International Association of Oil & Gas Producers

POLICY ANALYSIS | NOVEMBER 2023

Creating a sustainable business case for CCS value chains – the needed funding and de-risking mechanisms

Contents

Executive Summary

It is widely recognized that Carbon Capture and Storage (CCS) is needed to reach Europe's net-zero objective by 2050. Especially, deep decarbonization of the industrial sector needs CCS to avoid deindustrialization. EU policy making has recognized this and has established the EU CCUS Forum, and the European Commission is working on an Industry Carbon Management Strategy. Furthermore, the proposed Net Zero Industry Act (NZIA) recognizes CCS as a net-zero strategic technology. These initiatives will contribute to establish the legislative framework and the needed business case for the start of a CCS industry in Europe.

IOGP Europe represents the interests of oil & gas producers towards European institutions and has advocated for years for the important role of CCS on the path to net-zero. Core CCS related competencies of our members centre around the development of CO_2 storage sites and the development of associated (upstream) onshore and offshore transportation infrastructure. However, an enabling legal framework and the needed supportive funding and de-risking mechanisms are needed for all entities active along the CCS value chain, for CCS businesses to take investment decisions and scale up a CCS industry, comparable to the development of renewables.

This paper focusses on the discussion of needed funding and de-risking mechanisms, it describes the complex CCS value chains and its costs, describes CO_2 storage project development phases, provides an overview about funding mechanisms, informs about the status of 8 major CO_2 storage projects and related development barriers, and it provides policy recommendations.

Depending on scenarios, about 0.5 to 1 GtCO2/a need to be stored by 2050 for Europe to reach net-zero greenhouse gas emissions. The geology and the organizational capacity of our members exist to develop corresponding storage capacities and related upstream infrastructure. However, a supportive legislative framework and the needed funding and de-risking measures need to be put in place. Achieving the comparably low 50 MtCO2/a storage injection capacity objective proposed in the EU NZIA though will still be challenging: even if all known CO_2 storage projects in the EU are realized and startup on time, they add up to 35 MtCO2 injection capacity only by 2030. This is because CO_2 storage projects have 5-13 years project development durations (from inception to operations start up) and because the industry is waiting for the enabling legal framework and the needed funding and de-risking mechanisms to be put in place.

In this paper, the levelized cost of CCS value chains are calculated for three scenarios and by segment, using a relatively sophisticated simulation tool from the international consultant Rystad Energy. Results show that levelized cost range from 130 to 230 €/tCO2 for the integrated value chain, depending on the scenario. Compared with recent prices for EU emission allowances of 80-100 €/tCO2, this underlines that additional funding mechanisms are needed – at least during the industry build-up phase – to underpin investment decisions by businesses along the value chain.

Key funding and de-risking mechanisms recommended differ depending on the part of the value chain. Effective mechanisms include:

- for emitters considering investing into capture: long-term CO_2 offtake contracts; carbon contracts for difference (CCfDs) de-risking EU allowance price uncertainties; and targeted project funding;
- for investors into onshore transportation infrastructure: long-term capacity bookings from emitters, CO_2 aggregators or storage operators; government guarantees/ownership; regulated tariffs;
- for developers of storage and offshore/upstream infrastructure: long-term store-or-pay contracts with emitters or CO_2 aggregators; targeted funding.

1. Introduction

The European Union institutions and EU Members States recognise CCS as a key technology to reach net zero objectives by 2050 and to effectively decarbonise the industrial sector. CCS is also one of the most cost-effective technologies to reduce emissions from this sector (see also IEA 2020 and 2022 data[1,2]). A new momentum for CCS on the EU policy agenda exists having triggered the establishment of the EU CCS Forum[3] in 2021 and the announcement of a Communication on an Industrial Carbon Management Strategy[4] to be published by the end of 2023. Moreover, as part of its Green Deal Industrial Plan, the Commission's proposal of the Net-Zero Industry Act[5] includes CCS as one of the key net-zero technologies which can benefit from streamlined permitting processes and sets an objective of annual storage injection capacity of 50 MtCO2 by 2030 to be made available through an obligation for oil and gas producers in the EU to contribute to this objective.

IOGP Europe's members unite behind an ambition to develop 0.5 to 1.0 GtCO2/a storage injection capacity by 2050, subject to an enabling framework. The message is clear: the geological structures exist in Europe to store what is needed to be stored to get to net-zero, and IOGP's members have the organizational capacities to develop these storage capacities by 2050. Therefore, the storage injection capacities can be developed if a supportive legislative framework is put in place. **Figure 1-1** below illustrates IOGP Europe's members storage injection capacity ambition.

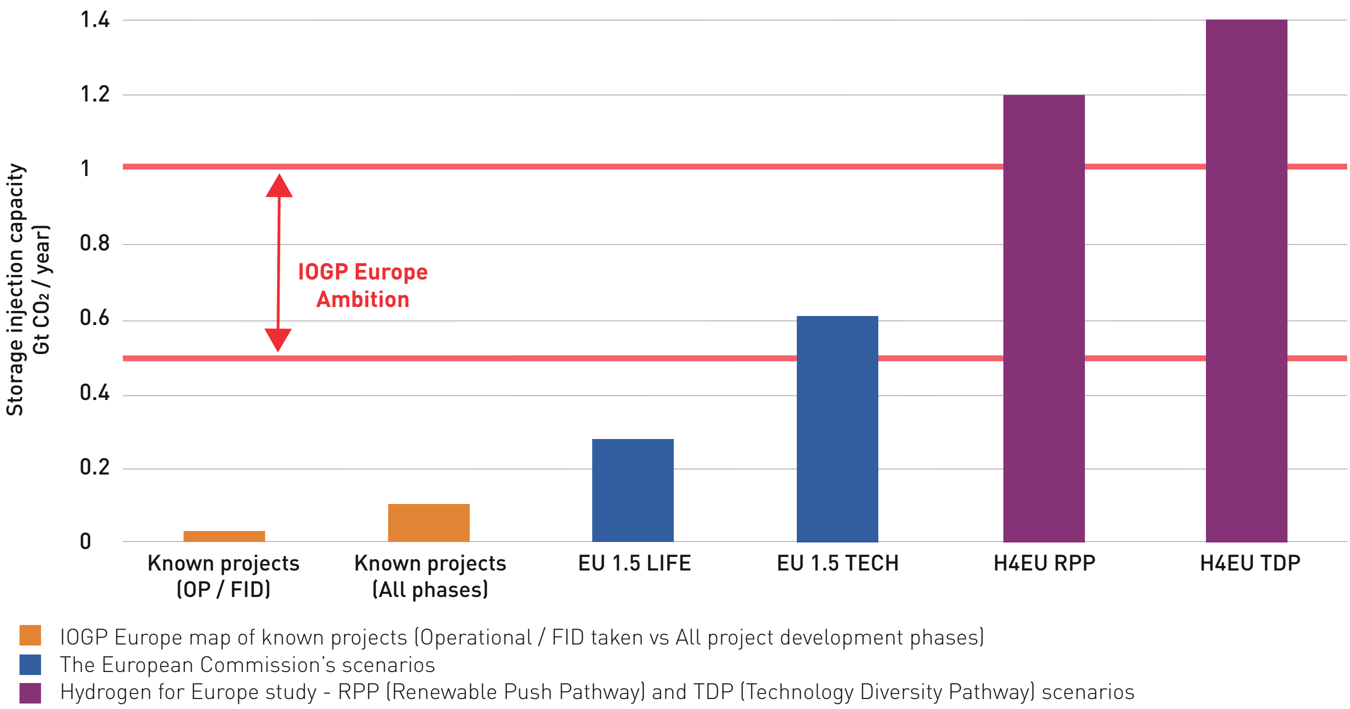


Figure 1-1: IOGP Europe CO_2 storage injection capacity ambition compared with different scenarios for CO_2 storage capacity [6,7]

Reaching the EU's annual 50 Mt CO_2 storage objective by 2030 will be a challenge given the current development status of the announced projects and the lack of an enabling framework and commercial viability: 17 CO_2 storage projects in only 8 countries in the EU have been announced so far and for none of them a final investment decision (FID) has been taken. Out of the 17 known CO_2 storage projects in EU, only 12 projects have announced a start-up date yet. If all these (12) projects are realized, and start-up on time, the total storage injection capacity would reach 35 Mt CO_2 p.a. by 2030 (see **Figure 1-2** below).

