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The potential for CCS and CCU in Europe

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COORDINATED BY IOGP

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Foreword

The 31st Madrid Forum invited IOGP to coordinate a report on the potential of Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) technologies, including technical, economic and public acceptance considerations, working with all interested stakeholders¹. A Taskforce composed of interested stakeholders was subsequently established, and this group began regular discussions, including on current regulatory barriers and incentives. Two workshops were held to facilitate in-depth discussions on CCS and CCU.

The Taskforce agreed on the importance of separating out the CCS and CCU value chains into their component parts, in order to identify the barriers, incentives and public financial support that could apply to individual segments of the chain (capture, transportation, and utilisation or storage). When the CCS and CCU value chain is disaggregated, it becomes easier to design targeted incentives which facilitate the deployment of capture, transport, use and storage as individual business cases, thereby creating an overall CCS and CCU system, which in turn encourages scale. Public financial support is, however, necessary to facilitate early deployment of the CCS and CCU infrastructure, since the business case for large-scale deployment in Europe requires a supportive ETS price in combination with an enabling regulatory framework. Once the required capture, transport, storage and utilisation infrastructure has been deployed, and economies of scale emerge, CCS and CCU unit costs will decline and public financial support, e.g. infrastructure funding or tax credits, may be reduced.

Where the policy recommendations in this report relate to future CO₂ transportation services provided by gas infrastructure companies, it should be understood that not all transmission or distribution system operators are necessarily interested at this stage to offer such services. There are, however, TSOs and DSOs in Europe that have expressed interest to the Taskforce in transporting CO₂, including both as a commercial and as a regulated activity. New regulatory flexibility and incentives to enable such companies to transport CO₂ from the capture location(s) to the storage site(s), including by enabling cross-border CO₂ transportation, should therefore be available as a potential option in their toolbox, where appropriate. The other Taskforce policy recommendations relate to targeted incentivisation of CO₂ capture, to clarifying CO₂ storage liability, and to other measures that can support CCS and CCU deployment.

¹ Conclusions: Thirty first meeting of the European Gas Regulatory Forum 16-17 October 2018. Available from: https://ec.europa.eu/info/files/31st-madrid-forum-conclusions-workshop_en

Executive Summary

CCS is a proven technology necessary to achieve climate neutrality in Europe in a cost-efficient manner, and to enable negative emissions. All credible scenario modelling shows that CCS will be essential to meeting the targets set by the Paris Agreement.

CCS technology is also critical for deployment of low-carbon hydrogen, as natural gas can be reformed to hydrogen with CCS, supporting decarbonisation of EU heating, transport and power generation sectors. CCS is necessary for the decarbonisation of industry, representing a cost-effective and realistic way to avoid post-combustion and process emissions. It is a crucial technology to safeguard existing industrial activity, jobs and growth while decarbonising economic activity to meet the Paris Agreement objectives. Estimates have shown that the sum of European jobs linked directly and indirectly to the emergence of a market for CCS may approach 150,000 in 2050.

There are 18 commercial projects in operation globally today with a total capture capacity of some 40 Mtpa CO₂. In Europe, CCS technologies and projects are currently more advanced than CCU projects, with Norway in particular having deployed CCS at Sleipner since 1996 and at Snøhvit since 2007. CCU covers a range of technologies at differing levels of maturity, cost and market size.

Ultimately CCS and CCU are mutually supportive solutions, since both require access to capture facilities and to gas infrastructure and transportation services. They should both be seen as technology options to cost-effectively meet the EU's climate targets for 2030 and 2050. Europe is well placed to benefit from CCS and CCU due to its extensive pipeline infrastructure which can be used to transport CO₂, hydrogen and synthetic methane, and other renewable and decarbonised gases. Europe also has extensive geological CO₂ storage capacity and subsea expertise, with countries such as Norway and the UK willing to enable shared access to their offshore storage facilities for CO₂ from EU industry.

Today, the largest CCS facilities are in the United States where Enhanced Oil Recovery (EOR) has been an important economic driver. In Europe, EOR applications are more limited and the current ETS price does not sufficiently support the CCS or CCU business case. Appropriate and timely policies coupled with regulatory and financial support are needed for CCS and CCU, as in many cases infrastructure must be put in place in advance of a mature market for decarbonised products and services. Support for CO₂ transportation and storage infrastructure will in particular be important, to help de-risk the early development of the CCS and CCU value chains. Large source emission clusters in Europe provide good opportunities to create economies of scale, by establishing shared CO₂ transportation infrastructure with third party access and efficient use of this infrastructure by multiple parties. Existing EU and national funding schemes should continue to apply to CCS and CCU, and these technologies should be recognised in the national energy and climate plans.

To further help development of CCS and CCU in Europe, the Taskforce arrived at key policy recommendations for the 32nd Madrid Forum, relating to the market uptake, capture, transport, storage and public financial support aspects of the CCS and CCU value chain.

As with all technologies, the costs of CCS and CCU will continue to reduce over time, as 'learning by doing' occurs. For systemic deployment of CCS and CCU in Europe, a regulatory framework is needed that both incentivises investment and maintains flexibility to accommodate new CCS and CCU approaches and technologies across the value chain.

Key policy recommendations

Market uptake	<ul style="list-style-type: none"> • Promote a market framework for decarbonised products and services, including Guarantees of Origin and/or other accreditation schemes, to incentivise new business models for CCS and CCU technologies. • Support Member State initiatives to promote early deployment of CCS and CCU infrastructure, such as: <ul style="list-style-type: none"> ○ Contracts for Difference in the power sector; ○ Tax incentives for CO₂ storage; ○ Funding of exploration and appraisal of potential CO₂ storages; ○ Absorbing early value chain risk by providing guarantees for CO₂ supply and/or offtake.
Capture	<ul style="list-style-type: none"> • Enable the economic incentives available under the EU ETS to recognise and reward CCU, subject to a lifecycle analysis and clear carbon accounting rules. • Ensure CO₂ transport by ship and other modes of transport in addition to pipeline for the purposes of storage is recognised and rewarded under the ETS.
Transport	<ul style="list-style-type: none"> • Enable gas infrastructure or other companies, where Member States so decide, to transport CO₂ as a commercial or regulated activity, including in an offshore environment towards the storage, overseen by NRAs with appropriate mandates. • Encourage Member States and other parties to the London Protocol to prioritise ratification of the 2009 amendment of Article 6, which allows for the cross-border transport of CO₂ for the purpose of offshore storage and support proposed temporary solutions including preliminary entry into force among the current ratifying parties. • Encourage studies which appraise offshore transport infrastructure to identify infrastructure suitable for re-use.
Storage	<ul style="list-style-type: none"> • Clarify the liabilities of CO₂ storage facility operators, whether state-entities, gas infrastructure companies, or exploration and production companies. • Encourage Member States to develop CO₂ storage atlases of suitable storage complexes, as well as promote relevant geological and infrastructure information sharing.
Public support	<ul style="list-style-type: none"> • Ensure CCS and CCU technologies and projects are eligible for available public support schemes across the various stages of development, including R&D, demonstration projects, and early roll-out of infrastructure. • Ensure CCS and CCU are recognised as economic activities contributing to climate change mitigation in the taxonomy developed in the context of the action plan on sustainable finance. • Ensure Member States consider concrete deployment strategies and supportive policies for CCS and CCU nationally and in the NECPs, in order to achieve the EU 2050 climate ambitions.

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1. Introduction to CCS

CCS is an integrated chain of technologies, comprising capture, transportation and geological storage of CO₂. This section provides an overview of CCS technology and its various applications.

- Capture involves either *post-combustion* separation of CO₂ from other gases produced at industrial installations or power plants, or *pre-combustion* separation of CO₂ prior to combustion. Most post-combustion capture technologies in operation today use amine-based absorption systems.² *Oxyfuel combustion* is another method of CO₂ separation, whereby oxygen is used for combustion of fuel, rather than air, to obtain an exhaust gas of high-purity CO₂ and water vapour.
- Transport typically involves the compression of CO₂ into its denser or liquid form and transmission from the capture location to the storage facility, which can be achieved in pipelines, ships, or using road/rail tankers. CO₂ can be transported in existing steel pipelines, driven by compressors, without the need for costly infrastructure upgrades.³ Liquid CO₂ can be transported efficiently and flexibly in ships, by rail or in trucks, thereby unlocking access to CO₂ from installations located onshore without ready access to pipeline infrastructure. North America has many thousands of kilometres of CO₂ pipelines, and Equinor operates an offshore CO₂ transportation pipeline in Norway, where a 160km pipeline transports CO₂ from the Snøhvit LNG terminal and CO₂ capture plant to offshore sub-sea injection wells.
- Storage involves the injection of CO₂ in dense or liquid form into sub-surface rock formations normally at depths of one kilometre or more. The CO₂ disperses within the pore space of the rock and is contained in the subsurface by impermeable sealing layers. Storage can take place both onshore and offshore, in depleted oil and gas fields or deep saline formations, with the deep saline formations typically offering significantly more storage capacity. In Europe, CO₂ storage will mostly be in the offshore, such as the North Sea Basin, where public perception to offshore activity is different to onshore local concerns.

CCS is proven technology, with the first carbon capture and storage facility having started operations in 1972 in the United States as part of an EOR project. Since that time, over 200 Mt of CO₂ has been stored globally, with no evidence of leakage.⁴ The cost estimates for CCS deployment vary depending on the costs of capturing CO₂ and the distance for its transport and storage. In the power sector, average first-of-a-kind costs⁵ in Europe are €62-131/tCO₂, and are expected to come down by up to approximately 30%.⁶ According to the Global CCS Institute, across a range of industries total CCS costs are currently estimated to be around €19-172/tCO₂, depending on the concentration of the CO₂ stream.⁷

Currently installed CCS projects globally have a capacity of 40 Mtpa of CO₂, accounting for less than one percent of EU emissions. Eighteen commercial projects are currently in operation, with ten of them located in the United States, nine of which are part of EOR operations. A further five large-scale facilities are now globally under construction, and another 20 are in various stages of development.⁸

² IEA (2017). *Energy Technology Perspectives 2017*. International Energy Agency, Paris.

³ In North America, the CO₂ pipeline network covers over 2500 km with a total transport capacity of around 50 Mtpa. Information available from the Global CCS Institute:

<https://hub.globalccsinstitute.com/publications/development-co2-transport-and-storage-network-north-sea-report-north-sea-basin-task-force/54-offshore-pipelines-co2-transportation>

⁴ Global CCS Institute (2017). *Global Status of CCS 2017*, p. 13. Available from:

<https://www.globalccsinstitute.com/wp-content/uploads/2018/12/2017-Global-Status-Report.pdf>

⁵ USD conversion to EUR using the 2017 average historical exchange rate of 1,13 \$/€.

⁶ Irlam, L (2017). *Global costs of carbon capture and storage: 2017 update*. Global CCS Institute publications.

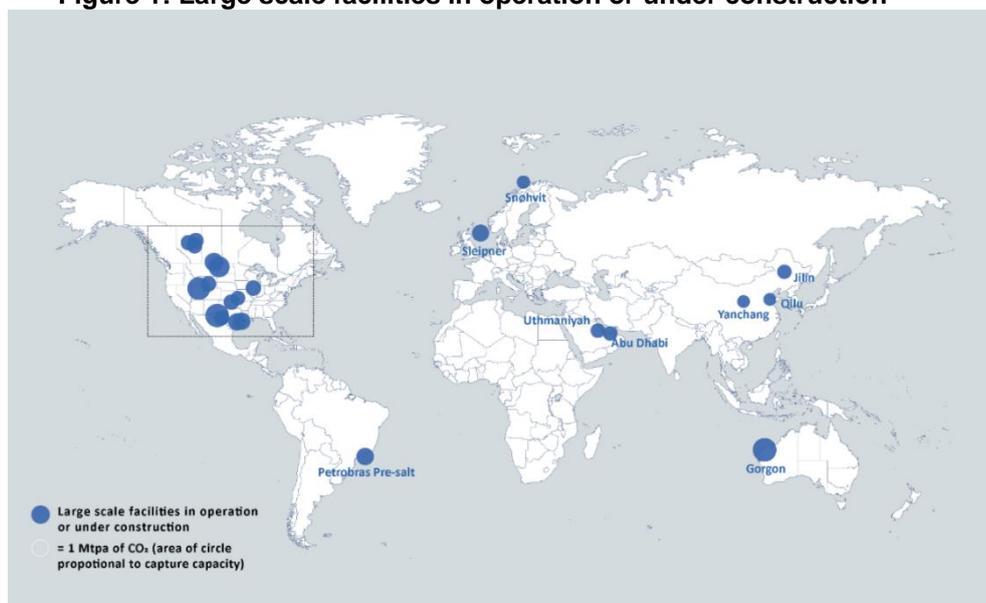
⁷ Ibid.

⁸ Global CCS Institute (2018). *Global Status of CCS 2018*. Available from:

<https://www.globalccsinstitute.com/resources/global-status-report/download/>

The main incentives currently underpinning existing CCS projects are provided by: EOR; carbon taxation; gas quality requirements; financial support schemes such as the EU Connecting Europe Facility; national grants; and tax incentives, notably the recent 45Q tax credit in the US. However, given the scale of CCS required by the Paris objectives, future CCS projects are more likely to require allocation of risks and responsibilities to specialist entities along the CCS value chain, with shared access to infrastructure to generate economies of scale rather than being linked to specific EOR projects. It should be noted that, whereas EOR has been a key driver for CCS in the US, the EOR opportunities in Europe are more limited.

Figure 1: Large scale facilities in operation or under construction



Reprinted from: Global CCS Institute (2018). *Global Status of CCS 2018*

CASE STUDY 1: 45Q tax incentives for CCS and CCU in the US

45Q refers to the relevant section in the US tax code that incentivises deployment of CCS and CCU, by providing a tax credit of up to \$50/tCO₂ for dedicated geological storage, and \$35/tCO₂ for EOR. Updated in 2018, the law lowers the eligibility threshold from 500,000/t to 100,000/t of CO₂ stored on an annual basis for industrial projects and maintained the original threshold of 500,000/t per year for power generation.⁹

45Q requires construction of CCS and CCU facilities to begin before January 1, 2024, with such facilities eligible for the credit for twelve years. The tax code is expected to lead to the development of new projects, though the US also recognises that further policy support is needed for wide-scale deployment¹⁰. The IEA has said 45Q “could trigger the largest surge in carbon capture investment of any policy instrument to date”, (...) “leading to potential capital investment ‘in the order of USD 1 billion’ by 2026.”¹¹

⁹ Global CCS Institute (2018). *US Enacts Landmark CO₂ Storage Policy*. Press release. Available from: <https://www.globalccsinstitute.com/news-media/press-room/media-releases/?page=2>

¹⁰ Information available from the US Department of Energy Office of Fossil Energy: <https://www.energy.gov/fe/science-innovation/carbon-capture-and-storage-research>

¹¹ Bennet, S. (2018). *Commentary: US budget bill may help carbon capture get back on track*. IEA Newsroom. Available from : <https://www.iea.org/newsroom/news/2018/march/commentary-us-budget-bill-may-help-carbon-capture-get-back-on-track.html>

2. Introduction to CCU

CCU refers to the capture and use of CO₂ as a feedstock in the production of chemical building blocks, synthetic fuels and building materials.¹² CCU can be used to limit CO₂ emissions by recycling CO₂ into products, permanently sequester CO₂ in building materials such as concrete, as well as to recirculate CO₂ with direct air capture and in combination with bio-sources. It can also offer electricity storage options through the production of synthetic methane, either by the processing of CO₂ with renewable hydrogen, or by the direct co-processing of CO₂ and water using renewable electricity as an energy source¹³. CCU can therefore also assist sector coupling, by enabling the integration of renewable energy into the gas grid. When renewable hydrogen is reacted with CO₂ to produce synthetic methane, this allows additional options for supply of renewable gas into the network with minimal infrastructure upgrades.

In some applications, CCU is already deployed at industrial scale in the EU in the fertilizer industry, where it is a key part of the production process for melamine and urea-based glues and resins, with around 1.8 Mtpa of CO₂ captured from steam methane reforming during the production of ammonia.¹⁴ CCU is also integral to calcium carbonate production, whereby CO₂ from ammonia production is reacted with ammonia to produce lime, part of which can be mixed with calcium nitrate to produce calcium ammonium nitrate, one of the most popular nitrogen fertilizers used in the EU. In general, however, CCU is less advanced in its deployment and maturity than CCS, and therefore requires continuing R&D support.

Further deployment of CCU in the EU would significantly benefit from recognition under the EU ETS, subject to a lifecycle analysis assessing the degree of emission reduction potential associated with individual CCU uses.¹⁵ In particular, it is important to include appropriate CCU applications into the EU ETS under Article 49 of Commission Regulation 601/2012 on Monitoring and Reporting (MRR)¹⁶. These CCU applications should be subject to appropriate rules on carbon accounting, measurement, reporting and verification of actually abated CO₂ quantities, in order to incentivise deployment of CCU technologies that contribute to emission abatement¹⁷. In addition to this, the business case for CCU will also depend on the value of the product using the CO₂.

