CO_2 Storage Act significantly limits possible locations of a potential CO_2

storage site by protecting suitable geothermal, hydrocarbon-bearing and similar structures, thereby assigning lower priority to CO_2 storage in comparison with other strategic ways of subsurface use (Mikunda et al. 2020).

The responsible state administration bodies according to the CO_2 Storage Act are the Ministry of Environment of the Slovak Republic, the Main Mining Office of the Slovak Republic and its District Mining Offices. The subsurface is owned by the state.

SK4. Research

SK4.1 National funding for research related to CCS and research priorities

There is no national funding for research related to CCS.

The project "Quantitative parameters of geological structures suitable for CO_2 storage (in Slovak)" was finished in 2011 and it has been the only national project in Slovakia with the main goal to identify and assess suitable geological structures for CO_2 storage in Slovakia (Kucharič et al. 2011 - in Slovak).

Table SK: Overview of research topics addressed by the nationally funded research project on CO_2 storage in 2011.

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	X	(X)	-	X	X	X	(X)	(X)	-

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

Other cooperation projects with private companies (iron and steel works plant and chemical industry plant) were prepared in 2008 and 2010 (Kucharič et al. 2008, 2010) as pre-feasibility studies.

SK4.2 Research institutions involved in research related to CO_2 storage

The main institution involved in CO_2 storage in Slovakia is State Geological Institute of Dionýz Štúr.

Other institutions involved in CO_2 storage are the Slovak University of Technology - Faculty of Material Science and Technology in Trnava, NAFTA a.s. and the Earth Science Institute of the Slovak Academy of Sciences.

SK4.3 Existing larger scale research infrastructure

None.

SK4.4 Involvement in EU-funded and other regional/international research projects related to CCS

The State Geological Institute of Dionýz Štúr has been involved in the international research project "Enabling onshore CO_2 storage in Europe (ENOS)".

There are no other institutions in Slovakia currently involved in projects related to CCS.

SK5. National actors driving CCS forward and public engagement

SK5.1 Awareness of CCS technology

CCS is not well known in general public, so there is not any reliable information about public acceptance of CO_2 storage in Slovakia.

SK5.2 National advocates for CCS

There are no national clubs/lobby groups for CCS in Slovakia.

SK5.3 Public engagement

None.

Summarising the state-of-play on geological CO_2 storage in SLOVENIA (SI; as of 30th June 2021)

SI1. National storage assessment, storage options, potential and capacity

No changes/progress in Slovenia's national storage assessment have been observed since 2013 (see summary below). There is no national storage atlas available. Also, there has been no application for a CO_2 storage exploration permit. Storage capacity (considering also the economic aspects) for CO_2 in Slovenia is largely hampered by its geographic position at the junction of the three major geological/tectonic units. Furthermore, the identified potential storage structures are a) small, which directly affects the economics of storage operations, and b) dissected by faults and therefore exposed to higher risks and a need of intensive monitoring, which again increases the cost of operations.

Slovenia's storage options were first estimated in 2006 in the frame of the CASTOR project. Storage capacities were assessed more precisely within EU GeoCapacity project (2006–2008). The national storage potential was evaluated in the frame of the national project 2009–2011: Seven major (i.e. emitting more than 100,000 t CO_2/year) stationary emitters were identified: three of them were power plants and the others come from manufacturing sector (cement, paper & pulp, metal). The largest point source emitted approx. 4.8 Mt CO_2 per year (in 2008). Total annual CO_2 emissions from point sources were in the order of 7 Mt. The existing pipeline infrastructure in Slovenia is relatively favourable. No economic factors, potential conflict of use, public acceptance or safety conditions were considered and/ or assessed by now.

The country's geological features are rather complex, particularly from a structural and tectonic point of view. The NW, central and S parts of Slovenia belong to the Internal Dinarides (Southern Alps) and External Dinarides; and the NE is a part of the Eastern Alps and the Pannonian Basin. The Sava folds are considered a sub-unit of the Internal Dinarides. The Periadriatic lineament divides the Southern Alps from the Eastern Alps. The territory of Slovenia is made up of magmatic, metamorphic and sedimentary rocks ranging in age from Precambrian to Cenozoic. Spatial distribution of rock types shows that about 49% of the Slovenian territory is covered by clastic rocks, about 39% are carbonates, about 4% belong to the mixture of the two and only about 7% are igneous, pyroclastic and metamorphic rocks. In geological history, several sedimentary basins were formed within each tectonic unit, varying in size and depth. The most prosperous basins for geological storage of CO_2 were found the Ljubljana Basin, the Celje Basin, the Slovenian part of the Pannonian Basin and the SW Flysch Basin. Sedimentary rocks are abundant and of appropriate depth, however the geological structure is complex. Any more precise evaluation of the storage potential would therefore require extensive further characterisation.

Seismological activity of the Mediterranean and its vicinity is governed by contact of the African and Eurasian tectonic plates. It is believed that W and S Slovenia form the northern part of the Adriatic plate, which lies between the two major plates. The Adriatic plate tends to rotate in counter clockwise direction, thus causing folding and thrusting on its northern and eastern rim. In contrast, its southwestern edge is extended, moving away from the Eurasian plate. Thus, folded and overthrusted structures are characteristic of the entire Slovenia. The thrust movement did not exceed 40 km. They are dissected by long regional faults, some of them stretching through entire country. The most important faults occurred in Upper Pliocene and Lower Pleistocene. Along the long regional faults, a horizontal shift of several kilometres took place, as well as a vertical shift. In between horst structures, large basins were formed. Three major seismogenic zones can be observed the NW part in the central part and in the SE part of Slovenia. According to Eurocode 8, seismic hazard is described by the design ground acceleration, which lies between 0.10g - 0.25g for rock or firm soil for the return period of 475 years.

Slovenia is relatively rich in thermal and mineral water resources. Some pumping wells for mineral water in SE Slovenia do contain substantial amounts of natural CO_2 dissolved. There are evidences of CO_2 seepage on the surface.

Because of the relative abundance of sedimentary rocks in Slovenia, its potential for underground storage of CO_2 in aquifers would expectedly be significant. However, the recent studies do not show the same outcomes. This is predominately a consequence of very limited geological data from the depth interval 800-2500 m that is currently available and of complex geological structure. As a result, conservative estimation of storage capacities assessed within different studies seems to be more appropriate for Slovenia.

In EU GeoCapacity, Slovenian effective storage capacity in aquifers was estimated to be 92 Mt. Only few reliable calculating parameters were available for calculations for particular aquifer. The individual structures are relatively small and scattered. In the national project, the potentiality of Slovenian territory was indeed studied for all most prosperous regions and structures. However, the storage capacity was evaluated only on theoretical level for three individual locations (Pečarovci, Dankovci and Besnica structure). Their total theoretical storage capacity was apx.63 Mt. Both studies concluded that further investigations would be required in order to confirm and to improve the storage capacity of individual fields.

The most reliable data existed for the assessment of storage capacities in hydrocarbon fields. The two most prosperous locations were identified in NE Slovenia: oil and gas fields Dolina and Petišovci. Their total capacity tended to be between 1.8-5.3 Mt. Some additional formations would be a challenge for further CGS studies, apparently.

Despite the fact that Slovenia is relatively well developed coal province with long mining tradition, the prospers for CO_2 storage in unmineable layers and /or ECBM are limited due to several reasons: i) the depth of coal layer in none of the known deposits is optimal for geological storage of CO_2 in liquid state; ii) the age of coal seams ranges from Triassic to Pliocene; iii) the low coal quality (the moisture content as well as ash and sulfur content are high). Different studies gave capacities ranging 0-100 Mt. The more conservative figures are more likely to be realistic, because low permeability and swelling effects (clearly identified for the Velenje lignite within MOVECBM project) were not taken into consideration, when calculations were made. Some attention and further investigation may go to the coal layers in the Mura formation in NE Slovenia.

The conclusions from EU GeoCapacity study showed that effective storage capacity of 94 Mt CO_2 could basically accommodate all emissions from stationary emitters in the country for about 13 years. However, the individual structures are relatively small and are therefore less appropriate for energy sector. Their suitability for emitters in the range of (few) 100,000 t/year would need to be examined.

SI2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

SI2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

None.

SI2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

SI2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

None.

SI2.4 Past and current full-chain CCS projects & projects/sites in preparation

None.

SI2.5 Plans for CCUS cluster development

None.

SI3. National policies, legislation and regulations

SI3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

Slovenia's vision aims at strengthening capacities for climate change adaptation, management of risks, while the ultimate objective is to reduce Slovenia's exposure, sensitivity and vulnerability to climate change impacts and to increase climate resilience and adaptive capacities of the society. In February 2020 a National Energy and Climate Plan (NECP) 2030 was adopted by the Government of Slovenia.

The energy policy goal (as defined in the Energy Concept of Slovenia) in its transition to a climate neutral society by 2030 is to ensure a reliable, safe and competitive energy supply in a sustainable manner to citizens and the economy. To achieve this, five key objectives are emphasised: decarbonisation – mitigation of climate changes mitigation and adaptation measures; decarbonisation – renewable energy sources (RES); energy efficiency; energy security and internal energy market; research, innovations and competitiveness. Reduction of the use of energy and other natural resources in all sectors is anticipated. According to NECP scenario, Slovenia's total GHG emissions shall be reduced from 17.4 Mt CO_2 (eq) in 2017 to 13.1 Mt $CO_{2\,eq}$ in 2030. Considering the principles of the just energy transition, Slovenia intends to gradually reduce the use of coal, the target for 2030 being 30% (total primary energy supply in 2018 for Slovenia: oil 34%, nuclear 22%, coal 16%, biofuels & waste 11%, natural gas 10%, hydro 6%, wind & solar 1%). In addition, the NECP is in favour of a pilot project for the production of synthetic methane and hydrogen. 27% share of RES in the final energy consumption by 2030 is anticipated. Investments in the improved resilience of the electricity distribution network are considered, including developments in energy storage technologies and infrastructure (3% GDP, from public and private sources). A high level connectivity of electricity infrastructure with its neighbouring states and in the wider region is also a priority. Minimum 35% increase in energy efficiency is expected.

In the NECP 2030, CCS is not considered as an option for decarbonisation for Slovenia. The principal arguments are the low price of CO_2 coupons (acceptable range 40-60 EUR/t CO_2 would not be reached before 2040 according to IEA's World Energy Outlook 2017 and prioritising other options, such as RES, nuclear and natural gas in the energy mixture of Slovenia.

SI3.2 National legislation and regulations

Slovenia has transposed the EU CCS Directive in February 2012 with the novel of Energy Law (EZ-E). The Slovenian standpoint is that "Slovenia does not foresee and does not plan CO_2 storage capacities on its territory". However, it recognises that "a need for CO_2 pipeline may arise which would a) enable connecting Slovenian manufacturing plants with storage capacities abroad and/or b) enable connecting CO_2 pipeline of two neighbouring countries". The EZ-E explicitly states the provisions and conditions to enable transport of CO_2 on Slovenian territory. The Energy Agency of the Republic of Slovenia is appointed as the national competent authority. In order to implement the Directive, a series of legal acts was adopted. According to currently valid legislation in Slovenia, injection and geological storage of CO_2 (onshore and offshore) is explicitly and unconditionally forbidden (Mining Act ZRud-1, Art.6 as of July 2010; Environment Protection Act ZVO-1F, Art.166.a as of November 2013).

SI4. Research

SI4.1 National funding for research related to CCS and research priorities

No national funding targeted to CCS since 2013.

SI4.2 Research institutions involved in research related to CO_2 storage

Research institutions involved in CO_2 geological storage issues come from public and private sector:

- Geoinženiring d.o.o.
- Geological Survey of Slovenia
- Nafta Geoterm d.o.o.
- HGEM d.o.o.
- University of Ljubljana – Faculty of Natural Sciences and Engineering

SI4.3 Existing larger scale research infrastructure

None.

SI4.4 Involvement in EU-funded and other regional/international research projects related to CCS

The ENOS project was the only recent research project related to CCS in which a Slovenian partner was involved.

SI5. National actors driving CCS forward and public engagement

SI5.1 Awareness of CCS technology

Overall knowledge/awareness on CCS technology in the general public is low. However, in the past few years, an increased interest for the CCS technology in media has been observed. This includes interviews, complex articles on CCS, short presentations of CCS as a GHG reduction measure etc. in various media (printed, electronic, radio). The journalists received substantial support from national researchers (from Geoinženiring and the Geological Survey of Slovenia) by providing information on the role of CCS, answers to the questions, graphic material, experts views, overview of the state of the art of CCS in Europe and globally etc.

In the curriculum of the course on Environmental Geology for geology students (3rd year) at the Faculty of Natural Sciences (University of Ljubljana) a 90 minutes slot is reserved for geological storage of CO_2. Geoinženiring has been invited to present this topic to the students each year since 2011.

Dedicated presentations on CCS and in particular on the geological storage of CO_2 have been organised for general and professional publics. The organisers (natural sciences societies, academy societies, NGOs) invited experts from Geological Survey of Slovenia to present the technology and the current status.

Slovenia is observing the progress in the field of CCS in Europe and worldwide. Particularly the industrial entities are interested in the outcomes and best practices gained through existing (and future) demo/pilot projects.

SI5.2 National advocates for CCS

None.

SI5.3 Public engagement

None. Partly covered in SI5.1.

Summarising the state-of-play on geological CO_2 storage in SPAIN (ES; as of 30th June 2021)

ES1. National storage assessment, storage options, potential and capacity

The estimated CO_2 storage capacity in Spain in deep saline aquifer formations is between 7 and 22 Gt CO_2 (IGME 2010). Most of this estimated capacity is located onshore (maximum 21 Gt (21,000 Mt) CO_2) although there are some interesting areas offshore along the Cantabrian, Atlantic and Mediterranean coasts. This estimate includes transboundary areas of the Gulf of Cádiz and the Alborán Sea, with a total of ca. 1 Gt (1,000 Mt) CO_2 estimated capacity offshore (Martínez et al. 2013a).

Storage potential in onshore and offshore oil hydrocarbon reservoirs appears limited. Spain suffers an almost complete lack of native hydrocarbon resources. Oil and gas reservoirs onshore are small but high porosity and permeability. Oil and gas reservoirs in the Mediterranean and the Gulf of Cádiz may offer potential for storage. Storage capacity in these fields has been estimated at 150 Mt (Gulf of Cadiz is not included). The storage potential of Spanish coal basins was studied in the EU GeoCapacity (2006–2008) project, which obtained an estimated capacity of 145 Mt CO_2, mainly concentrated in the north-western basins.

In 2010, the Geological Survey of Spain (IGME) initiated the ALGECO$_2$ Plan to identify suitable onshore structures, including seal and reservoir, for CO_2 injection and storage based on existing geological and seismic information. After completion, a second project phase included drilling some of the onshore structures, the static and dynamic modelling of the most promising structures, and the publication of the first Spanish Atlas of CO_2 geological storage structures (Suárez Díaz & Arenillas González 2014). In some areas, detailed subsurface information gathered in previous studies allowed the development of more detailed storage estimates. It was possible in many cases to use geological models at a structure scale, leading to more precise calculations and reducing uncertainties, and obtaining a better calculation of the storage capacities.

