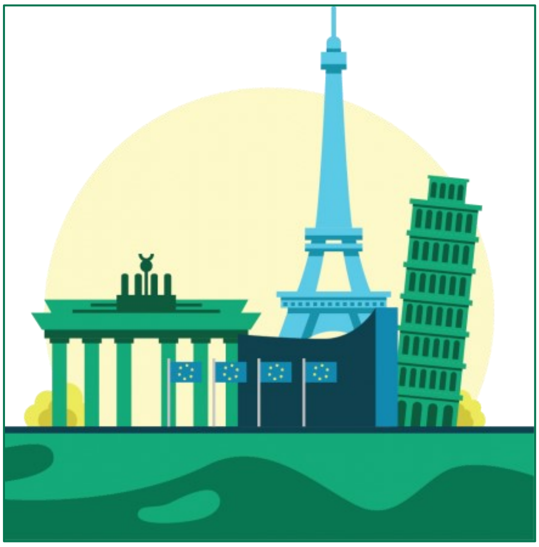
High Level Report: CCUS in Europe - at the verge of a real break-trough



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EU CCUS PROJECTS NETWORK (No ENER/C2/2017-65/SI2.793333)

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About the CCUS Projects Network

The CCUS Projects Network comprises and supports major industrial projects underway across Europe in the field of carbon capture and storage (CCS) and carbon capture and utilisation (CCU). Our Network aims to speed up delivery of these technologies, which the European Commission recognises as crucial to achieving 2050 climate targets. By sharing knowledge and learning from each other, our project members will drive forward the delivery and deployment of CCS and CCU, enabling Europe's member states to reduce emissions from industry, electricity, transport and heat.

http://www.ccusnetwork.eu/

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Executive summary

The CCUS Projects Network comprises and supports major ongoing industrial projects across Europe in the field of carbon capture and storage (CCS) and carbon capture and utilisation (CCU). The Network aims to speed up delivery of these technologies, which the European Commission recognises as crucial to achieving 2050 climate targets. The role of the CCUS Projects Network is to support successful development and implementation of CCUS projects through facilitating knowledge-sharing from which the projects can mutually learn and benefit. By sharing knowledge and learning from each other, our Network members drive forward the delivery and deployment of CCS and CCU, enabling Europe's Member States to reduce emissions from industry, electricity, transport and heat.

This second High-Level Report aims to provide an overview of the recent developments for Carbon Capture Utilization and Storage (CCUS) in Europe, as well as a short analysis of the key elements driving the deployment of CCUS. These elements can be considered 'game changers' for CCUS and include increased internal pressure to realise the ambitions stipulated in the European Green Deal and enshrined in the EU Climate Law as well as increased global climate ambitions. CCUS is currently the only viable alternative to address emissions from industry sectors such as cement where process emissions cannot be avoided by replacing the energy source by renewables. The 'game changers' also include the recent developments regarding carbon price under the EU ETS, the emergence of new business models focused on industrial hubs and clusters and CO_2 transport and storage as a service. Furthermore, the increased demand for low-carbon hydrogen can play a role in driving CCUS forward through demand for blue hydrogen. Finally, CCS could facilitate a stable, flexible and low-emissions source of power.

The report provides an overview of the most advanced CCS and CCU projects as well as a brief summary of remaining hurdles which need to be addressed in order to support CCUS deployment. Finally, the report concludes with a positive outlook on the future of CCUS in Europe. It is evident that the key elements to enable a successful deployment of CCUS are aligned and that CCUS is on the brink of a new era as it is becoming increasingly evident that CCUS is a necessity rather than an option if climate neutrality by 2050 is to be achieved.

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Table of Contents

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CCUS in Europe: at the verge of a real break-trough

1 Introduction

1.1 Role of CCS and CCU in Europe

Carbon Capture Utilization and Storage (CCUS) technologies can and should play an important role in achieving Europe's 2050 decarbonization goals. All credible scenario modelling shows that CCS will be needed to meet the goals set out in the Paris Agreement.[1] Based on the EU's long-term strategic vision described in the "Clean Planet for All" communication[2], the 1.5°C compliant scenarios (1.5 LIFE and 1.5 TECH) depend on the deployment of CCS to achieve climate neutrality and foresee an important role for CCU. In these scenarios CCUS technologies are forecasted to remove between 281 and 606 Mt of CO_2 in 2050. In particular, CCS is increasingly being recognised as a necessary technology to achieve climate neutrality in Europe in a cost-efficient manner. However, both CCS and CCU should be seen as mutually reinforcing solutions as both require similar infrastructure for capture and transport.

The industrial sector in Europe represents approximately one fourth of EU's GDP and provides about 50 million jobs. At the same time the European industry is responsible for producing more than 500 Mt of CO_2 emissions annually (including electricity and end-of life emissions). This represents around 14% of the EU's total emissions.[3] The deindustrialization of Europe due to mounting pressures for climate action would result in the loss of jobs, lead to diminished economic competitiveness, increased dependency from other global players and would have other macro-economic ramifications. In this context, CCUS represents one of the only available tools to support the decarbonization of industry while preserving industrial jobs and delivering low-carbon, essential products like chemicals, steel and cement. Moreover, based on available estimates, CCS could create 150,000 direct and indirect jobs by 2050.[4]

In addition, in the future, when coupled to gas-to-power or hydrogen technologies, CCS could facilitate a stable, flexible and low-emissions source of power. Thus, CCUS has an important role to

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[1] 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.
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
[2] COM (2018) 773 – A clean planet for all – A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy.
[3] Material Economics (2019). Industrial Transformation 2050" Pathways to Net-Zero Emissions from EU Heavy Industry
[4] IOGP (2019). The potential for CCS and CCU in Europe

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play in industry but also in many other important areas of economic activity including generation of electricity and heat, and the production of hydrogen and synthetic fuels.

Thus, CCUS can support the attainment of positive climate outcomes and mitigate climate change through[5]:

- Deep decarbonisation of industry;
- Low-carbon hydrogen production;
- Low-carbon dispatchable power; and
- Negative emissions[6].

1.2 A break-through is coming

In recent years, there has been a renewed interest and attention in CCUS technologies, given the growing urgency to decarbonise the economy and the increased realisation of the role CCUS can play in doing so. As described in sections 0 and 0 on most important CCS and CCU projects in Europe and seen from Figure 1, the pipeline of new CCUS projects in Europe has been growing. Political support at EU-level is highlighted by the fact that four out of the seven large-scale projects preselected for grant agreement preparations under the first call of the Innovation Fund are CCS projects. Furthermore, the first CCUS Forum organised by the European Commission on 11 October, 2021 is a testament of the political support that CCUS is gaining at EU-level. During the event, high-level EU officials including Commissioner Simson expressed their support for CCUS.[7]

The growing interest in CCUS has been driven by policy developments and underpinned by strengthened national climate targets, declining technology costs and the emergence of new business models with improved financial viability for CCUS.[8]

[5] GCSSI (2021) Global Status report 2021: Policy Fact Sheet. Available at: https://www.globalccsinstitute.com/wp-content/uploads/2021/10/GSR2021_Policy-Factsheet_2021_EN.pdf

[6] For more information on this topic see: CCUS Projects Network (2021) The role of Carbon Dioxide Removals for Net Zero (forthcoming). Will be available at: https://www.ccusnetwork.eu/knowledge-hub/thematic-reports

[7] Speech by Commissioner Simson at the Carbon capture, utilisation and storage forum. Available at: https://ec.europa.eu/info/events/carbon-capture-utilisation-and-storage-forum-2021-oct-11_en

[8] IEA (2020) Energy Technology Perspectives 2020 - Special Report on CCUS. Available at: https://iea.blob.core.windows.net/assets/181b48b4-323f-454d-96fb-0bb1889d96a9/CCUS_in_clean_energy_transitions.pdf