¹² Information available from CO₂ Value Europe: <http://www.co2value.eu/>

¹³ Information available from ENTSG/ENTSO-E (2018). Power to Gas – A Sector Coupling Perspective. Joint paper. Available from: https://www.entsog.eu/sites/default/files/2018-11/ENTSGs%20Position%20on%20Sector%20Coupling_Madrid%20Forum_0.pdf

¹⁴ Information provided by Fertilizers Europe (2019)

¹⁵ See the CEFIC-commissioned study “A Bridge Towards a Carbon Neutral Europe”, available from: https://www.ies.be/files/Industrial_Value_Chain_25sept.pdf

¹⁶ For an overview of recommendations on integrating CCU into the MRR Regulation, see report from the German Environment Agency (2019). Support for the revision of the Monitoring and Reporting Regulation for the 4th trading period (focus: Carbon Capture and Utilisation (CCU)). Available from: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-03-27_texte_36-2019_ccu.pdf

¹⁷ For further information on the ETS, see sections 12.2 and 12.3.

3. The contribution of CCS and CCU to global and European emission reductions

3.1 The IPCC Special Report on 1.5°C Global Warming

The Intergovernmental Panel on Climate Change Special Report on Global Warming of 1.5°C (SR1.5) showed the importance of limiting global warming to 1.5°C compared to pre-industrial levels. Techniques to remove CO₂ from the atmosphere are used in all 1.5°C pathways, with most scenarios favouring BECCS. The pathways generally rely on a significant scale-up of CCS in gas-fired power and industry, and in combination with bioenergy for carbon removal.¹⁸ Only one pathway does not rely on CCS due to its very low energy demand assumptions. The SR1.5 further identifies a number of challenges for widespread CCS deployment, including the inadequate pace of current investment and a lack of incentives for large-scale implementation.¹⁹ CCU was not extensively explored in the report, due to complex discussions on permanence of CO₂ abatement, and most models lacking the sectoral granularity to model different industrial sectors. CCU, which in many instances represents an industrial feedstock flow, is not included in any of the modelled pathways in the SR1.5.²⁰

Figure 2 illustrates the amount of CCS used in the IPCC's 1.5°C, 2°C and higher scenarios in terms of Gt CO₂ captured and stored per year, including industrial, biogenic and fossil sources of CO₂. One scenario uses 0 Gt CO₂/yr, a few use a little, and most scenarios (bold lines, median) use around 15Gt CO₂/yr in 2100, independent of temperature pathway.

Figure 2: CCS used in IPCC's 1.5°C, 2°C and higher scenarios

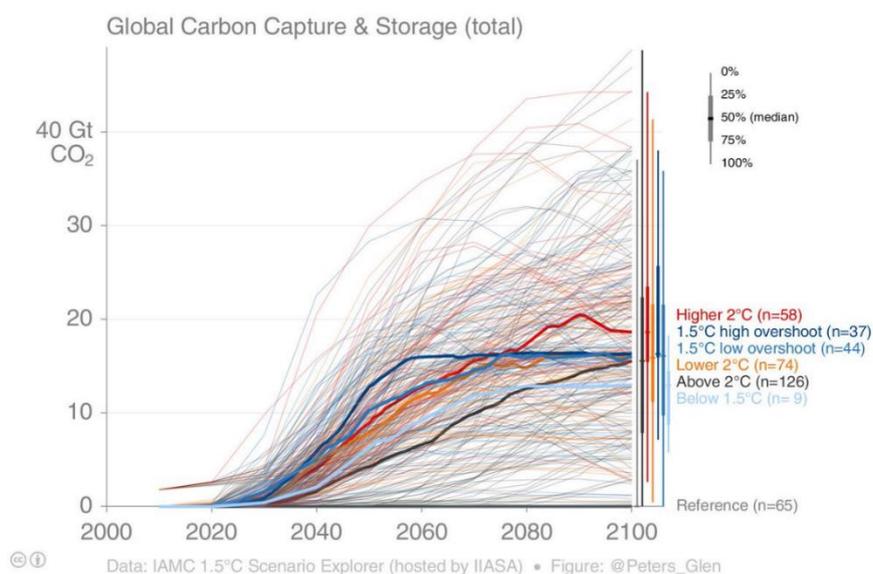


Figure provided by Glen Peters, CICERO (2018).

¹⁸ Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian, and M.V. Vilariño, 2018: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)], p. 135.

¹⁹ Ibid., p. 136.

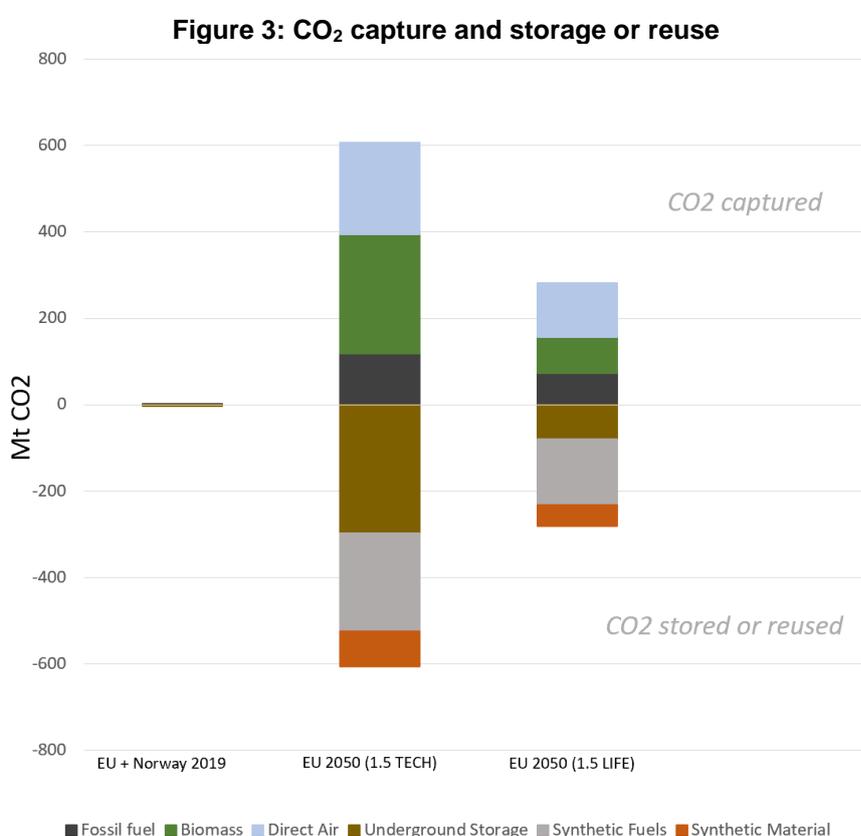
²⁰ De Coninck, H. (2018). *What can the IPCC Special Report on Global Warming of 1.5C tell us about a CCS and CCU agenda for Europe?* CEPS Publication.

3.2 CCS and CCU in the European Commission’s long-term strategic vision and National Energy and Climate Plans

In 2016, total greenhouse gas emissions in Europe were 4,300 Mt CO₂-eq. – a reduction of 24% compared to emissions in 1990.²¹ This corresponds to an average reduction of 50 Mt CO₂-eq. per year over that time period. In order to achieve climate neutrality by 2050, an average reduction of 130 Mt CO₂ eq. per year from 2017 to 2050 is required.

Similar to the SR1.5, the 1.5°C compliant scenarios in the European Commission’s strategic long-term vision depend on CCS and CO₂ removal techniques to achieve climate neutrality, while in addition foreseeing an important role for CCU.²² The scenarios that achieve climate neutrality rely on CO₂ capture and storage or use for mitigating 281-606 Mt of CO₂ in 2050 (the 1.5 LIFE and 1.5 TECH scenarios respectively)²³. In these scenarios, 80-298 Mt of the captured CO₂ is stored underground, and 201-307 Mt is used in synthetic fuels or synthetic material.

Scaling up CCS and CCU to meet these climate neutral ambitions is a significant challenge. As of 2019, there are two-large scale CCS facilities operating in Europe, capturing a total of 1.55 Mtpa CO₂ for offshore geological storage.²⁴ To meet the Commission’s climate neutral scenarios, CO₂ capture and storage or reuse capacity needs to increase by a factor of between 181 and 391 by 2050.



Adapted from: European Commission (2018). *Supplementary information: In-depth analysis in support of the Commission Communication COM(2018) 773*, p. 73

²¹ European Environment Agency, EU-28 and Iceland

²² European Commission (2018). *In-depth analysis in support of the Commission Communication COM(2018)773*, p. 192. Available from:

https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

²³ European Commission (2018). Figure 89: CO₂ capture and storage or reuse (2050). In: *Supplementary information IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM(2018) 773* (p. 73). Available from: https://ec.europa.eu/clima/sites/clima/files/strategies/2050/docs/long-term_analysis_in_depth_analysis_figures_en.pdf

²⁴ CCS facility data from the Global CCS Institute database CO₂RE. Available from: <https://co2re.co/FacilityData>

Under the Regulation on the Governance of the Energy Union, Member States are required to develop integrated National Energy and Climate Plans (NECPs). These set out the direction of national energy and climate objectives and policies in a way that is coherent with the objectives of the Energy Union, in particular the 2030 targets. The NECPs will cover the period from 2021-2030, including a perspective until 2050 to ensure consistency with long-term Energy Union objectives.

In the draft NECPs submitted to the European Commission at the end of 2018, eleven EU Member States refer to carbon capture storage or reuse technologies²⁵. Seven Member States have deployment strategies or policies in place to support CCS and CCU technologies, or explicitly consider the technologies necessary based on their national long-term modelling exercises. A further four Member States highlight the technologies in the research and innovation dimension of the draft NECPs, including references to participation in the Strategic Energy Technology Plan (SET-Plan) Technical Working Group 9 on CCS and CCU,²⁶ as part of an EU effort to accelerate the development and deployment of low-carbon technologies.

Considering the significant scale-up challenge towards 2050, all Member States should be encouraged to consider concrete deployment strategies and supportive policies for CCS and CCU nationally and in the NECPs addressing its role in achieving 2030 targets and in pathways to 2050.

Policy recommendation

- Ensure Member States consider concrete deployment strategies and supportive policies for CCS and CCU nationally and in the NECPs, in order to achieve the EU 2050 climate ambitions.

3.3 Potential of CCU-based gaseous and liquid fuels

CCU fuels (gaseous and liquid) can offer benefits in helping to achieve a more cost-effective energy transition in Europe relative to full-electrification alternatives, as demonstrated in the dena-Leitstudie study²⁷, which focused on the German energy system. The study revealed that decarbonisation scenarios (80% to 95% emissions reduction) relying on a technology mix with CCU fuels can help reach climate targets at around €600 billion lower cost in Germany than full electrification scenarios.

The main cost savings in this study result from the smoother transition regarding infrastructure, energy assets and end-use appliances, leading to lower capital costs. With methanation, whereby CO₂ is combined with hydrogen, renewable energy from surplus electricity can be stored and transported using existing infrastructure. Depending on the source of CO₂, existing appliances can be used in a climate neutral way, thereby avoiding disruptive and costly changes. Even in high-electrification scenarios, CCU fuels were necessary in very hard-to-electrify sectors such as aviation.

CASE STUDY 2: Power-to-methane as a key CCU technology in Germany²⁸

In Falkenhagen, Germany, the energy utility Uniper has constructed the world's first demonstration plant for storing wind energy in the natural gas grid. The plant is able to transform electricity generated by wind turbines into hydrogen, as well as hydrogen upgraded to synthetic methane.

²⁵ IOGP internal analysis of the status of CCS and CCU in draft NECPs. All draft NECPs available from: <https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/governance-energy-union/national-energy-climate-plans>

²⁶ SET-Plan TWG9 CCS and CCU Implementation Plan available from: https://setis.ec.europa.eu/system/files/set_plan_ccus_implementation_plan.pdf

²⁷ dena and ewi Energy Research & Scenarios gGmbH (2018). *dena-Leitstudie Integrierte Energiewende. Impulse für die Gestaltung des Energiesystem bis 2050*. Available from:

https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9261_dena-Leitstudie_Integrierte_Energiewende_lang.pdf

²⁸ Information provided by CO₂ Value Europe (2019)

At the project, around 360m³/h of hydrogen can be generated by means of electrolysis and is fed via a 1.6 km pipeline into the gas transport system. In the first year of operation, more than 2 million kWh of hydrogen was fed into the grid. In May 2018, the expansion of this power-to-gas plant into a methanation plant was successfully completed, as part of the European research project STORE&GO. The CO₂ is sourced from a bio-ethanol plant. In March 2019 an average of 14.500 kWh synthetic methane per day was produced.

The methanation project represents an important contribution to the energy transition in Germany, because synthetic methane in contrast to hydrogen can be used in more established ways. It can be made available to a variety of markets, such as the manufacturing sector, the electricity and heating markets, as well as the mobility sector. It also provides for unrestricted use of natural gas infrastructure, including transport and storage.

3.4 Accelerated decarbonisation through hydrogen from natural gas with CCS

There is growing interest in the potential role of hydrogen as an alternative fuel in multiple demand sectors. Hydrogen can be supplied via electrolysis or from methane reforming processes in which the resulting CO₂ can be captured. Early market development for hydrogen from natural gas with CCS would accelerate decarbonisation in Europe. European electricity consumption is foreseen to increase, and substantial investments are needed in electricity production from low-carbon sources in the coming decades to support decarbonisation of the power sector. Hydrogen from natural gas with CCS will for a considerable time produce fewer emissions than hydrogen from the average European grid electricity. Hydrogen from natural gas with CCS is therefore the hydrogen production technology that will enable the largest emission cuts for a considerable time, and would allow for more rapid development of the hydrogen economy.

In the EU, in 2016, average electricity emissions per MWh were 296 kg CO₂.²⁹ Production of hydrogen from electricity with such a CO₂ intensity would result in an emission rate of 15 kg CO₂ per kg of hydrogen³⁰. If the hydrogen was produced from natural gas with average European upstream and midstream CO₂ emissions combined with CCS, the emission rate would be 2 kg of CO₂ per kg produced hydrogen. CO₂ emissions are therefore 7.5 times lower for hydrogen produced from natural gas with CCS. Outlooks from the European Commission's strategic long-term vision³¹ and IRENA's Outlook for Europe³² give a corresponding ratio in the range of 4.6 to 4.9. It can therefore be assumed that emissions from hydrogen production from grid average electricity will be above that from natural gas with CCS well beyond 2030.

This is also indicated in Figure 4, where the CO₂ intensities of hydrogen production using electrolyzers and grid electricity or natural gas with carbon capture is compared. The pie charts illustrate the scenarios for desired electricity mix according to the IRENA REmap case for 2030³³ and the 1.5°C compliant scenarios of the European Commission's strategic long-term vision. Ongoing efforts to reduce upstream natural gas CO₂-eq. emissions as well as for hydrogen production with integrated CCS, will prolong the time period where natural gas-based hydrogen has the least emissions.

²⁹ SINTEF & IFPEN (forthcoming, 2019). Hydrogen for Europe pre-study report.

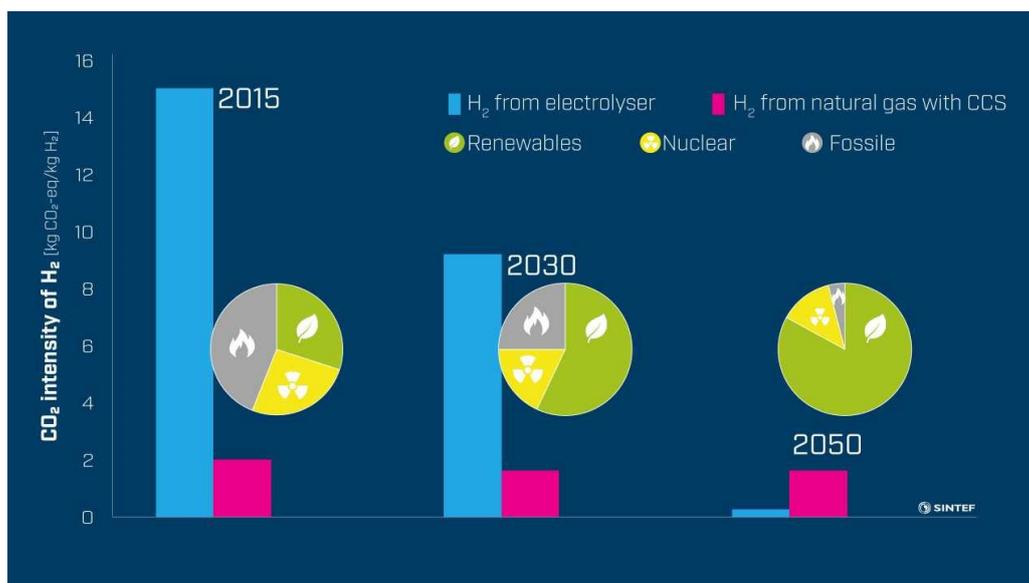
³⁰ Assuming production of hydrogen with a final state of 20 bar

³¹ European Commission (2018). COM(2018) 773 final. *A Clean Planet for all – A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*. Available from: https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_en.pdf

³² IRENA (2018). *Renewable Energy Prospects for the European Union*. Available from: <https://www.irena.org/publications/2018/Feb/Renewable-energy-prospects-for-the-EU>

³³ Ibid.