1 IEA - Energy Technology Perspectives (2020) https://iea.blob.core.windows.net/assets/181b48b4-323f-454d-96fb-0bb1889d96a9/CCUS_in_clean_energy_transitions.pdf
2 IEA - Global Hydrogen Review (2022) https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf
3 DG ENER, CCUS Forum https://energy.ec.europa.eu/topics/oil-gas-and-coal/carbon-capture-storage-and-utilisation/ccus-forum_en
4 DG ENER, June 2023, Call for evidence and public consultation on industrial carbon management https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13848-Industrial-carbon-management-carbon-capture-utilisation-and-storage-deployment_en
5 European Commission, March 2023, Proposal for a regulation of the European Parliament and of the Council on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act) https://single-market-economy.ec.europa.eu/publications/net-zero-industry-act_en
6 EU Commision – A Clean Planet for all (2018) https://climate.ec.europa.eu/system/files/2018-11/com_2018_733_analysis_in_support_en.pdf
7 Hydrogen for Europe study Home | Hydrogen4EU

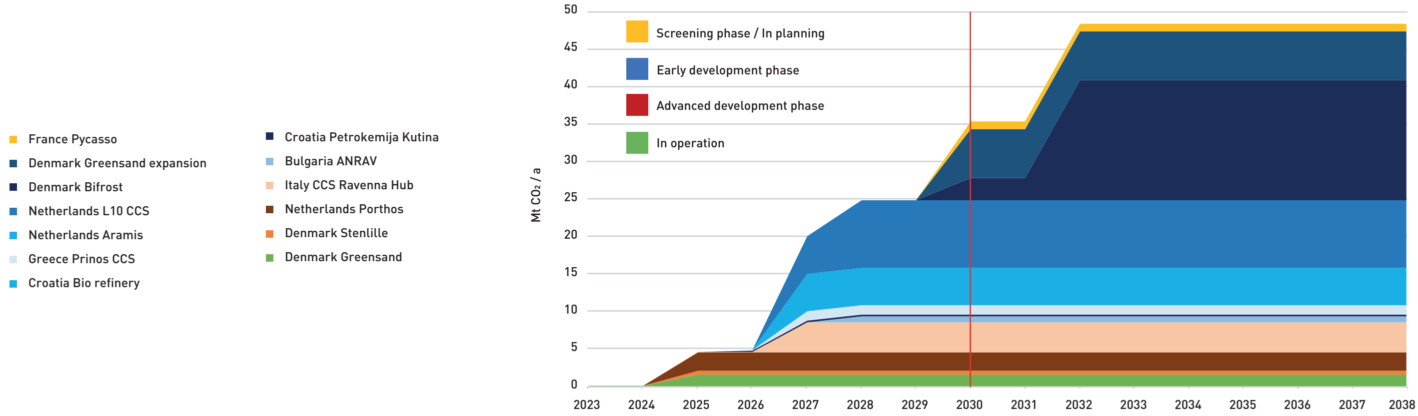


Figure 1-2: Build-up of CO_2 storage injection capacity in EU if all known projects start-up on time

If the scope of the assessment of all known CO_2 storage projects is expanded to all of Europe, then the total storage injection capacity could reach 110 Mt CO_2 p.a. by 2030 if all projects start-up on time. However, again, almost for none of these projects the final investment decision has been taken.

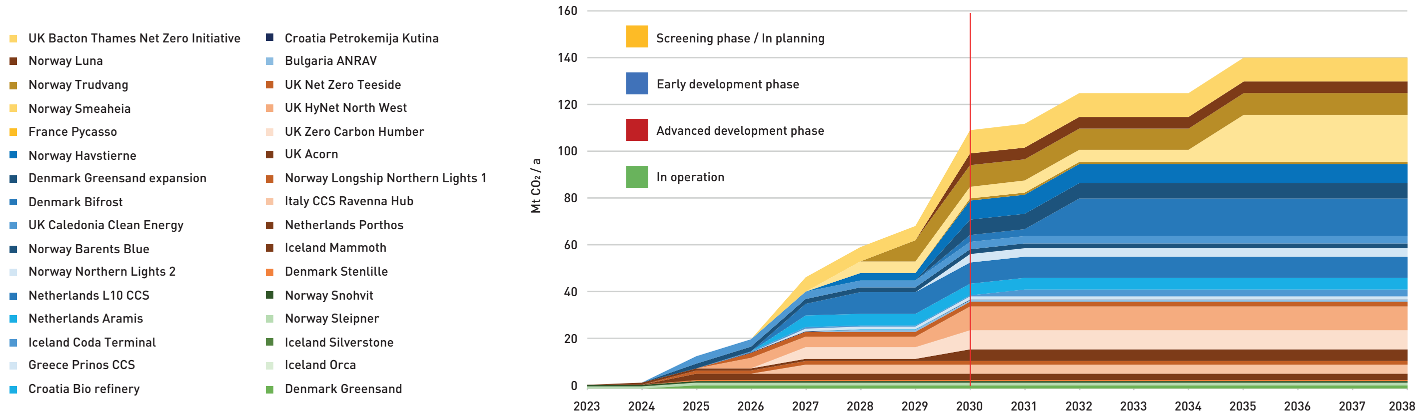


Figure 1-3: Build-up of CO_2 storage injection capacity in Europe if all known projects start-up on time

The underlying reasons for the lack of CCS project developments - next to a needed enabling legal framework - stem from the lack of a business case: prices for EU emission allowances (EUAs) were so far insufficient to incentivize investments by private entities into the capture, transport, and storage of CO_2. This paper describes considerations for the commercial development of CCS value chains and provides recommendations to policymakers on solutions to support business entities in taking investment decisions along the CCS value chain.

The paper's scope includes activities of entities along the full CCS value chain. The geographical scope is limited to Europe at large: EU, Norway, Iceland & UK. The paper is based on literature review, on data provided by Rystad Energy, a consultant, and direct input from IOGP Europe's members.

In chapter 2, value chains of CCS projects are described and for CO_2 storage projects the detailed project development phases are discussed. Furthermore, aggregated levelized cost for CCS value chain scenarios are assessed based on Rystad data. In chapter 3, an overview is provided about different funding mechanisms existing around the world and two effectively implemented mechanisms are described. In chapter 4, eight case studies of CCS projects in Europe are shown with descriptions of project status, enabling success factors, and remaining project barriers. Chapter 5 lists missing aspects for the successful establishment of CCS value chains. Finally, chapter 6 provides policy recommendations developed by IOGP Europe and its members and lists conclusions of the paper.

2. The commercial structure of CCS value chains

2.1 Description of activities of entities along CCS value chains and associated business risks

CCS value chains are long, complex, and involve investments and operations by multiple business entities, comparable for example with value chains in the natural gas business. The below **Figure 2-1** indicatively shows a CCS value chain.

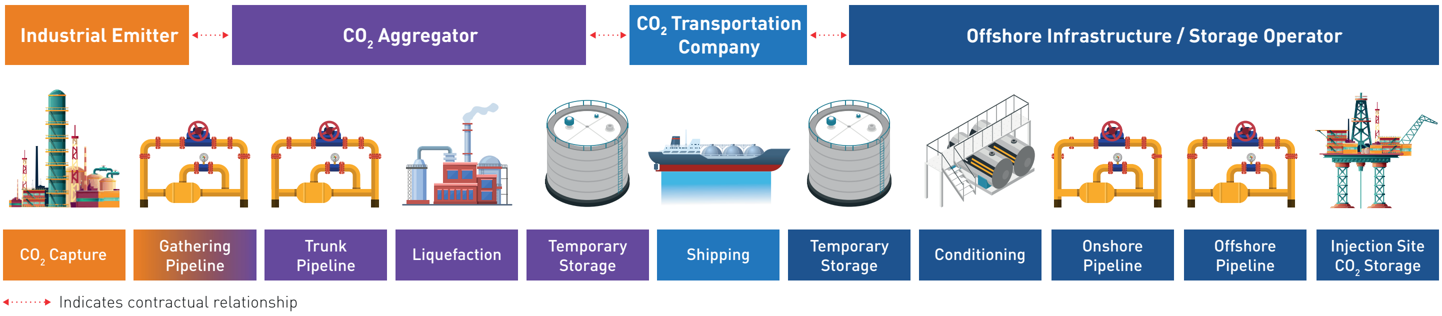


Figure 2-1: Indicative CCS value chain

In the following, the various business activities and some associated business risks along CCS value chains are described:

Operators capturing CO_2

The first step in the CCS value chain involves the capturing and conditioning (pressurizing, cooling, etc.) of CO_2 emissions from operations that ideally have relatively high volumes and high concentrations of CO_2 emissions, such as cement plants, steel mills, power plants, refineries or chemical industries. Emitters use carbon capture technologies to separate CO_2 from the rest of their emissions.