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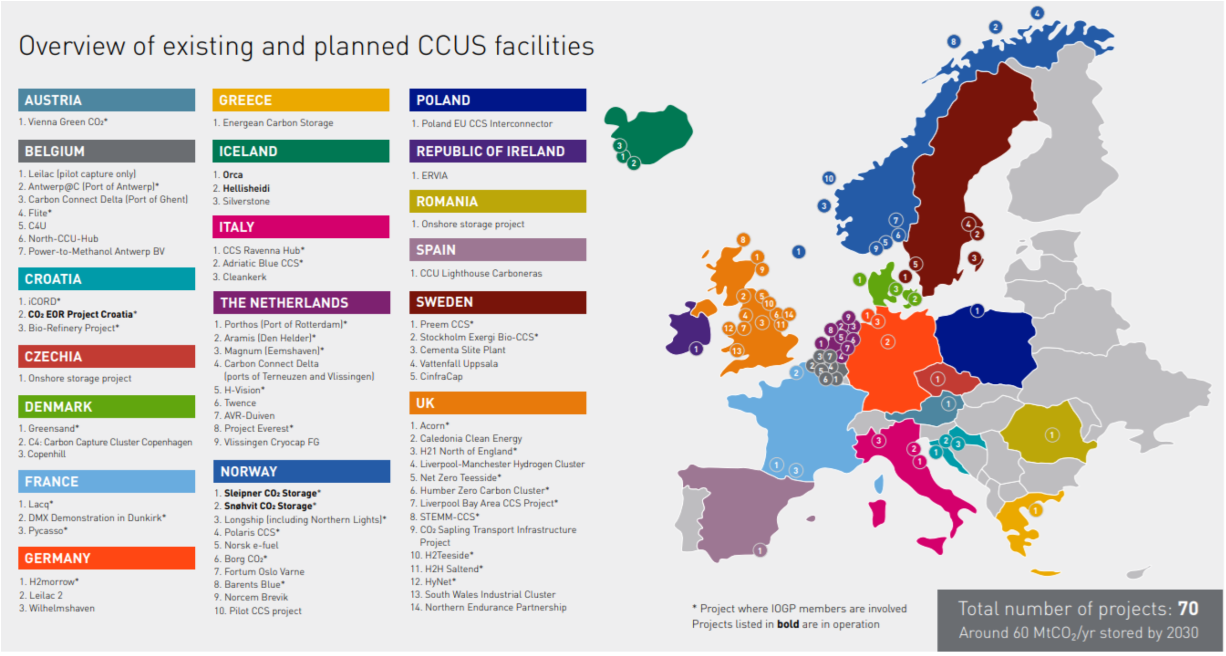
Figure 1 Overview of existing and planned CCUS facilities in Europe



Source: IOGP (2021) CCUS projects in Europe

1.3 Role of the CCUS Projects Network

The CCUS Projects Network comprises and supports major industrial projects under way across Europe in the field of CCUS. The Network was established in 2019 with the aim to speed up delivery of these technologies, which the European Commission recognises as crucial to achieving 2050 climate targets. By sharing knowledge and learning from each other, project members of the Network have actively contributed to moving forward the delivery and deployment of CCUS, enabling Europe's Member States to reduce emissions from industry, electricity, transport and heat.

2 Main game-changers and their impact

2.1 Internal motivation and outside pressure have changed industries' position

In recent years the environment for CCUS in Europe has been improving, in large part due to the adoption of more ambitious climate goals and increased policy support for clean energy technologies.

The growing momentum for CCUS is not only coming from internal, European, developments but is also reinforced by growing support for these technologies internationally. The deployment of CCUS has been concentrated in the United States and Canada, however, more recently, CCUS facilities have also been commissioned in Australia, Brazil, China, Saudi Arabia and the United Arab Emirates. Since 2017, more than 30 plans for new integrated CCUS facilities have been announced globally.[9]

A growing number of companies are also embracing CCUS as an answer to support the decarbonisation of their sectors. Companies like Dalmia Cement and Heidelberg Cement in the cement sector and ArcelorMittal in steel are focusing on CCUS to meet their decarbonisation goals.[10]

Negative emissions technologies based on CCS such as bioenergy combined with CCS (BECCS) and direct air capture with CCS (DACCS) have also received a lot of attention in the last couple of years. For example, Microsoft is establishing a USD 1 billion climate innovation fund to support development of carbon reduction, capture and removal technologies.[11]

2.2 Key elements

2.2.1 Carbon price

With the price of carbon under the EU Emissions Trading System (EU ETS) reaching close to 90 EUR/tonne in early December 2021[12], carbon prices are at a never-before seen high. With these unprecedently high prices, commercial interest in CCUS projects has been sparked by several companies.[13] If these carbon prices are maintained, the economic business case for CCUS will be much stronger. Furthermore, based on the proposed revisions of the EU ETS Directive which

[9] IEA (2020) Energy Technology Perspectives 2020 - Special Report on CCUS. Available at: https://iea.blob.core.windows.net/assets/181b48b4-323f-454d-96fb-0bb1889d96a9/CCUS_in_clean_energy_transitions.pdf
[10] Ibid.
[11] Microsoft (Accessed on 16/12/2021). Climate Innovation Fund. Available at: https://www.microsoft.com/en-us/corporate-responsibility/sustainability/climate-innovation-fund?activetab=pivot1%3aprimaryr6
[12] On December 8th, 2021, the price of carbon under the EU ETS was 88.88 EUR/ton. Reference: https://ember-climate.org/data/carbon-price-viewer/
[13] S&P Global Platts (Accessed on 16/12/2021) EU carbon prices of over EUR5-/mt spur CCS interest. Available at: https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/050621-eu-carbon-prices-of-over-eur50mt-spur-ccs-interest

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includes a proposition to allow for removing the obligation to surrender allowances for carbon stored in long-lived products, CCU projects would also be incentivised.

2.2.2 New Business Models and focus on Industrial Hubs

Commercial approaches to CCUS development are changing focus from large, stand-alone projects to the establishment of industrial hubs and clusters with shared CO_2 infrastructure for transport and storage. Approaches based on hub and cluster development support economies of scale and reduce commercial risks, with new business models focused on transport and storage services.

The development of shared infrastructure can act as a trigger for new investments. A good example is the development of the Northern Lights storage project (see section 0 for more information) – a central piece of Norway's Longship Full-chain project. The viability of the Northern Lights projects is linked to the potential development of at least nine capture facilities across Europe. Plans to equip these facilities with CO_2 capture would probably not have been viable in the absence of a potential CO_2 storage solution.[14] Around the world, there are almost 40 industrial hubs in development currently, half of them in Europe.[15]

2.2.3 Hydrogen

Globally, the growing interest in low-carbon hydrogen has resulted in almost 50 facilities under development to capture CO_2 from hydrogen-related processes.[16] In the EU, the European Commission adopted the Hydrogen Strategy in July 2020. Although the Strategy is based on a 'renewable hydrogen first' approach, it is increasingly becoming clear that if the EU is to meet its hydrogen and Green Deal targets in a cost-effective and timely way, it will need to make use of significant quantities of hydrogen produced through stem methane reforming with CCS, also called 'blue hydrogen'. The availability of sufficient, cheap, and reliable electricity from renewable sources is a key issue. It is arguable whether there will be enough renewable capacity to meet all the electrification needs in the transport, buildings and industry sectors in the coming decades and still have capacity to produce green hydrogen at a large scale.[17] For example, as of today the use of grid electricity to produce hydrogen in many EU Member States would increase CO_2 emissions when compared to fossil-based hydrogen production.[18] In addition, the cost of CCUS-based hydrogen can be around half of those where hydrogen is produced through electrolysis based on renewable

[14] IEA (2020) Report extract: A new era for CCUS. Available at: https://www.iea.org/reports/ccus-in-clean-energy-transitions/a-new-era-for-ccus
[15] McCulloch, S. for EnergyPost.EU (2021) Will this be the decade of Carbon Capture or another false start? Available at: https://energypost.eu/will-this-be-the-decade-of-carbon-capture-or-another-false-start/
[16] Ibid.
[17] Belmans, R. et al. (2021), Electrification and sustainable fuels: Competing for wind and sun. Available: https://cadmus.eui.eu/bitstream/handle/1814/71402/RSC%202021_55.pdf?sequence=1
[18] Bellona Europa (2021) Cannibalising the Energiewende? 27 Shades of Green Hydrogen. Available at: https://network.bellona.org/content/uploads/sites/3/2021/06/Impact-Assessment-of-REDII-Delegated-Act-on-Electrolytic-Hydrogen-CO2-Intensity.pdf

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power.[19] CCUS also offers the possibility to tackle emissions from existing hydrogen production based almost exclusively on fossil fuels and releasing more than 800 MtCO_2 each year.[20]

2.2.4 Changes to the energy system, renewables, and the need for low-carbon dispatchable power

CCS can contribute to a stable, flexible and low-emissions power sector and prevent stranded investments in existing and new power plants. The average age of gas-fired power plants in Europe is 17 years, whereas their average technical lifespan is 50 years. It is estimated that more than 25 Gt of CO_2 can be emitted until 2070 by the existing plants (and plants under construction or already planned) if these are not retrofitted with CCUS or retired early.[21]

Retrofitting existing power plants with CO_2 capture allows for significant emission reductions while ensuring that these plants and the associated infrastructure and supply chains can continue operating. This in turn, can positively contribute to energy security, supporting the diversification of generation options and integration of intermittent renewables with flexible dispatchable power. CCUS can also help to preserve jobs and economic prosperity in places where economic activity is based on energy-intensive industries. As an example, Germany's planned retirement of around 40 GW of coal-fired generation capacity before 2038 represents about EUR 40 billion in compensation to the owners of coal mines and power plants as well as support to affected communities.[22]

[19] IEA (2020) Report extract: A new era for CCUS. Available at: https://www.iea.org/reports/ccus-in-clean-energy-transitions/a-new-era-for-ccus
[20] Ibid.
[21] Jones, Ch.; Piebalgs, A. (2021) CCUS is Necessary to Reach Climate Neutrality. Available at: https://ec.europa.eu/info/sites/default/files/energy_climate_change_environment/events/documents/jones_piebalgs_ccus_and_the_green_deal.pdf
[22] IEA (2020) Report extract: A new era for CCUS. Available at: https://www.iea.org/reports/ccus-in-clean-energy-transitions/a-new-era-for-ccus

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3 Most important CCS Projects

3.1 Overview

CCS has been in operation in Europe for twenty-five years. In 1996 the Sleipner in Norway, operated by Equinor, was the first industrial-scale CCS project worldwide, with CO_2 from natural gas sweetening injected into a dedicated storage site (opposed to enhanced oil recovery (EOR)). One million tons per annum (Mtpa) CO_2 captured from natural gas from the Sleipner Vest and Gudrun offshore fields is injected in the Utsira formation in the North Sea. Equinor stared CCS operations in a second site in 2008 in Snøhvit, where 0.7M Mtpa CO_2 are captured from natural gas and stored in the Stø formation in the Barents Sea.