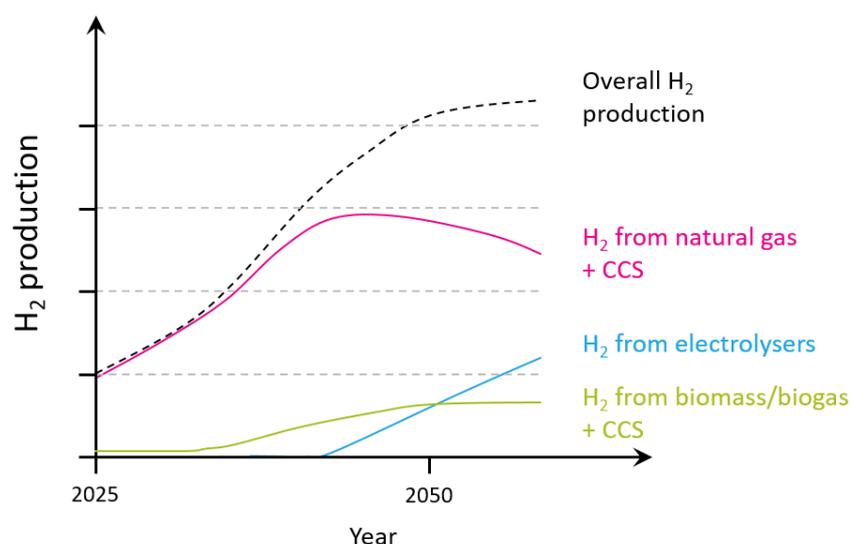
Figure 4: Comparison of the CO₂ intensities of hydrogen production using electrolysers and grid electricity or natural gas with carbon capture



Reprinted from: SINTEF & IFPEN (forthcoming, 2019). *Hydrogen for Europe pre-study report*.

In the near future, hydrogen can be produced from natural gas with CCS in sufficient volumes to establish a European market for low carbon hydrogen. The production of hydrogen requires investment in CCS infrastructure. This can be seen as a long-term investment, since the production of hydrogen can take place close to industrial clusters and provide access to both hydrogen and CO₂ transport infrastructure for industries requiring these services to continue operating in a climate neutral economy. Further, the CCS infrastructure will enable the removal of CO₂ from the atmosphere through the integration of biomass³⁴ into the hydrogen mix. Figure 5 represents one such scenario for future production of hydrogen from natural gas, electricity from renewables and biomass.

Figure 5: Qualitative scenario for future production of hydrogen from natural gas, electricity from renewables and biomass



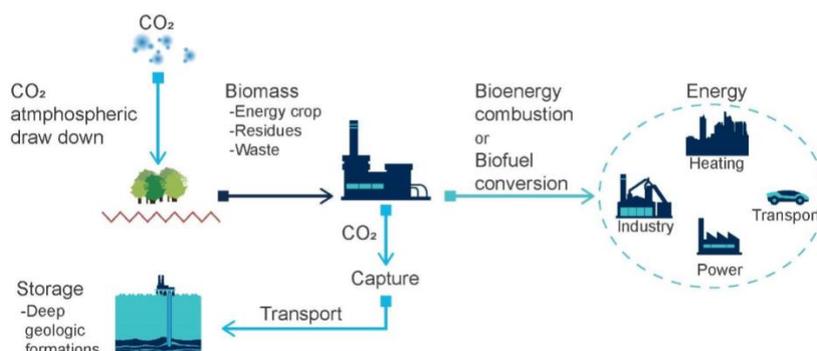
Reprinted from: SINTEF & IFPEN (forthcoming, 2019). *Hydrogen for Europe pre-study report*.

³⁴ The term biomass includes solid and gaseous biomass.

3.5 CCS and CCU in combination with bioenergy - towards negative emissions

CCS also enables the achievement of negative emissions, as highlighted by the IPCC in the SR15³⁵. When applied to sustainable biomass or biogas, CO₂ capture and storage can help to drive negative emissions by removing CO₂ from the atmosphere, making BECCS an important contributor to limiting global warming. Future direct air capture projects could lead to additional CO₂ streams into CCS infrastructure.

Figure 6: Bioenergy and carbon capture and storage schematic



Reprinted from: Consoli, C. (2019). *Bioenergy and Carbon Capture and Storage*. Global CCS Institute publications, p. 3. Available from: <https://www.globalccsinstitute.com/resources/publications-reports-research/bioenergy-and-carbon-capture-and-storage/>

Five bioenergy facilities in the world currently employ CCS technologies, capturing 1.5 Mtpa of CO₂ in total in projects ranging in maturity from large-scale to pilot and demonstration plants³⁶. Four of these projects are in bioethanol plants in the United States emitting near-pure streams of CO₂. The only post-combustion BECCS project globally is in Europe, at the Drax power plant in the UK. A further six facilities emitting biogenic CO₂ in North America, Europe and Japan employ CCU technologies, capturing over 0.8 Mtpa CO₂ for utilisation³⁷.

CASE STUDY 3: Drax BECCS

Drax power station in the UK has now converted four of its six generating units to use sustainably sourced wood pellets (biomass) instead of coal. In doing so, it has become Europe's largest decarbonisation project and the UK's single largest source of renewable electricity. Over the past 18 months, Drax has been exploring the option to install CCU and CCS technology on its biomass generating units at Drax Power Station. As biomass is deemed to be a carbon neutral fuel, capturing and storing CO₂ emissions at Drax would enable it to become the world's first "carbon negative" power station.

A pilot project started in January 2019, capturing up to one tonne of CO₂ per day throughout 2019 – a world first for a dedicated bioenergy plant. Drax's stated objective (subject to the right policy

³⁵ IPCC, 2018: Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, Maycock, M. Tignor, and T. Waterfield (eds.)]. *World Meteorological Organization, Geneva, Switzerland, 32 pp.*

³⁶ Consoli, C. (2019). *Bioenergy and Carbon Capture and Storage*. Global CCS Institute publications, Appendix 1. Available from: <https://www.globalccsinstitute.com/resources/publications-reports-research/bioenergy-and-carbon-capture-and-storage/>

³⁷ Ibid.

framework) is to fully convert the first of its four biomass units to CCS by the mid-2020s, with the other units being converted on a modular basis in the following years. If all four units were converted, Drax Power Station could generate up to 16 million tonnes of “negative emissions” every year – by comparison, the Humber Estuary industrial cluster generates around 14 million tonnes of CO₂ each year.

If Drax Power Station converts itself to CCU and CCS, the project could become the “anchor” project for a wider CCU and CCS network in the Humber Estuary region – the UK’s largest cluster of industrial emitters.

Cost estimates for BECCS vary widely depending on the feedstock and application, with bioethanol currently seen as the most cost-effective option.

Figure 7: Cost of BECCS in selected applications in terms of €/tCO₂ avoided³⁸

Application	CO ₂ avoided cost (€/tCO ₂)
Combustion	78-255
Ethanol	18-155
Pulp and paper mills	18-62
Biomass gasification	27-67

Adapted from: Consoli, C. (2019). *Bioenergy and Carbon Capture and Storage*. Global CCS Institute publications, p. 9.

³⁸ USD conversion to EUR using the 2017 average historical exchange rate of 1,13 \$/€.

4. Separating out the parts of the CCS value chain

The next suite of CCS projects in Europe aim to achieve greater efficiency in the capture and transportation of CO₂, notably by capturing the emissions from clusters of industrial facilities and transporting the collective CO₂ in shared transportation infrastructure to a storage location. Under this approach, risks and support mechanisms can be better spread across the CCS value chain, as industrial installations, gas infrastructure companies, upstream E&P companies, and / or new state-owned or regulated storage entities can have clear and coordinated roles for delivering and being compensated for capture, transport and storage activities. The shared approach to the transport and storage infrastructure also creates economies of scale, driving down unit costs for the CCS value chain.

CASE STUDY 4: Ervia CCS

Ervia and its subsidiary TSO Gas Networks Ireland is assessing the feasibility of implementing CCS in Ireland to capture and permanently store CO₂ from many of the largest emitters in the country, including gas-fired power stations, cement plants and an oil refinery. One key scenario being assessed is to capture around 2.5 Mtpa of CO₂ from two gas-fired Combined Cycle Gas Turbine (CCGT) power plants and an oil refinery located in an industrial cluster on the south-west coast of Ireland. The CO₂ would be compressed and transported to the depleted offshore Kinsale gas field, which has a CO₂ storage capacity of 300 Mt, using repurposed gas pipelines. A second scenario being assessed is to capture CO₂ from a number of CCGT's and heavy emitting industrial emitters in the Dublin region of Ireland, with the potential to export this CO₂ via ship for permanent offshore storage in Europe. Once the backbone CO₂ transport and storage infrastructure has been delivered, other industrial sites in both regions can tie-in their CO₂ to the pipelines at low incremental cost³⁹.

CASE STUDY 5: Rotterdam CCUS project Porthos

The Rotterdam CCUS project Porthos⁴⁰ (Gasunie, EBN, & Port of Rotterdam Authority) aims to collect the CO₂ from multiple industrial installations in the Rotterdam port area and transport it in an open-access, public pipeline for offshore storage in a depleted gas field 25km from the coast at a depth of around 3 km. CO₂ could also be used in Zuid-Holland greenhouses to stimulate plant growth. Under the plan, around 2.5 – 5 Mtpa CO₂ from the refineries and chemical plants in the port would be captured and stored. The CO₂ capture installations of industrial parties are not part of the project.

In February 2019, companies were invited to participate in an 'Expression of Interest', to signal their potential readiness to supply volumes of CO₂ into the planned public collector pipeline along with possible timelines. By aggregating emissions in this way in common infrastructure, the Porthos project aims to drive cost efficiencies relative to integrated point-to-point, single-project CCS business models. The project was awarded CEF funding in January 2019 and has had Project of Common Interest (PCI) status since 2017.

³⁹ Information provided by Ervia (2019)

⁴⁰ Rotterdam CCUS project Porthos information available from: <https://rotterdamccus.nl/en/>

5. CCS projects in the context of natural gas to hydrogen conversion

Reforming of methane to produce hydrogen is an established and deployed technology in the industrial sector. The coupling with CCS allows the production of decarbonised hydrogen from this technology. In 2018, six new large-scale CCS projects were listed in the Global CCS Institute database. All are in Europe, and all are related to the production of hydrogen from natural gas with CCS. The versatility of hydrogen as an energy carrier is shown by the potential of these projects to decarbonise different EU economic sectors, including heating, industry, transport and power.

CASE STUDY 6: Magnum

The Magnum hydrogen project in the Netherlands involves constructing a natural gas-to-hydrogen power production plant with integrated CO₂ capture and export facilities. The hydrogen will be used to fuel the Magnum gas power plant in Eemshaven, The Netherlands. Equinor, Vattenfall and Gasunie are assessing the feasibility of converting one of the three turbines at Vattenfall's CCGT power plant to run on hydrogen by 2023.⁴¹

As part of the project, Equinor will be responsible for the production of hydrogen from natural gas. The CO₂ will be stored in an offshore formation in Norway. Gasunie is looking at how the hydrogen can be transported to the Magnum power plant and can be stored at the Zuidwending location.⁴²

The three gas turbines have a capacity of 440 MW each, with each turbine emitting around 1.3 Mtpa CO₂. The CO₂ mitigation potential of converting all three turbines to run on hydrogen is around 4 Mtpa.⁴³

When CCS and CCU is integrated into hydrogen supply projects, they move beyond being stand-alone "waste disposal" equipment retrofitted on infrastructure such as power plants, and becomes instead an integral part of overall decarbonised energy *supply*.⁴⁴ The hydrogen revenue from such energy supply projects can help underpin and finance the integrated CCS and CCU components, for example in the case of the Magnum and North of England H21 projects, where the sale of hydrogen would help to finance the CCS infrastructure (since all value chain components are working together in an integrated, coordinated process).

CASE STUDY 7: H21 North of England

The H21 North of England project⁴⁵ aims to supply low carbon hydrogen to the heating, industry and transport sectors in the north of England. If delivered, this project would be the world's largest CCS scheme, avoiding up to 20 Mtpa of CO₂ by 2035. Total project CAPEX is estimated to be around £23 billion, with the CO₂ transport and storage component representing less than 5% of the overall total (£1.34 billion). The switching of 3.7 million household appliances from natural gas to hydrogen is planned to take place in incremental stages from 2028-2035.

The CO₂ transportation infrastructure, once installed, will be able to take additional CO₂ from regional clusters, e.g. an additional 12 Mtpa from the Humber industrial region, taking advantage of economies of scale to reduce unit infrastructure costs. Offshore CO₂ storage is located in the Bundter area, where three dedicated subsea aquifers can contain around 600 million tonnes of CO₂ at injection rates of 17 Mtpa. In total, the CO₂ transport and storage component of the project is reported

⁴¹ Global CCS Institute (2019). Facilities Database. Available from: <https://co2re.co/FacilityData>

⁴² MHPS (2018). MHPS to Participate in Hydrogen Conversion Project at Natural Gas GTCC Power Plant in the Netherlands – Will Support Feasibility Study to Reduce Annual CO₂ Output by 1.3 Million Tons per Year --. Press release. Available from: <https://www.mhps.com/news/20180308.html>

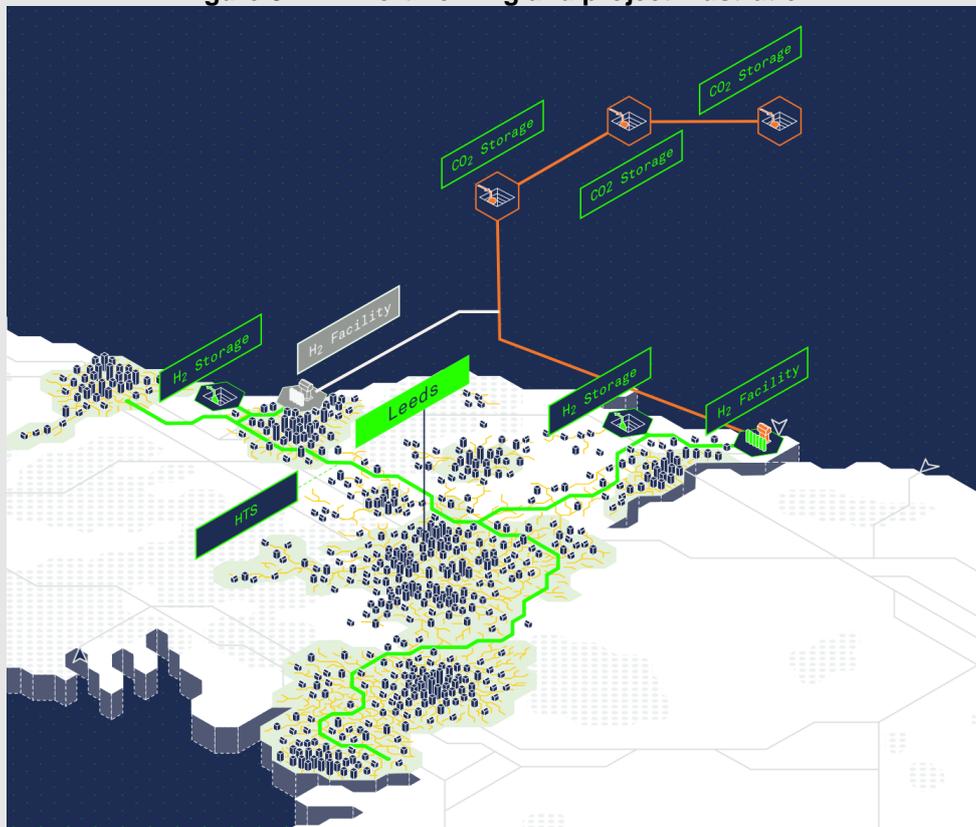
⁴³ Equinor (2017). Evaluating conversion of natural gas to hydrogen. Available from: <https://www.equinor.com/en/news/evaluating-conversion-natural-gas-hydrogen.html.html>

⁴⁴ Information provided by Equinor (2019).