Entities who consider investing into carbon capture will assess related cost (CAPEX and OPEX) versus the avoided cost for CO_2 emission allowances over a certain project lifetime. The absolute level and the future development of the value of the emission allowances is therefore a decisive component of the economic attractiveness of a capture project. The entity that considers capturing its emissions, needs to consider not only the investment into the capture facilities but also the cost related to the needed long-term contracts with transportation companies (who 'pick up' the CO_2 and transport it to the storage site) and with storage operators (for the permanent underground storage). This creates long-term payment obligations for the emitters.

Further down in the paper we discuss how Carbon Contracts for Differences (CCfDs) can be an effective mechanism to "de-risk" the investment decision of a business entity that plans to capture its emissions. CCfDs can be entered into by emitters with a body which assumes the CO_2 allowance value risk. Such a body can be Member State or EU funded. In addition, grants and loan guarantees can de-risk project economics and correspondingly reduce financing cost. Reducing uncertainty about future revenue streams for investors reduces financing cost and therefore further improves project economics, facilitating investment decisions. A description of funding and support mechanisms is provided in chapter 3.

Entities transporting CO_2

Once the CO_2 is captured and conditioned, it needs to be transported to a suitable storage site. Transportation companies operate pipelines, ships, compressors, and pumps that are specifically designed to transport CO_2. Other modes of transport include rail and barges.

Transportation companies who invest into new or repurposed infrastructure typically require some forms of long-term (ship-or-pay) capacity bookings at tariffs which provide a reasonable return on their investment. Depending on whether the transportation pipeline is a gathering pipeline, a major trunk (backbone) pipeline, or an offshore pipeline closely associated with the storage facility, such tariffs can be based on regulated or non-regulated (i.e. negotiated) terms. Tariffs for transport of goods by train or barge typically are not subject to regulation. When considering investments into CO_2 pipelines, appropriately sized pipeline capacity typically is larger than aggregated initial firm capacity booking commitments from emitters (or companies who aggregate CO_2 emissions from multiple entities, so called CO_2

aggregators). This creates the 'missing early money' risk for investors into transportation infrastructure. This risk can be addressed by public-private partnerships or by loan guarantees provided e.g. by public bodies. In this context it should be pointed out, that the development of hydrogen transportation infrastructure faces a similar challenge, and that CO_2 infrastructure can possibly learn from solutions developed for the build-up of a hydrogen market in Europe.

Storage operators

The final step in the CCS value chain is the storing of the captured CO_2 in underground geological formations, such as depleted oil & gas reservoirs or saline aquifers. Storage operators are responsible for ensuring that the CO_2 is stored safely and permanently (in the EU in accordance with the rules established by the CO_2 Storage Directive[8]).

Investors into CO_2 storage sites typically will also require long-term (10 to 15 years) CO_2 storage injection capacity bookings from emitters (or CO_2 aggregators) before taking final investment decisions. Investors into storage capacity will have different levels of economic risk appetite with regard to required firm capacity bookings but, for all of them, a minimum level of return on investment will need to be assured based on firm capacity bookings at the time of the FID. Where aggregated firm commitments from emitters are insufficient to underpin CO_2 storage investment decisions, CO_2 aggregators with public backing can play a role in establishing this part of the CO_2 value chain.

The successful establishment of CCS value chains and final investment decisions will depend on the ability of business entities to conclude long-term contracts which balance risks and rewards along the full CCS value chain, underpinning and de-risking the financing for the needed investments.

2.2 Zoom-in on CO_2 storage development projects and framework requirements

The development of projects for underground geological storage of CO_2 is complex and comparable to the development of oil and gas production projects. **Figure 2-2** below explains the development phases of CO_2 (greenfield) storage projects from project inception to the startup of operations, and it shows durations for each phase. The graph distinguishes activities by competent authorities, storage project developers, and site level activities by service providers/contractors. The graph also lists some key legislative and regulatory issues associated with such projects.

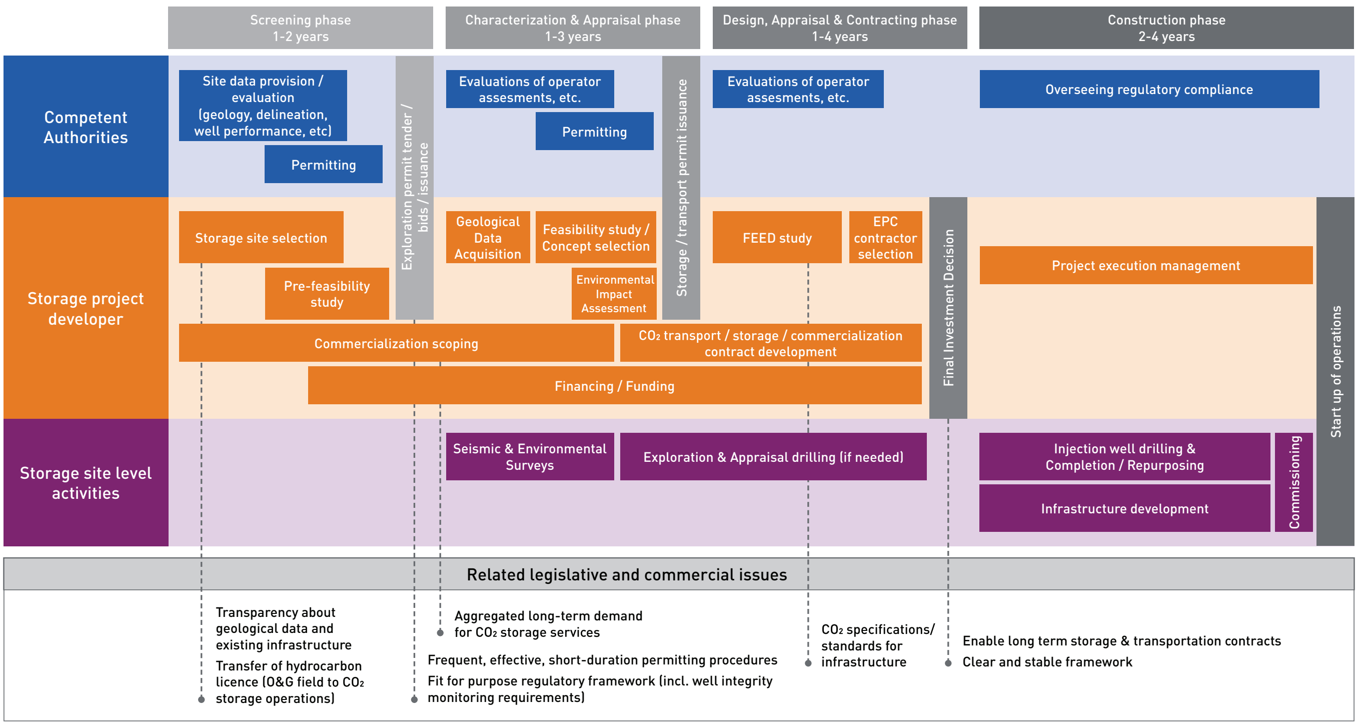


Figure 2-2: CO_2 storage project development phases and related legislative and commercial issues

8 Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide here.