According to the Global CCS Institute's Global Status of CCS 2021 report[23] , in September 2021 there were 27 commercial CCS facilities worldwide, with a capacity of 36.6 Mtpa. In addition, there were four facilities in construction, 58 in advanced development and 44 in early development, with capacities of 3.1 Mtpa, 46.7 Mtpa, and 60.9 Mtpa, correspondingly. Among the projects in development, 35 are in Europe, with capture from diverse sources such as hydrogen production, power stations, waste to energy plants, and cement production.

3.2 Innovation Fund

The EU Innovation Fund was established as part of the 2018 revision of the ETS directive by Article 10a(8) of Directive 2003/87/EC to support innovation in low-carbon technologies and processes across all Member States.[24] Currently, the Innovation Fund is expected to mobilise around EUR 22.5 billion in the period 2020-2030 (assuming a CO_2 price of 50 EUR/tonne).[25]

The results for the first call for large-scale projects, with a budget of EUR 1 billion, were published on 16 November 2021 and seven projects were pre-selected for grant agreement preparations, of which four were related to CCS. The CCS related projects are[26, 27]:

- **Kairos-at-C**, coordinated by Air Liquide, which aims to build a CCS value chain avoiding ~14.2 Mt CO_2 over the first 10 years of operation. The CCS value chain will include capture from

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[23] Global CCS Institute, 'Global Status of CCS 2021', 2021. [Online]. Available: https://www.globalccsinstitute.com/resources/global-status-report/

[24] European Commission, 'Innovation Fund', 2021. [Online]. Available: https://ec.europa.eu/clima/eu-action/funding-climate-action/innovation-fund_en.

[25] European Commission, 'Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation o', EU Emissions Trading System, 2021. [Online]. Available: https://ec.europa.eu/info/sites/default/files/revision-eu-ets_with-annex_en_0.pdf#page=130.

[26] European Commission, 'First call for large-scale projects. List of Proposals Pre-Selected for a Grant', Innovation fund, 2021. [Online]. Available: https://ec.europa.eu/clima/system/files/2021-11/policy_funding_innovation-fund_large-scale_successful_projects_en.pdf.

[27] European Commission, 'Large-scale projects', Innovation Fund, 2021. [Online]. Available: https://ec.europa.eu/clima/eu-action/funding-climate-action/innovation-fund/large-scale-projects_en.

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five different production units (hydrogen production plants, ethylene oxide plants and ammonia plant) and a multi-modal transport infrastructure for CO_2 in Antwerp, Belgium, with permanent CO_2 storage in the North Sea.

- **BECCS@STHLM**, coordinated by Stockholm Exergi, which aims to avoid ~7.8 Mt CO_2 over the first 10 years of operation in the heat and power biomass plant in Stockholm. The CO_2 will be transported by ship for permanent storage in Norway.
- **K6 program**, coordinated by EQIOM, in France, which aims to implement an industrial-scale combination of an oxy-fuel kiln with CO_2 capture, avoiding ~8.1 Mt CO_2eq over the first 10 years of operation in Dunkirk, France. The CO_2 will be transported by train and ship for permanent storage in the North Sea.
- **SHARC**, coordinated by Neste Oyj, in Finland. By introducing electrolysis and capturing CO_2 from the hydrogen production unit, SHARC aims to avoid more than 4 Mt CO_2 in the first 10 years of operation.

A second call for large-scale projects, with a budget of EUR 1.5 billion was launched the 26th of October 2021 and is open until the 3rd of March 2022.[28, 29]

3.3 Projects of Common Interest (PCI)

Projects of Common Interest (PCIs) are key cross border infrastructure projects that link the energy systems of EU countries. The PCIs are intended to help the EU achieve its energy policy and climate objectives: affordable, secure and sustainable energy for all citizens, and the long-term decarbonization of the economy in accordance with the Paris Agreement. Every two years since 2013, the European Commission draws up a new list of PCIs.[30] The fifth list, adopted in November 2021[31], includes six projects related to CO_2 infrastructure:

- **CO2 TransPorts**: aims to establish infrastructure to facilitate large-scale capture, transport and storage of CO_2 from Rotterdam, Antwerp and the North Sea Port.
- **Northern Lights project**: commercial CO_2 cross-border transport connection project between several European capture initiatives (United Kingdom, Ireland, Belgium, the Netherlands, France, Sweden) and transport the captured CO_2 by ship to a storage site on the Norwegian Continental Shelf.

[28] Ibid.
[29] European Commission, 'Boosting Europe's green transition: Commission invests €1.5 billion in innovative clean tech projects', Innovation Fund, 2021. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/ip_21_5473.
[30] European Commission, 'Candidate PCI projects in cross-border carbon dioxide (CO2) transport networks', 2021. [Online]. Available: https://ec.europa.eu/energy/sites/default/files/detailed_information_regarding_the_candidate_projects_in_co2_network.pdf.
[31] European Commission, 'Commission proposes new list of Projects of Common Interest for a more integrated and resilient energy market', 2021. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/IP_21_6094.

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- **Athos project**: proposed an infrastructure to transport CO_2 from industrial areas in the Netherlands and was opened to receiving additional CO_2 from others, such as Ireland and Germany. Developing an open-access cross-border interoperable high-volume transportation structure was an idea. However, this project was cancelled after Tata Steel, which was the main source of CO_2 for the project, decided to use an alternative technology (direct reduced iron, DRI) to produce steel.[32] [33]
- **Aramis**: cross-border CO_2 transport and storage project. It involves intake from emitters in the hinterland of Rotterdam harbour area and storage on the Dutch continental shelf.
- **Dartagnan:** CO_2 export multimodal HUB from Dunkirk, France, and its hinterland. It involves emitters from the industrial cluster in the area of Dunkirk with storage where available in the North Sea country territories.
- **Poland – EU CCS Interconnector**: emitters from the industrial cluster in the area around Gdansk, Poland, with storage where available in the North Sea country territories.

Projects of common interest are eligible for funding from the Connecting Europe Facility (CEF). The new CEF Programme for 2021-2027[34] allocates a total budget of EUR 5.8 billion to the energy sector. The first CEF Energy PCI call for proposal under this new CEF programme was open for submissions from 7th September to 19th October 2021.

3.4 Advanced Projects in Europe

A previous CCUS PN report[35] summarizes industrial scale and emerging CO_2 capture projects. Here, we update some of the more advanced projects.

Northern Lights

The Northern Lights project, which is a PCI, is part of the Norwegian full-scale CCS demonstration project and is the world's first large scale "open-source" infrastructure for receiving and storing CO_2 from multiple sources and industries. Equinor is executing the project, while Norske Shell and Total E&P Norge are equal partners.[36, 37]

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[32] S&P Global, 'Dutch CCS project scrapped after Tata Steel opts for hydrogen DRI production route', 2021. [Online]. Available: https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/092121-dutch-ccs-project-scrapped-after-tata-steel-opts-for-hydrogen-dri-production-route.

[33] Tata Steel, 'Tata Steel opts for hydrogen route at its IJmuiden steelworks', 2021. [Online]. Available: https://www.tatasteeleurope.com/corporate/news/tata-steel-opts-for-hydrogen-route-at-its-ijmuiden-steelworks.

[34] European Commission, 'Regulation (EU) 2021/1153 of the European Parliament and of the Council of 7 July 2021 establishing the Connecting Europe Facility and repealing Regulations (EU) No 1316/2013 and (EU) No 283/2014', Document 32021R1153, 2021. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2021/1153/oj.

[35] A. Reyes-Lúa and K. Jordal, 'Current and emerging industrial-scale CO_2 capture. A brief overview', TG2 Briefing Report on Industrial CO_2 capture- CCUS Projects Network Thematic Reports, 2019. [Online]. Available: https://www.ccusnetwork.eu/sites/default/files/TG2_Briefing-Industrial-CO2-capture.pdf.