⁴⁵ H21 North of England project information available from: <https://www.northerngasnetworks.co.uk/event/h21-launches-national/>

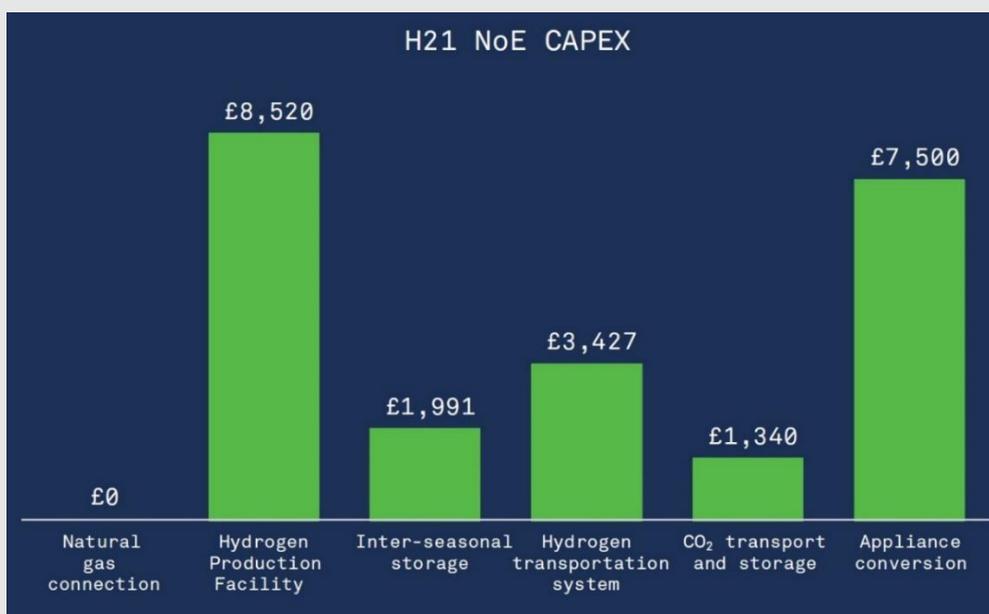
to be £5.54 per tonne of CO₂ based on a regulated asset finance model. Total gas bills for UK consumers are expected to increase by 7-8%, with costs socialised across UK consumers. When pre-combustion CCS is used to supply hydrogen, the financing options are greater, since CCS becomes an extension to the gas chain and can be financed as a regulated activity.

Figure 8: H21 North of England project illustration



Reprinted from: Northern Gas Networks, Equinor and Cadent (2018). *H21 North of England*. Available from: <https://www.northerngasnetworks.co.uk/event/h21-launches-national/>

Figure 9: H21 North of England estimated total CAPEX (£M)



Reprinted from: Northern Gas Networks, Equinor and Cadent (2018). *H21 North of England*. Available from: <https://www.northerngasnetworks.co.uk/event/h21-launches-national/>

The costs of converting natural gas to hydrogen in an auto-thermal reformer (ATR) with CCS range from €36 MWh–€56/MWh, with a 95% capture rate; or €39/MWh–€63/MWh in a steam methane reformer (SMR) with CCS, with a 90% capture rate.⁴⁶ Future costs of producing hydrogen from natural gas in a reformer will be dependent on the gas price. Hydrogen production with CCS from steam methane reforming is generally more costly than auto-thermal reforming, although there is greater scope for retrofitting capture equipment on SMRs due to their higher existing level of deployment in the EU (in refineries, chemical production, etc).

In its 2019 report *Hydrogen – Industry as Catalyst*, the World Energy Council estimates that hydrogen production linked to CCS could become economically viable with a carbon price of around €30 per tonne, provided the right policy conditions are in place for transport and storage.⁴⁷ Supply of low carbon hydrogen could stimulate the roll-out of wider hydrogen infrastructure, including pipeline networks and refuelling stations. The deployment of new hydrogen infrastructure and supply chains would also encourage future uptake of electrolysis-derived hydrogen, since the key infrastructure would be in place. Large-scale supply of hydrogen from natural gas with CCS and CCU enhances the efficiency of new hydrogen infrastructure, thereby keeping overall system costs lower.

Gas network topology in relation to the location of reforming plants requires further analysis. Installing such infrastructure at the entry points to the European network would require TSOs to transport high-pressure hydrogen. On the other hand, reforming gas at the exit points of the gas transmission system may either require additional infrastructure for the transport of CO₂ to relevant storage locations, or local solutions such as CCU or methane pyrolysis. The relative costs of these options for the EU system need further investigation.

In November 2018, Gasunie began transporting high-pressure hydrogen through a modified 12-kilometre natural gas pipeline between Dow Benelux and Yara-owned facilities in the Netherlands. This new hydrogen pipeline provides a basis from which to further develop regional hydrogen infrastructure, potentially up to 10 gigawatts or more by 2030.⁴⁸ If the broader EU gas network including transmission lines can be cost-effectively converted to hydrogen, then pre-combustion CCS and pyrolysis technology could be installed at the EU network entry points, in order to supply hydrogen into the system.

CASE STUDY 8: HyNet North West

HyNet North West⁴⁹ is a hydrogen project with CCS aimed at decarbonising industry, heating and transport in the Liverpool and Manchester areas of the UK. The project includes the development of a new hydrogen pipeline, and creation of CCS infrastructure in order to take CO₂ offshore for storage in depleted gas fields in Liverpool Bay, using existing gas production infrastructure such as the pipelines. The storage capacity of the field is 130Mt, and the wider region around the Morecambe gas fields is believed to have around 1Gt of storage capacity. The project is aiming for 2026 start-up and aims at supplying around 10-15 major industrial gas users with pure hydrogen, as well as injecting up to 20% in the surrounding network for heating.

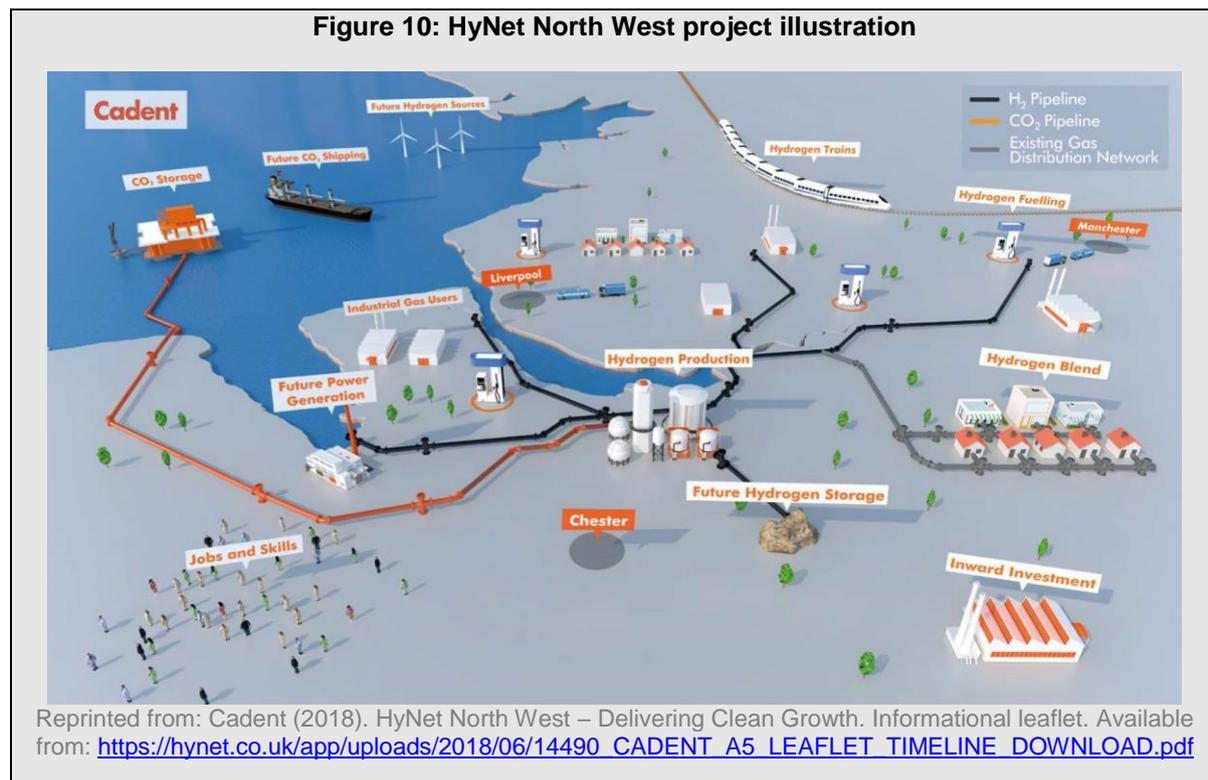
⁴⁶ Navigant (2019). Gas for Climate. The optimal role for gas in a net zero emissions energy system. Available from: https://www.gasforclimate2050.eu/files/files/Navigant_Gas_for_Climate_The_optimal_role_for_gas_in_a_net_zero_emissions_energy_system_March_2019.pdf

⁴⁷ World Energy Council Netherlands (2019). Hydrogen – industry as a catalyst: Accelerating the decarbonisation of our economy to 2030. World Energy Council, The Netherlands. Available from: <https://www.worldenergy.org/wp-content/uploads/2019/02/WEC-Netherlands-Hydrogen-Industry-as-Catalyst.pdf>

⁴⁸ Gasunie (2018). Gasunie hydrogen pipeline from Dow to Yara brought into operation. Press release. Available from: <https://www.gasunie.nl/en/news/gasunie-hydrogen-pipeline-from-dow-to-yara-brought-into-operation>

⁴⁹ HyNet North West project information available from: <https://hynet.co.uk/>

Figure 10: HyNet North West project illustration



5.1 Methane pyrolysis – conversion of natural gas to hydrogen and solid carbon

Methane pyrolysis is a form of direct decarbonisation of natural gas, a process that obtains solid carbon (“carbon black”) and hydrogen ($\text{CH}_4 \rightarrow \text{C} + 2\text{H}_2$). Pyrolysis separates the methane molecule, CH_4 , into its fundamental components (carbon and hydrogen) in the absence of oxygen, thereby avoiding the production of CO_2 .⁵⁰ There are different concepts for methane pyrolysis. In one of them, methane is supplied into the bottom of a high-temperature reactor filled with molten metal, such as tin, at temperatures of up to 1000°C , or with a catalyst such as nickel.⁵¹ Conversion of natural gas into carbon black and hydrogen has been reported with different configurations and temperature levels. When using a molten metal column, the carbon floats to the surface where it can be siphoned off.⁵² The separated carbon can then be stored or used in production of other materials (e.g. graphite), while the hydrogen can be used as energy. Carbon black is necessary in a number of chemical and industrial processes, such as reduction of iron ore. Europe currently only produces around 1% of worldwide demand, and it is considered a critical raw material in the European Union.⁵³ The ability to sell carbon black provides a potential additional revenue component associated with the production of hydrogen. The business case for methane pyrolysis depends on the value of the commodity carbon black as well as conversion costs and the costs of CO_2 emissions. This technology is still in the development phase, and will benefit from R&D support.

⁵⁰ Abanades, A. (2016). Production of hydrogen from methane decarbonization in Power-to-Gas scenarios. In: Carriveau, R. and Ting, D S-K. (2016). *Methane and Hydrogen for Energy Storage*. The Institution of Engineering and Technology, London, UK.

⁵¹ Ozin, G. (2018). Decarbonizing Natural Gas: Methane Fuel without Carbon Dioxide. *Advanced Science News*. Available from: <https://www.advancedsciencenews.com/decarbonizing-natural-gas-methane-fuel-without-carbon-dioxide/>

⁵² Cartwright, J. (2016). The reaction that would give us clean fossil fuels forever. *The New Scientist*, Vol. 232, Issue 2094. Available from: <https://www.newscientist.com/issue/3094/>

⁵³ See COM(2017) 0490 on the 2017 list of Critical Raw Materials for the EU. Available from: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017DC0490>

5.2 Third Energy Package considerations

DSOs and TSOs play a crucial role in facilitating the development of a competitive market. Unbundling rules under the Third Energy Package guarantee that network operators act as neutral market facilitators in undertaking their core functions. As such, TSOs and DSOs are limited in the activities they can undertake in compliance with the unbundling requirements to strictly separate gas infrastructure operations from the supply of gas to consumers.

There is a key opportunity to develop a liquid and flexible functioning market for hydrogen. The integration of hydrogen into the gas market may be facilitated by applying the same market rules for natural gas to any gaseous form of energy transported through the gas transmission or distribution system. Under this model, gas could be traded on the wholesale market as energy, irrespective of whether it is natural gas, renewable gas or hydrogen. Only at the consumption offtake point would the type of gas supply be determined, based on the gas carried by the physical connection to the grid.

The priority should be the development of an enabling framework for the commercial development of hydrogen from natural gas. If the enabling framework is not sufficient for the deployment of conversion units producing hydrogen from natural gas, then one option could be for regulated entities to operate these units for a limited time period. It should be underlined that in this case, TSOs and DSOs would own and operate facilities that convert natural gas into hydrogen without taking ownership of the natural gas or the hydrogen.

6. CCS and CCU business case – tools and support mechanisms

6.1 Current EU schemes in support of CCS and CCU

The EU offers a set of funding programmes to help finance European energy projects, including for CCS and CCU. These cover the full range of technology development levels, from research under Horizon 2020 and Horizon Europe to commercial scale projects in the Innovation Fund. EU funding schemes and innovation networks are vital in supporting early deployment of CCS and CCU. The Connecting Europe Facility (CEF) is a European Commission funding initiative which has a series of calls aimed at developing cross-border CO₂ infrastructure. There is a strong portfolio of projects from the 3rd CO₂ infrastructure call which have secured CEF funding or PCI status, including the Porthos, Acorn⁵⁴ and Northern Lights projects. Furthermore, there are currently five projects under review for the 4th CO₂ infrastructure call.⁵⁵ The sections in this report relating to CO₂ shipping, transmission and transport regulation should also be read in light of the current CEF PCI funding mechanism for development of cross-border CO₂ transport infrastructure.

Policy recommendation

- Ensure CCS and CCU technologies and projects are eligible for available public support schemes across the various stages of development, including R&D, demonstration projects, and early roll-out of infrastructure.

6.2 Support mechanisms and tools to strengthen the CCS and CCU business case

In the absence of an adequate carbon price, public financial support is also a necessary tool to enable the early deployment of CCS and CCU, since on their own these are currently pre-commercial technologies. Tradable investment and production tax credits in the capture segment could significantly enhance commercial attractiveness, as 45Q aims to achieve in the US. The UK's CCUS Cost Challenge report in July 2018 recommended that a tax credit system per tonne of CO₂ stored should be considered in order to incentivise energy intensive industries to invest in CO₂ capture facilities.⁵⁶ Such fiscal incentives would also positively impact the business case for CCS and CCU more widely in other EU Member States.

“Cross-chain risk” - whereby failure of one segment of the CCS value chain to operate as intended negatively impacts the commerciality of the other segments, leaving them potentially ‘stranded’ – is a key uncertainty for early-stage CCS value chains, in particular for projects that foresee separating out the value chain into autonomous component parts. The planned Norwegian full-scale CCS project will attempt to mitigate cross-chain risk by separating the government support funding for the capture and storage segments. Guarantees will be provided by the Norwegian government to the participating CO₂ capture facilities (in this case a cement plant and a waste facility in southern Norway) regarding CO₂ offtake for a defined time period. At the other end of the value chain, financial support will also be given to the storage operators in the Norwegian North Sea. As the overall coordinator of the project, the government can thereby absorb key early value chain risks until such time as economies of scale can be achieved. In future, a diversity of CO₂ suppliers from across the EU can underpin efficient and

⁵⁴ Acorn project information available from: <https://pale-blu.com/acorn/>

⁵⁵ Detailed information regarding the CO₂ network candidate projects available from: https://ec.europa.eu/info/sites/info/files/detailed_information_regarding_the_candidate_projects_in_co2_network_0.pdf

⁵⁶ CCUS Cost Challenge Taskforce (2018). *Delivering Clean Growth: CCUS Cost Challenge Taskforce Report*. Independent Report, BEIS. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/727040/CCUS_Cost_Challenge_Taskforce_Report.pdf

commercial operations in the transport and storage segments of the CCS value chain in Norway, as the risks from reliance on a limited number of capture locations will be reduced. This role for government in the early phase of the project helps to support the business case by providing financial support and certainty.

A market framework for decarbonised products, with accreditation for low carbon products, could also help create value for activities along the CCS and CCU value chain. An accreditation scheme for decarbonised products, including decarbonised electricity, hydrogen, steel, chemicals, lime, cement, and other, would introduce incentives and business models for energy intensive industries to develop products and services using CCS and CCU.⁵⁷ Such an accreditation scheme could build on the EU's Green Public Procurement framework, which aims to encourage low carbon development in Europe.⁵⁸ Any new clean industrial products certification system could use Guarantees of Origin as a way of improving the competitiveness of decarbonised products, and this is explored more in section 12.3.

For electricity generation projects with CCS, one public financial support option that could be considered in the early stages of CCS power sector deployment are Contract for Difference (CfD) mechanisms that reflect the costs of CO₂ capture and provide stable income for low carbon generation, thereby incentivising investment.⁵⁹ Such a scheme was outlined in the Caledonia Clean Energy Project feasibility study⁶⁰, in which a gas-fired power station in Grangemouth, Scotland was proposed to generate around 1.3GW with a CfD of around €90-105/MWh to cover the costs of post-combustion capture. For the transport and storage segments of the project, existing onshore and offshore gas pipelines were proposed to be repurposed for 95% of the project's pipeline requirements. CCS in the power sector will provide grid resilience and help promote system flexibility as renewables penetration grows, e.g. CCGTs with CCS would enable gas to continue playing its role as a flexibility provider also under stricter carbon constraints.

