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.