[36] Equinor, 'Northern Lights Project Concept report-DG2 report', RE-PM673-00001, 2018.

[37] 'Northern Lights Project', 2020.

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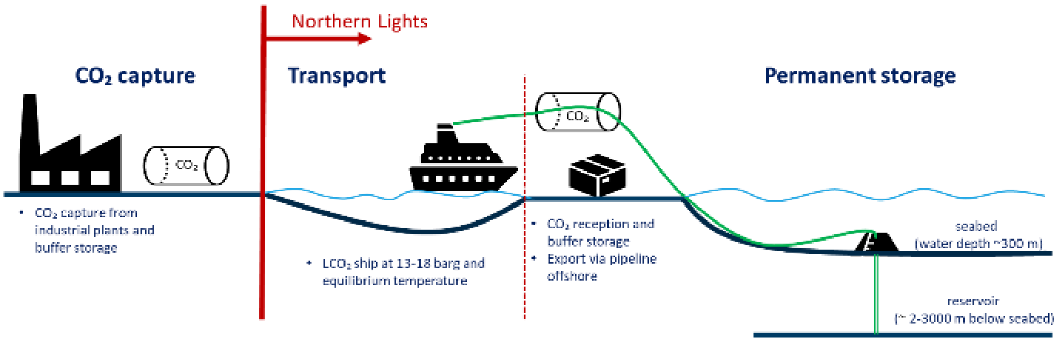
As shown in Figure 2, Northern Lights comprises transportation, reception, and permanent storage of CO_2 in a reservoir under the North Sea. The receiving terminal will be in the Naturgassparken industrial area in Øygarden, Western Norway. The facilities are scheduled to be operational in 2024.[38] Northern Lights is planned to be developed in two phases, with storage capacities of up to 1.5 and 5 Mtpa respectively.[39] Different expansion scenarios, for up to 100 Mtpa have been explored.[40]

Figure 2 Northern Lights project as part of the Norwegian CCS demonstration project (adapted from 'Northern Lights Project', 2020).



The Norwegian government has approved funding in December 2020 for a CO_2 capture and storage project, Longship[41], that involves shipping CO_2 from the cement manufacturer Norcem in Brevik on the southern coast of Norway to the Northern Lights storage site on the west coast of Norway. This means that the infrastructure for receiving and storing CO_2 will be built over the next few years and be operational in 2024. It is foreseen that 400 ktpa CO_2 will be captured from Norcem and liquified on site, followed by transport and storage by Northern Lights. In addition, Fortum Oslo Varme (FOV), a waste-to-energy plant in the Oslo area with the potential to capture additional 400 ktpa CO_2 (of which 50% biogenic), will be partially funded by the Longship project, if FOV can secure sufficient own funding as well as funding from the EU Innovation Fund or other sources.

Porthos

Porthos, based in Rotterdam, is the most developed full-chain CCS project in the Netherlands, which expects to take a Final Investment Decision (FID) in the first quarter of 2022, with a planned starting

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38 'Northern Lights Project', 2020

39 Equinor, 'Northern Lights Project Concept report-DG2 report', RE-PM673-00001, 2018.

40 Equinor ASA, 'Northern Lights Contribution to Benefit Realisation', 2019.

41 Regjeringen (Norwegian Government), 'The Government launches "Longship" for carbon capture and storage in Norway', 2020. [Online]. Available: https://www.regjeringen.no/en/aktuelt/the-government-launches-longship-for-carbon-capture-and-storage-in-norway/id2765288/.

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date of injection in 2024. Porthos has already secured CO_2 supply for its Phase 1 plans, which are already reaching the maximum capacity for current P-18 fields. Based on the new Dutch SDE++ scheme[1], emitters associated with Porthos have been granted subsidy which would allow for the capture of approximately 37.5 Mt of emissions (2.5 Mtpa for 15 years). The planned CO_2 sources and timeline for their Phase 2 of storage is still unclear.

Porthos is part of a PCI, the overarching project for the collaboration between Port of Antwerp, Porthos and North Sea Ports is called CO_2Transports. The overall objective of CO_2TransPorts is to provide an 'open access' CO_2 transportation service for CO_2 capture sites in the Port of Rotterdam, Antwerp and the North Sea Port partnership. One of the key goals of this collaboration is to provide Belgium with access to safe and suitable CO_2 storage sites on the Dutch Continental Shelf (via the Porthos project in Rotterdam) through a physical cross-border connection.

CO_2TransPorts will be developed in 3 phases, listed below (with an indicative timeline[3]). Phases 1 and 2 will provide CO_2 transport infrastructure for up to a maximum of 16 MtCO_2/year. However, existing studies indicate that extra capacity will be needed. This will be developed in Phase 3.

Phase 1 (beginning 2024): This phase is focused on the development of CO_2 transport and storage infrastructure at the Port of Rotterdam and includes:

- Development of an onshore pipeline through the port of Rotterdam, a compressor station, and an offshore pipeline to access the P18 gas fields for CO_2 storage.
- The option of shipping CO_2 from Rotterdam from 2025 onwards is also being investigated.
- Front End Engineering Design (FEED) studies for these Port of Rotterdam infrastructure developments are now almost finalised and a final investment decision (FID) is expected in the first quarter of 2022. Based on a positive FID outcome, the Phase 1 Rotterdam infrastructure is expected to begin construction in 2022 and become operational in 2024.

Phase 2 (2026): In this phase the cross-border transport of CO_2 from Antwerp and North Sea Port will be initiated:

- CO_2 pipeline collection network and potential shipping links to Rotterdam will be developed in Antwerp and the North Sea Port areas.
- Access to CO_2 storage sites in the North Sea for Dutch and Belgian CO_2 sources will be provided.
- Feasibility work will be required in addition to that conducted for Phase 1 by Porthos to allow for further storage site selection. Pre-FEED work is also required on the extension of the offshore transport system from Rotterdam to the Phase 2 storage fields.
- North Sea Port and the Port of Antwerp are currently conducting feasibility studies for these Phase 2 infrastructure developments. The Port of Antwerp has recently begun the FEED phase for their location collection network.

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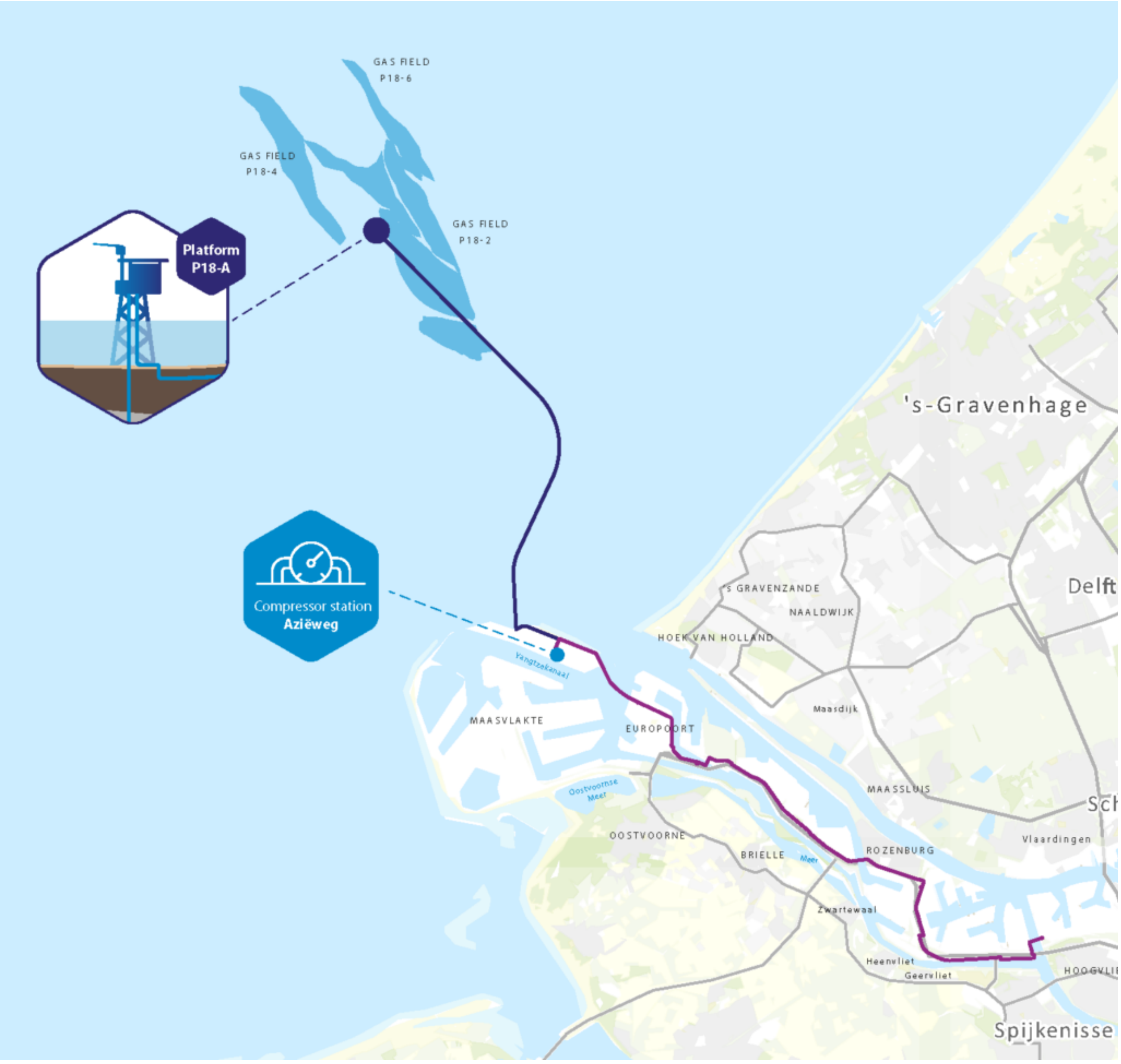
Phase 3 (2030+): Should the total CO_2 transport demand from the three regions exceed the maximum design capacity of 16 Mtpa expected in Phases 1 and 2 there is the potential for expansion. This is currently in the pre-feasibility stage and realisation is expected from 2030 onwards.