CO₂ storage would also benefit from greater levels of public financial support until economies of scale are created. Given that Europe's largest CO₂ storage capacity can be found in deep saline aquifers offshore, which have not been explored or developed previously, exploration and appraisal activity in these formations can and - in Norway is - being supported financially to ensure early development of these structures for the purpose of CO₂ storage. In April 2019, the Norwegian government announced funding of around €36 million for most of the cost of an exploration well as part of the Norwegian full-scale CCS project⁶¹. Such funding for storage appraisal could also be provided from EU infrastructure schemes such as the Connecting Europe Facility.

Policy recommendation

- Support Member State initiatives to promote early deployment of CCS and CCU infrastructure, such as:
 - Contracts for Difference in the power sector;
 - Tax incentives for CO₂ storage;
 - Funding of exploration and appraisal of potential CO₂ storages;
 - Absorbing early value chain risk by providing guarantees for CO₂ supply and/or offtake.

⁵⁷ Ibid.

⁵⁸ Information available from the European Commission: http://ec.europa.eu/environment/gpp/index_en.htm

⁵⁹ Ibid.

⁶⁰ Summit Power Caledonia UK Ltd. (2018). *Caledonia Clean Energy Project: Feasibility Study Phase 2 Final Report – Summary version*. Available from: <https://summitpower.com/wp-content/uploads/2018/06/CCEP-Feasibility-Final-Report-MAY-2018-SUMMARY-VERSION.pdf>

⁶¹ Ministry of Petroleum and Energy (2019). *The Government proposes state contributions for funding of CCS exploration well*. Press release. Available from: <https://www.regjeringen.no/en/aktuelt/foeslar-statlig-bidrag-til-undersokelsesbronn-for-co-lager/id2641931/>

7. Costs of carbon capture, transportation and storage

While discussions on CCS often focus on the potential for cost reduction, it is also necessary to recall the benefits provided by CCS. CCS is a crucial way to safeguard existing industrial activity, jobs and growth while decarbonising economic activity to meet the Paris Agreement objectives. For example, estimates have shown that the sum of European jobs linked directly and indirectly to the emergence of a market for CCS may approach 150,000 in 2050.⁶²

For industries that emit CO₂ as an integral part of the manufacturing process, e.g. cement, steel and refining, CCS represents the only cost-efficient and realistic method of decarbonisation currently available. Sustaining these industries in Europe will provide significant economic and social benefits, and narrow discussions focusing on the costs of CCS risks missing these broader aspects.

7.1 Costs of capture

CO₂ capture is typically the largest cost component in the CCS and CCU value chain, as a result of the technology costs and energy requirements.⁶³ Costs of capture equipment are determined by the percentage volume of CO₂ in the flue gas from which it is captured. As Figure 11 shows, the higher the CO₂ purity, the lower the cost in terms of CO₂ avoided. In addition, the figure highlights that indicative carbon capture for many processes is currently more expensive than the EU ETS price and will need support in the near-term. Higher purity sources of CO₂ include hydrogen production from reforming natural gas, and ethanol and ammonia production. Many current and emerging capture technologies are engineered to remove 80% - 90% of the CO₂ from flue gas. Higher capture rates are possible, with the H21 North of England project having modelled 95% capture rates. Recent work by the IEAGHG suggest that 99% capture rates on CCGTs are achievable with an increased cost below 10% compared to 90% capture rates.⁶⁴

The advantage of hydrogen production from natural gas with CCS is that the CO₂ stream resulting from the process is significantly purer compared with post-combustion CCS, where the CO₂ is dispersed in flue gas and needs to be separated.⁶⁵ The pre-combustion capture process is therefore more cost-effective.

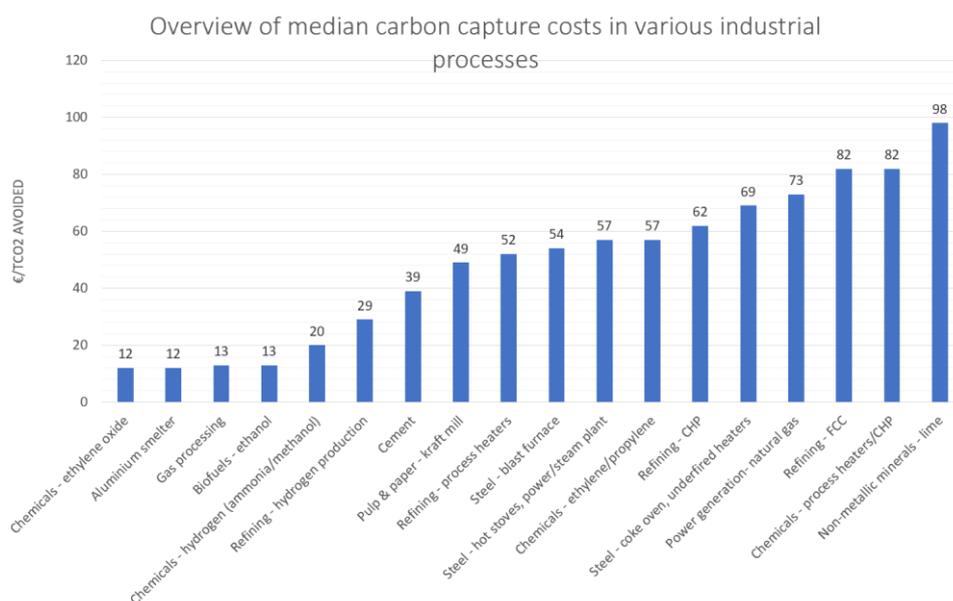
⁶² Størset, S. Ø., Tangen, G., Wolfgang, O. and Sand, G. (2018). Industrial opportunities and employment prospects in large-scale CO₂ management in Norway. SINTEF Report 2018:00450. Available from: https://www.nho.no/contentassets/e41282b08ceb49f18b63d0f4cc9c5270/industrial-opportunities-ccs_english-ii.pdf

⁶³ IEA (2017). *Energy Technology Perspectives 2017*. International Energy Agency, Paris, p. 373. Available from: <https://webstore.iea.org/energy-technology-perspectives-2017>

⁶⁴ Information provided by ZEP (2019)

⁶⁵ World Energy Council Netherlands (2019). Hydrogen – industry as a catalyst: Accelerating the decarbonisation of our economy to 2030. World Energy Council, The Netherlands. Available from: <https://www.worldenergy.org/wp-content/uploads/2019/02/WEC-Netherlands-Hydrogen-Industry-as-Catalyst.pdf>

Figure 11: Overview of median carbon capture costs in various industrial processes



Adapted from: Navigant (2019). *Gas for Climate. The optimal role for gas in a net-zero emissions energy system*, Appendix E.

It will be important to develop new technologies in relation to capturing low-concentration CO₂ from small point sources.⁶⁶ One option may be to explore the extent to which multiple small CO₂ sources can be clustered, in order to share common CO₂ capture equipment, with absorbers placed on each plant site and large-scale desorbers and compressors placed at a central location to achieve economies of scale.⁶⁷

7.2 Cost and technical feasibility of CO₂ transportation

On the basis of existing and planned CCS and CCU projects in Europe, the key options for CO₂ transportation are pipeline transport using new or repurposed infrastructure, and shipping. CO₂ transportation by ship will benefit from future standardisation of the key ship components, including connection valves and flanges between ship and storage facilities, as well as optimisation of the size and number of CO₂ transport vessels to efficiently match the CO₂ volumes. Equipment standardisation will also increase the potential for cost reduction and will facilitate the construction and deployment of new CO₂ transport ships relatively quickly using a “design one, build many” strategy.⁶⁸

Repurposing offshore oil and gas pipelines to transport CO₂ to depleted oil and gas fields or saline aquifers suitable for CO₂ storage can help to avoid installing new offshore infrastructure. The costs savings of reusing existing infrastructure, which would otherwise be decommissioned, depends on the condition of the existing pipelines, as well as any necessary technical interventions, e.g. installing additional concrete mattresses or repairing corrosion.⁶⁹

Reusing offshore oil and gas pipelines to transport CO₂ may represent 1 – 10% of the cost of building a new CO₂ pipeline. Offshore CO₂ pipelines costs can vary between €2–€29/tCO₂.⁷⁰ Costs for ship

⁶⁶ IEA (2017). *Energy Technology Perspectives 2017*. International Energy Agency, Paris, p. 373. Available from: <https://webstore.iea.org/energy-technology-perspectives-2017>

⁶⁷ Ibid., p. 375

⁶⁸ Information provided by Equinor (2019)

⁶⁹ Pale-Blu Dot and Bellona. *Acorn ERA-NET ACT Factsheet 3: Pipeline re-use. Can oil & gas pipelines be re-used for CO₂ transportation?* Available from: http://www.actacorn.eu/sites/default/files/ACT%20Acorn%20Pipeline%20Re-use%20Factsheet_0.pdf

⁷⁰ Navigant (2019). *Gas for Climate. The optimal role for gas in a net-zero emissions energy system*. Available from:

transport range between €10–€20/tCO₂ and this option is usually preferable when smaller volumes need to be transported over longer distances.⁷¹ For onshore transportation of CO₂ from industrial and power facilities to the storage location or port, gas infrastructure companies are exploring both the repurposing of existing gas pipelines, and also new-build CO₂ pipelines (see case studies in this report).

The hydrocarbon network in the North Sea has over 45,000km of pipeline. In the UK and Norwegian North Sea sectors, around 850 pipelines covering 7,500km are planned to be decommissioned over the next decade, at a cost of around one billion euros.⁷² Repurposing existing pipelines could mitigate decommissioning costs. However, not all offshore infrastructure is suitable for re-use. Only pipelines and producing wells with sufficient specifications can be repurposed to handle pure CO₂. Studies which appraise offshore infrastructure to locate suitable assets should be encouraged.

Policy recommendation

- Encourage studies which appraise offshore transport infrastructure to identify infrastructure suitable for re-use.

7.3 Regulatory aspects of CO₂ transportation

An optimal European transport and storage network will need cross-border connections as certain Member States do not have sufficient storage capacity to store their emissions. Public acceptance issues and / or legislative constraints may also restrict the use of onshore storage in certain Member States. It is therefore important that gas infrastructure operators, including TSOs and DSOs where Member States so choose, are enabled to transport CO₂, either as a commercial activity or as a regulated activity.

The regulated asset base (RAB) approach to funding gas infrastructure should be available to CO₂ transportation infrastructure operators. TSOs should be allowed to offer CO₂ transportation services, as a regulated or commercial activity, using non-discriminatory third-party access and regulated or negotiated tariffs in the same way as for natural gas, with this activity overseen by NRAs. Such a regulated approach, as an alternative to negotiated access, would also help to predictably fund CO₂ transportation over the long-term, with users paying a tariff to access the infrastructure.

The current Gas Directive defines transmission in relation to natural gas. Given the increasing volumes of other gases such as biomethane and hydrogen, this definition could be expanded and also include CO₂.

Based on Taskforce discussions, it appears to be the case that many NRAs are restricted to overseeing regulated transportation of gas on land only. Moreover, in many EU Member States, the gas transport which NRAs are authorised to oversee - and which TSOs/DSOs are authorised to transport – is natural gas. For the CCS and CCU value chain to work effectively, Member States should have the option to authorise NRAs to oversee CO₂ transport, including in an offshore environment, since CO₂ will often need to be taken to offshore storage. TSOs and DSOs among other interested companies should also be authorised to transport CO₂ as commercial or regulated activities, where Member States decide that this would be helpful in achieving climate targets. Such regulatory changes should not seek to make the service of CO₂ transportation in any way mandatory; rather it should aim to provide an option to infrastructure companies with an interest in offering these new types of CO₂ transportation services on a case-by-case basis.

Without a clear legislative basis enabling CO₂ transport by TSOs/DSOs, Member States may be reluctant to authorise NRAs to oversee such activity.

https://www.gasforclimate2050.eu/files/files/Navigator_Gas_for_Climate_The_optimal_role_for_gas_in_a_net_zero_emissions_energy_system_March_2019.pdf

⁷¹ Ibid., p 121

⁷² Pale-Blu Dot and Bellona. Acorn ERA-NET ACT Factsheet 3: Pipeline re-use. Can oil & gas pipelines be re-used for CO₂ transportation?

The authority granted to NRAs typically limits their oversight responsibilities to safeguarding consumer interests in relation to competitive and secure natural gas supply. Expanding NRA oversight to include CO₂ transportation as a regulated activity may therefore require changes to NRA mandates, to ensure that in addition to competition and security of supply, CO₂ transport may be additional considerations for NRAs in their regulation of the gas market.

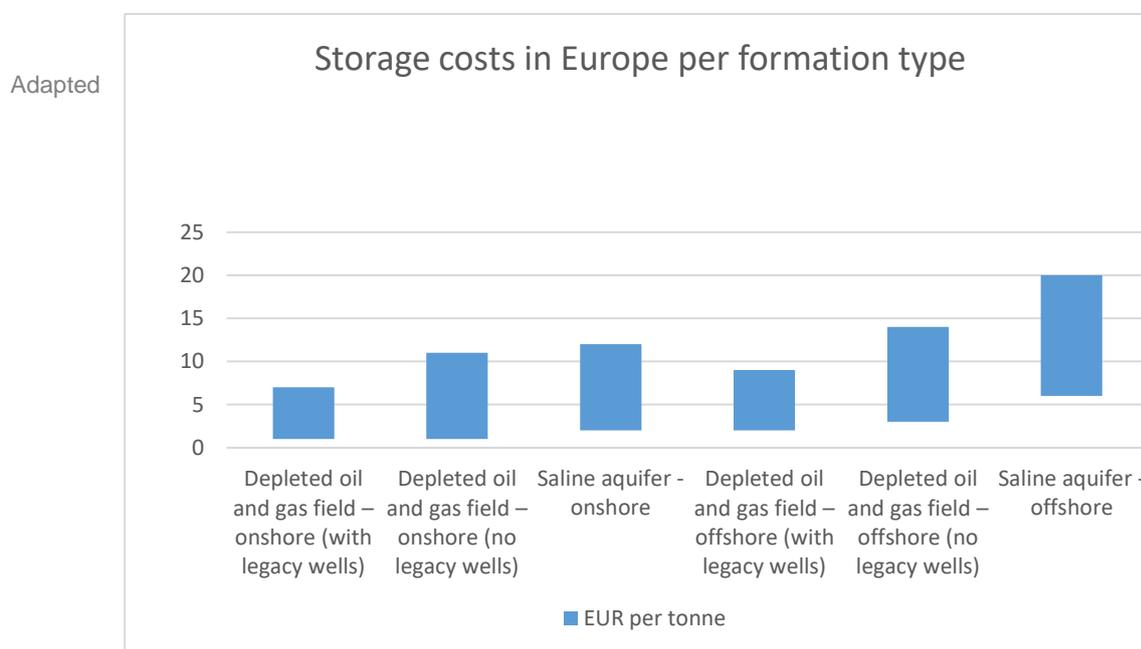
Policy recommendation

- Enable gas infrastructure or other companies, where Member States so decide, to transport CO₂ as a commercial or regulated activity, including in an offshore environment towards the storage, overseen by NRAs with appropriate mandates.

7.1 Costs, technical and regulatory aspects of CO₂ storage

The cost of CO₂ storage depends from location to location, but in general it is highest in offshore deep saline aquifers. The storage capacity in deep saline aquifers is much greater compared to onshore basins or offshore depleted oil and gas fields; these deep saline formations therefore have a better scaling-up and cost reduction potential.⁷³ The upfront storage costs are lower in depleted oil and gas fields due to the presence of infrastructure that can be (re)used for CO₂ injection. However, risks associated with securing legacy wells for storage operations may add additional risks and costs. Storage costs, while much lower than capture costs, are site dependent and require some upfront investment in mapping and understanding storage complexes (including, e.g. formation pressures, reservoir characteristics, cap rock efficiency, faults, trapping structures, mineralogy, salinity); estimating storage capacity; and designing infrastructure. Well costs are usually the highest component.

Figure 12: Storage costs in Europe per geological formation type



from: ZEP (2011). *The Costs of CO₂ Capture, Transport and Storage*

⁷³ ZEP (2011). *The Costs of CO₂ Capture, Transport and Storage*. Available from: <http://www.zeroemissionsplatform.eu/library/publication/165-zep-cost-report-summary.html>

Identifying and exploring appropriate sub-surface geological formations and characterising them accurately are key steps in developing suitable CO₂ storage locations. The costs of activities related to offshore saline aquifer exploration - including seismic acquisition, drilling and geological data processing - are high, amounting potentially to several tens of millions of euros (€6 – 20 per tonne of CO₂).⁷⁴ In depleted oil and gas fields, these costs are lower but the storage capacity is also lower. The efficiency of CO₂ storage is likely to be enhanced if a few large storages are filled, rather than multiple smaller storages located in different European countries.⁷⁵ In addition, onshore depleted oil and gas fields may encounter public concerns when used for CO₂ storage. It is therefore likely that CO₂ storage in the EU will take place primarily offshore.