The CO_2 geological storage atlas, properly the "Atlas of subsoil structures susceptible to CO_2 storage in Spain (Atlas de estructuras del subsuelo susceptibles de almacenamiento de CO_2 en España)", is available as a printed book (ISBN: 978-84-7840-935-8) or from the open access of IGME.

The Atlas differentiates four regions, each formed by an onshore sedimentary basin completed with a mountain range (Suárez Díaz & Arenillas González):

1) **Duero Basin and Cantabrian Range**: Located along the Spanish course of the Duero River. The most interesting formations are found in the Triassic and Cretaceous, with very porous sandstones and thick carbonated rocks. The potential in the basin is complemented by structures contained in the Cantabrian Mountain Range, mostly in the Eastern areas. The potential combined storage capacity is between 5.7 and 8 Gt CO_2, and the main studies for pilot and demonstration projects in Spain are taking place in some of the more favourable formations of the Duero Basin and Cantabrian Range.
2) **Ebro Basin and Pyrenees**: This region covers the North East part of Spain and has a wide variety of potential storage formations, from Lower Triassic to Miocene, both in sandstones and carbonate rocks. The Ebro basin potential was studied together with the Spanish Pyrenees, although most of the total storage potential of 3.6 to 5.2 Gt is located in the Southern part of the basin.
3) **Guadalquivir Basin and Baetic Range**: This is a thin sedimentary basin located in the South of Spain, following the Northern border of the Baetic Mountains, which are also included in this study. The most interesting formations for CO_2 storage are Lower Triassic sandstones and Miocene sandstones. The small hydrocarbon deposits in the basin lead to significant (compared to other locations in Spain) subsurface exploration including geophysical campaigns and borehole drilling. This basin extends under the sea in the Gulf of Cádiz, and to the Portuguese Algarve basin.
4) **Madrid-Tajo and Almazán Basins and Iberian Range**: Located in a wide plane to the South of Madrid, this region is divided in two parts: the Madrid Basin in the West and the Intermediate Depression in the East. The structure of the Eastern part is better known because of oil exploration in the last century. The "Buntsandstein" is the most promising formation in the East as is the Cretaceous "Utrillas sandstone" in the West. The Utrillas formation is not considered for storage in the Intermediate Depression because of low salinity. In this study, this basin has been combined with the Iberian Mountain Range, where Mesozoic formations have a large potential.

Offshore studies were developed in the **COMET Project**. The COMET Project (2010–2013) was funded by the European Commission for the study of an integrated CO_2 transport and storage network in Spain, Portugal and Morocco, being the first systematic work evaluating offshore capacities for geological storage of CO_2 in Spain. Ten locations were included in this study, four in the Cantabrian Sea, two in the Atlantic Ocean and four in the Mediterranean Sea. Locations of Galicia and Gulf of Cádiz in the Atlantic are shared with Portugal and the Alborán Sea location in the Mediterranean is shared with Morocco and could lead to a more extensive cooperation in the future. Preliminary studies of capacity in these offshore areas have estimated about 1 Gt CO_2 although total offshore capacity could be much higher if a complete screening is developed.

To date, there are 6 CO_2 storage exploration licences active (3 from 2012 and 3 from 2013) and 15 submitted and waiting for a work proposal from a few years ago (it looks like coal power station owners asked for exploration permits but they lost interest due to the close of the facilities). During this period, two exploration permits have been withdrawn due to relinquishment by the owners.

An experimental pilot with a storage volume under 100 kt was set up under the Mining Law at the Hontomín Technology Development Plant (Burgos province). A storage permit was granted (de Dios & Martínez 2019), first time in Spain, but finally the injection has not been done due to administrative and political problems.

ES2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

ES2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

- **La Pereda (2008–2012):** The project goal was to develop CO_2 capture technology by using limestone as a sorbent. In Mieres (Asturias), a 1.8 MW_{th} CO_2 capture demonstration plant was built for post-combustion capture of gases using carbonation-calcination technology (1.8 MW). The plant consisted of two interconnected circulating fluidised-bed reactors. In the calcination reactor, the limestone is transformed into calcium oxide and highly concentrated CO_2. The calcium oxide is sent to the carbonation reactor where it reacts with flue gases by capturing CO_2 to form limestone again and prevent discharge into the atmosphere. The project was subsidised under the Seventh European Framework Programme with a budget of more than EUR 6.8 million.
- **Planta GICC** (Gasificación integrada con ciclo combinado; ElCOGAS): In 2010, the installation of a 14 MW_{th} pilot plant at the GICC plant in Puertollano was completed. It was the world's first integrated gasification and combined-cycle plant to demonstrate that pre-combustion technology for CO_2 capture is viable in conjunction with hydrogen and electric power production, bringing GICC technology to the forefront of clean coal technologies. This project was subsidised by Spanish national funds as part of the Spanish initiative "Advanced technologies of conversion, capture and storage of CO_2".
- **CENIT-CO_2 (2006–2009):** The main objective of the CENIT-CO_2 project was the research, development, and validation of integrated solutions to accelerate the development of advanced technologies for the reduction of greenhouse gas emissions. The project included three pilots:
  (1) the construction of an experimental plant of 500 kW_{th} for post-combustion CO_2 capture by chemical absorption by amines integrated into the Thermal Power Plant of Compostilla (Leon), treating 800 m^3/h of flue gases and with a capture capacity of 3-5 t CO_2 per day with a capture efficiency of 90%;
  (2) construction of an experimental CO_2 capture plant on biomass combustion using the carbonation-calcination technology, a 300 kW_{th} plant connected to the Thermal Power Plant of La Robla;

(3) construction of an experimental CO_2 capture plant using the real coal combustion gases for feeding microalgae.
The project was funded by EUR 9.5 million from the Spanish strategic funding (CDTI) and an additional EUR 10.5 million from private companies.

- **Carbonera Cement plant:** LafargeHolcim will start building a capture plan at the end of 2022 in its cement plant of Almeria using the Carbon Clean Ind. (UK) technology. It will start capturing 10% of emissions ramping up to 100%. The final goal is to implement capture plants along its four cement plans in the country.

ES2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

The Compostilla project (2009–2012), a full-chain project, included an experimental transport installation located in Ponferrada (operator: ENDESA together with the City of the Energy Foundation, CIUDEN). This small-scale CO_2 transport demonstration was a 3000 m long, 5 cm diameter pipeline working in a loop, where CO_2 streams with different compositions were tested. Operational pressure ranges: 80-110 bar; operational temperature ranges: 10-31°C. This installation is still available although plans for future use, if any, are unknown.

ES2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

The **Hontomín site** (Burgos) hosts the Technological Development Plant (TDP) for CO_2 geological storage operated by "Fundación Ciudad de la Energía" (CIUDEN), a research organisation connected to the Spanish Ministry of Ecological Transition. The plant has been recognised by the European Parliament as a key test facility. The principal reservoir/seal pair is formed by Lower Jurassic carbonate rocks (limestones and dolostones) sealed by marls and black shales. The rocks at around 1,500 m depth take the form of a structural dome, where the main seal is the Marly Lias and Pozazal Formations and the reservoir is the Sopeña Formation. The reservoir has a high level of fracturing and it is compartmentalised, but this does not affect the seal integrity. As part of the TDP, two wells have been drilled: H-I (CO_2 injection well) and H-A (observation well).

As the Hontomín site is an experimental pilot with a lower than 100 kt CO_2 storage plan, it is regulated under the Mining Law 22/ 1973. The exploration permit was granted for three years and had two extensions of two years each (May 2010 to 2017). Subsequently, Hontomín was granted a storage permit under the Law 22/1973, in which the Mining Authority and CIUDEN agreed to use requirements established in the Law 40/2010 complementary to the existing mining legal framework. The storage permit was granted for a period of 30 years (from July

2018), 10 years to inject a maximum amount of 100 kt of CO_2 and 20 years for site monitoring. At the time of writing, the situation of Hontomín pilot is unclear due to political and administrative reasons.

ES2.4 Past and current full-chain CCS projects & projects/sites in preparation

In 2009, the only full-chain project in Spain to date was initiated: **Compostilla OXYCFB300**. The project was co-funded by the European Energy Programme for Recovery (EEPR) and the Spanish Government through the City of the Energy Foundation (CIUDEN, Ciudad de la Energía). "Compostilla OXYCFB300" was a carbon capture and storage demonstration project led by the power sector company ENDESA, Foster Wheeler Inc. as an industrial partner, and CIUDEN.

The main goal of the project was the design, construction, commissioning and operation of a coal-fired power plant (300 MW) equipped with CCS technologies. The CO_2 captured would be injected in a deep saline aquifer named Duero site. The second phase of OXYCFB300 project, to build the power plant, was not performed by ENDESA, but the EEPR action was completed in October 2013 when the above-described three pilots for CO_2 capture and transport in Cubillos (León), and storage in Hontomín (Burgos) were operational in Spain.

ES2.5 Plans for CCUS cluster development

Under the EU-funded project STRATEGY CCUS (H2020, 2019–2021) a cluster development is being analysed for potential future development in the industrial area of Tarragona (north-east) and the surrounding area within a 150 km distance, where a high geological storage potential was identified both onshore and offshore as well as transport pipelines and international ports.

ES3. National policies, legislation and regulations

ES3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

The Spanish **Strategy Frame for Energy and Climate** is based on the Law of Climate Change and Energy Transition (Ley 7/2021, de 20 de mayo, de cambio climático y transición energética), the National Integrated Energy and Climate Plan 2021–2030 (approved in March 2021), the Long-Term Decarbonisation Strategy 2050 (defined at the end of 2020) and the Fair Energy Transition Strategy (2021). The Strategy envisages a reduction in greenhouse gas (GHG) emissions in 2030 of 21% compared to 1990, a 42% share of energy end-use from renewables (74% in electricity generation), and a 39.6% improvement in energy efficiency and net zero emissions at 2050. These targets, which go well beyond those agreed previously for Spain with the EC, are feasible, and widely supported by many stakeholders.

The **Climate Change and Energy Transition Law** is a normative framework focussing on renewables development up to 100% of electricity system by 2050, promoting hydrogen as a green energy source and new emission-free vehicles, banning by 2050 the use of coal for electricity generation, and the oil and gas exploration and production. Nothing is said about how to deal with CO_2 emissions up to 2050 from power generation or industry.

The National Integrated Energy and Climate Plan (PNIEC) 2021–2030, defines the targets for reducing greenhouse gas emissions, renewable energy penetration and energy efficiency.

The Long-term Decarbonisation Strategy 2050 will allow Spain to reduce its greenhouse gas (GHG) emissions by 90% compared to 1990 by 2050. This involves reducing CO_2 emissions from the 334 Mt $CO_{2\,eq}$ emitted in 2018 to a maximum of 29 Mt $CO_{2\,eq}$ emitted in 2050. The remaining 10% of emissions will be absorbed by carbon sinks, which will be able to capture some 37 Mt $CO_{2\,eq}$ by mid-century, which means achieving climate neutrality.

The **Fair Energy Transition Strategy** includes the necessary tools to optimise transition employment opportunities through vocational training frameworks, active employment policies, support, and accompanying measures.

ES3.2 National legislation and regulations

CO_2 storage is regulated by Law 40/2010, 29th December 2010, on the geological storage of carbon dioxide, which resulted from a direct transposition of the EU Directive 2009/31/EC. Unfortunately, the development of specific regulations to tackle the bases and specificities of each project case has not been carried out to date. This law, as it is the European Directive, is not applicable for research projects where the planned amount of CO_2 injected is less than 100 kt. For such cases, the Law 40/2010 sets that a specific regulation will be developed to address the specificities of these projects, and as long as this regulation does not enter into force, CO_2 Storage for research purposes will be regulated by Mining Law 22/1973 and the General Regulation for Mining Regime (Royal Decree 25th August 1978). In this case, the Mining Authority is responsible for granting the exploration and storage permits.

ES4. Research

ES4.1 National funding for research related to CCS and research priorities

In Spain, national funding of CO_2 storage research activities has been very variable over the last years. The greatest proportion of national funds has come from the Ministry of Industry, Trade and Tourism and the Ministry of Science and Innovation. The government investment from 2007 to 2013 is here estimated at EUR 10 million. The investment since 2013, considering approved projects and initiatives, has increased considerably.

At date, the CDTI (Centre of the Development of Industrial Technology, included in the Ministry of Industry, Trade and Tourism), is the main entity responsible for innovation funding and support of national and international I&D projects using its own budget and co-funding from European grants (ERA-NET and ERDF funds).

Regarding private companies' investment during 2008–2013, the main actor in Spain was Endesa, the power company with the highest emission rates in the country. Other power companies like Gas Natural Fenosa (Naturgy today) and Iberdrola have also done some work but with much lower investment. At date, considering an important new interest in CCUS technologies, a few companies are initiating new projects such as ENAGAS and REPSOL.

ES4.2 Research institutions involved in research related to CO_2 storage

Major research institutions:

- **Geological Survey of Spain (IGME)**: The main national centre for research in the Earth Sciences. IGME has developed an intensive work programme for site selection and characterisation at different scales, participating many European- and nationally-funded projects (EU GeoCapacity, CO_2StoP, COMET, ENOS, STRATEGY CCUS, pilotSTRATEGY) and following national initiatives such as CENIT CO_2, ALGECO$_2$, INNSONDA and SENSE.
- **CIEMAT**: The main research centre of Spain in the field of environment and energy. Most of their activity is developed around nuclear and renewable energies. A research line is being developed on CO_2 storage using natural analogues to constrain impacts and guide risk assessment relating to CO_2 storage. In this, the participation of CIEMAT-CISOT in the social analysis and public acceptance of CCS technologies is truly relevant.
- **Scientific Research Superior Council (CSIC)**: The main institution in Spain in all fields of basic research. Some of the institutes integrated in the Council have specific works on research related to the geological storage of CO_2, for example in geophysics. It is especially worth mentioning CSIS-INCAR and its works related to CO_2 capture from power station and CO_2 capture and reduction on the cement industry.

Some main actors of the CCS development in Spain during last years are now out of the CCS scenario. That is the case of CIUDEN, the main actor in CCS research in Spain in the past, having a new strategy plan (2019) where CCS is not included. Thus, the future of the Hontomín pilot is particularly uncertain.

Also counting as actors contributing to Spanish CCS research are several departments of Spanish universities involved in different fields of research related to CO_2 geological storage (this list is not exhaustive): Schools of Mines in Oviedo and Madrid and several Faculties of Geology are developing studies, for example, about safety of storage, modelling, or shallow aquifer protection. The Groundwater Department of the School of Civil Engineers of La Coruña has published some impact articles about CO_2 behaviour under deep geological storage conditions. The Polytechnic University of Catalonia is developing research on several hydrogeological aspects and tests, based on close cooperation with CIUDEN in Hontomín.