Project duration

The development of a CO_2 storage project can take as little as 5 years or – as some recent project experiences suggest – up to 13 years. Crucial factors that impact the project development duration are the proximity of the storage site to emitters (reducing needed infrastructure to transport the CO_2), whether infrastructure and permits exist or can be re-purposed, whether existing (depleted) oil or gas fields and related permits can be used / converted, and whether they are located offshore or onshore. In the following, we describe the key CO_2 storage project development phases:

- Screening phase
- Characterization & appraisal phase
- Design, appraisal & contracting phase
- Construction phase

Screening phase

In the screening phase, project developers conduct pre-feasibility studies and do early commercialization assessments, possibly including an initial screening of available financing and funding means. In the case of a positive outcome of the feasibility study, project developers will seek from the competent authority a permit (or the conversion of an existing permits) to explore a specific area (block) in search for suitable geological formations that could be considered for CO_2 storage. Such permits are issued by the competent authorities based on tender procedures. The screening phase typically takes 1 – 2 years.

Screening phase related regulatory & legislative solutions: Activities in the screening phase can be facilitated/ accelerated if data about geological formations suitable for CO_2 storage, delineations, well performance, and existing infrastructure is transparently made available by competent authorities; existing hydrocarbon licenses can be transferred from oil & gas operations to CO_2 storage operations; permitting procedures take place frequently, are efficient, and take a short and limited period of time.

Characterization & appraisal phase

During this phase, project developers seek to obtain sufficient data about geological formations to properly assess the possibility to store CO_2. Obtaining such data generally includes 2D & 3D seismic surveys (often done by service providers), data acquisition from 3rd parties, and/or the drilling of exploration and appraisal wells. Such data is key input for a feasibility study leading to the selection or not of a development concept. Complementing this work, project developers conduct environmental impact assessments based on environmental surveys (also often done by service providers). Based on these works and the results of the commercialization scoping and financing / funding concepts, a project developer can decide whether to progress a project further and to apply for the needed storage, transportation, etc. permits. The characterization & appraisal phase typically takes 1 – 3 years.

Characterization & appraisal phase related regulatory & legislative solutions: A fit-for-purpose regulatory framework with non-ambiguous terms and clearly stipulated rights and obligations for competent authorities and permit applicants is a prerequisite for a successful project development. The commercialization is supported if an important level of certainty about demand for CO_2 storage services exists (while storage project developers will compete against each other for offering storage services).

Design, appraisal & contracting phase

In this phase, project developers conduct Front-End Engineering Design (FEED) studies and subsequently tender for and select Engineering, Procurement & Construction (EPC) contractors who will procure or construct the needed installations (including the drilling of wells, construction of above ground facilities and needed infrastructure to connect the storage facility to the market). Before a final investment decision is taken by a project developer, the below key activities typically need to have taken place:

- FEED study concluded and the EPC contractor selected,
- CO_2 storage services contracts concluded with CO_2 emitters or aggregators,
- CO_2 infrastructure contracts concluded (e.g. for transport or shipping services), and
- Financing and funding secured.

With the final investment decision (FID), project developers typically enter into significant financial and contractual commitments. Stopping the project after FID has been taken generally would imply significant capital losses and contractual issues. The Design, Appraisal & Contracting Phase can take 1 to 4 years.

Design, appraisal & contracting phase related regulatory & legislative solutions: The ability to conclude long-term contracts for the use of the storage services and related infrastructure, and a clear and stable legislative framework are pivotal elements for an investment decision. For the FEED study, the existence of appropriate CO_2 standards facilitates the facility design.

Construction phase

During this phase the EPC contractor manages the drilling, the construction and procurement of the designed facilities (wells, platforms, pipelines, processing plants, etc.), or the repurposing of existing infrastructure up to completion and operations start-up. The competent authority has amongst others a role to ensure compliance of the building works and the final facility with the permitting requirements. The Construction Phase typically takes 1 to 4 years.

2.3 CCS value chain costs in the EU

The analytical approach

This chapter analyses levelized costs of CCS value chains by segment and for the full value chain. It compares these costs with the price for EUAs to identify possible needs for additional funding and de-risking mechanisms.

As basis for the analysis, the interactive DynamiX CCUS Levelized Cost tool from the international consultant, Rystad Energy has been used. The tool allows to distinguish the below cost segments:

- Capture (for different industrial emitters, capture capacities, etc.)
- Onshore and offshore pipeline transport (for different transport capacities, distances, etc.)
- Shipping (for different ship sizes, shipping distances, etc.)
- Storage (for different storage types, water depths, storage depths, etc.)

The costs are 'levelized' by taking into account CAPEX and OPEX over the lifetime of a project and assuming a certain return on investment, plus various other needed assumptions by the tool. The analysis will show the segments contributing most to the aggregated cost of the value chain and key parameters influencing the cost, including a sensitivity analysis.

The interactive levelized cost tool from Rystad Energy requires that various general, as well as value chain specific input parameters are set. All input parameters are either proposed by Rystad or based on assumptions made by IOGP Europe and are transparently shown in this paper.

General assumptions are that final investment decisions for projects are taken in 2027 with corresponding technology status, operations start up in 2030, industrial power prices in Europe of $80/MWh (73€/MWh), a discount rate for future cash flows of 10% and an exchange rate of 1.1 $/€. Multiple other parameters set by value chain segment include: capture efficiencies, project life-times, capture technologies used, CAPEX overruns, prices for steel and fuel, pipeline and ship capacities, interim storage requirements, emission source / density, permitting costs, well reuse (%), contingencies, injection well capacities, etc. Individual project cost will vary depending on individual cost parameters. All assumptions made are listed in Annex 1. In the following sections levelized cost are discussed:

- for the capture segment, costs for different industry sectors are compared,
- for integrated CCS value chains, costs for three scenarios are shown, and
- cost sensitivities are discussed depending on power prices, discount rate, capture capacity, capture efficiency, capture technology status, capex overrun, and project lifetime.

CO_2 capture costs in EU by industry sector

Based on the assumptions presented in Annex 1, the Rystad Energy's DynamiX CCUS Levelized Cost tool was used to calculate the levelized cost to capture CO_2 for different industrial sectors in the EU. **Figure 2-3** below shows the results of the calculation. The vertical axis of the diagram represents the levelized cost of CO_2 capture (€/tCO2) whereas the horizontal axis the CO_2 capture potential (Mt CO_2/a) for every industrial sector. The aggregate CO_2 capture potential for all industrial point sources (excluding coal fired power plants) in the EU is around 900 Mt CO_2/a (based on Rystad's CCUS Screening Dashboard, 2023 data).