For both cost and residual liability reasons, existing owners and operators of oil and gas pipelines and platforms plan to decommission their infrastructure as soon as practical after cessation of operations. It is therefore important to be able to transfer the infrastructure and associated liabilities to potential CO₂ storage operators in an efficient and timely manner, to prevent decommissioning of assets that could be used for CCS. Such transfer of operatorship and liability will require coordination between existing operators of oil and gas infrastructure and potential new CO₂ storage operators.

One challenge is ensuring that suitable offshore infrastructure can be kept in place while CCS projects are developed, rather than prematurely decommissioned and removed. An option for Member States is to authorise new state-owned entities or other potential storage operators to inherit ownership or operatorship of the subsea infrastructure necessary for the development of CO₂ storage, including relevant subsea pipelines and wells. This could help facilitate an efficient transfer of necessary facilities away from incumbent operators, who will otherwise decommission this infrastructure. CO₂ storages could be developed by commercial entities, new state-owned entities or gas infrastructure companies using existing or newly developed subsea infrastructure. Access to the CO₂ storage could be given through non-discriminatory third-party access, and if needed using a RAB remuneration model with costs shared between the users of the infrastructure through a tariff (negotiated or regulated). In order for NRAs to oversee any regulated approach to storage in an offshore environment, their oversight mandate would need to be expanded beyond onshore transmission and storage activities. Alternatively, existing operators could provide assets and/or services to a transport storage entity on a commercial basis, e.g. a leasing type arrangement.

It is important that potential CO₂ storage operators can efficiently access existing geological data of areas already explored by oil and gas exploration and production companies. The review of the directive on the geological storage of CO₂ reported challenges in obtaining geological information from areas explored or used by oil & gas companies.⁷⁶ Enhancing knowledge of CO₂ storage capacity and mapping of the location of key potential storage sites could help planning of future transport and storage networks. Norway and the UK have both developed CO₂ storage atlases for parts of their respective Continental Shelves⁷⁷. These atlases are based on existing seismic data from oil and gas operations and show significant potential for large-volume CO₂ storage in both aquifer formations and decommissioned oil and gas fields. Member States should be encouraged to develop similar CO₂ storage atlases, as well as promote technical information sharing between relevant stakeholders. Such information sharing could also include potentially relevant oil and gas infrastructure, which could be used in the future for CO₂ storage.

Policy recommendation

- Encourage Member States to develop CO₂ storage atlases of suitable storage complexes, as well as promote relevant geological and infrastructure information sharing.

⁷⁴ Ibid.

⁷⁵ World Energy Council Netherlands (2019). *Hydrogen – industry as a catalyst: Accelerating the decarbonisation of our economy to 2030*. World Energy Council, The Netherlands. Available from:

<https://www.worldenergy.org/wp-content/uploads/2019/02/WEC-Netherlands-Hydrogen-Industry-as-Catalyst.pdf>

⁷⁶ European Commission (2015). COM (2015) 576 final. ANNEX 2: *Report on review of directive 2009/31/EC on the geological storage of carbon dioxide*. Available from:

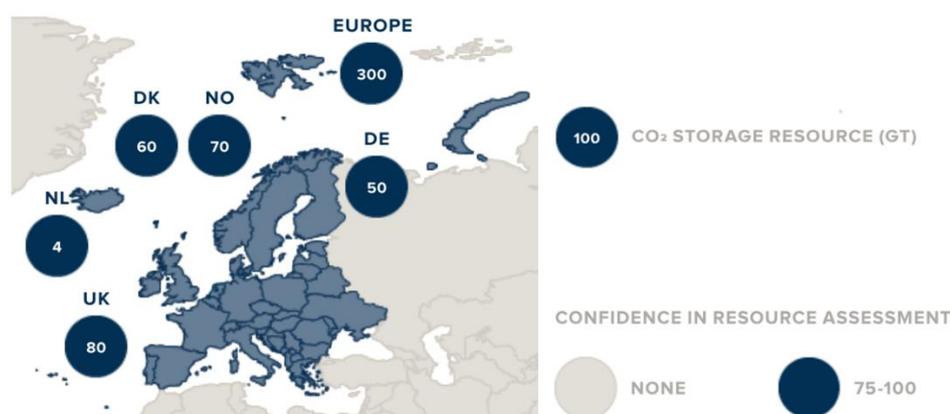
https://ec.europa.eu/clima/sites/clima/files/strategies/progress/docs/com_2015_576_annex_2_en.pdf

⁷⁷ Norwegian CO₂ storage atlas available from: <https://www.npd.no/en/facts/publications/co2-atlases/>. UK CO₂ storage atlas available from: <http://www.co2stored.co.uk/home/index>

8. CO₂ geological storage capacity in Europe

In the Commission's 1.5 TECH scenario, around 300 Mtpa CO₂ must be captured and stored by 2050 (see figure 3). Global storage capacity is currently estimated to be over 10,000 GtCO₂.⁷⁸ In Europe, 300 GtCO₂ of storage capacity has been estimated at a high-level⁷⁹, with work ongoing in some countries to develop a more precise understanding of suitable complexes and identifying "investable storage". Existing high-level estimates therefore show ample storage capacity, both globally and within Europe. However, these capacity estimates should be viewed as the resource base for storage, whereas actual project capacity is site dependent and influenced by availability of the resource. Building confidence in storage capacities of each area and its specific sites is essential.

Figure 13: Estimated CO₂ storage capacity in Europe



Adapted from: Global CCS Institute (2018). *Global Status of CCS 2018*

Some EU Member States have placed restrictions on the ability to store CO₂ underground⁸⁰. These policies have the impact of reducing the availability of storage capacity and increasing the need for cross-border CO₂ transportation to countries where such storage is allowed, e.g. offshore in the North Sea where existing oil and gas production takes place. There is also ample storage capacity in southern Europe, e.g. in Spain where probable storage capacity is estimated to be between 12.9 GtCO₂ – 14 GtCO₂.⁸¹ When storage restrictions are considered, the geological storage potential for CO₂ in the EU, including Norway, is likely to be around 134 GtCO₂,⁸² which amounts to 446 years worth of CO₂ storage at a rate of 300Mtpa.

⁷⁸ de Coninck, H., A. Revi, M. Babiker, P. Bertoldi, M. Buckeridge, A. Cartwright, W. Dong, J. Ford, S. Fuss, J.-C. Hourcade, D. Ley, R. Mechler, P. Newman, A. Revokatova, S. Schultz, L. Steg, and T. Sugiyama, 2018: Strengthening and Implementing the Global Response. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [MassonDelmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

⁷⁹ Global CCS Institute (2018). *Global Status of CCS 2018*. Available from:

<https://www.globalccsinstitute.com/resources/global-status-report/download/>

⁸⁰ See Appendix B – Government attitudes and legislative restrictions on CO₂ storage in Europe.

⁸¹ Information available from the GeoCapacity project website: <http://www.geology.cz/geocapacity/publications>

⁸² Navigant (2019). *Gas for Climate. The optimal role for gas in a net-zero emissions energy system*. Available from:

9. Public acceptance for CCS

The perceived risk of CO₂ leakage from storage locations into the atmosphere – while in reality very low - has contributed to public concern with CCS. It is therefore important to communicate the very low chances of any leakage, and even lower chances of significant leakage.^{83,84,85} Given the public concern in this area, it is relevant that the IPCC has established on the basis of their analysis of current CO₂ storage sites, natural systems, and engineering systems and models, that appropriately selected rock formations are *very likely* to retain 99% of injected CO₂ over 100s of years, and are *likely* to exceed 99% containment over 1000 years.⁸⁶ Furthermore, the risk of leakage decreases over time, as the CO₂ migrates in the reservoir away from the injection location and can become chemically bound to fluid and mineral phases.

Other factors also contribute to risk reduction in relation to CO₂ storage. These include: equilibration of formation pressure over time,⁸⁷ and when the CO₂ within the rock undergoes transformation, often trapping it in a more “secure” form. Over time, the injected CO₂ will be found in the formation in four physical states: 1) as injected liquid/gas; 2) trapped in minute pore throats against sand grains by capillary forces (in a conventional clastic reservoir); 3) dissolved in the formation waters; 4) mineralised often as calcium carbonate within the formation pore space.⁸⁸

https://www.gasforclimate2050.eu/files/files/Navigant_Gas_for_Climate_The_optimal_role_for_gas_in_a_net_zero_emissions_energy_system_March_2019.pdf

⁸³ Jewell, S. and Senior, B. (2014). *CO₂ storage Liabilities in the North Sea – An Assessment of Risks and Financial Consequences – Summary Report for DECC May 2012*. DECC Independent report. Available from: <https://www.gov.uk/government/publications/co2-storage-liabilities-in-the-north-sea-an-assessment-of-risks-and-financial-consequences-summary-report-for-decc-may-2012>

⁸⁴ Le Guen, Yvi, et al. (2018). CO₂ Storage-Managing the Risk Associated with Well Leakage over Long Timescales. *SPE Asia Pacific Oil and Gas Conference and Exhibition*. Society of Petroleum Engineers. Available from: <https://www.onepetro.org/conference-paper/SPE-116424-MS>

⁸⁵ Alcade, L. et. al. (2018). Estimating geological CO₂ storage security to deliver on climate mitigation. *Nature communications*, 9(1), 2201.

⁸⁶ Information available from ZEP: <http://www.zeroemissionsplatform.eu/safe-storage.html>

⁸⁷ In stores where pressure will increase significantly as a result of injection, over time once injection has ceased, the pressure gradient will equilibrate, and in certain sites the pressure will continue to fall close to the hydrostatic pressure of the formation. Risk of storage failure is highest during injection periods; once this stops, risk falls significantly. Information provided by ZEP. Also, see IPCC (2005). *IPCC Special Report on Carbon dioxide Capture and Storage*. Metz, B., Davidson, O., de Coninck, H., Loos, M. and Meyer, L (Eds.) Cambridge University Press, UK. pp 431. Available from: https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf

⁸⁸ Information provided by ZEP (2019)

CASE STUDY 9: CO₂ storage monitoring programmes

The world's most extensive monitoring programme of post-storage CO₂ occurred between 2000 and 2012 at the Weyburn CO₂-EOR project in the Williston Basin, a geological structure reaching from south-central Canada to north-central United States. The monitoring was performed in Saskatchewan, Canada by the IEA Greenhouse Gas Programme (IEAGHG), a research programme under the IEA that studies decarbonisation technologies. The CO₂ stored was the largest single amount of anthropogenic ('man-made') CO₂ injected in the world. Over the lifetime of the CO₂-EOR monitoring project, around 22 Mtpa were injected 1.5 km into the subsurface. The monitoring programme was extensive, using high-resolution seismic surveys and surface monitoring to analyse the movement of the CO₂ underground and whether leakage was occurring. The results of the monitoring showed no indication of CO₂ leakage from the geological reservoir. A best practice manual for post-storage CO₂ monitoring and verification was subsequently developed by IEAGHG with lessons from this project.

In Europe, CO₂ injection at the Sleipner field 250 km offshore Norway has occurred since 1996. This was the first CO₂ project involving permanent, dedicated geological storage of CO₂, with 20 Mtpa stored in the Utsira Sand saline aquifer to date. Around 1 Mtpa is stored, with this CO₂ originally produced from the Sleipner West field along with natural gas, before being separated and injected into the Utsira formation more than 800m below the seabed. Equinor has worked with IEAGHG to perform the monitoring and research activities, including time-lapse seismic imaging to understand the migration of the CO₂. Based on the monitoring performed to date, there is no evidence of leakage of CO₂ from the formation.

As part of the Taskforce discussions, the Norwegian State CCS enterprise Gassnova and industry described their ambition for Norway to import CO₂ from EU industrial installations for permanent geological storage offshore Norway. In Norway public acceptance of CCS is generally positive. There is general recognition of the value of CCS as a climate abatement technology and it also has support from the main NGOs in the country. Offshore CO₂ storage in the North Sea (as well as potentially other European offshore regions) may provide a more acceptable solution for concerned citizens than onshore storage of CO₂. Offshore storage of CO₂ avoids objections by onshore neighbours, as well as leveraging existing European subsea infrastructure, and engineering skills and expertise.

Greater public support for CCS and CCU may also be achieved by highlighting the potential for CCS and CCU to decarbonise societal activities and important sectors of the economy, such as buildings, steel and heating, thereby ensuring continuous use of existing infrastructure and promoting local and regional economic activity. It is important to recognise that many industrial processes require high heat-intensity, such as steel manufacturing, which cannot be provided by electrification, and some industries emit unavoidable process CO₂ emissions. CCS and CCU should be seen as one of a number of different technology options by which to achieve cost-effective decarbonisation in the EU, none of which should be seen as mutually exclusive.

Policymaker and political support will ultimately make a major difference in securing public acceptance for CCS. From a broader European perspective, positive EU policy signals can provide confidence across the CCS value chain, increasing the likelihood that coastal Member States (and Norway) continue to put in place supportive regulatory and funding schemes for offshore storage, in order that they are capable of receiving CO₂ emissions from elsewhere in Europe.

EU Member States currently have a variety of policy attitudes towards CCS.⁸⁹ As Member States develop their national and energy climate plans, the potential for CCS and CCU should be considered and incorporated, including as a way of promoting cross-border infrastructure cooperation.

⁸⁹ Appendix B - Government attitudes and legislative restrictions on CO₂ storage in Europe

10. Cross-border CCS and CCU infrastructure cooperation

A number of planned CCS projects in Europe aim to transport CO₂ from one country to another for storage. Cross-border CO₂ transport in regional projects can foster regional cooperation and infrastructure links. Two such projects following this approach are Norway's Northern Lights and the Teesside project in the UK.

CASE STUDY 10: Northern Lights and The Norwegian full-scale CCS project

The Northern Lights project aims to deliver a ship-based European CO₂ transport and storage network. By importing CO₂ emissions from European industries, the project is looking to achieve economies of scale and lower costs, while also making a larger-scale contribution reducing EU CO₂ emissions. Due to its pan-European approach, standards to promote the interoperability of the CO₂ ships and storage sites with EU Member States will be important.

The CO₂ shipping component of this project received PCI status in 2017. In 2019, the project submitted a request to update the PCI application, which would expand its geographical scope to capture sites located in Belgium, France, Germany, Ireland, the Netherlands, Sweden and the UK.

Equinor, Total and Shell are responsible for the transport and storage parts of the project. The partners are currently conducting FEED studies and aim at final investment decisions in 2020.⁹⁰ The Northern Lights CO₂ transport and storage project is then planned to start operating in 2023, and the project's extension to cross-border shipping of CO₂ is expected to take place from 2024-25.

Figure 14: Participants in the Northern Lights PCI application of March 2019



Information provided by Equinor (2019)

The Norwegian full-scale CCS project,⁹¹ of which Northern Lights is the transport and storage part, aims to become the world's first CCS project receiving CO₂ from several industrial sources. The concept of the Norwegian full-scale CCS project foresees CO₂ capture in two onshore industrial facilities for transport by ship to a receiving point in Naturgassparken in Øygarden municipality, where it will be sent through pipelines to injection wells on the Norwegian Continental Shelf.

⁹⁰ Information provided by Equinor (2019)

⁹¹ Norwegian full-scale CCS project information available from: <https://ccsnorway.com/>

CASE STUDY 11: Preem CCS

Preem⁹² is a Swedish oil refiner and renewable fuel producer and the owner of two refineries emitting 2 Mtpa of CO₂, including from hydrogen production. The location of Preem's Lysekil refinery (emitting 1.5 Mtpa CO₂) on the west coast of Sweden has created an opportunity to capture and export the CO₂ from the refinery's hydrogen production plant as part of the Norwegian full-scale CCS project for permanent storage on the Norwegian west coast. The company is aiming to construct a full-scale CCS facility by 2025.

The project is co-funded by Norway's state CCS entity, Gassnova, through its CLIMIT program and the Swedish Energy Agency by its program Industriklivet ("*the industrial leap*"), as well as by industrial partners.⁹³

10.1 CO₂ emission clusters in Europe for CCS and CCU

The cost-effectiveness and efficiency of future CO₂ transportation infrastructure will be shaped by its ability to capture the emissions from clusters of industrial installations, rather than single sources, as such a collective approach drives economies of scale. According to a 2018 report by Endrava and Carbon Limits, emissions from power and heat plants, industrial sites and waste management installations in Europe amounted to 2.4Gt/CO₂, accounting for two thirds of all CO₂ emissions (around 3.8 Gt CO₂) in Europe. Within these two-thirds, 89% of the emissions come from installations emitting more than 100 ktCO₂/year, which represent 32% of these installations.

This indicates that decarbonising the larger installations will enable efficient and timely progress in reducing overall EU CO₂ emissions. As larger installations tend to be located in clusters, CO₂ can be efficiently gathered and transported to the site of the storage.