ES4.3 Existing larger scale research infrastructure

None.

ES4.4 Involvement in EU-funded and other regional/international research projects related to CCS

EU GeoCapacity – Assessing European capacity for Geological Storage of Carbon Dioxide; FP6 (2006 -2008): Led by GEUS, it was the first project with a Pan European perspective for the identification of suitable sites for geological storage in Europe, evaluating saline aquifers, coal basins and hydrocarbon fields. IGME and ENDESA participated to provide data from Spain.

CO_2StoP (2011–2014): IGME contributed to the first European database of the potential geological storage sites for carbon dioxide, providing information from European and National projects.

COMET – Integrated infrastructure for CO_2 transport and storage in the west MEdiTerranean; FP7 (2010–2013): Project aimed at identifying and assessing the most cost-effective infrastructure of CO_2 transport and geologic storage in Portugal, Spain and Morocco, while considering the temporal and spatial aspects of the development of the energy sector and other industrial activities, as well as the location, capacity and availability of potential CO_2 storage in geological formations.

ENOS - Enabling Onshore CO_2 Storage in Europe; H2020 (2016–2020): ENOS strove to enhance the development of CO_2 storage onshore, close to CO_2 emission points. Several field pilots in various geological settings were studied in detail and best practices that stakeholders can rely on were produced. In this way, ENOS helps to demonstrate that CO_2 storage is safe and environmentally sound and increase the confidence of stakeholders and the public in CCS as a viable mitigation option.

STRATEGY CCUS; H2020 (2019–2021): The objective of the STRATEGY CCUS project is to develop strategic plans for CCUS development in Southern and Eastern Europe in the short term (up to 3 years), medium term (3-10 years) and long term (more than 10 years) developing local CCUS development plans, with local business models, within promising start-up regions, and defining connection plans with transport corridors between local CCUS clusters, and with the North Sea CCUS infrastructure, in order to improve performance and reduce costs, and contribute to build a Europe-wide CCUS infrastructure.

SENSE – Assuring integrity of CO_2 storage sites through ground surface monitoring; ERA-Net ACT (2019–2022): The integrity of CO_2 storage sites is dependent upon the intrinsic properties of the geological formations involved as well as operating parameters such as injection pressure, injection rate, temperature and injection strategy. Although in-situ characteristics of geological formations can be assessed prior to injection through, inter alia, well logs, well tests and laboratory experiments, their actual response may still differ from the predicted behaviour. The SENSE project utilises new technologies and optimised data processing to develop reliable and cost-efficient monitoring programmes based on ground movement detection combined with geomechanical modelling and inversion techniques.

pilotSTRATEGY; H2020 (2021–2026): The PilotSTRATEGY project (Pilot studies in regions with promising geological resources) is investigating geological CO_2 storage sites in industrial regions of Southern and Eastern Europe for the purpose of large-scale CCS development. This detailed geological characterisation and proposed development plan will be carry out on three selected storage sites located in Paris Basin (France), Ebro Basin (Spain) and Lusitania Basin (Portugal) and in lower detail also in Silesia area (Poland) and Macedonia area (Greece).

ES5. National actors driving CCS forward and public engagement

ES5.1 Awareness of CCS technology

Several surveys were conducted after the Spanish Law on Carbon Dioxide Geological Storage was issued 30th December 2010. At that time (2012–2013), it was concluded that public awareness was not high in Spain. The several surveys conducted by CIUDEN and CIEMAT indicated that more than 75% of the population were not aware of CCS as a climate change mitigation option. However, local public awareness campaigns had been carried out in the areas where pilot and demonstration projects were planned; in these areas, the public opinion of the CCS technology was mostly favourable (Lupion et al. 2013).

More recently, CIEMAT-CISOT (2017) report on a public engagement in CCS after as study ordered by PTECO$_2$, the Spanish technological platform for CO_2.The study sample was constituted by 1000 persons from all around Spain plus another 350 +375 in two specific areas (Asturias, and Castilla y Leon) where CCS projects were expected to have higher changes to be developed due to the coal dependency. The study indicated that fewer than 15% of the total had previous knowledge of CCS, but in the Castilla-Leon and Asturias samples the proportion was higher: 18% and 30%, respectively.

In 2020, a similar study was carried out by CIEMAT-CISOT under the umbrella of the European project STRATEGY CCUS. The study was based on 14 interviewees selected from different sectors (administration, industry, NGO, labour works, …) (Oltra et al. 2020). Some of them were relatively optimistic about the future development of CCUS technologies in Spain based on the existence of pilot projects proving that the technology is almost ready. With the proper incentives (supportive regulation and taxation, etc.), the technology could play a significant role in reducing CO_2 from the process industry in Spain. Interviewees are usually more optimistic about the development, in the medium term, of small-scale projects to use of CO_2, relative to big capture and storage projects, perceived as more complex and dependent on an active political support.

ES5.2 National advocates for CCS

PTECO$_2$ – Plataforma Tecnológica Española del CO_2: The Spanish CO_2 Technology Platform Association is an initiative developed by Spain's private sector, research centres and universities. It is partly funded by the Ministry of Finance and Competitiveness (MINECO) and contains representatives of that ministry and of the Ministries of Industry, Energy and Tourism (MINETUR) and Agriculture, Food and the Environment (MAGRAMA). PTECO$_2$'s general brief is to promote the development and deployment of CCUS technologies with the aim that Spain should meet its emission reduction commitments, build a competitive CO_2 sector, and reduce the environmental, social and economic impacts of climate change.

PTECO$_2$'s chief goal is to create a favourable environment for investment in R&D and innovation, foster the creation of an innovative business fabric and increase technological capacity in processes for efficiency improvement and CCUS, and to support the rolling out of these technologies in industry.

ES5.3 Public engagement

In 2017, a study on public engagement in CCS was conducted by CIEMAT-CISOT ordered by PTECO$_2$. The study sample, as it was mentioned before, was completed by 1000 persons from all around Spain plus 350 from Asturias and 375 from Castilla y Leon. The main conclusions were, considering the previous lower public awareness of CCS, that:

- After a CCS technology presentation, most of the respondents (38%) were tech-friendly, 34% neutral and 28% against CCS technology.
- The most common concerns regarding CCS were related to the potential impact on the local environment, long-term uncertainty, the possibility of leaks and the potential impact on the health of the local population.

The final recommendation made by the authors is to improve public understanding of CCS, promoting trust in the organisations and entities responsible for management, and establishing mechanisms to incorporate and respond to the concerns and values of the local communities where CCS projects would be implemented.

New studies have been conducted now under the Strategy CCUs project and the pilotSTRATEGY project.

Summarising the state-of-play on geological CO_2 storage in SWEDEN (SE; as of 30th June 2021)

SE1. National storage assessment, storage options, potential and capacity

Potential CO_2 storage sites in Sweden have been identified and mapped in a number of smaller studies and in a few large projects, for example the MUSTANG project in 2009–2013, the Bastor 2 project in 2012–2014 (Elforsk 2014), and the Nordic CCS Competence Centre, NORDICCS, in 2011–2015. To date, studies focusing on CO_2 storage in Sweden have been based primarily on data collected during oil- and gas exploration activities conducted between 1970 and 1990. In many cases, the quality and coverage of these old exploration data are limited. Hence, in order to perform safer and more accurate storage assessments in Sweden additional investigations and data are needed.

NORDICCS was performed under the Top-level Research Initiative CO_2 Capture and Storage programme (project number 11029) and Nordic Innovation (NORDICCS 2016). The project included mapping of potential CO_2 storage sites in the Nordic countries (Iceland, Norway, Denmark, Sweden, and Finland). The mapped CO_2 storage sites were published in the Nordic CO_2 Storage Atlas as an interactive map for all the Nordic countries (except from Finland where no potential storage sites were identified). The Nordic CO_2 Storage Atlas contains, beside the interactive maps, descriptions of the geology of the storage sites, CO_2 terminology and metadata. The following descriptions and capacity assessments are results from NORDICCS, but one should keep in mind that different studies/projects have somewhat different assessments.

In Sweden eight storage units and one trap were mapped and assessed within the NORDICCS project, all located in the southernmost part of Sweden, primarily offshore in the Baltic Sea (Lothe et al. 2014). Three of the potential storage units (reservoirs) are located in the south-eastern part of the Baltic Sea. These storage units consist of Cambrian sandstones which have a combined total thickness of approximately 138 m and sand net/gross ratios varying from 0.65 to 0.90. These sandstone units are interlayered with shales and siltstone. On top of the storage units is a thick caprock sequence beginning with a layer of late Cambrian–early Ordovician shale a few metres thick (which pinches out to the eastern side of the Swedish sector of the Baltic Sea). This is followed by a 65-125 m thick Ordovician sequence which consists of limestone with varying clay content. On top of the Ordovician sequence lies an approximately 700 m thick Silurian sequence consisting of marlstone and clayey limestone interbedded with layers of clay. The storage units in the south-eastern part of the Baltic Sea have an estimated static storage capacity of ca 1.7 Gt, using a storage efficiency factor of 2%.

However, it should be noted, that all three reservoirs in this part of the Baltic Sea are challenged by somewhat low porosities and permeabilities.

The remaining five storage units are located in south-west Scania and adjacent sea (i.e. south-western part of the Baltic Sea). In the south-western part, which lies within the Danish Basin, four of the five storage units represent one storage complex, delimitated by faults. The storage units consist of different types of sandstone interlayered with claystone and siltstone, all Mesozoic in age. The storage units have a combined thickness of approximately 385 m with sand net/gross ratios varying from 0.51 to 0.80. On top of the storage units is an approximately 1200 m thick bed of Mesozoic-Paleogene clayey limestone with local interbeds of silt- and sandstone. The fifth storage unit is located in the Vomb Trough, to the northeast of the Danish Basin. This storage unit is approximately 200 m thick and has a sand net/gross value of 0.65. This storage unit is capped by an approximately 600 m thick heterogeneous sequence of lime-, sand-, clay- and marlstone interbedded with coal seams and conglomerate. Altogether, the storage units in the southwestern part of the Baltic Sea have an estimated static storage capacity of ca 1.7 Gt, using a storage efficiency factor of 2%. In general, the storage units in the southwestern part of the Baltic Sea have good porosities and permeabilities.

The static storage capacity estimations above are based on the method described in the EU GeoCapacity project (Vangkilde-Pedersen et al. 2009b). A storage efficiency factor of 2% is used in all cases, based on the U.S. DOE standard for open saline formations (Goodman et al. 2011). A method for screening and ranking of the identified storage sites was developed in NORDICCS (Aagaard et al. 2014). The method assesses the physical parameters of the storage formation as well as the available knowledge and level of technical maturity. In the two most prospective storage units, one in each part of the Baltic Sea, dynamic reservoir simulations and modelling were performed (Mortensen et al. 2016). For this work the commercial software ECLIPSE 100 (Schlumberger 2007) and the basin modelling SEMI (Sylta 2004) was used. As ECLIPSE 100 model the complete system within the aquifer, this method was deemed most suitable for the Swedish aquifers due to limited numbers of traps. Considering “safe storage” scenarios (i.e. avoiding scenarios with potential leakage through mapped faults), the simulations gave a storage capacity of 250 Mt CO_2 for each of the two modelled storage units. The large gap between the static and dynamic assessments is partly due to the limited data (i.e. incomplete 2D seismic surveys, few offshore wells) which leads to uncertainties in assumptions and input parameters. The results also demonstrate the large span between capacity estimates using different methods.

There is no national CO_2 storage atlas in Sweden beside from the Swedish part in the Nordic CO_2 Storage Atlas produced in the NORDICCS project.

In Sweden there has never been any application for a CO_2 storage exploration licence, nor any storage permit.

There are several limiting factors for CO_2 storage in Sweden. Beside the need for modern subsurface data, these limitations are mostly due to local and regional legislation. For example, former oil and gas activities in the southeast Baltic Sea indicate local accumulations of oil and gas in the Cambrian sandstone which represents one of the most promising CO_2 storage units in Sweden. In the case of CO_2 injection into this reservoir, it is likely that extraction of formation fluid (water and possibly oil/gas) would be required as part of pressure maintenance. The challenge is that Swedish legislation prohibits all extraction of oil and gas offshore. Hence, there is currently no legislation regulating how eventual oil or gas findings should be handled. Furthermore, local legislation and required permits to start up a CCS project in Sweden would result in very long lead time before it could get started. In a more regional perspective, CO_2 storage in Sweden and neighbouring countries is challenged by the Helsinki Convention, the London Protocol, and the EU CCS Directive.

SE2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

SE2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

Preem CCS – capture and storage of CO_2: Preem's project aims to conduct a feasibility study and demonstration ahead of a full-scale realisation of carbon capture at Preemraff in Lysekil on the Swedish west coast. The project explores the possibilities of carbon capture from the hydrogen production plant and is carried out together with Norwegian actors. The projects adopts a holistic perspective by looking at the entire value chain as well as policy and legislation. CO_2 capture utilising Aker Solutions mobile test facility has been demonstrated at Preemraff in Lysekil by capturing a slip stream of CO_2 from its existing hydrogen production plant. Based on the results from the process part of the project, a feasibility study is carried out including cost estimates for a full-scale capture facility which includes pre-liquefaction and intermediate storage of CO_2. The Swedish Energy Agency has granted SEK 7.7 million and the Norwegian based Gassnova NOK 9.5 million to support the project. (See also SE4.3)

Stockholm Exergi test facility for Bio-CCS: The CO_2 capture test plant at Stockholm Exergi was connected to the bio-cogeneration plant in Värtan, Stockholm, applying the Hot Potassium Carbonate (HPC) process. The testing continued as planned until June 2020. In the autumn of 2020, The Swedish Energy Agency granted Stockholm Exergi additional funds to expand the plant. The goal is that the plant, together with a CCS integration study, will form the basis for Stockholm Exergi to invest in a large-scale capture plant. The aim of the test facility was to evaluate and adapt the bio-CCS technology to the biomass-co-generation plant in Värtan. In the test facility, detailed test programmes were implemented to understand how different parts of the process such as flue gases, pressures and temperatures affect implementation of large-scale CCS. The facility's response to stress tests were also investigated. Simulations were conducted in parallel to the physical tests in the plant to provide complimentary data. The Swedish Energy Agency has granted SEK 4.3 million to support the project. (See also SE4.3)

SE2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None. Export and storage in Norwegian reservoirs through the Northern Lights project is the primary scenario being considered by both Preem and Stockholm Exergi's projects.

SE2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

None.

SE2.4 Past and current full-chain CCS projects & projects/sites in preparation

None.

SE2.5 Plans for CCUS cluster development

In the project "Carbon Infrastructure Capture (Cinfracap)" two refineries, two combined heat and power plants (CHPs), a port owner and a gas transport company analyse possible options for a shared CO_2 capture and transport infrastructure in the area of Gothenburg and western Sweden. A pilot study phase was completed in March 2021. Cinfracap received some funding from the Swedish Energy Agency. A second project phase is currently being planned.