Figure 3 Map of the planned pipeline route and storage location for the Porthos project.



3.5 Hurdles

CCS is technically feasible and progressing, with currently several technology providers available. Transport and storage projects are being developed, including the Projects of Common Interest (PCIs) in Europe. However, realising CCS is more than just identifying and selecting the technology, and installing CO_2 capture at an industrial site. To reach industrial-scale operation, CCS

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projects must be developed along several axes. Business models and a favourable policy and regulatory framework, preferably with long-term predictability, are essential for the large-scale deployment of CCS projects. Fluent collaboration between project owners and governments, with good timing with respect to access to funding, implementation of necessary regulations and access to transport and storage infrastructure is important, as well as good models for risk sharing. Political support, public acceptance, and implementation plans are very important on all levels: EU, national, and local.[42]

Input from CCUS PN members was used to compile the report " Industrial CO_2 capture projects: Lessons learned and needs for progressing towards full-scale implementation"[43], which discusses some of these issues. Aspects to be defined for shipping, including transboundary CO_2 transport of are discussed in the report " CO_2 ship transport: Benefits for early movers and aspects to consider".[44]

3.6 The London Protocol

The London Protocol[45] was designed in order to protect the marine environment from dumping of wastes. This however turned out to provide a barrier to transboundary CO_2 transport for storage, since Article 6 of the protocol banns transport of wastes to other countries for dumping at sea. In 2006 an amendment was made to the London Protocol allowing storage of CO_2 under the seabed and in 2009 an amendment was made to Article 6 allowing for transborder movement of CO_2 for the purpose of offshore storage.[46] However, for the amended Article 6 to enter into force it must be adopted by two thirds of the 53 parties of the protocol, which has not happened so far.

However, in October 2019, based on a suggestion from Norway and the Netherlands, the International Maritime Organization (IMO) decided to allow for provisional application of the 2009 amendment to Article 6 of the London Protocol. In practice, countries who wish to allow for export or import of CO_2 for injection and permanent storage under the seabed must *deposit a Unilateral Declaration* on the provisional application of the 2009 amendment to the London Protocol Article 6 to the Depositary (Secretary-General of the IMO). Thereafter, a *bilateral agreement must be established between the CO_2 exporting and importing countries*, which shall include confirmation and allocation of permitting responsibilities between the two countries, consistent with the

[42] A. Reyes-Lúa and K. Jordal, 'Industrial CO_2 capture projects: Lessons learned and needs for progressing towards full-scale implementation', 3rd Report of the Thematic Working Group on: CO2 capture and utilisation, 2020. [Online]. Available: https://www.ccusnetwork.eu/sites/default/files/TG2_Briefing-Industrial-CO2-Capture-Projects-Lessons-Learned.pdf.
[43] Ibid.
[44] A. Reyes-Lúa, Y. Arellano, I. T. Røe, L. Rycroft, T. Wildenborg, and K. Jordal, 'CO_2 ship transport. Benefits for early movers and aspects to consider', 2021.
[45] International Maritime Organization, 'Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter', Marine Environment, 2006. [Online]. Available: https://www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx.
[46] International Maritime Organization, 'Resolution LP.3(4) on the amendment of Article 6 of the London Protocol', 2009. [Online]. Available: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/LCLPDocuments/LP.3(4).pdf.

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provisions of the London Protocol and other applicable international law, to define a stable framework for the transboundary CO_2 transport. This agreement should be expected to cover items such as cost sharing, monitoring of the transport, reporting and liability in addition to the mentioned permitting regimes. This bilateral agreement shall also be notified to the Secretary-General of the IMO.

3.7 The EU-ETS

Each year industrial installations that are included in the EU Emission Trading System (EU ETS) must surrender a number of allowances that are equal to the total amount of fossil CO_2 emissions from that installation during the preceding calendar year. The EU ETS allows subtracting emissions that are captured and thereafter transferred to a transport network with the purpose of long-term geological storage or directly to a storage site.

Provided that the suggested amendment of the ETS directive (2003/87/EC), dated 14 July 2021[47], enters in force, the situation would be the following for ship transport of CO_2[48]:

- The CO_2 capture installation can subtract emission allowances for captured fossil CO_2 when it is delivered from a ship to a pipeline transport network or directly to a storage site (provided that the storage site is permitted under Directive 2009/31/EC). I.e. there is a time delay between when the CO_2 is captured and when the emission allowances can be subtracted.
- The owner/operator of the ship that is transporting the captured CO_2 from the capture installation to the transport network will be responsible for the CO_2 emissions during this transport.
- The CO_2 capture installation will not be able to subtract emissions that occur during ship transport to the pipeline network, i.e. the amount of CO_2 emissions to be subtracted would during normal operations be slightly lower than the amount of CO_2 captured – contractual agreements will be needed between the capture installation and the ship owner/operator to cover this. This, in turn, will call for accurate fiscal metering during on- and offloading. Also, CO_2 emissions from the ship propulsion system could be relevant to include in the contractual discussions/agreements.

Fair financial transactions along the CCS chain and accurate subtraction of emissions under the EU ETS will depend on accurate CO_2 measurements throughout the CCS value chain, including on- and offloading on ships, that enable accurate emission monitoring and reporting. However, this is an

[47] European Commission, 'Proposal for a Directive of the European Parliament and of the Council amending directive 2003/87/EC', Document 52021PC0551, 2021. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0551.
[48] A. Reyes-Lúa, Y. Arellano, I. T. Røe, L. Rycroft, T. Wildenborg, and K. Jordal, 'CO_2 ship transport. Benefits for early movers and aspects to consider', 2021.

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area where large knowledge gaps remain.[49] Transport conditions pose a challenge for fiscal metering technologies, where no capacities to provide traceable fiscal metering exist worldwide.[50] Emissions monitoring and reporting within EU ETS is regulated by the ETS M&R Regulation 2018/2066.[51, 52] Continuous measurement systems (i.e., fiscal metering) with uncertainties below 2.5% are required for reporting of captured CO_2 at the capture site (article 49). There are cases where it is technologically or financially infeasible to meet the 2.5 % requirement and there is ongoing research to solve these issues.[53, 54] It is also unclear if the regulations controlling the type of measurements at the capture site apply for the emission control during shipping, even if the uncertainty requirements are expected to be the same.

In article 10a(8) of the suggested amendment to the EU ETS directive, the scope of the Innovation Fund is extended to allow it to provide support to projects through competitive tendering mechanisms such as carbon contracts for difference (CCDs). CCDs can offer the EU the opportunity to guarantee investors in innovative climate-friendly technologies a fixed price that rewards CO_2 emission reductions above the current price levels in the EU ETS.

[49] A. Reyes-Lúa, Y. Arellano, I. T. Røe, L. Rycroft, T. Wildenborg, and K. Jordal, 'CO_2 ship transport. Benefits for early movers and aspects to consider', 2021.
[50] A. M. Moe et al., 'A Trans-European CO2 Transportation Infrastructure for CCUS: Opportunities & Challenges', Advisory Council of the European ZeroEmission Technology and Innovation Platform (ETIP ZEP), 2020. [Online]. Available: https://zeroemissionsplatform.eu/wp-content/uploads/A-Trans-European-CO2-Transportation-Infrastructure-for-CCUS-Opportunities-Challenges-1.pdf.
[51] European Commission, 'Monitoring, reporting and verification of EU ETS emissions', EU Emissions Trading System. [Online]. Available: https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets/monitoring-reporting-and-verification-eu-ets-emissions_en.
[52] European Commission, 'COMMISSION IMPLEMENTING REGULATION (EU) 2018/2066 of 19 December 2018 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council and amending Commission Regulation (EU) No 601', 2018. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02018R2066-20210101.
[53] A. M. Moe et al., 'A Trans-European CO2 Transportation Infrastructure for CCUS: Opportunities & Challenges', Advisory Council of the European ZeroEmission Technology and Innovation Platform (ETIP ZEP), 2020. [Online]. Available: https://zeroemissionsplatform.eu/wp-content/uploads/A-Trans-European-CO2-Transportation-Infrastructure-for-CCUS-Opportunities-Challenges-1.pdf.
[54] Hollander, Jukes, Løvseth, and Arellano, 'The challenges of designing a custody transfer metering system for CO2', 39 NSFMW, 2021.