Potential industrial clusters exist in Europe which may provide the basis for the adoption of a regional, shared approach to CO₂ capture and transmission infrastructure, including pipelines.

Figure 15: Potential emission clusters in Europe

Industrial cluster	CO ₂ emitted (Mtpa)
Yorkshire	60
Marseille	35.5
Teesside	26
Antwerpen	18
Rotterdam	17.5
Le Havre	14.5
Skagerrak/Kattegat	14
Firth of Forth	7.6
Ruhr region	No data available

Adapted from: Endrava (2018). *Potential for CCS in Europe: Report for the Norwegian Oil and Gas Association*. Available from: <https://www.globalccsinstitute.com/resources/publications-reports-research/bioenergy-and-carbon-capture-and-storage/>

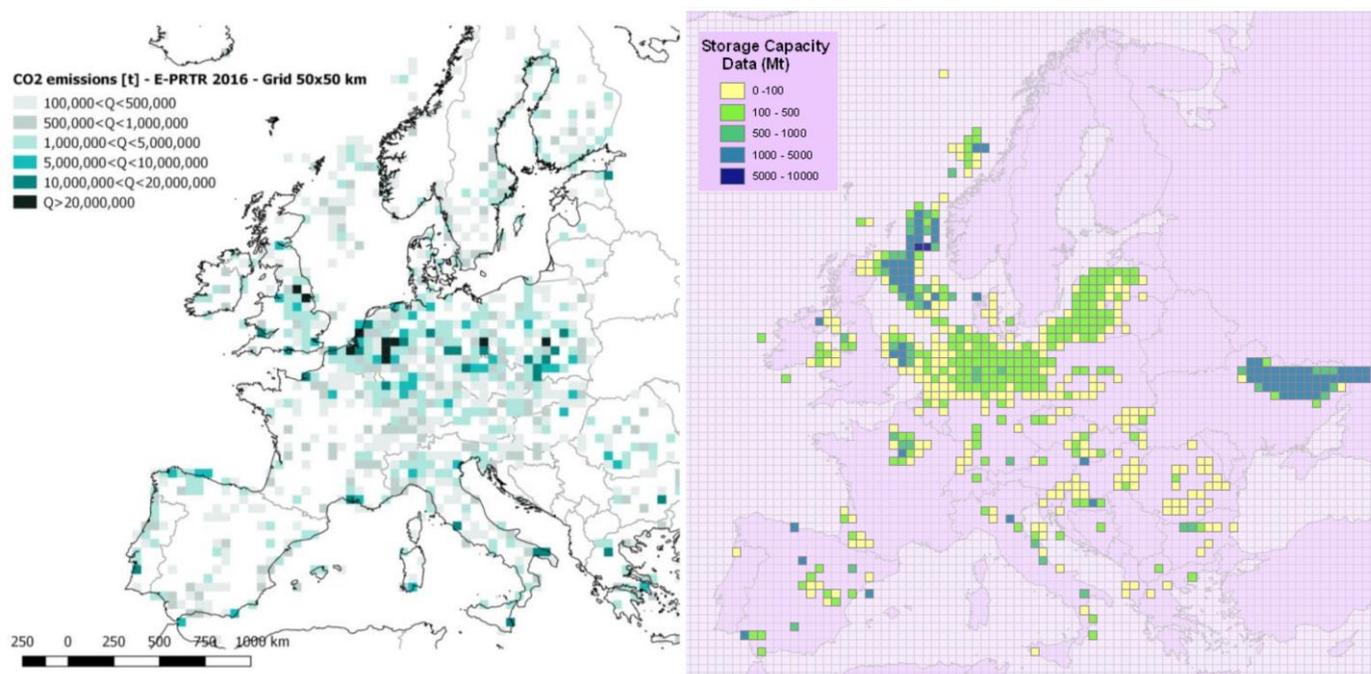
The highest density of Europe's stationary emission clusters is in the north. This is a convenient location in the context of dedicated geological storage in the North Sea. The maps below show Europe's stationary industry, power and waste emissions clusters, and the location of the CO₂ storage capacity.

⁹² Preem CCS project information available from: <https://www.sintef.no/en/projects/preem-ccs/>

⁹³ Information provided by Preem AB (2019)

The emission clusters and storage locations are proximate, creating relative ease of access for EU energy intensives to CO₂ storage.

Figure 16: Comparison of CO₂ emission clusters and CO₂ storage capacity in Europe



Adapted from: Endrava (2018). *Potential for CCS in Europe: Report for the Norwegian Oil and Gas Association* and DG ENER/ARUP (2010). *Feasibility study for Europe wide CO₂ infrastructure*

In order to facilitate a cluster-based approach to CCS and CCU, it is necessary to map the emission sources in the region and develop a joint approach between Member States and industry to deploying common-user infrastructure. This could be performed by Member States working in a coordinated way with industry, to better identify where cluster opportunities for efficient capture and transport of CO₂ exist and how public financial support for early CO₂ infrastructure could be targeted. Examples of the cluster-based CCS and CCU approach are the Porthos (see case study 5), the Port of Antwerp project⁹⁴, and the planned Teesside project.

CASE STUDY 12: The Teesside Collective

The Teesside Collective⁹⁵ aims to decarbonise a cluster of energy-intensive installations in the Tees Valley, UK. The initial CO₂ capture capacity of the project is planned to be around 0.8 Mtpa, with potential to grow up to 10 Mtpa once the regional CO₂ network has been fully developed. Capture operations would begin in the mid-2020s, with the CO₂ transported via pipeline to an offshore site in the North Sea for dedicated geological storage.⁹⁶

The project, which has been granted PCI status, is led by the Tees Valley Combined Authority and is planned to include a series of regional CO₂ pipeline networks and shipping facilities to import CO₂ from across Europe. The vision of the project is to become a European CCS hub capable of receiving

⁹⁴ Port of Antwerp and Fluxys CCS and CCU project information is available here:

https://www.fluxys.com/en/press-releases/fluxys-group/2018/180509_press_port_of_antwerp_co2capture

⁹⁵ Teesside Collective project information available from: <http://www.teessidecollective.co.uk/>

⁹⁶ Global CCS Institute (2019). Facilities Database. Available from: <https://co2re.co/FacilityData>

CO₂ from different parts of Europe by ship for offshore storage in the North Sea. The project will also involve capturing CO₂ from one of the UK's largest hydrogen plants.⁹⁷

The total unit cost of the proposed CCS network in Teesside, including access to the CO₂ transport and storage network, is estimated to be around £58/tCO₂. The project would store 189 Mt of CO₂ over its lifetime.⁹⁸

⁹⁷ Teesside Collective (2017). Teesside Carbon Capture and Storage (CCS) Transport Infrastructure Backed By European Commission. Press release. Available from: <http://www.teessidecollective.co.uk/teesside-carbon-capture-and-storage-ccs-transport-infrastructure-backed-by-european-commission/>

⁹⁸ Ibid.

11. Regulatory incentives and barriers for CCS and CCU

This section examines a number of barriers identified within the Taskforce that should be addressed in order to better incentivise widespread deployment of CCS and CCU in Europe.

11.1 London Protocol

Article 6 of the London Protocol, a global convention to prevent pollution of the sea by dumping of wastes and other matter, states that “*Contracting Parties shall not allow the export of wastes and other matter to other countries for dumping or incineration at sea*”. An amendment exempting export of CO₂ for storage purposes from this restriction was agreed in 2009, but its entry into force requires two-thirds (34 out of 50) of Contracting Parties to ratify the amendment. As of March 2019, only six countries have ratified.

A possible temporary solution allowing for the development of early cross-border CO₂ transport projects could be to allow for preliminary entry into force between the current ratifying Contracting Parties. To facilitate cross-border CO₂ transport, Contracting Parties should be further encouraged by the European Commission to prioritise ratification or to support proposed temporary solutions until the full ratification threshold has been reached.

Figure 17: Overview of Contracting Party ratification status as of March 2019

Ratified	EU Member States, not ratified	Other countries, not ratified but with an interest in CCS	Other countries, not ratified
The UK, The Netherlands, Finland, Iran, Estonia, Norway	Denmark, Germany, Sweden, France, Belgium, Ireland, Spain, Italy, Luxembourg, Slovenia, Bulgaria, Croatia, Cyprus	South Africa, Canada, Australia, Saudi Arabia, China, Japan, Mexico, South Korea, The United Arab Emirates, Oman	Vanuatu, Trinidad and Tobago, Georgia, Switzerland, New Zealand, Angola, Tonga, Egypt, St. Kitts & Nevis, Barbados, Surinam, Kenya, Sierra Leone, Marshall Islands, Ghana, Nigeria, Yemen, Chile, the Philippines, Uruguay, Congo, Peru, Iceland

Information provided by the Norwegian Ministry of Foreign Affairs (2019)

Policy recommendation

- Encourage Member States and other parties to the London Protocol to prioritise ratification of the 2009 amendment of Article 6, which allows for the cross-border transport of CO₂ for the purpose of offshore storage and support proposed temporary solutions including preliminary entry into force among the current ratifying parties.

11.2 EU Emissions Trading Scheme incentives

The EU ETS is a mechanism that could underpin the commercial viability of new CCS and CCU technologies but in its current form does not allow the full realisation of their potential. In the context of CCU, the ETS does not reward the capture and use of CO₂ in materials, for example building and construction materials. The only exception is precipitated calcium carbonate production, which following

a European Court of Justice ruling in 2017, was included in Article 49 of the MRR and is now eligible for ETS credits⁹⁹. While the ETS clearly rewards underground storage in the case of CCS, CCU is not similarly incentivised, as companies must still surrender ETS allowances when using captured CO₂ in infrastructure materials.

The production of e-fuels using air captured CO₂ does not currently benefit from ETS credits. However, such e-fuels could be used in transportation and industry as part of the circular economy. Industrial users of CCU fuels are required to surrender one ETS allowance per tonne of CO₂, in the same way as if fossil fuels were being used directly. For example, this means that any ETS installation wanting to use e-fuels derived from air captured CO₂ is not incentivised to participate in the CCU-based innovative fuels value chain. Allowing appropriate CCU-derived fuels to benefit through the ETS would facilitate the development of e-fuels¹⁰⁰. In general, CCU applications require a life-cycle analysis to establish the final CO₂ emission reduction effect. Clear CO₂ accounting rules are required for integrating CCU into the ETS.

Policy recommendation

- Enable the economic incentives available under the EU ETS to recognise and reward CCU, subject to a lifecycle analysis and clear carbon accounting rules.

The ETS could further support the deployment of CCS in Europe by recognising and rewarding the transportation of CO₂ by ship, trains, or trucks, in a similar way that exists currently for transport by pipeline. Currently installations that export their CO₂ to relevant storage locations through pipelines do not need to surrender ETS allowances; however, if installations export their CO₂ in other forms of transport, ETS allowances must be surrendered as this activity is viewed as an emission under the ETS.¹⁰¹ By expanding the ability of energy-intensive installations to export their CO₂ emissions using modalities other than pipelines, efficient deployment of the CCS value chain in the EU could be better supported. This is particularly important since some planned CCS projects as noted above anticipate the transport of CO₂ using ship, including Northern Lights and the Ervia CCS project. CO₂ transport along EU rivers and waterways towards the coast could therefore be made more economically feasible. One option to achieve the required legislative change is by amending the MRR (Article 52), due to be reviewed in the second half of 2019.¹⁰² Negative emissions technologies and how to incentivise these under the ETS should also be considered.

As mentioned above, CCS costs are higher than current EU ETS prices. Support will therefore be needed in the interim to make the necessary investments viable. Market incentives could be provided via a variety of mechanisms, with some described in this report, and continuing discussion is needed to identify the most appropriate mechanisms for different parts of the value chain.

⁹⁹ Judgment of the Court (First Chamber) of 19 January 2017. Schaefer Kalk GmbH & Co. KG v Bundesrepublik Deutschland. Request for a preliminary ruling from the Verwaltungsgericht Berlin. Reference for a preliminary ruling — Environment — Scheme for greenhouse gas emission allowance trading within the European Union — Directive 2003/87/EC — Monitoring plan — Regulation (EU) No 601/2012 — Article 49(1) and point 10 of Annex IV — Calculation of the emissions of an installation — Subtraction of carbon dioxide (CO₂) transferred — Exclusion of CO₂ used in the production of precipitated calcium carbonate — Legality of the exclusion. Case C-460/15.

¹⁰⁰ For an overview of recommendations on integrating CCU into the MRR Regulation, see report from the German Environment Agency (2019). Support for the revision of the Monitoring and Reporting Regulation for the 4th trading period (focus: Carbon Capture and Utilisation (CCU)). Available from: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-03-27_texte_36-2019_ccu.pdf

¹⁰¹ Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC, ANNEX 1: CATEGORIES OF ACTIVITIES TO WHICH THIS DIRECTIVE APPLIES.

¹⁰² Information available from the European Commission: https://ec.europa.eu/clima/policies/ets/monitoring_en

Policy recommendation

- Ensure CO₂ transport by ship and other modes of transport in addition to pipeline for the purposes of storage is recognised and rewarded under the ETS.

11.3 Guarantees of Origin for CCS and CCU

One example of a potential support mechanism could be the expansion of the Guarantees of Origin (GoO) concept. Trading of GoOs and other certificated products for renewable electricity has been gaining in liquidity, and markets are also developing in similar products for biogas and biomethane, with hydrogen under discussion. The ability to separate environmental credentials from the energy content and to trade both separately introduces market-based principles that can help to achieve EU decarbonisation in economic ways. The extension of such products to additional environmental initiatives such as low carbon and renewable hydrogen are also being considered. Where CCS and CCU can contribute to these same objectives – whether as part of low carbon hydrogen production or other forms of carbon removal – then the development of tradable certificates can help create a market.

Currently, GoOs and certificates are tradable only in narrow markets, with extremely limited cross-border and cross-product capability. A market where different environmental attributes can be aggregated and traded against each other in order to help promote the most economic or most favoured technologies is still some way off. Confidence in the reliability of different techniques and confidence in the market's ability to measure them accurately without double-counting are pre-requisites to success. If CCS and CCU is also capable of contributing to EU targets in a reliable and accurately measurable way, then the introduction of a GoO or certificates trading scheme would help to bring this technology more readily onto the table of available options. This would more clearly give European industry another tool with which to demonstrate environmental commitment and send signals to providers of CCS and CCU that help them to undertake economic investments and operations.

Policy recommendation

- Promote a market framework for decarbonised products and services, including Guarantees of Origin and/or other accreditation schemes, to incentivise new business models for CCS and CCU technologies.

11.4 Sustainable Finance

Under the sustainable finance action plan, the European Commission set up a technical expert group (TEG) on sustainable finance to assist in the development of a unified classification system for sustainable economic activities.¹⁰³ In this context, CCS and CCU should be in the scope of economic activities contributing to climate change mitigation. Financing natural gas projects, such as CCGTs that are CCS-ready, should be recognised and eligible under the EU Taxonomy. The TEG should also recognise CCS, and CCU with appropriate carbon accounting, including CO₂ transport and storage, as essential climate mitigation activities.

¹⁰³ Information available from the European Commission: https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance_en

Policy recommendation

- Ensure CCS and CCU are recognised as economic activities contributing to climate change mitigation in the taxonomy developed in the context of the action plan on sustainable finance.

11.5 CO₂ storage liability

As case study 9 shows, CO₂ storage risks are very low. However, potential CO₂ storage operators are more likely to develop storage facilities if their liability is clearly understood and linked to exposures that can be insured using available financial security instruments.

Before being able to transfer liability to a Competent Authority, the directive on the geological storage of CO₂¹⁰⁴ requires a minimum period of post-closure storage monitoring by the operator of 20 years, although this can be shortened with permission from the Competent Authority.¹⁰⁵ In the event of CO₂ leakage, the storage operator must surrender ETS allowances reflecting the volume of leaked CO₂ in accordance with the ETS price at the time of the incident. Since this potential future ETS cost exposure is unknowable, liability exposure becomes difficult to quantify, making financial security provision challenging. One option to clarify liability could be to link the ETS liability exposure to the ETS price at the time of injection instead.

Unavailability of CO₂ storage may also create negative impacts across the CCS value chain. For example, cessation of CO₂ storage operations in the event of planned downtime or unplanned facility technical problems may require capture and transportation facilities along the chain to also stop their CO₂ activities, since the storage is unavailable. Under this scenario, it will be important to avoid that the storage operator is liable for the economic losses of the capture and/or transport segments of the CCS and CCU value chain, as compensation for such financial loss would significantly expand the liability exposure of the storage operator and act as a disincentive to investment. As noted in the Northern Lights case study, interoperability of CO₂ ships and storages across Europe would help to ensure back-up storage is available in the event of storage downtime. Other potential solutions could be found by learning from pipeline operator and natural gas producers' management of unplanned disruptions to pipeline availability.