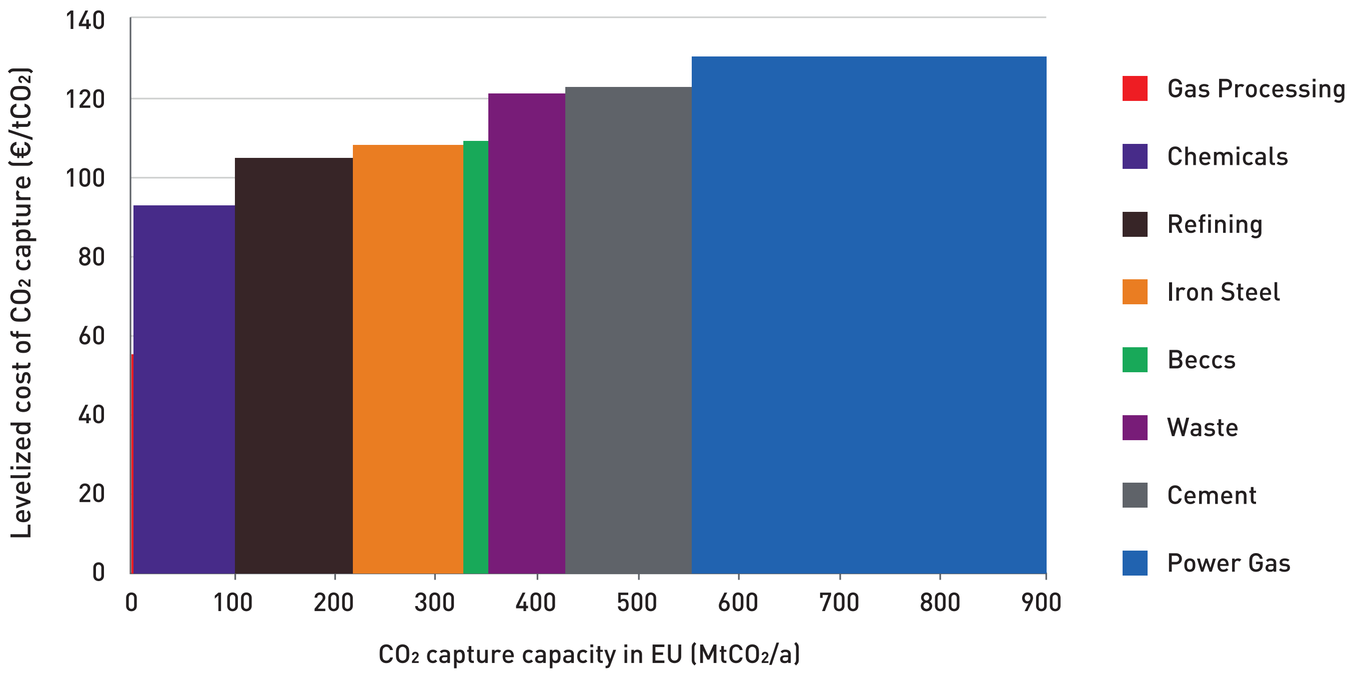


Figure 2-3: CO_2 capture costs in EU by industry sector

This analysis shows that the Gas Processing sector (pre-combustion capture technique) has the lowest capture cost but with a limited capture potential (around 2 Mt CO_2/a). The cost to capture CO_2 from the vast majority of industries in the EU amounts to around 90 to 130 €/tCO2 depending on the sector. These costs do not yet include the transport and storage.

CO_2 capture costs are largely determined by the CO_2 concentration in the exhaust gases. High CO_2 concentrations in the exhaust gases result in low CO_2 capture costs as less power is required to capture the same amount of CO_2. Because significant amounts of power are needed to capture the CO_2, the levelized cost much depend on the cost of power. At the assumed power price of 72 €/MWh, the Rystad model shows that OPEX (predominately the cost of power) make up for 62% to 78% of the levelized cost to capture the CO_2, depending on the industry sector. For reference purposes, ranges of CO_2 concentrations in the exhaust gases for industrial sectors and those values used in this analysis are shown in Annex 2.

CCS value chain cost build up for three scenarios

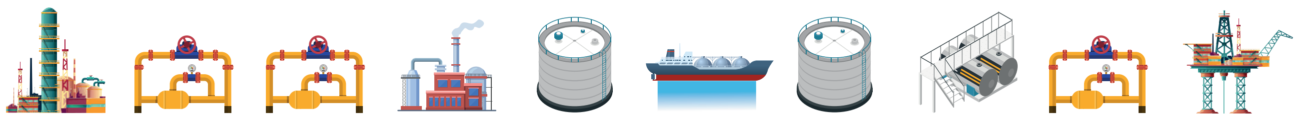
In this section, levelized aggregated cost of CCS value chains for three scenarios are calculated with cost assumptions chosen to lead to a minimum, medium and maximum cost case.

Minimum Cost Scenario: Inland industrial emitter (steel mill) to near onshore storage: It is assumed that 1 Mt CO_2 is captured annually from a steel mill, located inland, and transported through an onshore pipeline for 50 km to a nearby onshore storage, where the CO_2 stream is injected and stored in a depleted gas field in 3000m depth. The storage rate is assumed to be 2.5 Mt CO_2 p.a. with an injection rate per well of 0.35 Mt CO_2 annually.

Medium Cost Scenario: Big coastal industrial cluster to near offshore storage: a coastal, refinery-centered industrial cluster is assumed where 5 Mt of CO_2 are captured annually and transported through an onshore pipeline for 50 km to the shore. The CO_2 is then transported through an offshore pipeline for 200 km to offshore installations (in 300 m water depth) where the CO_2 stream is injected and stored in a 3000m deep depleted gas field. The storage rate is assumed to be 2.5 Mt CO_2 p.a. with an injection rate per well of 0.35 Mt CO_2 p.a.

Maximum Cost Scenario: Industrial inland emitter (cement plant) to far offshore storage: 1 Mt CO_2 is captured annually from a cement plant located inland, far away from the shore. The CO_2 is transported through a gathering pipeline for 50 km where it is transferred into a 10 Mt CO_2 p.a. capacity trunk pipeline which collects CO_2 streams from various emitters. The trunk pipeline transports the CO_2 for 200 km to a CO_2 export hub, where it is liquefied, stored temporarily, and then shipped for 1000 km in ships with a capacity of 10.000 to offshore facilities to be stored in a saline aquifer situated at a depth of 3.000 m. The storage rate is assumed to be 2.5 Mt CO_2 p.a. with an injection rate per well of 0.35 Mt CO_2 p.a.

The three CCS value chain scenarios are summarized in **Figure 2.4** below :



	CO_2 Capture	Gathering Pipeline	Trunk Pipeline	Liquefaction	Temporary Storage	Shipping	Temporary Storage	Conditioning	Offshore Pipeline	Injection Site CO_2 Storage
Minimum cost scenario	Iron Industry	50 km								Onshore Depleted Oil and Gas Field
Medium cost scenario	Industrial Cluster (5 Mtpa)		5 Mtpa / 50 km						200 km	Offshore Depleted Oil and Gas Field
Maximum cost scenario	Cement Industry (1 Mtpa)	50 km	10 Mtpa / 200 km			1000 km			100 km	Offshore Saline Aquifer

Figure 2-4: CCS value chain - three scenarios

The resulting levelized cost of full CCS value chains for the three scenarios are illustrated in **Figure 2-5** below. Aggregated levelized cost of the three CCS value chain scenarios vary from about 130 to 230 €/tCO2. Depending on the scenario, 53% to 80% of the aggregated cost can be attributed to the cost of capturing the CO_2 whereas only 10 - 23% to the cost of transport and 10 - 25% to the cost of storage.

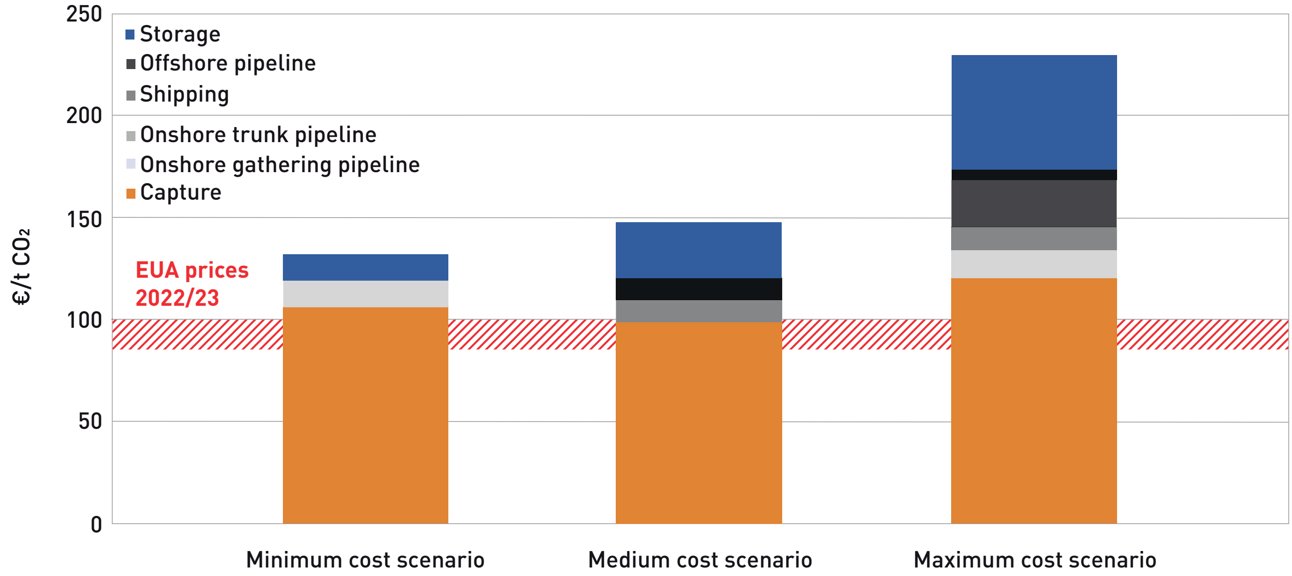


Figure 2-5: Levelized aggregated cost of CCS value chains for three scenarios

When comparing the total levelized cost of 130 to 230 €/t CO_2 with the price for CO_2 emission allowances in the EU of recently between 80 and 100 €/t CO_2, it becomes clear that CCS value chains are not yet economic. There is therefore currently a lack of a business case for CCS. Investors will have different views about the development of prices for CO_2 allowances in the future, however, they will have a limited appetite to assume the risks associated with future allowance price developments. E.g. a steel mill is used to manage the risk of steel prices but is unlikely to be willing (or able) to manage the risk of future allowance price volatility as these are just not part of their business. Therefore, financial support, de-risking mechanisms and a fit-for-purpose framework are needed.