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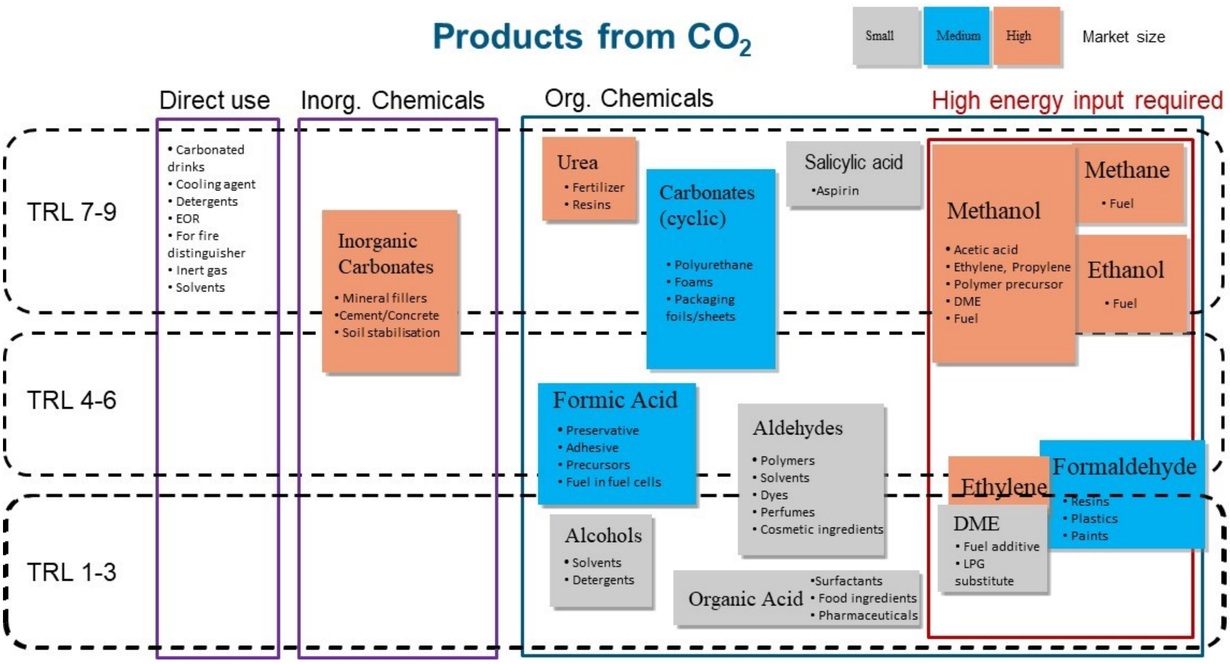
4 Most important CCU projects

4.1 Overview of projects and activities

The use of CO_2 as a raw material for the chemical industry has been discussed and researched for decades by now. Especially within the last ten years, huge advantages in research and development (R&D) were made. However, carbon capture and utilisation (CCU) processes have many facets, which makes it complicated to summarise the potential of the technologies as well as the associated hurdles: There are more than 100 different products that can be produced with CO_2 as educt, furthermore, there are also different motivations why to establish specific CCU processes.

The technical maturity of routes for the CCU lies over the entire range of the so-called TRL-scale (Technology Readiness Level). The scale classifies technologies according to certain criteria into maturity levels from 1 to 9, where 1 is the outline of an idea and where technologies with a maturity level of 9 have been on the market for more than five years. Figure 4 lists various products that can be manufactured with the help of CO_2.

Figure 4: Products from CO2 (Source: DECHEMA)



On the right-hand side within the red frame of the picture are products that can be called platform chemicals or fuels. These products can only be synthesised with the help of CO_2 and a reactant that brings a lot of energy into the reaction, such as hydrogen, to obtain higher-value chemicals like CO_2. The synthesis routes to produce CO_2-based methanol, methane and ethanol are quite mature and the market size of those products is high too. For the CO_2-based production of other organic chemicals such as cyclic carbonates (e.g. polyurethane, foams, packaging) or formic acid (e.g. preservatives, adhesives), the reaction does not involve a very high energy input. In contrast to fuels

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and bulk chemicals, the market size of such chemicals is rather low. Inorganic carbonates are very interesting as a pathway to store CO_2 permanently into materials like cement and thus, in concrete.

As stated above, the motivation to employ CCU processes varies. The reduction of CO_2 emissions of specific processes and products is one reason, another is to lower the dependence of the chemical industry from fossil raw materials.

There are several promising projects in each of the above areas. The following are examples of companies or technologies whose work underpins the technological status of CCU processes to produce fuels, chemicals/polymers or carbonates.

4.1.1 Bulk chemicals/fuels – Example Methanol

Methanol is a much-used, basic chemical. As a basic material in the chemical industry, about 40 % of methanol is processed into formaldehyde and from this further into pharmaceuticals, resins or dyes. There are commercialised processes to produce urea, melamine and phenol formaldehyde resins, acetic acid (Monsanto and Cativa processes) and subsequent polymers via vinyl acetate to Polyvinyl acetate (PVA) (for paints and adhesives) or to cellulose acetates (films, textiles), as well as via the mobile process to aromatics (MTA - Methanol to Aromates) to olefins (MTO, Methanol to Olefins) or to fuel (MTG - Methanol to Gasoline).

The following examples depict the development of using CO_2 to produce methanol:

Carbon Recycling International has built and commissioned the largest power-to-methanol plant to date in Iceland (George Olah plant) and produces 5 million litres (approx. 4000 tonnes) of methanol (brand name Vulcanol®) per year. The annual production corresponds to about 2.5 % of the fuel market in Iceland. Approximately 5500 tonnes of CO_2 are recycled in the process.[55] At the beginning of 2019, CRI started to expand the George Olah plant, among other things, as part of the EU Horizon2020 project Circlenergy.[56] The CO_2 and the energy for hydrogen production come from the Svartsengi geothermal power plant. The renewable energy required for the plant is used from the Icelandic electricity grid, which contains a high proportion of hydro, geothermal and wind power.

Furthermore, CRI has delivered the process design for the world's first CO_2-to-methanol plant with a capacity of 110000 tonnes per year, which recycles industrial waste gases. Ground preparation and foundation work is already underway at the site of project partner Henan Shuncheng Group in Anyang, Henan Province, China. Commissioning and the start of methanol production are expected before the end of this year. The plant, which is financed and owned by the joint venture company Shunli, will recycle over 160000 tonnes of CO_2 per year. The low-carbon methanol produced will be sold to the growing local market for chemicals and fuels. The project can strongly contribute to bringing more CO_2-to-methanol technology to the market.

[55] Mitsui Chemicals Group, ESG Report 2018, https://www.mitsuichem.com/en/sustainability/report/pdf/esg2018web_e.pdf (Page 112)
[56] Grant number 848757, EUR 2.6 million investment, 70% funding

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Since 2018, twenty public and industrial partners in the port area of Ghent in Belgium have joined forces under the name **North-CCU Hub** to reduce CO_2 emissions by focusing on new developments to capture and reuse CO_2. The partners of the North-CCU Hub aim to develop new circular value chains in which CO_2 emitted by industry will be used as a raw material. The initiative combines the expertise of companies with that of knowledge institutions and leading-edge clusters and is supported by numerous public partners. Through cross-border cooperation, the North-CCU-hub aims to become the global reference for CO_2 capture and reuse. In this way, innovative technologies with a high TRL are to be implemented on an industrial scale in the short term. For example, a large-scale "first of its size" demonstration plant is being built, using renewable energy, green hydrogen and CO_2 as feedstocks for the production of green methanol. Under the North-CCU Hub initiative, "**North-C-Methanol**" is to be launched as the first large-scale demonstration project. It consists of a 63 MW electrolyser plant that splits water into green hydrogen and oxygen, using renewable energy from offshore wind. The oxygen will be used locally in the steel industry. Green hydrogen is combined with captured CO_2 coming from industrial point sources in a catalytic methanol synthesis plant with a production capacity of 45000 tonnes of methanol per year. The initiative's goal is to establish an electrolyser with a capacity of 600 MW by 2030. If this ambitious project goes according to plan, it could become a lighthouse project for CO_2 utilisation.