In the unlikely event of leakage, other forms of liability relate to the cost of the intervention to re-establish containment, the cost of taking necessary corrective measures to ensure it does not happen again and the potential cost of enhanced monitoring to verify the leak has been effectively addressed. The costs of these incident response liabilities are predictable, unlike the ETS and financial loss exposures, and can therefore be insured using established financial security instruments.

In order to procure cost-effective financial security, it is generally the case that liability exposures must either be capped or limited by the types of claims that can be made. Such liability caps allow providers of financial security, including insurance companies, to develop relevant products for the market. CO₂ insurance products would be new market instruments and would benefit from more predictability as regards storage operator liability.

The monitoring regime in the directive on the geological storage of CO₂ during the CO₂ injection and post-closure phases is time-based and prescriptive, requiring yearly reporting to the Competent Authority based on a Monitoring Plan which itself should be updated every five years. Adjusting these requirements to enable risk-based monitoring would facilitate a more streamlined regulatory approach, whereby monitoring could be tailored according to the project-specific risks rather than a uniform, one-size-fits-all requirement. Such a goal-setting approach would also align with other relevant EU

¹⁰⁴ Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006 (Text with EEA relevance)

¹⁰⁵ Ibid.

regulations, such as the Environmental Impact Assessment Directive, which states that project post-closure monitoring “*shall be proportionate to the nature, location and size of the project and the significance of its effects on the environment*”.¹⁰⁶

Policy recommendation

- Clarify the liabilities of CO₂ storage facility operators, whether state-entities, gas infrastructure companies, or exploration and production companies.

¹⁰⁶ Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment Text with EEA relevance, Article 8a

12. Conclusions and policy recommendations

CCS is a proven technology which has been in safe operation for decades and will continue to be deployed both globally and in Europe as a means to help achieve the Paris Agreement.

CCS and CCU are key technologies to enable decarbonised industry, heat, power, negative emissions and hydrogen.

Transportation of CO₂ also creates potential new opportunities for gas infrastructure companies, subject to the right policy and regulatory framework.

Europe is well placed to take advantage of the benefits of CCS, given the EU's ample CO₂ storage capacity, existing subsea infrastructure, and wide range of European industries that could decarbonise by capturing, using and storing their CO₂.

New and scale-able volumes of low carbon hydrogen will also enhance the efficiency, sustainability and cost effectiveness of the future European gas market.

CO₂ storage risks are very low, and liability would benefit from greater clarity in order to better develop relevant financial security instruments.

Public financial support is necessary, in particular during the early stages of CCS and CCU value chain deployment, until economies of scale are achieved.

The Taskforce established to develop this report identified key policy recommendations, to be considered in the context of potential new market regulation.

Key policy recommendations

Market uptake	<ul style="list-style-type: none"> • Promote a market framework for decarbonised products and services, including Guarantees of Origin and/or other accreditation schemes, to incentivise new business models for CCS and CCU technologies. • Support Member State initiatives to promote early deployment of CCS and CCU infrastructure, such as: <ul style="list-style-type: none"> ○ Contracts for Difference in the power sector; ○ Tax incentives for CO₂ storage; ○ Funding of exploration and appraisal of potential CO₂ storages; ○ Absorbing early value chain risk by providing guarantees for CO₂ supply and/or offtake.
Capture	<ul style="list-style-type: none"> • Enable the economic incentives available under the EU ETS to recognise and reward CCU, subject to a lifecycle analysis and clear carbon accounting rules. • Ensure CO₂ transport by ship and other modes of transport in addition to pipeline for the purposes of storage is recognised and rewarded under the ETS.
Transport	<ul style="list-style-type: none"> • Enable gas infrastructure or other companies, where Member States so decide, to transport CO₂ as a commercial or regulated activity, including in an offshore environment towards the storage, overseen by NRAs with appropriate mandates. • Encourage Member States and other parties to the London Protocol to prioritise ratification of the 2009 amendment of Article 6, which allows for the cross-border transport of CO₂ for the purpose of

Storage

- offshore storage and support proposed temporary solutions including preliminary entry into force among the current ratifying parties.
- Encourage studies which appraise offshore transport infrastructure to identify infrastructure suitable for re-use.
- Clarify the liabilities of CO₂ storage facility operators, whether state-entities, gas infrastructure companies, or exploration and production companies.
- Encourage Member States to develop CO₂ storage atlases of suitable storage complexes, as well as promote relevant geological and infrastructure information sharing.

Public support

- Ensure CCS and CCU technologies and projects are eligible for available public support schemes across the various stages of development, including R&D, demonstration projects, and early roll-out of infrastructure.
- Ensure CCS and CCU are recognised as economic activities contributing to climate change mitigation in the taxonomy developed in the context of the action plan on sustainable finance.
- Ensure Member States consider concrete deployment strategies and supportive policies for CCS and CCU nationally and in the NECPs, in order to achieve the EU 2050 climate ambitions.

Annex 1: List of Abbreviations and Acronyms

Abbreviation/Acronym	
ATR	Auto-thermal reformer
CCGT	Combined-cycle gas turbine
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CEF	Connecting Europe Facility
CfD	Contract for Difference
CH ₄	Methane
CO ₂	Carbon dioxide
CO ₂ -eq.	Carbon dioxide equivalent
EOR	Enhanced oil recovery
ETS	EU Emission Trading Scheme
GoO	Guarantees of Origin
Gt	Gigaton
H ₂	Hydrogen
IPCC	Intergovernmental Panel on Climate Change
MRR	Monitoring and Reporting Regulation
Mt	Million tonnes
Mtpa	Million tonnes per annum
NECP	National Energy and Climate Plan
NRA	National Regulatory Authority
PCI	Project of Common Interest
RAB	Regulated asset base
SMR	Steam methane reformer
TEG	Technical Expert Group

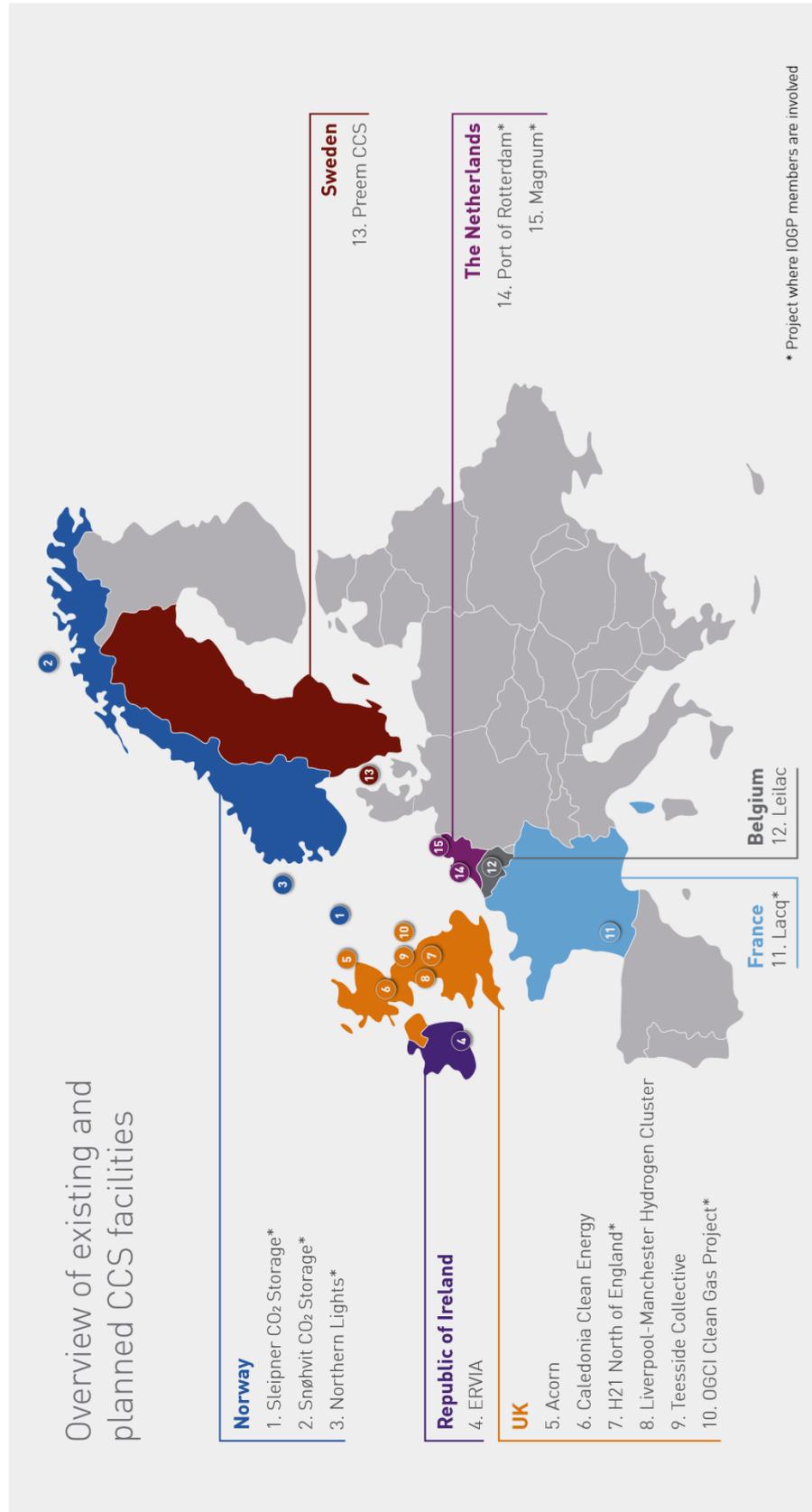
Appendix A – Map of CCS projects in Europe



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CCS projects in Europe

Overview of existing and planned CCS facilities



LOCATION	PROJECT NAME	PROJECT TYPE	DESCRIPTION	CO ₂ CAPTURED/YEAR	STARTING DATE (OPERATION)	STATUS OF THE PROJECT	PARTICIPANTS	IOGP MEMBERS INVOLVED
Belgium	Leilac	Industrial Capture	Cement plant carbon capture (pilot project)	N/A	2018-2020	2-year CO ₂ capture test	HeidelbergCement, Calix	
France	Lacq	Capture Storage (Oxy fuel combustion)	CCS Oxy fuel combustion CO ₂ captured and storage in depleted natural gas field at Rousse (Pyrenees)	Approx. total 50,000 tonnes	2009	Capture and storage phase ended on 15/03/2013	Total	Total
The Netherlands	Port of Rotterdam CO ₂ Transport Hub & Offshore Storage	Industrial Capture	CCS-equipped industrial cluster, CO ₂ transportation and storage in the North Sea	Approx. 5 Mtpa	2020	Feasibility study	Gasunie, the Port Authority and EBN	BP, Shell
	Magnum	Natural Gas-to-H ₂ (pre-combustion)	CCS-equipped production of hydrogen for power generation, CO ₂ transportation and storage in the North Sea	Approx. 4 Mtpa	N/A	Feasibility study	Equinor, Vattenfall, Gasunie, MHPS	Equinor
Norway	Sleipner CO ₂ Storage	Industrial Capture	CCS-equipped natural gas production, CO ₂ directly injected into North Sea reservoirs	Approx. 1 Mtpa, and over 17 million tonnes has been injected since inception to date.	1996	Operational	Equinor (operator) ExxonMobil Total	Equinor (operator) ExxonMobil Total
	Snohvit CO ₂ Storage	Industrial Capture	CCS-equipped LNG facility, CO ₂ transportation and storage in the Barents Sea	0.70 Mtpa	2008	Operational	Equinor (operator) Petoro, Total, Engie, Norsk Hydro, Hess Norge	Equinor, Total, Hess
	Northern Lights	Industrial Capture	CCS-equipped industrial capture, CO ₂ transportation and storage in the North Sea	0.8 Mtpa from possible 2 industrial plants; cement and waste to energy	2023-2024	Feasibility study	Shell, Equinor, Total	Shell, Equinor, Total
Republic of Ireland	ERVIA	Power & Capture (post-combustion)	CCS-equipped CCGTs and refinery, CO ₂ transportation and storage in the Celtic Sea	2 Mtpa	2028	Feasibility study	ERVIA	
Sweden	Pream CCS	Industrial Capture	CCS-equipped refinery, CO ₂ transportation and storage in the North Sea (pilot study)	N/A	N/A	Pre-study	Sintef, Preem AB, Gassnova, Chalmers University of Technology	
UK	Acorn	Industrial Capture	CCS-equipped natural gas processing plant, CO ₂ transportation and storage in the North Sea	The Reference Case assumes a flat rate of 200,000t/yr can be captured from one of the gas terminals at St Fergus	2022	Feasibility Study	Pale Blue Dot Energy (Project leader) along with University of Aberdeen, University of Edinburgh, University of Liverpool, Heriot Watt University, Scottish Carbon Capture & Storage (SCCS), Radboud University and The Bellona Foundation	
	Caledonia Clean Energy	Power & Capture (post-combustion)	CCS-equipped natural gas power plant, CO ₂ transportation and storage in the North Sea	3 Mtpa	2023	Feasibility Study	Summit Power	
	H21 North of England	Natural Gas-to-H ₂ (pre-combustion)	Natural gas-to-hydrogen conversion with CCS, CO ₂ transportation and storage in the North Sea and salt caverns	Approx. 3 Mtpa	2020s	Feasibility study	Northern Gas Networks, Cadent and Equinor	Equinor
	Liverpool-Manchester Hydrogen Cluster	Natural Gas-to-H ₂ (pre-combustion)	Natural gas-to-hydrogen conversion with CCS, CO ₂ transportation and storage in the North Sea	1.5 Mtpa (100% H ₂) - 9.5 Mtpa (100% H ₂)	2020s	Feasibility study	CADENT	
	Teesside Collective	Industrial Capture	CCS-equipped industrial cluster, CO ₂ transportation and storage in the North Sea	0.8 Mtpa (phase 1) - 10 Mtpa (fully operational)	N/A	Feasibility study	Tees Valley Combined Authority, Sembcorp Utilities UK, BOC, CF Fertilisers, Lotte, NEPIC, SABIC, The Department of Business, Energy and Industrial Strategy	
	OGCI Clean Gas Project	Power & Capture (post-combustion)	CCS-equipped natural gas power plant, CO ₂ transportation and storage in the North Sea	5 Mtpa	2026	Technical evaluation and business model options	OGCI	ENI, Repsol, Shell, Equinor, Total

Appendix B - Government attitudes and legislative restrictions on CO₂ storage in Europe

Table B.1: Overview of government attitudes and current legislative restrictions on CO₂ storage in the EU28 and Norway

Country	Government attitude	Government strategy source	Current legislative restriction
Austria	Unfavourable	#mission2030	No storage
Belgium	Favourable	Scenarios for a Low-Carbon Belgium	Not in Brussels Capital Region
Bulgaria	Favourable	Energy Strategy 2020	Max. storage of 160 Mt CO ₂ up to 2030
Croatia	Neutral	Seventh National Communication to UNFCCC	No storage
Cyprus	Neutral	No government source. EU 2050 Energy Strategy Towards Sustainable Energy Systems	-
Czech Republic	Neutral	Climate Protection Policy of the Czech Republic	No storage until 2020
Denmark	Neutral	Energy Strategy 2050	No onshore storage until 2020
Estonia	Neutral	General Principles of Climate Policy until 2050	No storage
Finland	Favourable	Energy and Climate Roadmap 2050	Only for demonstration until 2024
France	Favourable	Pathways 2020-2050 Towards a Low-Carbon Economy in France	-
Germany	Neutral	Climate Action Plan 2050	Max. storage of 4 Mtpa CO ₂ . No storage allowed in five federal states
Greece	Favourable	No government source. National Energy Plan: Roadmap to 2050	-
Hungary	Favourable	No government source. Climate Change Policy in Hungary	-
Ireland	Favourable	2050 Low-Carbon Roadmaps	-
Italy	Neutral	Deep Decarbonization In Italy	No storage in seismic areas or unconfined aquifers. No negative impact on marine traffic and oil and gas exploration
Latvia	Neutral	Sustainable Energy Strategy for Latvia: Vision 2050	No storage
Lithuania	Favourable	Lithuania Energy Strategy	-
Luxembourg	-	No sources found	-
Malta	-	No sources found	-
Netherlands	Favourable	Key Elements of Climate Agreement	No onshore storage
Poland	Neutral	Polish draft NECP	Only for demonstration until 2024
Portugal	Favourable	Low Carbon Roadmap for Portugal	-
Romania	Favourable	ERA-NET ACT	-
Slovakia	Neutral	No government source. Slovakia Country Report	-
Slovenia	Neutral	Sostanj Thermal Power Project	No storage
Spain	Favourable	ERA-NET ACT	-
Sweden	Favourable	Swedish Environmental Protection Agency, 'Climate Action Roadmap'	No onshore storage
UK	Favourable	Clean Growth Strategy	No onshore storage
Norway	Favourable	The full-scale CCS project in Norway	No onshore storage

Adapted from: Navigant (2019). ANNEX E. Carbon capture, storage and utilisation. In: *Navigant (2019). Gas for Climate. The optimal role for gas in a net zero emissions energy system.*