SE3. National policies, legislation, and regulations

SE3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

Sweden has decided on a climate policy framework consisting of climate goals, a climate law, and a climate policy council. The framework provides long-term conditions for business and society to carry out the change needed to solve the climate challenge. The law stipulates that each Government's climate policy should be based on the climate goals and describe how the work should be conducted. The Government must present an annual climate report and every four years produce a climate policy action plan. By 2045, Sweden is to have zero net emissions of greenhouse gases (GHG) into the atmosphere meaning that GHG emissions from activities in Sweden should in 2045 be at least 85 percent lower than in 1990. The remaining 15 percent can be achieved through supplementary measures such as increased carbon sequestration in forest and land, CCS and emission reduction efforts outside of Sweden. The climate policy framework can thus not be implemented without a policy for supplementary measures.

In 2019, a government inquiry (SOU2020:4) was conducted to propose a strategy and action plan for how Sweden could use such supplementary methods to attain the goal of net zero emissions by 2045. In this, BECCS is identified as a potential tool for negative emissions. The inquiry proposes 1.8 Mt/year of BECCS in 2030 and between 3 and 10 Mt/year in 2045 (with a large uncertainty as the contribution from other measures in 2045 is unclear). The inquiry proposes a reversed auctioning system for providing incentives to mitigate biogenic emissions (the state as buyer and emitters as potential sellers of negative emissions). The inquiry also highlighted the need of a national CCS-centre which was assigned to the Swedish Energy Agency by the Swedish government in the beginning of 2021. The Swedish Energy Agency is also developing a suggestion on the above mentioned auctioning system.

SE3.2 National legislation and regulations

The Swedish transposition of the EU CCS Directive was completed in 2014, mainly by the Swedish Environmental Act (1998:808) and the Swedish Continental Shelf Act (1966:314). The specific rules regarding geological storage of CO_2 were implemented in the regulation (2014:21) of geological storage of CO_2.

The regulation came into force on 15th July 2014 and the purpose of the regulation was to guarantee an environmentally safe storage, by the permanent containment of CO_2. Since then, the regulation has been changed on 2nd August 2016, 1st January 2017, 1st September 2018 and 1st August 2019. According to the regulation, CCS projects involving geological storage of more than 100 kt CO_2 are only allowed offshore. The regulation is not applicable to smaller CCS projects (e.g. research projects) involving geological storage of less than 100 kt CO_2. Such projects, which are also allowed onshore, will have to fulfil requirements according to the Swedish Environmental Act.

The Swedish subsurface belongs to the Swedish state. But the Government can according to the Continental Shelf Act give permits for exploration or exploitation of the Swedish continental shelf.

The Swedish government is the competent authority for granting permits for geological storage of CO_2. The Geological Survey of Sweden (SGU) is the regulatory authority regarding supervision of the storage complex.

SE4. Research

SE4.1 National funding for research related to CCS and research priorities

In recent years, the main focus of CCS research in Sweden has been on capture and transportation, where several pilot and demonstration projects have begun to investigate CO_2 capture. Presently, relatively little research focuses on geological storage in Sweden, as it is generally assumed that CO_2 will be transported and stored in Norway, at least initially. Listed below are a range of different national funding organisations. Most of these do not have specific programmes for funding CCS research, however, it is possible in some cases to receive funding for CCS related research through their more general programmes.

The Swedish Energy Agency (Energimyndigheten) is the main body responsible for funding in Sweden which specifically focuses on CCS. Over the last 10 years this organisation has funded several projects addressing various aspects of CCS. Many of them have been funded on a case-by-case basis and have not been part of a specific funding initiative. However, there have been several specific funding programmes, from which projects focusing on CCS have received funding. These funding programmes focus mainly on energy systems, sustainability, and the transition to zero net CO_2 emissions. A notable funding programme which has recently begun is called Industriklivet. This began in 2018 and will continue until 2040. The objective of this initiative is to fund research that will aid industry in the transition to zero-net-CO_2 emissions in 2045. Funding is available for research, feasibility studies and demonstration projects.

The Swedish Research Council (Vetenskapsrådet) is a government agency which funds research in all scientific disciplines. It does not have a specific programme for funding CCS based research, however, it has been an important national funding source for CCS research in Sweden, where several projects have been funded (or part funded) from their general natural sciences research project programme.

The Swedish institute (Svenska institutet) is a governmental agency which can provide funds for smaller projects. It does not have a specific programme for CCS, but some small CCS related projects have been funded.

Formas is a government research council for sustainable development. The funding programmes from Formas address environmental issues and aim to provide results which will aid Sweden in reaching its environmental objectives. CCS related projects would fall within the scope of some of the funding programmes from Formas.

The Swedish Foundation for Strategic Research (SSF) supports projects over a broad range of scientific disciplines (including engineering, medicine, and natural science) in areas deemed to be of strategic importance for Sweden. CCS projects could fall within the scope of some of the funding programmes from SSF.

Sweden's innovation agency, Vinnova. Vinnova funds research and innovation projects that can benefit the Swedish society and they do so through various offers, announced in the form of various calls for proposals. CCS projects could fall within the scope of some of the funding programmes (they have for example funded a project on business models for CCS).

Table SE: Overview of research topics addressed by recent nationally funded research projects on CO_2 storage.

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	X	X	(x)	(x)			X		X
Project examples	MUSTANG BASTOR NORDICCS	NORDICCS	NORDICCS	NORDICCS			BASTOR NORDICCS		NORDICCS

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

SE4.2 Research institutions involved in research related to CO_2 storage

There are several research institutes and institutions currently investigating CCS in Sweden. Some examples are as follows:

- Luleå University of Technology
- Uppsala University
- Chalmers University of Technology
- Energiforsk (formally Elforsk)

SE4.3 Existing larger scale research infrastructure

In recent years, the focus of CCS-related research in Sweden has been on capture, where several demonstration and pilot CO_2 capture projects have been established.

Pilot plant at Preem's Lysekil refinery: Preem, Sweden's largest fuel company, has recently begun a project to demonstrate capture technology at its Lysekil refinery in Sweden. The project began in 2019 and will continue until 2021. Chalmers University of Technology, SINTEF, Aker solutions and Equinor are partners in the project. The project is funded by the Swedish Energy Agency as part of their Industriklivet programme and GASSNOVA as part of their CLIMIT demonstration programme. As part of the project the entire CCS chain will be investigated, including capture, transport, and storage. Geological storage in Norway, rather than Sweden, is assumed in this project (see also SE2.1).

Demonstration plant at Stockholm Exergi central heating plant, Värtan, Stockholm: Stockholm Exergi began operations at a demonstration plant for the capture of CO_2 at their central heating plant in Värtan in autumn 2019 and will continue until summer 2020. The central heating plant uses biofuel and hence, the project can be considered as Bio Energy Carbon Capture and Storage (BECCS). The project is part funded by the Swedish Energy Agency. Geological storage in Norway, rather than Sweden, is assumed in this project (see also SE2.1).

Presently, there are no projects focusing on transport or geological storage in Sweden.

The INSURANCE project (Utilisation of industrial residues for an efficient geological BECCS) is conducted by the research groups Ore Geology and Biochemical Process Engineering at Luleå University of Technology, in collaboration with the paper- and pulp company Billerud Korsnäs. In the project that is funded with SEK 10 million by the Swedish Energy Agency 2020–2024, the aim is to develop the CO_2 capturing technique and to investigate the potential for geological storage of CO_2 in the Swedish onshore bedrock. The development of the capturing technique will involve the use of the industry's own by-products/waste with the aim of producing a more energy-efficient technique for capturing the CO_2 from the industrial off-gases. In the geological part of the project, volcanic bedrock around seven Swedish paper mills will be investigated with the aim of finding chemically favourable rocks for CO_2 storage. A comparison between the older Swedish bedrock is made with the younger Icelandic bedrock (ongoing Carbfix project) where CO_2 is successfully injected into volcanic rocks.

SE4.4 Involvement in EU-funded and other regional/international research projects related to CCS

The Swedish geological survey is currently not involved in any active EU funded regional/international CCS projects.

SE5. National actors driving CCS forward and public engagement

SE5.1 Awareness of CCS technology

There are few studies polling the attitudes of the general public. Von Borgstede et al. (2013) surveyed the general public with respect to their opinions on energy and climate related issues. The survey asks if respondents have heard of CCS and if they think it is a technology that should be used to tackle climate change. Von Borgstede et al. found that few people had heard about CCS. Yet, repetitions of the survey in 2015 and 2020 show an increased awareness in the technology with a slightly more-positive attitude towards using the CCS technology. Johnsson et al. (2010) published a 2006 poll on stakeholders' attitudes to CCS. Johnsson et al. concluded that "there was a widespread belief that CCS as well as renewable technologies such as solar power will achieve major market entry into the electricity sector within the next 10-20 years". This would mean 2016 to 2026 and it can be concluded that this did not occur for CCS but did for renewables. However, in 2006 CCS was mainly associated with coal power generation in Europe whereas today, CCS is generally (within industry and the political sphere) seen as an important part of a mitigation portfolio for the Swedish industry (although there are also some opponents to CCS). Media awareness regarding CCS has increased in recent years.

SE5.2 National advocates for CCS

Most parts of the emission-intensive industry in Sweden are engaged in CCS. This includes the pulp and paper industry which may act as CO_2 sinks since emissions are biogenic. Fossil Free Sweden, a governmentally supported initiative which gathers a large segment of Swedish industry to present sector-specific roadmaps for the Swedish industry which comply with the Swedish emission targets, have pointed to the need for CCS and BECCS in several of their roadmaps. The same goes for some reports presented by the Royal Swedish Academy of Engineering Sciences. The Forum for Reforms, Entrepreneurship and Sustainability, FORES, a liberal think tank, has also been generally positive towards CCS and BECCS. The public inquiry (SOU2020:4) mentioned earlier proposed targets for negative emissions by BECCS as part of a set of measures to reach a certain level of negative emissions by the years 2030 and 2045. There are also research groups in Sweden that point to the need for CCS mainly highlighting that 1) CCS is today the only feasible mitigation option for certain industries (cement and waste-to-energy heat and power plants) and 2) the need for net carbon removal from the atmosphere (BECCS) to remove residual emissions to reach net zero emissions and, on the longer term, to reach net negative emissions.

SE5.3 Public engagement

Relatively little public engagement has been performed in Sweden with regard to CCS; see SE5.1. There is a good awareness of the need for CCS/BECCS among Swedish politicians, relevant Government offices, institutions, academia as well as within the industry. When it comes to the general public, they are very concerned and engaged with regard to the issue of climate change much because of the broad coverage this issue gets in the press. The more technical aspects of solving the problem, like for instance the use of CCS/BECCS, appears to be less understood and therefore, the public engagement for – or against – the use of CCS/BECCS appears to be very low. This also applies to the press.

Summarising the state-of-play on geological CO_2 storage in Switzerland (CH; as of 30th June 2021)

CH1. National storage assessment, storage options, potential and capacity

In 2008, the Swiss Federal Office for the Environment (FOEN) commissioned a short report that highlighted, among other issues, the lack of a CO_2 storage potential assessment in Switzerland (Wallquist et al. 2009). Also in 2008, the Swiss Federal Office of Energy (SFOE) commissioned a Swiss Molasse Basin basin-scale assessment of the potential for geological storage of CO_2 in Switzerland (Diamond et al. 2010). The Swiss Molasse Basin, the country specific foreland basin north of the Alps extends from Lake Constance in the Northeast to Lake Geneva in the Southwest of Switzerland. The basin scale assessment led to a theoretical CO_2 storage capacity based on the calculation of a pore volume for the basin or storage formations being considered and then discounted to account for the sweep efficiency. In line with established practices of CO_2 storage assessments (IEA 2013), a simultaneous consideration of nine geological attributes (including faulting and natural seismicity) allowed the theoretical storage potential to be mapped at a resolution of a few km^2. At least four suitably capped reservoir formations of permeable sandstones and limestones (saline aquifers) underlie large areas of the Swiss Central Plateau (and to lesser extent below the western Jura Chain) within the technically favoured depth interval of 800-2,500 m. The composite theoretical storage assessment arrived at a theoretical (unproven) storage capacity of approximately 2,680 Mt CO_2. The theoretical CO_2 storage capacity estimate has not yet been constrained in a further techno-economic way.

In parallel, the Domain of the Swiss Federal Institutes of Technology (ETH Domain) initiated CARMA (Carbon Dioxide Management in Power Generation), a research and development project which investigated the state of development of CCS in Switzerland (Sutter et al. 2013).

More recently, new petrophysical data, albeit sparse, have been used to re-assess a marine sequence within the Swiss Molasse Basin considered to have a particularly high CO_2 storage potential. This Sequence, the Muschelkalk, is one of four geological formations considered suitable for saline aquifer storage: The Muschelkalk comprises today a deep saline aquifer with an associated low permeability cap rock sequence (Diamond et al. 2019). In Northeast Switzerland, in the Olten-Schaffhouse-Zurich area, the storage capacity of the Muschelkalk is estimated to be 52 Mt CO_2. Other site-specific studies have indicated CO_2 storage potential in southwestern Switzerland, but this has not yet been quantified.

The data have not been assembled in a comprehensive national CO_2 storage atlas for Switzerland. Neither site-specific characterisation nor site deployment studies have been undertaken to date, which hinders the development of effective, practical or matched storage-capacity figures for Switzerland. Due to the low degree of exploration maturity the resulting poor knowledge of the Swiss subsurface, more detailed investigations and pilot studies to prove storage feasibility are required.

To date CO_2 storage in deep saline aquifers is thought to be the best storage option in Switzerland. Considering the kinematics and dynamics of the Swiss Molasse Basin it is presently unclear to what extent CO_2 storage in saline aquifers will be constrained by buoyancy-limited storage or pressure-limited storage.

While Switzerland has no depleted oil/gas fields to speak of, it is worth remembering that there are hydrocarbon accumulations. Some 75 million m^3 of natural gas have been produced from the Finsterwald gas field during the 1980s. There are no published estimates of the gas initially in place (GIIP) and hence no estimates of CO_2 storage capacity. A 2013 geothermal exploration well has encountered a natural gas pocket at a depth in excess of 4,500 m underneath the city of St. Gallen in Eastern Switzerland. Using simple volumetrics the amount of natural gas accumulated in the reservoir is estimated to be very small, on the order of 500 million m^3 of GIIP.

No applications for a CO_2 storage concession or permit to undertake exploration and development activities have been filed yet with cantonal authorities; the 26 cantons that constitute the Swiss Confederation have the jurisdiction over their subsurface. The CO_2-emitting industries of Switzerland have not undertaken any work on CO_2 storage in Switzerland.

A parliamentary motion which authorises the Swiss federal government to, among other aspects, develop and implement a CO_2 storage exploration and development programme was submitted to the Swiss parliament in autumn 2020. The aim will be to create the necessary conditions for exploiting the subsurface, in particular for the acquisition of resources (heat, energy, minerals), for storage purposes (heat, cold, CO_2) or for the creation of new infrastructure (transport). Adopted by the two chambers of parliament in June 2021, a plan to process this motion is currently being prepared and will be submitted to the Swiss federal government for validation in early 2022.