Sensitivity Analysis

As CO_2 capture is the segment of the CCS value chain with the highest cost-share, this section analyses in more detail the cost of capturing CO_2 for each industry segment, and in particular, how these costs depend on some key cost parameters.

Using Rystad Energy's DynamiX CCS Levelized Cost tool, levelized cost sensitivities have been calculated by varying the below parameters:

- Size of the emission capture facility (i.e. MtCO2 captured p.a.)
- Capture efficiency (i.e. share of CO_2 captured from exhaust stream)
- Cost of power
- Discount rate (%) for future cash-flows
- CAPEX overrun (in % of total CAPEX for capture facility)
- Lifetime of capture facility (years)

The results of this analysis are shown in detail in Appendix 3. The below **Figure 2-6** summarizes the results of the sensitivity analysis taking the cement sector as example.

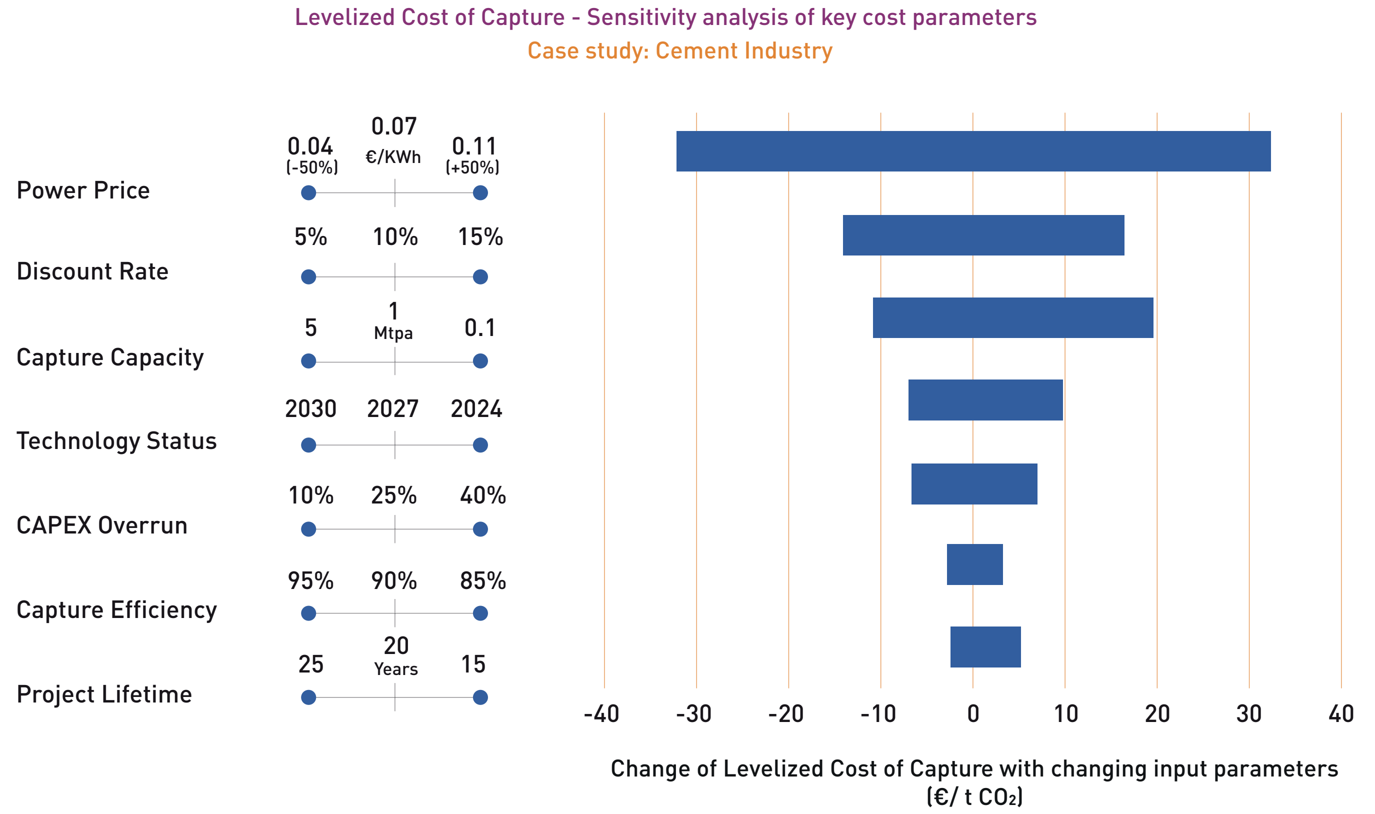


Figure 2-6: Sensitivity analysis of key parameters affecting levelized cost of capture

The results of the sensitivity analysis are described below in further detail:

- The power price has a strong impact on the LCOC: low CO_2 concentrations in exhaust gases require significant energy to capture the CO_2 and thus result in relatively high OPEX. An increase or decrease of the power price by 50% (0.04 €/KWh) increases or decreases the LCOC by 33 €/t CO_2 respectively.
- The discount rate has a moderate impact on the LCOC. An increase of the discount rate by 50% will increase the LCOC by 17 €/t CO_2 whereas a decrease of the discount rate by 50% will decrease the LCOC by 15 €/t CO_2.
- Changes of the size of a capture facility (capture capacity) have a moderate impact on the LCOC. Capturing less CO_2 is more expensive per tonne CO_2 than capturing more CO_2. Decreasing the capture capacity of a facility from 1 Mtpa to 0.1 Mtpa will increase the LCOC by 20 €/t CO_2 whereas by increasing the capture capacity of a facility to 5 Mtpa will decrease the LCOC by 11.5 €/t CO_2.
- The expectation is that CO_2 capture cost will reduce over time. However, assumptions about technology advancements have a moderate impact on the LCOC. The Rystad tool assumes that if project FIDs are taken later in time (3 years later) the LCOC will decrease by 7.5 €/t CO_2.
- CAPEX overruns have a moderate impact on the LCOC. An increase or decrease of CAPEX overruns by 60% increases or decreases the LCOC by 7.15 €/t CO_2.
- Capture efficiencies are high already (above 90%). Further increases in the capture efficiency (i.e. the percentage of the CO_2 in the exhaust stream which is captured) have a relatively low impact on the LCOC. Increasing the capture efficiency to 95% decreases the LCOC by 3.14 €/t CO_2.

3. Existing CCS project funding and support mechanisms

3.1 Overview of existing mechanisms

In order to promote investment in CCS technologies and mitigate associated risks, various policy mechanisms can be put in place. Some of the most used options are funding support by which the government incentives investments by providing revenue support (eg. CAPEX and OPEX support) and/or by charging a price of carbon to emitters (e.g. carbon tax, emission trading schemes). A summary of some of the main CCS incentive policies and funding mechanisms is provided in the table below[9]. It shows also how the mechanisms are used to support CCS projects both, at Member State and EU level.

Funding mechanism	Description	Considerations	Application examples
Grants	CAPEX and/or OPEX funding of projects. Funds are typically granted based on bidding or tender schemes. Such schemes aim at ensuring competitive and transparent processes for the selection of projects and the allocation of funds.	Grants can specifically target the risks of first movers (e.g. first of a kind cost, pre-investment for future expansion). In many cases, one grant scheme is insufficient to ensure a business case for the investment, so projects may need to rely on multiple funding mechanisms thus increasing project complexity and uncertainty.	In the EU, various grant programmes exist to fund CCS projects at different levels of development. Some provide funds for investors along the full CCS value chain others only for parts of it. A key example of EU grant support is the Innovation Fund financed from the auctioning of EU Emissions Trading System allowances, focusing on large scale CCS projects. Member States have also the possibility to provide grants support through Recovery and Resilience Facility (RRF) but also to offer financial support through State Aid.
Tax credits	Tax credits create incentives to invest in CCS, by reducing tax obligations. The extent and nature of tax credits differ based on the jurisdiction and the specific program. Tax credits may be awarded for various aspects such as the procurement or building of CCS infrastructure, or the actual process of CO_2 capture, transport and storage. The determination of tax credits may be contingent on the volume of CO_2 that is sequestered, or other criteria established by the specific program.	Tax credits provide simplicity and predictability for investors, translating into significant cost reductions. They have a direct and easy to calculate impact on future project cash flows.	There are no EU level tax credit schemes as tax policies are a matter of member state competence. Outside the EU, in the US, the '45Q tax credit' available under the Inflation Reduction Act (IRA) provides tax discounts between \$50 and \$80 /tCO2 captured and stored. The credit is available for the first 12 years of operation of a CCS facility and can be claimed by both power plants and industrial facilities.