The **Siemens Haru Oni** project, funded by the German Federal Ministry for Economic Affairs and Energy with around EUR 8 million, is intended to demonstrate a broad spectrum of innovative, climate-relevant technologies at a single location. Synthetic fuel is to be produced there from water, wind energy and CO_2 captured from the air. In this way, a so-called e-fuel is to be created as a liquid energy carrier that causes about 90 % less CO_2 emissions than its fossil counterpart. In the pilot phase, e-methanol production will initially reach about 750000 litres per year by 2022. Part of the e-methanol will be converted into e-gasoline (130000 litres per year). E-gasoline, for example, is compatible with the existing liquid fuel infrastructure. In two steps, the capacity will be increased to 55 million litres of e-gasoline per year by 2024 and to more than 550 million litres per year by 2026. The project benefits greatly from the conditions in southern Chile, as the necessary renewable energy is available with the help of the prevailing strong wind. Siemens Energy, together with several international companies, is thus on its way to realising the world's first integrated and commercial large-scale plant for the production of climate-neutral e-fuel. The targeted size of the plant clearly illustrates that the topic of CCU is considered relevant in the industry.

4.1.2 Polymers

An innovative polyol to produce polyurethane is polyether carbonate polyol. Covestro patented a method for the production of polyether carbonate polyols in 2010. In the process developed, part of the oil in polyether carbonate polyol is replaced by CO_2. The novel polymer reaction is intended to support a change in the raw material base and contribute to sustainability. In the process, polyether carbonate is synthesised from CO_2 and epoxides. The use of special catalyst classes leads to the copolymerisation of epoxide and CO_2 to polymers containing both carbonate and ether groups.

Covestro has used its own funds to build a commercial plant in Dormagen, Germany which was commissioned in 2016. The target product is the novel polyol with a CO_2 content of 20% based on product mass. The polyol is a central component for a polyurethane foam (Cardyon™) that is to be used, among other things, to produce foam mattresses. The commercial plant in Dormagen has a production capacity of 5000 tonnes of polyether carbonate polyol per year. The CO_2 used comes from an ammonia plant operated by Ineos at the site. High-purity CO_2 is produced as a by-product during ammonia synthesis.[57]

4.1.3 CO_2-carbonation

The company **Carbon8 Systems** from the UK treats industrial wastes (e.g. contaminated soil, slag from steel making, ash, cement kiln dust) that contain calcium or magnesium with CO_2 to produce carbonates that can be used as lightweight aggregate, fertiliser, ready mix concrete, green roofing, or other building materials. The process Accelerated Carbonation Technology (ACT) offers a fast and, according to Carbon8, cheap way to process wastes and natural minerals. Carbonation takes place during a 15-minute process. In England, Carbon8 has installed two plants. One in Brandon, Suffolk, were Carbon8 produces aggregates with a capacity of 30000 tonnes of APCr (Air Pollution Control residues - hazardous waste from municipal solid waste incineration) per year. Another plant exists in Avonmouth near Bristol. Also a commercial contract was set up with the Vicat Group in 2020. Here, a cement plant in France is equipped with a Carbon8 container. Furthermore, a plant is planned in Duiven near Rotterdam, The Netherlands. At the site, 100 tonnes of a building product will be produced in a pilot project for validation and use, with the possibility of using more CO_2 from the plant in the future. In Duiven, a so-called CO_2ntainer from Carbon8 Systems will use the CO_2 from the flue gases of an energy-from-waste (EfW) plant that would normally be emitted into the atmosphere.[58, 59]

The company Mineral Carbonation International from Canberra, Australia, is currently generating also a lot of attention. The start-up has built a demonstration plant in Newcastle, which is rated at a TRL of 6. The company uses alkaline waste containing calcium or magnesium, which is processed through grinding, theming and a slurry process, with CO_2 captured and used from Orica's ammonia plant. The CO_2 is blown through the industrial waste in a continuous reactor system. This produces products such as silica, carbonates and metal oxides that can be used in the construction industry. The company’s stated goal is to scale the technology to capture and store 1 billion tonnes of CO_2 by 2040 in construction and industrial products for the circular economy.

4.2 Perspective and main hurdles

CCU is accorded a high level of interest in Germany, in Europe as well as in many places around the world. The high frequency of events on the topic, the abundance of scientific publications and the high number of announcements of pilot and demonstration plants strongly support this. In addition to the examples mentioned above, for example, another Sunfire/Nordic Blue Crude "E-Fuel 1" plant is planned for 2021/2022 in Herøya, Norway. The use of CO_2 also continues to be an integral part of

[57] CA2814382A1, „Method for the production of polyether carbonate polyols “, 2010, BAYER INTELLECTUAL PROPERTY GMBH

[58] Carbon8 Systems Website, visited on December the 1st, 2021

[59] Presentation by Dr. Paula Carrie, CCUS Projects Network meeting on 29th of November 2021

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calls for proposals in the national, European and global funding landscape. At the national level, in addition to the BMBF, the BMWi and the UBA, for example, also support activities for the material use of CO_2. The European Commission is also planning calls under Horizon Europe on the topic of CO_2 utilisation. In addition, projects on CCU are being promoted within the framework of the Innovation Fund.

The multitude of different utilisation paths and the different motivations for using CO_2 as a raw material, as well as the complexity of assessing economic and ecological impacts, raise many unanswered questions for the topic area of "CO_2 utilisation". Especially when it comes to assessing the ecological impacts of processes for use of CO_2, there are still no conclusive answers in many cases. One reason for this is that so far there are few processes for CO_2 utilisation that have already been applied on a large scale. Because of the complexity and in some cases low technical maturity, no robust forecasts exist today on the climate mitigation potential of CCU in general. Also the CO_2-circulation aspect makes a prediction of the reduction of CO_2-emissions more sophisticated.

Nevertheless, there are main hurdles that can be named and need to be overcome to establish CCU processes. First, CO_2-based bulk materials and fuels are more expensive than fossil-based fuels as the production of green hydrogen that is needed for a clime-reasonable approach is not yet available or cheap. The consequence is that fossils must become more expensive, renewable energy sources need to be expanded, the production of hydrogen established and a CO_2-infrastructute built. In case of polymers or building materials, more good examples of working processes need to be built to show the rather conservative markets of polymer or cement production that the new products can compete in terms of price and quality.

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5 Conclusion: Looking forward to the role of CCS and CCU in Europe

Based on the analysis in previous sections of this report it is evident that the key elements to enable a successful deployment of CCUS are aligned and that CCUS is on the brink of a new era. These changes are mainly a result of the realisation that the net zero target makes CCUS a necessity rather than an option. Published scenarios indicate that CCS is required for Europe to reach net zero CO_2 emissions by 2050 and remain on a path consistent with the 1.5°C global target. The Communication on Sustainable Carbon Cycles published by the European Commission on December 15, 2021, reinforces this notion, and provides a strong backing for deployment of CCUS in Europe.

The best evidence to support the statement that CCUS is gaining momentum are the numerous projects that are currently being developed across Europe and which have been described in this report – many of which are members of the CCUS Projects Network.

Despite the favourable momentum, hurdles to the deployment persist and include technical barriers, policy and regulation, business models and funding, as well as the need for further public acceptance. Nonetheless, there is sufficient potential for development of CCUS technologies and infrastructure at the scale required to achieve carbon-neutrality by 2050. Europe is already well positioned to benefit from CCUS based on the extensive existing pipeline infrastructure which can be used to transport CO_2, hydrogen and synthetic methane, and other renewable and decarbonised gases. In particular, large source emission clusters are good options to create economies of scale, by establishing shared CO_2 transportation infrastructure with third-party access for efficient use of the infrastructure by multiple users. In addition, Europe has extensive geological CO_2 storage capacity and subsea expertise, with countries such as Norway and the UK willing to enable shared access to their offshore storage facilities for CO_2 from EU industry.