CH2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

CH2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

Technical CO_2 capture for the purposes of meeting climate targets is novel for Switzerland. There are a number of pilot projects, mostly early stage (technology readiness level 4, laboratory pilot scale) in connection with 2nd and 3rd generation capture materials, and novel processes around integrated hydrogen- and CO_2-separation in connection with biomethane production. Switzerland's waste-to-energy, wastewater treatment, cement and chemicals sector are at various planning stages, generally at low readiness or commercial readiness levels, for piloting CO_2 capture in their industrial processes.

Of note is the impact of Climeworks, a Swiss company that develops and manufactures direct air capture units that have been piloted in a number of locations in Switzerland. Climeworks direct air capture process is an integral part of the Carbfix process that has been demonstrated in Iceland.

CH2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None. A prefeasibility study is in progress to identify the opportunities for developing a Swiss CO_2 collection network, possible routes and opportunities to integrate within a wider European CO_2 transport infrastructure to export CO_2 to geological CO_2-storage sites abroad.

Domestically, there are a few conceptual studies related to the topology of an integrated CO_2-pipeline network in Switzerland in connection with a hydrogen transport network, and in connection with the Carbon Hub concept of Switzerland's waste-to-energy sector.

CH2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

To date there is no project that pilots or demonstrates CO_2 geological storage in a comprehensive manner in Switzerland. There have been and currently are a number of research and innovation studies that feature site selection criteria for finding and developing CO_2 storage sites (undertaken in the framework of the ELEGANCY project, see CH4.4 for project list); petrophysical studies on typical storage and their associated cap rock formation (undertaken in the framework of the SCCER-SoE programme of work); conceptual studies that link geothermal energy utilisation and CO_2 storage (a joint Swiss-Canadian R&D project

Aquistore) and a number of specific studies that address cap rock integrity and CO_2 storage risk management (undertaken mostly in the framework of ELEGANCY and SFOE sponsored research).

Within the framework of the SFOE/ERANET ACT funded project ELEGANCY various aspects of geological CO_2-storage in saline aquifers have been studied including storage capacities, viable rates of CO_2 injection, magnitude and predictability of induced seismicity, cap-rock integrity and longevity of trapping.
Some experimental work is also taking place at the Mont Terri rock laboratory in Switzerland.

CH2.4 Past and current full-chain CCS projects & projects/sites in preparation

A few full-chain CCS projects are in early phases of preparation with a view towards application for innovation funding.

CH2.5 Plans for CCUS cluster development

None.

CH3. National policies, legislation and regulations

CH3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

In August 2019 the Federal Council (the government of Switzerland) decided to set a climate neutrality target for Switzerland by 2050. This target is indicative only and has not been endorsed or approved by Parliament and the Swiss people. Government's intent was the starting point for the long-term climate strategy announced on 27th January 2021 (FOEN 2021) and submitted to the UN Climate Change Secretariat as required by the Paris Agreement. The strategy builds on the measures and goals of the revised CO_2-Act, which targets a greenhouse gas emission reduction of 50% by 2030 relative to 1990. At least 75% of the 2030 target must be achieved domestically and thus the revised CO_2-Act will be a key step in achieving the net zero target.

The target of the long-term climate strategy is a circa 90% reduction in greenhouse gas emissions by 2050 relative to the 1990 level. The remaining gap must be balanced with negative emissions (permanent removal of greenhouse gases from the climate-relevant carbon cycle). The Federal Council addressed the possible role of negative emission technologies (NETs) in Switzerland's long-term climate policy to some detail in autumn 2020 in its reply to the postulate Thorens Goumaz (18.4211) and outlined possible courses of action (FOEN 2020). CO_2 geological storage could have gained access to CO_2 compensation certificates, should the revised CO_2-Act had passed the public referendum in June 2021. Parliamentary proceedings on a new revision of the CO_2-Act are currently ongoing. Support mechanisms for the exploration for CO_2 geological storage sites in Switzerland will be under consideration during the processing of the parliamentary motion previously mentioned.

CH3.2 National legislation and regulations

Carbon capture is to some extent legislated and regulated in the framework of industrial processes. There exists neither legislation nor regulation for CO_2 transport via pipelines, only for rail and road transport.

In Switzerland, the 26 Cantons comprising the Swiss Confederation have sole sovereignty over the subsurface: they are in charge of defining the regulatory framework for geological CO_2 storage. No canton has replicated the EU CCS Directive; there is no obligation for Switzerland and its Cantons to transpose this EU Directive.

There is no ban on carbon capture, transport or storage. It is questionable whether a fully integrated legal framework for CCS needs to be created in Switzerland.

CH4. Research

CH4.1 National funding for research related to CCS and research priorities

In 2019, public funding for CCS research and innovation amounted to CHF 8.7 million (approx. EUR 8 million). The principal funding agencies are the ETH domain, the Swiss National Science Foundation, Innosuisse, the Swiss Federal Office of Energy SFOE, the Federal Office for the Environment FOEN, the Cantons and the European Union. In particular, the Swiss Federal Offices that deal with energy and climate have increased investment in research and innovation as of 2020 and 2021. The statistics for 2020 will be published towards the end of 2021.

To date there does not exist an integrated research and innovation strategy and plan for CCS. As CCS research and innovation is primarily connected with Switzerland's energy systems (at least 70% of relevant greenhouse gas emissions are energy related), coordination of CCS research and innovation is to be coordinated by the Swiss Federal Office of Energy SFOE. The Federal Commission for Energy Research has included CCS in its 2021–2024 energy research strategy and implementation plan.

However, CCS efforts are in their infancy and no detailed CCS strategy and implementation plans have been developed. As the impact of CCS is directed on meeting the nation's climate targets, the Federal Office for the Environment has been charged to develop a roadmap for negative emission technologies, which will feature CCS as an ensemble of basic technologies common to a number of negative emission technologies. Low TRL (up to level 4) research on CO_2 capture, transport and storage is mostly administered by the Swiss Federal Office of Energy's industrial-processes and geo-energy research programmes. Higher technology-readiness-level activities, dominantly pilot and demonstration projects, are funded by the SFOE pilot and demonstration programmes.

Table CH: Overview of research topics addressed by recent nationally funded research projects on CO_2 storage.

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	(x)	(x)	(x)	(x)	(x)	(x)	(x)	-	(x)
	ELEGANCY (2017 – 2020)						Aquistore (2020-2021)		

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

CH4.2 Research institutions involved in research related to CO_2 storage

CO_2 storage research is undertaken by the University of Bern, University of Geneva, EPFL (École polytechnique fédérale de Lausanne) and ETHZ (Eidgenössische Technische Hochschule Zürich).

CH4.3 Existing larger scale research infrastructure

A number of national and international consortia use the Mont Terri underground rock laboratory operated by the Swiss Geological Survey, swisstopo. Participation in ECCSEL is currently under discussion.

CH4.4 Involvement in EU-funded and other regional/international research projects related to CCS

ERA-NET ACT:

- ELEGANCY
- GaSTech –Demonstration of Gas Switching Technology for Accelerated Scale-up of Pressurized Chemical Looping Applications
- PrISMa
- AC²OCem
- 3rd call ERANET ACT – submitted projects are being evaluated

Aquistore, a joint Swiss-Canadian research project on CO_2-plume geothermal energy utilisation.

EU funded project (ongoing or concluded in 2021):

- DMX – Demonstration in Dunkirk
- CLEANKER – CLEAN clinKER production by Calcium looping process
- CarbFix2 - Upscaling and optimizing subsurface, in situ carbon mineralization as an economically viable industrial option (HE)
- Leilac: Low Emissions Intensity Lime and Cement (H2020)
- MEMBER: Advanced MEMBranes and membrane assisted procEsses for pre- and post- combustion CO_2 captuRe (H2020)
- GENESIS: High performance MOF and IPOSS enhanced membrane systems as next generation CO_2 capture technologies (H2020)
- AMADEUS: Advancing CO_2 Capture Materials by Atomic Scale Design: the Quest for Understanding (ERC consolidator grant)
- MaGic - The Materials Genome in Action (ERC Advanced Grant)

CH5. National actors driving CCS forward and public engagement

CH5.1 Awareness of CCS technology

Even though no scientific public awareness survey has been performed in Switzerland, it is fair to say that general public knowledge about the CCS technology is very limited because of the lack of public discussion as well as visible activity (e.g. Wallquist et al. 2009).

CH5.2 National advocates for CCS

There are no national clubs or lobby groups supporting CCS in Switzerland. CCS is generating interest among emission-intensive industries, such as cement and waste-to-energy, but the only sector that is taking an advocacy role for CCS is the waste-to-energy/waste-to-value sector.

CH5.3 Public engagement

None.

Summarising the state-of-play on geological CO_2 storage in TURKEY (TR; as of 30th June 2021)

TR1. National storage assessment, storage options, potential and capacity

Assessment of possible geologic sites for CO_2 storage in Turkey was conducted in the scope of a project run by the Ministry of Energy and Natural Resources and funded by the Turkish Scientific and Technology Council (TUBITAK, KAMAG Project 106G110 (2009): Preparation of the Inventory of CO_2 Emissions from Thermal Power Plants and Industrial Facilities and Determination of the Potential of CO_2 Storage in Underground Geological Formations in Turkey). The assessment was carried out by the Petroleum Research Center at the Middle East Technical University (METU-PAL) and the Turkish Petroleum Corporation. Using the IPCC methodology, CO_2 emissions were calculated from major Turkish sources including from thermal power plants with capacities greater than 500 MW_e, cement factories, the steel industry, sugar factories and refineries. Storage potential was assessed in oil and gas fields and deep saline aquifers in Turkey, including the Dodan natural CO_2 field and the Mersin Soda Industry salt caverns. The suitability for storage of each was considered. Data from producing oil and natural gas reservoirs were confidential, as a result, only the fields licensed to Turkish Petroleum Corporation were studied (results are confidential).

Coupling sources and sinks resulted in a decision to make technical and economic evaluations for CO_2-EOR and storage operation in the Çaylarbaşı oil field in Adıyaman Region, with the source being CO_2 emissions from a cement factory about 130 km distant. The transportation plan considered both pipeline and tanker alternatives. EOR modelling was based on the assumption that CO_2 would be available at the cement factory. The modelling indicates that for a project life of 20 years, 8 years of CO_2 injection for EOR would produce 2 million barrels of oil followed by a 12 year storage phase in which 220 million Sm^3 CO_2 can be stored (Okandan et al. 2011).

Turkey's underground energy storage data were collected as part of the two-year ESTMAP project (2015–2016) under the B.2.7 call "Energy Storage Mapping and Planning". For the geographical database indicating existing, future and potential energy storage both subsurface and above-ground in Europe, METU-PAL assessed two hydrocarbon reservoirs currently developed in Turkey and two Turkish hydrocarbon reservoirs planned to be developed for underground gas storage. Two salt caverns were also included, both planned for underground gas storage. Direct operational capacities (gas working volumes) were determined. Although additional potential may also be present, only publicly available data or the potentials that have been assessed to a sufficient degree were reported in the project.

Identified underground gas storage sites may be considered as future potential CO_2 storage options.

The CO_2 storage potential in the Adıyaman, Batman and Thrace Basin oil and gas fields in Turkey was studied in the "Low Carbon Development Project" beginning in 2017. This work was carried out by METU-PAL. The "Low Carbon Development Project" was continued by a Consortium of the Turkish Ministry of Environment and Urbanisation, Human Dynamics, Regional Environmental Center (REC) and Agriconsulting Europe S.A. (AESA). Using available reservoir data, CO_2 storage volumes values were calculated considering the amounts of free CO_2 gas and CO_2 dissolved in water for each field (Low Carbon Development Project 2017). The preliminary results show that after analysing 103 oil fields, 79.5 Mt CO_2 can be stored in Batman Region, 28.7 Mt CO_2 can be stored in Adiyaman Region, and only 473 kt CO_2 can be stored in Trace region fields (Akin 2019).

TR2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

TR2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

The only known CO_2 capture research activity is the Turkish participation in the H2020 MOF4AIR project in which 14 partners will evaluate carbon capture based on Metal Organic Frameworks (MOFs) technologies. TUPRAS, a partner in the project and Turkey's largest oil enterprise and the 7th largest refinery enterprise in Europe, will host a MOF carbon capture pilot study in their Izmit facility.

TR2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

A 90 km long high-pressure carbon-steel pipeline has, since 1986, been used to transport CO_2 from the Dodan natural gas field to the Bati-Raman oil field where it is used for CO_2-EOR (see TR2.3). At Dodan, the naturally occurring CO_2 is separated from the natural gas, processed in absorption and dehydration units to remove H_2S and H_2O, then compressed for transportation by pipeline (Sahin et al. 2012).

TR2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

In Turkey, CO_2-EOR projects were mainly conducted for increasing oil recovery rather than for CO_2 storage as the main objective. The first large scale commercial CO_2-EOR project in Turkey was started in 1986 in Bati Raman by the Turkish Petroleum Corporation. The Bati Raman Field, discovered in 1961 in Southeastern Turkey, is the largest oil field in Turkey with approximately 300 million Sm^3 (1,850 million barrels) of initial oil in place (OOIP). Primary recovery driven by natural depletion was slow: in the 25 years from 1961 to 1986 less than 2% of the original oil in place was produced. The producing formation is Garzan limestone, a heterogeneous carbonate. The reservoir fluid is heavy crude oil with 9.7-15.1 API gravity and 450 to 1000 cp viscosity at reservoir conditions. To increase recovery and support the declining reservoir pressure, an immiscible CO_2 flooding project (EOR) was commenced in 1986 using natural CO_2 from the Dodan gas field as described in TR2.2). By the end of December 2011, the cumulative production at Bati Raman was 106.3 million barrels oil of which 70.4 million barrels were obtained during CO_2 injection. The total gas reserve of Dodan gas field had been estimated as 383 Bscf. The cumulative amount of CO_2 injected into the Bati Raman Field was 352.88 Bscf and the cumulative amount of CO_2 that reached the production wells was 252.9 Bscf. However, in 1991, recycle compressors were installed at Bati Raman and 115.8 Bscf of CO_2 was re-injected into the reservoir (Sahin et al. 2012).

The second full field CO_2 injection was performed in the Batı Kozluca Field, located in Southeastern Turkey, by Turkish Petroleum in operation since 1985, using natural CO_2 from the Camurlu Field, 10 km away. In 2004, a CO_2-EOR project was started at Batı Kozluca with a primary recovery of about 3%. After 5 years of injection, recovery reached above 4% (Sahin et al. 2010).

Another CO_2-EOR operation was conducted in the Camurlu Field, which has 60 million Sm^3 (380 million barrels) of heavy oil (284 cp viscosity) in place. The CO_2 used in the pilot tests was sourced from a CO_2-rich natural gas zone underlying the oil reservoir. Due to the insufficient capacity of surface facilities, the desired amount of CO_2 could not be injected in the planned time period and the project was stopped (Sahin et al. 2010).