9 Many studies are available which list the risks, pros and cons of various models: e.g .Zero Emission Resource Organisation (ZERO), 2016 https://www.zero.no/wp-content/uploads/2016/06/policy-instruments-for-large-scale-ccs.compressed.pdf; ElementEnergy, 2018 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/759286/BEIS_CCS_business_models.pdf; Oil & Gas Climate Initiative (OGCI), 2023 https://ccushub.ogci.com/ International Energy Agency (IEA), 2020 https://iea.blob.core.windows.net/assets/181b48b4-323f-454d-96fb 0bb1889d96a9/CCUS_in_clean_energy_transitions.pdf

Funding mechanism	Description	Considerations	Application examples
Carbon pricing (cap and trade and carbon taxes)	Carbon pricing models are market-based mechanisms that put a price on CO_2 emissions. They can take different forms, including carbon taxes and cap-and-trade systems such as the EU ETS. Carbon taxes are a form of carbon pricing that imposes a tax on each unit of greenhouse gas emissions released into the atmosphere.	Cap and trade systems such as the EU ETS are exposed to important emission allowance price volatility resulting from changing demand and supply of such allowances. This volatility creates uncertainty for investors as they cannot firmly take into account benefits from avoided cost for emission allowances. Carbon taxes are less complex to implement and administer, requiring fewer regulations and market structures than cap-and-trade mechanisms. However, in the EU, they would need to be implemented at member state level. Implementation would need to be reasonably consistent to avoid tax evasion effects.	In the EU carbon pricing exists under the EU ETS. Companies emitting CO_2 are required to hold allowances for each ton of CO_2 emitted. The allowances can be bought and sold on the carbon market, allowing companies to either reduce their emissions or purchase allowances to cover their emissions. Companies that successfully reduce their emissions can sell their allowances to other companies that have not yet met their reduction targets.
Contracts for Difference	Entities who enter into (carbon) contracts for difference (CfDs) are paid the difference between a contractually agreed 'CO_2 strike price', and a 'reference price' (e.g., the CO_2 market price). This mechanism provides certainty for the investor regarding the avoided cost for CO_2 emission allowances, or in other words, it derisks the CO_2 market price volatility for investors.	CFDs work well when integrated in jurisdictions with an existing CO_2 emission trading scheme such as the EU ETS. As the ETS price increases in line with expectations, the 'cost' of guaranteeing CfDs by Member States falls to zero and may be expected to progressively generate an income stream for Member States.	Currently used in the Netherlands (SDE++). See section in chapter 4.
Regulated Asset Base (RAB) model	Includes the Regulated Asset Base model, in which a regulated return is provided to investors. A regulator sets the rate of return based on the reasonable cost incurred for the project's construction and operation. Tariffs are then set at a level ensuring revenues which result in the set rate of return.	Typically considered for transportation and storage part of the value chain, where non- discretionary access to infrastructure can play an important role. A low risk / low return model typically adopted by utility companies. Regulator will need to ensure that new infrastructure is required and costs are minimized. The model can help to ensure that CCS infrastructure is built in a timely and cost-effective manner by incentivizing investors to achieve construction and operational cost efficiencies.	Currently being evaluated as a model to support CO_2 transportation and storage in the UK.

Funding mechanism	Description	Considerations	Application examples
Loan Guarantees	Loan guarantees support bank lending to project developers and investors thereby reducing risks of project failure and encouraging investment in CCS. They reduce financial risks by covering the debt of project developers in the event of loan default.	Loan guarantees help to attract private investment and reduce financing cost, making projects more economically viable. Loan guarantees need to be backed by secure funds. In case loans cannot be paid back by the investors such funds need to step in. Typically, public funds are needed to secure guarantees. Such guarantees can be important to secure financing of infrastructure, in the form of front-loaded investments, similar to mechanisms envisaged in some Member States to finance hydrogen grids.	In the EU, the InvestEU Fund aims to mobilize public and private investment backed by EU budget guarantees. It is managed centrally by the European Commission through the European Investment Bank (EIB), the European Investment Fund (EIF), the European Bank of Reconstruction and Development (EBRD) and other implementing partners.
Tradable carbon storage units / removal certificates	Carbon Storage Units (CSU) can be based on a verified record of CO_2 securely stored. Such carbon storage units could be purchased by emitters to offset emissions and possibly also used under cap & trade schemes. Carbon removal certificates (CRC) could be used to certify the effective removal of carbon from the atmosphere through natural based (e.g. afforestation) or technological based solutions (bioenergy with carbon capture and storage BECCS, or direct air carbon capture and storage, (DACS). This, when applied for BECCS and DACS can help developing shared and integrated CO_2 transport and storage networks, by expanding the range of potential network users.	CSU can incentivize the adoption and implementation of CCS technologies by providing a financial incentive to capture and store carbon emissions. CSU and CRC schemes interact with carbon prices under other schemes. Thihowever can lead to uncertainties due to volatile prices.	The EU is establishing an EU carbon removal certification framework. The framework will set rules to certify the removal of carbon from the atmosphere, as well as ensuring the integrity and transparency of carbon removal projects. The certification scheme covers a range of carbon removal technologies, including afforestation and reforestation, ocean-based approaches, soil carbon sequestration, and direct air capture, among others. It is not envisaged to be expanded into tradable certificates yet, but this can be a longer term goal of the framework.
Other mechanisms	• Pain-gain risk-sharing mechanisms involving sharing certain project risks among partners. • CO_2 liability ownership where governments assume some of the liability for CO_2 stored, especially after the project has closed.		

3.2 Description of effective mechanisms (country case studies)

Effective mechanisms supporting CCS project developments already exist in the UK and The Netherlands. They are briefly described below:

The Netherlands: SDE++ (Stimulating Sustainable Energy Production)

The Dutch government has set a 49% reduction target for CO_2 emissions by 2030 compared to 1990. The corresponding Dutch Climate Agreement includes agreements made to achieve this reduction target in various sectors. Similarly to its predecessor, the SDE+ scheme, the new SDE++ program stimulates emission reduction technologies and it now includes CCS.

The SDE++ subsidizes the "unprofitable top" calculated as the difference between the cost price of the technique (the "basic amount") and the market value of the product that the technique delivers (the "correction amount"). The basic amount does not change during the subsidy period. The correction amount is determined annually and fluctuates. The moment the market value rises, the unprofitable top decreases and therefore the subsidy to be received. The SDE++ scheme therefore functions comparable to carbon contracts for difference.

All technologies (i.e. CO_2 abatement solutions) under the SDE++ scheme compete with each other for cost effectiveness. The technologies that are able to abate the most CO_2 emissions at the lowest price will receive the subsidy.

For more information: https://english.rvo.nl/subsidies-programmes/sde/features

The United Kingdom: Business models for Industrial Carbon Capture (ICC)

The UK Government has the ambition to deploy CCS at scale during the 2030s, with a target to capture and store between 20 to 30 Mt CO_2 p.a. by 2030. Through a process called 'cluster sequencing' up to 4 industrial CCS clusters will be selected for government support and aim to be operational by 2030. Financial support for the development of these clusters will be provided through a series of business model contracts for CO_2 transport and storage, power, industrial carbon capture, low carbon hydrogen production and potentially bioenergy with carbon capture and storage (BECCS). Owners and operators of transport and storage infrastructure will be given an economic license which allows them to charge a regulated transport and storage fee to emitters. The emitter business model contracts are adapted from the Contracts for Differences which have been used extensively to deploy renewable power projects. In addition, there will be some capital co-funding from the £1 billion Carbon Capture and Storage Infrastructure Fund.