Thus, the unprecedented momentum in 2021 allows for optimism that CCUS may finally be on its way to free itself from its previous, underwhelming track record. As has been recently concluded by the Head of Carbon Capture Utilisation and Storage Unit at the IEA '**If net zero is to remain within reach, CCUS cannot spend another decade sitting on the side lines of climate mitigation efforts'**.[60]

[60] McCulloch S. for Energypost.eu (2021) Will this be the decade of Carbon Capture of another false start? Available at: https://energypost.eu/will-this-be-the-decade-of-carbon-capture-or-another-false-start/

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Glossary

Acronym	**Full Term**
ACT	Accelerated Carbonation Technology
APCr	Air Pollution Control residues
BECCS	Bioenergy with CCS
CCD	Carbon Contracts for Difference
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture Utilisation and/or Storage
CO_2	Carbon Dioxide
DACCS	Direct Air Capture with CCS
DRI	Direct Reduced Iron
EOR	Enhanced Oil Recovery
ETS	(EU) Emissions Trading System
EU	European Union
FEED	Front End Engineering Design
FID	Final Investment Decision
FOV	Fortum Oslo Varme
Gt	Giga Tonne
IMO	International Maritime Organisation
Mt	Mega tonne
Mtpa	Million tonnes per annum
MTA	Methanol to Aromates
MTG	Methanol to Gasoline

MTO	Methanol to Olefines
M&R	Monitoring and Reporting
PCI	Projects of Common Interest
PVA	Polyvinyl acetate
TRL	Technology Readiness Level

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References

A. M. Moe *et al.*, 'A Trans-European CO2 Transportation Infrastructure for CCUS: Opportunities & Challenges', *Advisory Council of the European ZeroEmission Technology and Innovation Platform (ETIP ZEP),* 2020. Available: https://zeroemissionsplatform.eu/wp-content/uploads/A-Trans-European-CO2-Transportation-Infrastructure-for-CCUS-Opportunities-Challenges-1.pdf

A. Reyes-Lúa and K. Jordal, 'Current and emerging industrial-scale CO_2 capture. A brief overview', *TG2 Briefing Report on Industrial CO_2 capture- CCUS Projects Network Thematic Reports*, 2019. Available: https://www.ccusnetwork.eu/sites/default/files/TG2_Briefing-Industrial-CO2-capture.pdf

A. Reyes-Lúa and K. Jordal, 'Industrial CO_2 capture projects: Lessons learned and needs for progressing towards full-scale implementation', *3rd Report of the Thematic Working Group on: CO2 capture and utilisation*, 2020. Available: https://www.ccusnetwork.eu/sites/default/files/TG2_Briefing-Industrial-CO2-Capture-Projects-Lessons-Learned.pdf

A. Reyes-Lúa, Y. Arellano, I. T. Røe, L. Rycroft, T. Wildenborg, and K. Jordal, 'CO_2 ship transport. Benefits for early movers and aspects to consider', 2021.

Bellona Europa, Cannibalising the Energiewende? 27 Shades of Green Hydrogen. 2021. Available: https://network.bellona.org/content/uploads/sites/3/2021/06/Impact-Assessment-of-REDII-Delegated-Act-on-Electrolytic-Hydrogen-CO2-Intensity.pdf

Belmans, R. et al., Electrification and sustainable fuels: Competing for wind and sun.2021. Available: https://cadmus.eui.eu/bitstream/handle/1814/71402/RSC%202021_55.pdf?sequence=1

CA2814382A1, „Method for the production of polyether carbonate polyols ", 2010, BAYER INTELLECTUAL PROPERTY GMBH

Carbon8 Systems Website, visited on December the 1st, 2021. Available: https://c8s.co.uk/

CCUS Projects Network (2021) The role of Carbon Dioxide Removals for Net Zero (forthcoming). Will be available: https://www.ccusnetwork.eu/knowledge-hub/thematic-reports

European Commission (2018) A clean planet for all – A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0773

Equinor ASA, 'Northern Lights Contribution to Benefit Realisation', 2019.

Equinor, 'Northern Lights Project Concept report-DG2 report', RE-PM673-00001, 2018.

European Commission (2018). In-depth analysis in support of the Commission Communication

This project is financed by the European Commission under service contract No ENER/C2/2017-65/SI2.793333.

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

European Commission, 'Boosting Europe's green transition: Commission invests €1.5 billion in innovative clean tech projects', *Innovation Fund*, 2021. Available: https://ec.europa.eu/commission/presscorner/detail/en/ip_21_5473

European Commission, 'Candidate PCI projects in cross-border carbon dioxide (CO2) transport networks', 2021. Available: https://ec.europa.eu/energy/sites/default/files/detailed_information_regarding_the_candidate_projects_in_co2_network.pdf

European Commission, 'COMMISSION IMPLEMENTING REGULATION (EU) 2018/2066 of 19 December 2018 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council and amending Commission Regulation (EU) No 601', 2018. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02018R2066-20210101

European Commission, 'Commission proposes new list of Projects of Common Interest for a more integrated and resilient energy market', 2021. Available: https://ec.europa.eu/commission/presscorner/detail/en/IP_21_6094

European Commission, 'First call for large-scale projects. List of Proposals Pre-Selected for a Grant', *Innovation fund*, 2021. Available: https://ec.europa.eu/clima/system/files/2021-11/policy_funding_innovation-fund_large-scale_successful_projects_en.pdf

European Commission (2021) 'Innovation Fund'. Available: https://ec.europa.eu/clima/eu-action/funding-climate-action/innovation-fund_en

European Commission, 'Large-scale projects', *Innovation Fund*, 2021 Available: https://ec.europa.eu/clima/eu-action/funding-climate-action/innovation-fund/large-scale-projects_en

European Commission, 'Monitoring, reporting and verification of EU ETS emissions', *EU Emissions Trading System*. Available: https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets/monitoring-reporting-and-verification-eu-ets-emissions_en

European Commission, 'Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation o', *EU Emissions Trading System*, 2021. Available: https://ec.europa.eu/info/sites/default/files/revision-eu-ets_with-annex_en_0.pdf#page=130

European Commission, 'Proposal for a Directive of the European Parliament and of the Council amending directive 2003/87/EC', *Document 52021PC0551*, 2021. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0551

European Commission, 'Regulation (EU) 2021/1153 of the European Parliament and of the Council of 7 July 2021 establishing the Connecting Europe Facility and repealing Regulations (EU) No 1316/2013 and (EU) No 283/2014', *Document 32021R1153*, 2021. Available: https://eur-lex.europa.eu/eli/reg/2021/1153/oj

Global CCS Institute, 'Global Status report 2021: Policy Fact Sheet'.2021. Available at: https://www.globalccsinstitute.com/wp-content/uploads/2021/10/GSR2021_Policy-Factsheet_2021_EN.pdf

Global CCS Institute, 'Global Status of CCS 2021', 2021.Available: https://www.globalccsinstitute.com/resources/global-status-report/

Hollander, Jukes, Løvseth, and Arellano, 'The challenges of designing a custody transfer metering system for CO2', *39 NSFMW*, 2021.

International Energy Agency. Energy Technology Perspectives 2020 - Special Report on CCUS. 2020. Available: https://iea.blob.core.windows.net/assets/181b48b4-323f-454d-96fb-0bb1889d96a9/CCUS_in_clean_energy_transitions.pdf

International Energy Agency, Report extract: A new era for CCUS. 2020. Available: https://www.iea.org/reports/ccus-in-clean-energy-transitions/a-new-era-for-ccus

International Maritime Organization, 'Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter', *Marine Environment*, 2006. Available: https://www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx

International Maritime Organization, 'Resolution LP.3(4) on the amendment of Article 6 of the London Protocol', 2009. Available: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/LCLPDocuments/LP.3(4).pdf

IOGP, The potential for CCS and CCU in Europe, 2019. Available: https://ec.europa.eu/info/sites/default/files/iogp_-_report_-_ccs_ccu.pdf

Material Economics, Industrial Transformation 2050" Pathways to Net-Zero Emissions from EU Heavy Industry. 2019.

McCulloch S. for Energypost.eu, Will this be the decade of Carbon Capture of another false start? 2021. Available: https://energypost.eu/will-this-be-the-decade-of-carbon-capture-or-another-false-start/

Microsoft (Accessed on 16/12/2021). Climate Innovation Fund. Available: https://www.microsoft.com/en-us/corporate-responsibility/sustainability/climate-innovation-

This project is financed by the European Commission under service contract No ENER/C2/2017-65/SI2.793333.

fund?activetab=pivot1%3aprimaryr6

Mitsui Chemicals Group, ESG Report 2018, https://www.mitsuichem.com/en/sustainability/report/pdf/esg2018web_e.pdf

Northern Lights Project, 2020.

Presentation by Dr. Paula Carrie, CCUS Projects Network meeting on 29th of November 2021

Regjeringen (Norwegian Government), 'The Government launches "Longship" for carbon capture and storage in Norway', 2020. [Online]. Available: https://www.regjeringen.no/en/aktuelt/the-government-launches-longship-for-carbon-capture-and-storage-in-norway/id2765288/

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.

S&P Global Platts (Accessed on 16/12/2021) EU carbon prices of over EUR5-/mt spur CCS interest. Available at: https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/050621-eu-carbon-prices-of-over-eur50mt-spur-ccs-interest

S&P Global, 'Dutch CCS project scrapped after Tata Steel opts for hydrogen DRI production route', 2021. Available: https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/092121-dutch-ccs-project-scrapped-after-tata-steel-opts-for-hydrogen-dri-production-route

Simson, K. (speech) at the Carbon capture, utilisation and storage forum. Available: https://ec.europa.eu/info/events/carbon-capture-utilisation-and-storage-forum-2021-oct-11_en

Tata Steel, 'Tata Steel opts for hydrogen route at its IJmuiden steelworks', 2021. Available: https://www.tatasteeleurope.com/corporate/news/tata-steel-opts-for-hydrogen-route-at-its-ijmuiden-steelworks.

This project is financed by the European Commission under service contract No ENER/C2/2017-65/SI2.793333.