A CO_2-EOR pilot application was conducted at Ikiztepe field by Japan National Oil Corporation (JNOC) and Turkish Petroleum Corporation (TPAO) in a collaboration with the Japan EOR Research Association (JEORA) in 1987. The primary recovery was only 0.07% of the original oil in place. The CO_2-EOR pilot test showed an improvement in oil viscosity (Ishii et al. 1997).

The current GECO H2020 project focuses re-injecting greenhouse gases, such as CO_2, produced from the subsurface during exploitation of geothermal energy. This decreases the emissions from geothermal power plants. The GECO - Geothermal Emission COntrol project is funded by the HORIZON 2020 Framework Programme of European Union and coordinated by Reykjavík Energy. From Turkey, Zorlu Enerji Elektrik Üretim Inc. and Middle East Technical

University are taking part in the GECO consortium, which also has industrial and research and technology development partners from France, Italy, Spain, Norway, Germany, UK and Iceland. In the project, geothermal demonstration sites were selected in Turkey, Iceland, Germany and Italy. Through the GECO project, a pilot CO_2 injection will be conducted in the Kizildere geothermal field, located in the Denizli and Aydin provinces of western Turkey. In addition to reducing the CO_2 emissions of geothermal power production, the project aims at maintaining the sustainability of the reservoir.

Another pilot-scale study is the SUCCEED (Synergetic Utilisation of CO_2 storage Coupled with geothermal EnErgy Deployment) project, which is funded by ACT – Accelerating CCS Technologies, an ERA-NET Co-fund. The objective of the project is demonstrating the feasibility of the re-injection of produced CO_2 to improve geothermal performance, as well as storing the CO_2. For this purpose, eight partners from industry and academia will be working together. Project coordinator is the Imperial College London and partners from Turkey are Zorlu Enerji Elektrik Üretim Inc. and Middle East Technical University. In the project, CO_2 injection operations, site performance and reservoir behaviour will be monitored at the Kizildere Field in Turkey and Hellisheidi in Iceland. Pre- and post-CO_2 injection simulations and different CO_2 injection strategies will be applied.

The first pilot-scale injection of CO_2 into a geothermal reservoir in Turkey (along with other non-condensable gases) was done in 2016–2017 at the Umurlu Geothermal Field. During the pilot study, a total of 134,400 m^3 (1248 t) CO_2 were injected into the reservoir for 20 days, with an average flow rate of 2.65 t/hour (Yücetaş et al. 2018).

TR2.4 Past and current full-chain CCS projects & projects/sites in preparation

None.

TR2.5 Plans for CCUS cluster development

The Ministry of Environment and Urbanisation has a programme for the industry to officially monitor national greenhouse gas emissions in accordance with the Regulation on the Monitoring of Greenhouse Gas Emissions that went into force on 25th April 2012 (Official Gazette Number: 28274). The regulation has been revised and republished on 17th May 2014 (Official Gazette Number: 29003). The industrial facilities that carry out activities including fossil fuel combustion, refinery processes, cement, coke, iron, steel production and processing are obliged to monitor and report the greenhouse gas emissions each year to the Ministry. Emission reports prepared by facilities are verified by independent accredited bodies. By this reporting system, greenhouse gas emissions of industrial facilities are obtained. After the assessment of CO_2 emissions of industrial facilities, new strategies and plans should be developed to use available pipelines and facilities or construct new networks to transport CO_2 to the potential storage sites. One of the ERA-Net ACT Projects, ECOBASE (2017–2021), focused on creating business models required to realise CO_2-EOR and storage projects as an accelerating factor for developing CCUS clusters in southeastern Europe. From Turkey, the Middle East Technical University METU PAL was a partner.

TR3. National policies, legislation and regulations

TR3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

Turkey, an OECD member, was recognised by the Parties as a country having a special position in comparison to that of other countries listed in Annex 1 of the United Nations Framework Convention on Climate Change (UNFCCC) in 2001. It was decided to exclude Turkey from the list of countries in Annex 2 of the Convention. After this decision, Turkey has become a party to the UNFCCC in 2004. Following the legislation accepted in the Turkish National Assembly on 5th February 2009 (Official Gazette Number: 5386) and Cabinet Decision on 13th May 2009, Turkey became a part of the Kyoto Protocol. However, as Turkey was not a part of UNFCCC at the signing of the Protocol, it was not included in the Annex B of the Protocol where the emission targets are set. As a result, Turkey does not have any quantified emission limitation or reduction obligations in the first (2008–2012) and second (2012–2020) commitment periods.

On 3rd May 2010, the National Climate Change Strategy (NCCS) was approved by the Higher Planning Council, including the activities that should be carried out by each sector for the prevention of climate change. In the NCCS, the main Turkish objective was stated as "to take part in the global efforts for preventing climate change, which is a common concern of mankind, determined with common mind in cooperation with the international parties and in the light of objective and scientific evidence; in accordance with the sustainable development policies, and within the framework of the principle of 'shared but differentiated responsibilities' and Turkey's special circumstances" and to provide "its citizens with a high quality of life and welfare with low carbon intensity". Greenhouse gas emissions from electricity generation are envisaged to be 7% less than what they would have been in the Reference Scenario by 2020.

The National Climate Change Action Plan (NCCAP) 2011–2013 was prepared for the implementation of the National Climate Change Strategy within the framework of the Developing Turkey's National Climate Change Action Plan Project that was coordinated by the Turkish Ministry of Environment and Urbanisation and carried out through the agency of United Nations Development Programme (UNDP) in Turkey. The purposes and objectives of the action plan are divided into different sectors, such as energy, building, industry, transportation, waste, agriculture, land use and forestry. The aims for the adaptation to climate change are also explained separately. Reduction of greenhouse gas emissions is targeted in vegetal and animal production, new settlements and industrial processes. In the building sector, the aim is a 10% emission reduction compared to existing settlements. However, in other sectors there is no set value for the emissions limitations. Increasing the sequestration of carbon in forestry by 15% of the 2007 value, using clean coal technologies, increasing energy efficiency, and increasing the share of renewable energy are among the mitigation plans.

TR3.2 National legislation and regulations

There is no law that regulates carbon capture and geological storage. The usage of the underground is regulated by the General Directorate of Mining and Petroleum Affairs (MAPEG). The General Directorate of Petroleum Affairs and the General Directorate of Mining Affairs were abolished and the General Directorate of Mining and Petroleum Affairs (MAPEG) was established with the decree issued in the Official Gazette dated 9th July 2018 and numbered 30473. MAPEG gives exploration and operation licences for related natural resources and takes inventory of the natural resources according to the Turkish Petroleum Law number 6491 accepted on 30th May 2013. Mainly the law regulates the exploration, development and production of petroleum sources. The law states that CO_2 that is produced from the petroleum fields could be used for enhanced oil recovery purposes. In order to use a petroleum field as a storage medium, it should be depleted completely and the Directorate should give consent. If a field could be used technically as a storage medium, for other energy activities and at the same time for petroleum production, the storage operation is allowed. Otherwise the Ministry would choose which use has priority. As a state corporation Turkish Petroleum has the rights and duties to make all petroleum related activities such as exploration, drilling, production, transportation, storage and refinery processes. There is no regulatory barrier that directly prevents using the underground for CO_2 storage purposes.

In Turkey, industries that carry out activities including fossil fuel combustion, refinery processes, cement, coke, iron, steel production and processing are subject to annual monitoring, reporting and verification processes for greenhouse gas emissions. Emission reports and monitoring plans are delivered to the Ministry of Environment and Urbanisation in accordance with the Regulation on the Monitoring of Greenhouse Gas Emissions that went into force on 25th April 2012 (Official Gazette Number: 28274). The regulation has been revised and republished on 17th May 2014 (Official Gazette Number: 29003). Obligations on monitoring and reporting under the regulation are stated in “Communique of Monitoring and Reporting Greenhouse Gas Emissions” (Official Gazette Number: 29068, Date: 22nd July 2014).

“Communique on Verification of Greenhouse Gas Emission Reports and Authorization of Verifiers” went into force on 2nd April 2015 (Official Gazette Number: 29314) and was replaced on 2nd December 2017 by the "Communique on Verification of Greenhouse Gas Emissions and Accreditation of Verifiers" (Official Gazette Number: 30258).

TR4. Research

TR4.1 National funding for research related to CCS and research priorities

University funds or TUBITAK (Turkish Scientific and Technology Council) funds are available for interested researchers. There is no specific national programme for research related to geological storage of CO_2.

Table TR: Overview of research topics addressed by recent nationally funded research projects on CO_2 storage.

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	X	-	-	-	-	-	X	-	-
Project examples	TUBITAK, KAMAG Project 106G110 (2009)						TUBITAK, KAMAG Project 106G110 (2009)		

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

TR4.2 Research institutions involved in research related to CO_2 storage

Some of the research institutions involved in research related to CO_2 storage are listed below:

- Turkish Petroleum Corporation (Research and field application)
- Middle East Technical University - Petroleum Research Center
- Izmir Technology Institute
- TÜPRAŞ – ARGE

TR4.3 Existing larger scale research infrastructure

- TÜPRAŞ Izmit Refinery (capture pilot site, MOF4AIR project is ongoing).
- Umurlu Geothermal Field (CO_2 injection pilot tests have been done).
- Kizildere Geothermal Field (GECO and SUCCEED projects are ongoing). Gas analyses are conducted at METU PAL.

TR4.4 Involvement in EU-funded and other regional/international research projects related to CCS

Middle East Technical University- Petroleum Research Center (METU PAL) has been involved in the following EU-funded research projects addressing aspects relevant for/related to CCS:

- CGS Europe – Pan-European coordination action on CO_2 Geological Storage (2010–2013).
- ESTMAP – Energy Storage Mapping and Planning project (2015–2016).
- ENOS – Enabling onshore CO_2 storage in Europe (2016–2020)
- ECOBASE – Establishing CO_2 Enhanced Oil Recovery Business Advantages in South Eastern Europe (2017–2020)
- GECO – Geothermal Emission Control (2018–2022)
- SUCCEED – Synergetic Utilisation of CO_2 storage Coupled with geothermal EnErgy Deployment (2019–2022)

TÜPRAŞ has been involved in the following EU-funded research projects addressing CO_2 capture and usage:

- MOF4AIR – Metal Organic Frameworks for carbon dioxide Adsorption processes in power production and energy Intensive industRies (2019–2022)
- COZMOS – Efficient CO_2 conversion over multisite Zeolite-Metal nanocatalysts to fuels and olefins.

TR5. National actors driving CCS forward and public engagement

TR5.1 Awareness of CCS technology

Although there is general knowledge about climate change in the public, there is not a common, detailed knowledge and understanding about CCS technology. In 2011, the CO_2GeoNet educational brochure “What does CO_2 geological storage really mean?” was translated into Turkish (translated title: CO2’nin yeraltında depolanması gerçekte ne anlama geliyor?) as part of a study carried out by METU-PAL to increase the awareness of the public.

Also, a CO_2 Capture and Storage Regional Awareness-Raising Workshop was organised by METU-PAL in June 2012 in Ankara and distinguished speakers gave valuable information about CCS operations.

In November 2019, a presentation entitled “Climate Change and CO_2 Storage” was given by METU-PAL to the students of Hacı Bektaş-ı Veli Secondary School to enhance public awareness of CCS.

Moreover, in 2020, in the scope of the ECOBASE project, a questionnaire survey was used to find out the level of the public's perception about the capture, storage and use of CO_2.

TR5.2 National advocates for CCS

None.

5.3 Public engagement

None.

Summarising the state-of-play on geological CO_2 storage in UKRAINE (UA; as of 30th June 2021)

UA1. National storage assessment, storage options, potential and capacity

At present, modern geophysical research methods are used to search for and assess promising CO_2 storage sites in Ukraine. According to the experts, on the territory of Ukraine there are conditions for CO_2 storage in the Dniprovsko-Donetskiy basin in the east, and in the Lvivskiy depression in the west. It should be noted that the storage capacity of CO_2 in depleted hydrocarbon deposits in Ukraine is limited. The saline aquifers apparently have a much greater potential for CO_2 storage. These are deep sedimentary rocks, saturated with formation waters or waters with a high concentration of dissolved salts, which are identical to saline aquifers in hydrocarbon provinces. Saline aquifers are widespread in Ukraine and can potentially serve as the storage for large amounts of CO_2.

Under the EU-funded project "Low carbon opportunities for Industrial Regions of Ukraine (LCOIR-UA)" (Grant Contract No. DCI/ENV 2010/243-865)", work was underway in Ukraine to develop a CO_2 storage atlas. Currently, the detailed quantitative assessment work being carried out includes: structural analysis, seismic exploration, injection testing, and modelling. There is a need to raise additional funds to continue creating a knowledge base so that the storage of CO_2 in the Ukrainian subsurface becomes cost-effective. Further development of CCS projects in Ukraine is negatively affected by economic and political factors.

Within the targeted interdisciplinary project of the National Academy of Sciences of Ukraine (NASU) "Scientific, technical and economic-ecological principles of low-carbon development of Ukraine" under the project section "Challenges and opportunities of low-carbon development of Ukraine: the national context of the global problem", the NASU Radio-Environmental Centre has carried out a study "Possibilities of greenhouse gas disposal in the subsurface of Ukraine, criteria and prospects for the search of hydrogen in the areas of modern degassing of oil and gas basins of Ukraine" in 2019. A previous project was carried out to assess the possibility of CO_2 storage in the subsurface of Ukraine. The possibilities of CO_2-EOR and CO_2 storage in carbonate reservoirs of oil and gas regions - Dniprovsko-Donetskiy Basin, northern outskirts of Donbas, Outer zone of Fore-Carpathian Depression, and Lvivska Depression, were considered. The estimated storage potential for CO_2 could be around 30 billion m^3.

UA2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

UA2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

See UA 2.4

UA2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

UA2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

None.

UA2.4 Past and current full-chain CCS projects & projects/sites in preparation

The project "Low Carbon Capabilities for Industrial Regions of Ukraine" (LCOIR-UA) was implemented in 2011–2015 by Donetsk National University (Donetsk, Ukraine) funded by the EU Thematic Programme "Environment and Sustainable Management of Natural Resources including Energy (ENRTP; theme "Cooperation on clean coal technologies and carbon capture and storage "; grant contract No. DCI/ENV 2010/243-865). The aim of the project was to improve the knowledge of the Ukrainian context for the implementation of climate-friendly technologies, to identify potential targets for current climate adaptation programmes in Ukraine, and to create awareness among key stakeholders about climate technologies as the tools to combat climate change. As a result of the project, GIS models for the sources and sinks of CO_2 were created, as well as an integrated GIS database with information about existing coal mines and opportunities to use the Ukrainian gas transportation system for climate-friendly technologies in order to see the opportunities and obstacles to climate-friendly technologies in Ukraine. Recommendations were provided on the actual implementation of climate technologies for facilities in the industrial regions of Ukraine.

UA2.5 Plans for CCUS cluster development

None.

UA3. National policies, legislation and regulations

UA3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

To fulfil Ukraine's international obligations under paragraph 19 of Article 4 of the Paris Agreement, paragraph 35 of Decision 1/CP.21 of the Conference of the Parties to the UN Framework Convention on Climate Change, as well as to comply with the orders of the Cabinet of Ministers of Ukraine of 7th December 2016, № 932-r “On approval of the Concept for the implementation of state policy in the field of climate change until 2030”, and of 28th March 2018, № 244-r “On approval of the Government's priority action plan for 2018”, the Strategy for Low Carbon Development of Ukraine until 2050 was developed. This regulatory document envisages the introduction of innovative technologies for carbon capture, storage and reuse, which, in addition to policies and measures in the field of energy efficiency and renewable energy, will allow for the years 2012–2050 for reducing greenhouse gas emissions by 1064 Mt $CO_{2\ eq}$.

According to the Draft Strategy for Low Carbon Development of Ukraine until 2050 (released in 2018), it is planned to increase the volume of carbon sequestration and retention. Under the policy item “Introduce incentives, support or define requirements for advanced fossil fuel energy technologies”, assistance in the development of new technologies is foreseen, including coercion and / or incentives to use advanced technologies for thermal power plants (TPP) using non-renewable energy sources (primarily coal). Coercion implies that all or a certain part of coal-fired power plants use a certain technology, in particular IGCC (Integrated Gasification Combined Cycle) and CCSR (Carbon Capture and Storage Ready). Incentives will include direct subsidies and / or assistance in raising finance for the introduction of the latest technologies and / or long-term agreements for the purchase of TPP products or services.

UA3.2 National legislation and regulations

To date, the Draft National Waste Management Strategy for Ukraine until 2030 has been developed, which is based on the Framework Directive № 2008/98 / EC on waste, Directive № 1999/31 / EC on waste disposal, Directive № 2006/21 / EU on waste management industry. The aim of this strategy is to create an effective waste management system on an innovative basis, which in the long run should ensure comprehensive recycling of natural resources and waste recycling.

According to Article 13 of the Constitution of Ukraine "The land, subsurface, air, water and other natural resources located within the territory of Ukraine, natural resources of its continental shelf, exclusive (marine) economic zone, are the property of the Ukrainian people." On behalf of the Ukrainian people, the rights of the owner are exercised by state authorities and local governments within the limits set by the Constitution. The competent authority in the field of subsoil use in Ukraine is the Ministry of Environmental Protection and Natural Resources.

UA4. Research

UA4.1 National funding for research related to CCS and research priorities

The project "Possibilities of greenhouse gas disposal in subsurface of Ukraine, criteria and prospects for searching for hydrogen in areas of modern degassing of oil and gas basins of Ukraine" was implemented by NASU Radio-environmental Centre in 2019 within the NASU targeted interdisciplinary project "Scientific, technical and economic-ecological principles of low carbon development". It was funded from the State Budget of Ukraine.

Table UA: Overview of research topics addressed by the recent nationally funded research project "Possibilities of greenhouse gas disposal in subsurface of Ukraine, criteria and prospects for searching for hydrogen deposits in areas of modern degassing of oil and gas basins of Ukraine".

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	X	(x)	(x)	(x)	X	(x)	X	X	–

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

UA4.2 Research institutions involved in research related to CO_2 storage

- Donetsk Vasyl Stus National University
- Radio-Environmental Centre, NASU
- S.I.Subotin Institute of Geophysics, NASU
- M.P.Semenenko Institute of Geochemistry, Mineralogy and Ore Formation, NASU

UA4.3 Existing larger scale research infrastructure

None.

UA4.4 Involvement in EU-funded and other regional/international research projects related to CCS

The project "Low Carbon Capabilities for Industrial Regions of Ukraine" (LCOIR-UA) was implemented in 2011–2015 by Donetsk National University (Donetsk, Ukraine) funded by the EU Thematic Programme "Environment and Sustainable Management of Natural Resources including Energy (ENRTP; theme "Cooperation in clean coal and carbon capture and storage technologies"; grant contract No. DCI/ENV 2010/243-865) - see UA2.4.

UA5. National actors driving CCS forward and public engagement

UA5.1 Awareness of CCS technology

No information available.

UA5.2 National advocates for CCS

None.

UA5.3 Public engagement

In order to discuss carbon capture and storage in Ukraine, the Norwegian non-governmental organisation "Bellona" had prepared a publication "Low-carbon opportunities for industrial regions of Ukraine" in 2013. This publication emphasised public participation in CCS projects in Ukraine. According to this document, in particular the CCS technology should be introduced and discussed as an integrated technology in the final decarbonisation strategy for the Ukrainian economy; early introduction of CCS as a technology tool, along with other technologies such as renewable energy and bioenergy, will raise awareness and provide solutions to continue CCS implementation on a stronger basis. The benefits of CCS technologies in the Ukrainian environment should be noted from the beginning, including the benefits for Ukrainian heavy industry and the continued use of local energy sources. The planning and management of any pilot or demonstration facility should be transparent, with active advocacy and sustained engagement with local groups and stakeholders.

Summarising the state-of-play on geological CO_2 storage in the UK (GB; as of 30th June 2021)

GB1. National storage assessment, storage options, potential and capacity

The UK has a national storage database called CO_2 Stored. CO_2Stored provides an overview of CO_2 storage data for over 500 potential CO_2 storage sites around offshore UK. Overall theoretical capacity (P50) is 68,666 Mt CO_2. The original data in CO_2Stored was developed by the UK Storage Appraisal Project (UKSAP), which was commissioned and funded by the Energy Technologies Institute (ETI). CO_2Stored was hosted and developed by the British Geological Survey and The Crown Estate between 2013 and 2018 and is now wholly operated and maintained by the British Geological Survey.

GB2. CO_2 capture, injection and storage projects — large-scale, demonstration and pilot projects

GB2.1 Past and current large-scale/demonstration/pilot projects for CO_2 capture & projects/sites in preparation

None.

GB2.2 Past and current large-scale/demonstration/pilot projects for CO_2 transport & projects/sites in preparation

None.

GB2.3 Past and current large-scale/demonstration/pilot projects for CO_2 geological storage & projects/sites in preparation

There are storage sites under development as parts of full chain projects (see later section).

GB2.4 Past and current full-chain CCS projects & projects/sites in preparation

A FEED study for a CCS project with CO_2 capture from the Peterhead power plant and storage by BP in the Miller field was proposed in 2005–2007. This project did not move forward in the end as funding was not available on the required timescale.

The first UK CCS competition was launched in 2007 with significant funding to come from the UK government. The aim was to fund a full chain demonstration or post-combustion capture. Four projects were submitted which were whittled down to two preferred bidders: Kingsnorth CCS project (E.ON) and Peterhead/Longannet CCS project (SSE). E.ON withdrew and negotiations with SSE were unsuccessful (2011) so the first CCS competition did not in the end result in a CCS demonstration project in the UK.

The second CCS competition was launched in 2012, four projects were shortlisted and two preferred bidders were announced:
1) White Rose CCS project with capture at the Drax power plant, storage in a saline aquifer in the Bunter Sandstone Group, closure 5/42, also known as the Endurance structure (Capture Power Ltd formed by General Electric, Drax, BOC to work on the White Rose project, with National Grid subcontracted to work on storage) and,
2) Peterhead CCS project with capture at Peterhead power plant and storage in the Captain Sandstone Formation in the Goldeneye field (Shell and SSE).
White Rose was also successful in applying for NER300 funding. Key documents from the Front End Engineering and Design (FEED) studies for both projects are available online. As of 2021, a number of these CCS projects are still under development with new partnerships and funding even though the second competition did not provide the expected funding at the time.

In 2016, the Oil and Gas Authority (OGA) became responsible for licencing CO_2 storage (previously it was the Secretary of State for Business, Energy and Industrial Strategy) for the UK offshore with the exception of the territorial sea adjacent to Scotland, which Scottish ministers authorise.

A list of applications for CO_2 appraisal and storage licences is available through the UK Oil and Gas Authority. These licences are granted under the UK Energy Act 2008, which is part of the transposition of the EU Directive 2009/31/EC on the geological storage of CO_2. The main document is the Carbon Dioxide Regulation SI 2010/2221 which transposes many of the other requirements of the Directive, this came into force in the UK on 1st October 2010. In addition to the licence, the operator also requires a lease for the site from the Crown Estate/Scottish Crown Estate (the governmental body that owns the rights to the subsurface). Under the appraisal and storage licence, the operators can carry out studies to confirm the suitability of the site for geological storage. When site viability is confirmed, the operator can then ask the Crown Estate to activate their full Storage Lease.

There are four active appraisal and storage licences (see also large-scale projects under preparation).

Northern Endurance Partnership: BP, Eni, Equinor, National Grid, Shell and Total have formed a partnership to develop offshore CO_2 transport and storage infrastructure in the UK North Sea, with BP as operator. The plan is to develop infrastructure that will store CO_2 from the proposed Net Zero Teesside (NZT) and Zero Carbon Humber (ZCH) projects. A licence for CO_2 storage in the offshore "Endurance" structure was granted to National Grid during 2012, this was then amended and BP and Equinor joined National Grid in the licence for Endurance during 2020. The carbon dioxide appraisal and storage licence ID is **CS001.**

Goldeneye (Carbon dioxide appraisal and storage licence **CS002**): A full scale project was planned that would store CO_2 in offshore Scotland. The proposed Peterhead CCS Project planned to store CO_2 in the Goldeneye gas field in the North Sea. The plan was to capture up to 10 Mt CO_2 from the Peterhead gas-fired power plant over a 10-year period. The CO_2 storage licence was granted in 2013 but terminated in 2016 after the decision was made not to move the project forward when the UK CCS Commercialisation Programmes did not move forward.

The ACORN project (Carbon dioxide appraisal and storage licence **CS003**): This project aims to deliver low-cost CCS in the north east of Scotland by 2023. To achieve this, the project is utilising existing infrastructure wherever possible. CO_2 will be captured at the St Fergus Gas Terminal (near Aberdeen). Existing pipelines will be used to transport the CO_2 offshore. Storage will be in the Captain Formation. The project is led by the company Pale Blue Dot. The aim is to start storing CO_2 in the mid 2020s.

HyNet (Carbon dioxide appraisal and storage licence **CS004):** ENI UK has obtained an appraisal and storage licence. This project aims to provide a tangible pathway to energy transition and de carbonisation. The project plans to capture and transport CO_2 from exiting industries and future hydrogen production sites for fuel switching, heating, power and transportation in the context of the UK targets for net zero emissions by 2050. The project aims to store CO_2 in the Hamilton, Hamilton North and Lennox depleted hydrocarbon fields (Liverpool Bay area).

GB2.5 Plans for CCUS cluster development

The UK Industrial Strategy White Paper sets out the UK strategy "to put UK at the forefront of the industries of the future". One of four "Grand Challenges" identified was "Clean Growth". The Clean Growth challenge includes the mission to "establish the world's first net-zero carbon industrial cluster by 2040 and 4 low-carbon clusters by 2030". The mission is backed by GBP 170 million public investment through the Industrial Strategy Challenge Fund (ISCF) matched by GBP 261 million from industry. The deployment, cluster plans and UK Industrial Decarbonisation Research and Innovation Centre (IDRIC) workstreams will operate on a collaborative basis through knowledge sharing, industry engagement and collective leadership. The ISCF has a two-phase funding model, at the date of writing, a number of projects have been funded under phase 1. Six industrial decarbonisation feasibility studies were carried out under phase 1 through an investment of GBP 132 million:

Scotland's Net Zero Infrastructure - NECCUS which is an alliance of industry, government and experts. This includes CCUS focused around the ACORN project which aims to eventually develop the St Fergus Gas Terminal as a Hub for CCS.

Net Zero Teesside is a Carbon Capture, Utilisation and Storage (CCUS) project, based in Teesside. This project aims to decarbonise a cluster of carbon-intensive businesses by as early as 2030 and deliver the UK's first zero-carbon industrial cluster. Net Zero Teesside is a full chain CCUS project comprising of a consortium of five members of the Oil and Gas Climate Initiative (OGCI) BP, ENI, Equinor, Shell and Total. CO_2 storage is planned in the offshore Endurance structure (saline aquifer).

Zero Carbon Humber/Humber Industrial Decarbonisation Deployment project is focused around the Equinor-led Hydrogen to Humber (H2H) Saltend project that will establish the world's largest hydrogen production plant with carbon capture (Zero Carbon Humber Partnership includes Associated British Ports, British Steel, Centrica Storage Ltd, Drax Group, Equinor, Mitsubishi Power, National Grid Ventures, px Group, SSE Thermal, Saltend Cogeneration Company Limited, Uniper, and the University of Sheffield's Advanced Manufacturing Research Centre (AMRC). CO_2 storage is planned in the offshore Endurance structure (saline aquifer)

HyNet North West is based on the production of hydrogen from natural gas. It includes the development of a new hydrogen pipeline; and the creation of the UK's first carbon capture, and storage (CCS) infrastructure. From 2025, HyNet will produce, store and distribute hydrogen as well as capture and store carbon from industry in the North West of England and North Wales. (see also UK2.4)

South Wales Industrial Cluster: A "clustering" group of major industrial companies in the region stretching from the Pembrokeshire Coast to the Severn Bridge along the M4 corridor. The SWIC plans to implement smart technologies following a clear roadmap to decarbonisation (Efficiency, Fuel, Switching, Smart Networks, CCU, CCS). SWIC will develop smart integrated projects towards regional decarbonisation to drive net zero carbon in energy and heavy industry in South Wales.

Green Hydrogen for Humberside, deployment study: ITM Power, an energy storage and clean fuel company, with its partner Element Energy plan to assess the feasibility and scope of deploying green hydrogen in Humberside.

On 19th October 2021, the UK Government published a policy paper under the 2008 Climate Change Act; Net Zero Strategy: build back greener. In this document, two industrial clusters have been taken forward for development in Stage 1 and are now in the negotiation phase: The East Coast Cluster (Northern Endurance partnership, comprising Net Zero Teesside and Zero Carbon Humber with CO_2 storage in the Endurance saline aquifer store) and Hynet in North Wales (blue hydrogen production with CO_2 storage in depleted natural gas reservoirs in Liverpool Bay). The Acorn Project in NE Scotland is currently on the reserve list, but is expected to be developed in Stage 2.

In addition to the industrial decarbonisation projects above, the ISCF funded GBP 8 million for cluster plans:

- Net Zero Tees Valley (led by Tees Valley Combined Authority)
- Scotland's Net Zero Roadmap (led by NECCUS)
- Humber Industrial Decarbonisation Roadmap (led by Humber Local Enterprise Partnership)
- North West Hydrogen and Energy Cluster: Route to net zero (led by Peel Environmental)
- South Wales Industrial Cluster (Led by CR Plus Consultancy)
- Repowering the Black Country (led by Black Country Consortium)

The ISCF also invested GBP 20 million in the Industrial Decarbonisation Research and Innovation Centre (IDRIC). The aim of IDRIC is to become a world-leading, high impact research and innovation centre, acting as the national focal point and international gateway for UK industrial decarbonisation research and innovation. At the date of writing, IDRIC was in the launch period.

GB3. National policies, legislation and regulations

GB3.1 National policies w.r.t. GHG emission reduction targets/climate strategies

The UK Climate Change Act 2008 amends the Energy Act 2004 and sets out targets for 2050 including emission reduction and carbon budgeting. The Climate Change Act led to the establishment of an independent statutory body during 2008 that sets the carbon budget for the UK, the Climate Change Committee. Progress and priorities on CCUS are reviewed by the ministry-led CCUS council. The Climate Change Act, was again amended in 2019, committing the UK to "net zero" by 2050 and enshrining these targets in law.

Under the Climate Change Act, the UK government launched their Clean Growth Strategy in 2017. Within this strategy, CCUS played a significant role in reducing industrial emissions. During 2020, the Government set out their 10 point plan for a Green Industrial Revolution which was followed by the Energy White Paper setting out plans for a net zero emission future for the UK. The envisioned role for CCUS in reaching emission targets was again clearly set out, with the ambition to capture 10 Mt CO_2 per year by 2030 and the announcement of investment of up to GBP 1 billion in establishment of four industrial clusters in the UK. The Industrial Decarbonisation Strategy was launched in 2021, setting out plans to achieve net zero. decarbonise regions and clusters (see section on clusters section).

The UK aims to become a global technology leader for CCUS and to ensure the option of deploying CCUS at scale during the 2030s, subject to costs coming down sufficiently. To achieve this ambition, the UK has three main actions: i) re-affirming commitment to deploying CCUS in the UK subject to cost reduction; ii) international collaboration on CCUS; iii) CCUS innovation. The government continues to work with the ongoing initiatives in Teesside, Merseyside and Grangemouth to test the potential for development of CCUS industrial decarbonisation clusters.

A review of business models that could enable CCUS in the UK was published in late 2020.

GB3.2 National legislation and regulations

EU Directive 2009/31/EC on the geological storage of carbon dioxide was transposed into UK law in 2010. The Energy Act 2008 forms part of this transition and enables the licencing regime for offshore storage of CO_2 in the UK. In the UK, the Crown owns the subsurface and all mineral rights and a lease from them is required to carry out activities such as drilling and CO_2 storage; a licence for CO_2 storage and appraisal can be obtained through the Oil and Gas Authority.

Given the abundance of offshore storage, the UK is focussed in developing offshore storage with the associated economies of scale that brings. It is also generally expected that societal acceptance of offshore storage will be easier to obtain than onshore storage. Onshore UK does not have individual sites where large amounts of CO_2 could be stored, but smaller pilot scale projects would be possible. Onshore storage is permissible and is not legally banned but the UK focus is on developing offshore storage.

GB4. Research

GB4.1 National funding for research related to CCS and research priorities

The UK is part of Mission Innovation, CEM, CSLF and ERA-NET ACT as part of their commitment to international collaboration on CCUS. National funding for CCUS and hydrogen covers the full range of TRL from R&D on innovative new concepts to assessing the feasibility of decarbonisation of industrial clusters and deployment of CCUS projects. Through the CCUS Innovation Programme, the UK government aimed to reduce costs for CCUS. Most recently, projects have been invited to request support through the Industrial Strategy Challenge Fund – Decarbonisation of Industrial Clusters Deployment. Projects invited through to the second stage focus on decarbonised industrial clusters utilising CCUS and/or hydrogen. UKRI distributed funding to support decarbonisation of large industrial clusters in the UK through the Industrial Clusters Mission which is part of the Grand Challenges Mission set out in a policy paper issued by the Department for Business, Energy & Industrial Strategy (BEIS). The Net Zero Innovation Portfolio provides funding for low carbon technologies. The UK government is investing in biomass and CDR and a new biomass strategy is expected in 2022, this strategy is expected to include consideration of biomass and CCS following recommendations from the UK Committee on Climate Change. CCUS is also included in the UK COVID recovery strategy.

The Engineering and Physical Science Research Council (EPSRC) is the main UK government agency for funding research and training in engineering, physical sciences and information and communication technologies. EPSRC distributes government funding including CCS specific grants to largely academic consortia. The UK CCS Research Centre (UKCCSRC) is supported by the EPSRC. The mission of UKCCSRC is to ensure that CCS plays an effective role in helping the UK achieve net zero emissions by 2020. UKCCSRC draws together a number of Universities and the BGS to provide a national focal point for CCS research by bringing together the UK's leading CCS research centres.

In Scotland, a number of Universities and the BGS have joined together to form SCCS – Scottish Carbon Capture and Storage. They have been involved in many CCS project over the past 15 years. Detailed reports may be found at SCCS's homepage. Example SCCS projects are:

CO_2Multistore joint industry project (2012–2015): This project assessed the impacts of multiple storage projects injecting into a regional storage asset, in this case, the Captain Sandstone in the Northern North Sea. This project was funded by The Crown Estate.

ACT **ACORN** (2017–2019): The aim of the study was to explore a variety of options to create a hub in St Fergus that would be the starting point for a regional CCS network in Scotland. The work funded under ACT carried out a number of studies to prepare ACORN for the Front End Engineering and Design stage. Research by Aberdeen University, University of Edinburgh, University of Liverpool, Heriot-Watt University, Scottish Carbon Capture and Storage, Radboud University and the Bellona Foundation. It was funded by ACT (Accelerating CCS Technologies), BEIS (UK), RCN (NO), RVO (NL), and was co-funded by the European Commission under the ERA-NET instrument of the Horizon 2020 programme.

Table UK: Overview of research topics addressed by recent nationally funded research projects on CO_2 storage.

Topic	Storage capacity assessment	Land planning & infrastructure	Complex management	Well technologies	Environmental impact	Mitigation & remediation	Modelling	Monitoring	Social acceptance
Addressed	X	X	X	X	X	X	X	X	X
Project examples	ACCORN CO_2Multistore	ACORN	SENSE ACORN CO_2Multistore ALIGN-CCUS DETECT ELEGANCY Pre-ACT ECCO	REX-CO2 Pre-ACT	DETECT QICS	QICS	SENSE CO_2Multistore ELEGANCY Pre-ACT CRIUS	SENSE DETECT QICS	ALIGN CCUS ELEGANCY

X: topic addressed, (x): topic addressed to some extent, -: topic not addressed.

Project names and acronyms:

- ACORN ACT Acorn programme
- SENSE Assuring integrity of CO_2 storage sites through ground surface monitoring (ACT)
- REX-CO2 Reusing existing wells for CO_2 storage operations (ACT)
- ALIGN-CCUS Accelerating Low carbon Industrial Growth through CCUS (ACT)
- DETECT Determining the risk of CO_2 leakage along fractures in caprocks using an integrated monitoring and hydro-mechanical-chemical approach (ACT)
- ELEGANCY Enabling a Low-Carbon Economy via Hydrogen and CCS (ACT)
- Pre-ACT Pressure control and conformance management for safe and efficient CO_2 storage – Accelerating CCS Technologies (ACT)
- CO_2MultiStore CO_2MultiStore Joint Industry Project
- CRIUS Carbon Research into Underground Storage
- QICS Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage
- ECCO Evolution of Conformance and Containment Risk Over Time in CO_2 Storage Projects – the Link to Post Closure Stewardship and Handover

GB4.2 Research institutions involved in research related to CO_2 storage

CCUS is an important research topic in the UK.

Major players: Please see previous description of UKCCSRC and SCCS in GB4.1. The national geological survey (BGS) is very active in CO_2 storage research – see website for details. The UK is a member of the SET Plan Implementation Working Group 9 on CCS and BGS is a member of the current CSA which supports the IWG9. BGS is also a member of the European Energy Research Alliance (EERA) Joint Programme on CCS and a member of its management board. BGS is a partner in the Norwegian CCS Research Centre which addresses the major barriers identified within leading CCS projects.

There are many universities researching CO_2 storage including the Universities of Aberdeen, Cambridge, Coventry, Cranfield, Durham, Edinburgh, Leeds, Liverpool, Newcastle, Nottingham, Heriot Watt and Imperial College London, Strathclyde. National research centres such as National Oceanography Centre and Plymouth Marine Laboratory are also involved in CO_2 storage related research.

GB4.3 Existing larger scale research infrastructure

GeoEnergy Test Bed (GTB): The GTB is an initiative of the University of Nottingham and the British Geological Survey. The site represents a GBP 6 million investment to support new and emergent geo-energy sectors critical for a sustainable energy future, including GBP 2.5 million UK government-funding through the Energy Research Accelerator (ERA) project.

The geology at the GTB offers the opportunity to access rocks equivalent to those under the North Sea that are of interest for geological storage. Although CO_2 is stored at much greater depths than we are studying at the GTB, this field laboratory enables researchers to refine strategies for monitoring the zone above the reservoir - an essential part of proving site conformance for large-scale storage projects. Studying the subsurface in detail as the CO_2 is injected will improve understanding of processes and mechanisms around CO_2 migration and storage in the shallow subsurface. This improved understanding will in turn be used to advance monitoring strategies for large-scale storage sites.

The GTB comprises seven monitoring wells plus surface sensors forming an array focused around two injection wells. Depth of CO_2 injection is ~ 210 and ~10 m. First CO_2 injection tests are planned for 2022. Deep CO_2 injection is into the Helsby Sandstone Formation (part of the Sherwood Sandstone Group which is the onshore equivalent of the Bunter Sandstone), shallow CO_2 injection is in the Arden Sandstone Formation within the Mercia Mudstone Group.

CO_2 storage laboratory: A new study undertaken by the BGS, on behalf of the Natural Environment Research Council (NERC), will scope out the need and potential for a CO_2 storage research testbed. The early scoping phase of the project is running 2021–2022.

PACT – Capture Technology Facility: The "Pilot-scale Advanced Capture Technology (PACT)" facilities were funded jointly by the Engineering and Physical Sciences Research Council and the Department of Energy and Climate Change (now BEIS) with five academic partners: Cranfield, Edinburgh, Imperial, Leeds, Nottingham and Sheffield, and are part of the UKCCSRC.

GB4.4 Involvement in EU-funded and other regional/international research projects related to CCS

Some examples of large CCS international collaboration research projects with UK involvement are given below:

European Space Agency Carbon Capture and Storage - Integrated Spaceborne Site Monitoring (**SPACEMON**, 2011–2013): The objective of this study was to design an "Integrated Spaceborne Site Monitoring" service for CCS projects.

FP7 Characterisation of European CO_2 storage (**SITECHAR**, 2011–2013): This project aimed to facilitate the implementation by improving site characterisation workflows, and by establishing the feasibility of CO_2 storage on representative potential CO_2 complexes suitable for development in the near term.

FP7 Understanding the Long-Term fate of geologically stored CO_2 (**ULTIMATECO$_2$**, 2011–2015): This project focused on the long-term processes involved in the geological storage of CO_2 in order to increase confidence in the long-term efficiency and safety of CCS.

H2020 Strategies for Environmental Monitoring of Marine Carbon Capture and Storage (**STEMM-CCS**, 2016–2020): This project improved understanding of fluid flow pathways in the sub-seafloor and their implications for reservoir integrity; establishing environmental baselines; improved methodologies for detecting, tracing and quantifying CO_2 leakage in the marine environment, and the development and testing of new technologies to enable cost-effective monitoring of marine CCS operations.

H2020 Enabling Onshore Storage in Europe (**ENOS**, 2016–2020) aimed to enable onshore storage of CO_2 by developing, testing and demonstrating in the field, under "real-life conditions", key technologies specifically adapted to onshore storage and contributing to the creation of a favourable environment across Europe through public engagement and knowledge sharing with key stakeholders.

The European Carbon Dioxide Capture and Storage Laboratory Infrastructure (**ECCSEL**) was established in June 2017 as a permanent pan-European distributed research infrastructure, ERIC (European Research Infrastructure Consortium): There are UK CO_2 capture and storage facilities in ECCSEL. The H2020 ECCSEL and H2020 ECCSELERATE projects support research for ECCSEL.

ACT Enabling a low-carbon economy via hydrogen and CCS (**ELEGANCY**, 2017–2020) aimed at providing innovative, cutting edge solutions to key technical challenges for H_2-CCS chains. Three key R&D aspects delivered by the ELEGANCY programme: the decarbonisation of heating and transport based on an existing fuel and infrastructure, a commercial model for industrial CCS; the opportunity to broaden public awareness of CCS.

ACT Pressure control and conformance management for safe and efficient CO_2 storage (**Pre-ACT**, 2017–2020) assessed the main storage related challenges for accelerated deployment of CCS - capacity, confidence and cost. The project developed, alongside major industry partners, a quantitative conformance assessment system that could be adapted to incorporate any incoming data stream that provided information on the operation of the storage complex.

The H2020 Subsurface Evaluation of CCS and Unconventional Risks (**SECURe**, 2018–2021) gathered scientific evidence relating to monitoring the environment and mitigating risk in order to guide subsurface geoenergy development. The project produced a set of best practice recommendations for establishing environmental baseline conditions for unconventional hydrocarbon production and the geological storage of anthropogenic CO_2.

ACT Reusing existing wells for CO_2 storage operations (**Rex-CO_2**, 2019–2022) is developing a procedure and tools for evaluating the re-use potential of existing hydrocarbon wells for CO_2 storage to help stakeholders make informed decisions on the potential of certain wells or fields for CO_2 storage.

ACT Assuring integrity of CO_2 storage sites through ground surface monitoring (**SENSE**, 2019–2022) aims to develop reliable and cost-efficient monitoring based on ground movement detection combined with geomechanical modelling, inversion, utilising new technologies and optimising data processing. The goal of this project is to demonstrate how ground surface movement can be used as an integral part of the monitoring program to effectively verify safe storage of CO_2 underground.

ACT Stress history and reservoir pressure for improved quantification of CO_2 storage containment risks (**SHARP**, 2021–2024) aims to reduce this uncertainty with the ambitious goal of improving the accuracy of subsurface CO_2 storage containment risk management to a level acceptable to both commercial and regulatory interests.

GB5. National actors driving CCS forward and public engagement

GB5.1 Awareness of CCS technology

Through the H2020 ENOS project, local stakeholders were engaged through dialogue around CO_2 capture and storage. General awareness of CCS before the series of discussion sessions was low.

GB5.2 National advocates for CCS

The Carbon Capture and Storage Association (CCSA) is a Trade Association promoting the commercial deployment of CCUS. It comprises specialist companies from academic, engineering, energy, law, finance, manufacturing, power generation, transportation and other sectors.

GB5.3 Public engagement

SCCS undertakes research projects to support public engagement and understanding of CCS. BGS has open days for the public where CO_2 storage is usually presented (e.g. see Fig. GB).

Figure GB: BGS open day – CCS display with posters and the “fishtank” which is used to illustrate CO_2 injection and storage.

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