For more information: https://www.gov.uk/government/consultations/carbon-capture-usage-and-storage-ccus-industrial-carbon-capture-business-model

4. CCS Project Case Studies

There are 36 CO_2 storage projects in Europe. The below graph shows where they are located by country. In this chapter, eight of these projects are discussed in case studies. Text and data have been provided by the respective project promoters Equinor, Neptune Energy, ENI, SNAM, WintershallDea, TotalEnergies, MOL Group and Energean.

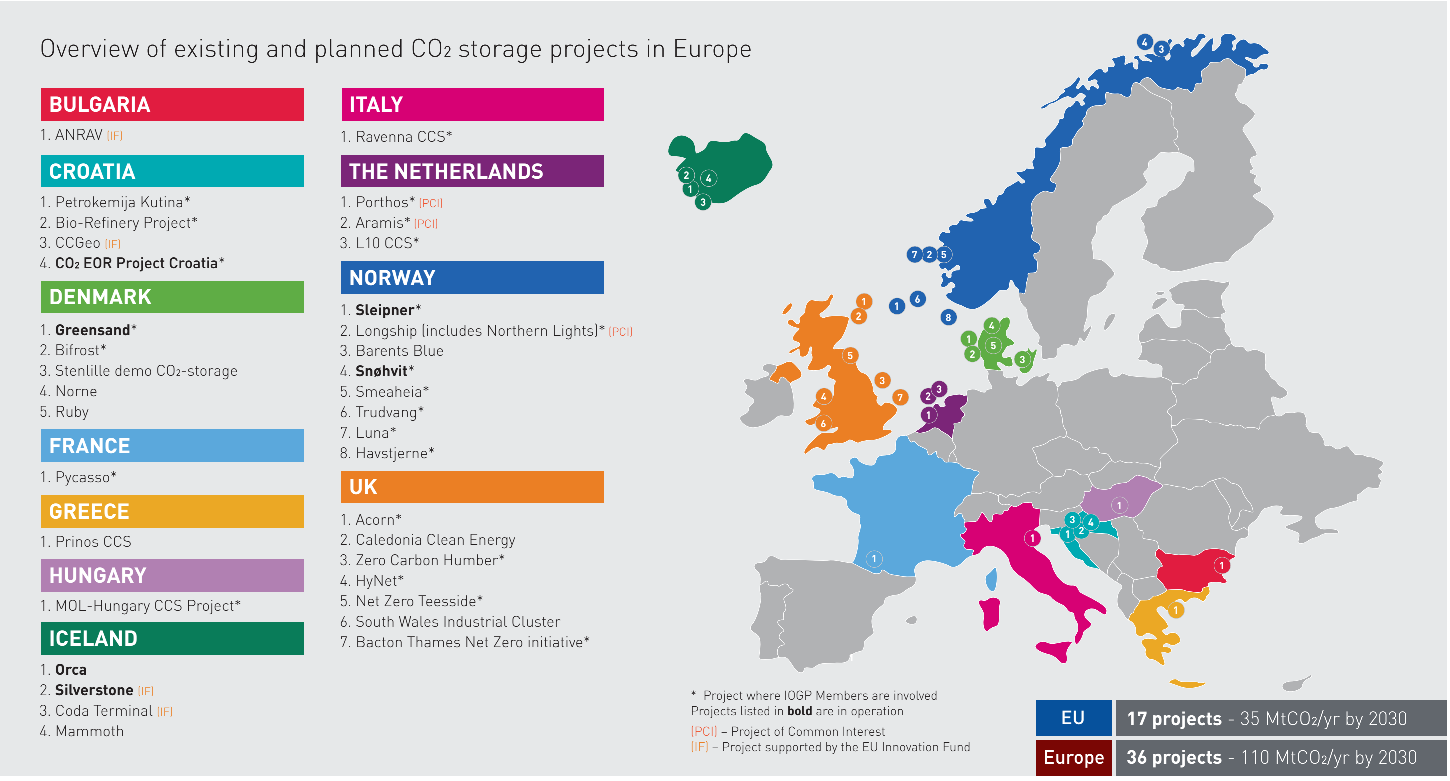


Figure 4-1: Map of known CO_2 storage projects in Europe (October 2023)

For each of the projects a summary table with key data is provided, the project and its status are described, and key enabling factors and main barriers / obstacles are listed. In some cases, missing elements for commerciality are described. This chapter therefore provides an excellent overview about the status quo of some of the major CCS projects in Europe.

4.1 Longship (Norway)

Key data of the CCS Project	
Project Name	Longship (includes Northern Lights 1)
Location	Norway – North Sea
Elements of CCS value chain covered	Capture / Transport / Storage
Participants	Equinor, Shell, TotalEnergies
Status of the project	Advanced development
Planned start of operations (date)	2024
CO_2 storage injection capacity at start date (Mtpa)	1.5
CO_2 storage injection capacity after expansion (Mtpa)	5 (Northern Lights 2)
Type of CO_2 storage	Offshore – Saline Aquifer

Project description and participants

Northern Lights Joint Venture is equally owned by Equinor, Shell and TotalEnergies. Northern Lights is developing an open-source CO_2 transport and storage infrastructure, providing CO_2 transport and storage as a service. Northern Lights aims to enable decarbonization of industrial emissions that cannot be avoided and provide safe and permanent CO_2 storage.

Once the CO_2 is captured from industrial sources, it will be transported by ship to the Northern Lights onshore receiving terminal on the Norwegian west coast for intermediate storage before the liquefied CO_2 will be transported by pipeline to an offshore storage location under the seabed of the North Sea, for permanent storage.

The first phase of the Northern Lights development with a storage capacity of 1.5 Mt CO_2 per annum is part of the Longship project. Longship includes CO_2 capture from the Heidelberg Materials cement factory (Norcem) and the Hafslund Oslo Celsio (Celsio) waste-to-energy plant, and CO_2 transport and storage by Northern Lights. The project reflects the Norwegian Government's ambition to develop a full-scale CCS value chain in Norway.

With support of the Norwegian Government and its owners, Northern Lights provides realistic decarbonization opportunities for Norwegian and European industries. Northern Lights plans further commercial expansion to meet an increasing market demand.

Status of the project

Northern Lights is on schedule to start operations in 2024 as planned. The construction of the CO_2 transport ships, onshore receiving facilities and storage infrastructure is progressing.

As the first of their kind, two 7,500 m3 LCO2 ships are currently being built at Dalian Shipbuilding Industry. The ships have purpose-built cargo tanks for the transportation of liquefied CO_2.

The construction of the Northern Lights onshore infrastructure is more than 80% completed. The storage tanks have been successfully installed, and control cable (umbilical), power cable and fibre optic connections have been installed between the Oseberg platform and the wells. The line pipe sections have been welded together for the 110 km long pipeline, and subsea equipment fabricated and delivered for installation in 2023.

During the first half of 2022, detailed well planning was performed and the drilling and completion programs for the phase 1 injection well A-7 AH and contingent well C-1 H were finalised. In November 2022, Northern Lights concluded the drilling campaign within the EL001 license in the North Sea, meeting the objectives for subsurface and well functionality. Preliminary results confirmed the estimated storage capacity of at least 5 Mt CO_2 per annum.

To meet an increasing market demand, Northern Lights is planning a commercial expansion of the facilities (phase 2) and has finalised technical Front End Engineering Design (FEED) studies. Customer development is ongoing to support an expansion investment decision.

The milestone of signing the main terms of a commercial agreement for CO_2 transport and storage with Yara in August 2022, marked an important shift from a market potential to customer demand. The agreement includes transport and storage of 0.8 Mt CO_2 annually from Yara's ammonia and fertiliser plant in the Netherlands.

In May 2023, Northern Lights announced its second commercial customer with the signing of a CO_2 Transport and Services Agreement (TSA) with Ørsted. Northern Lights will transport and store 0.43Mt biogenic CO_2 annually from Ørsted's biomass power stations Asnæs and Avedøre in Denmark to its receiving terminal at Øygarden, Norway. Because biomass absorbs CO_2 from the atmosphere, bio-CCS results in net removal of CO_2.

Key enabling factors

The key enabling factors of the project was the combined strong commitment from private and public investors Equinor, Shell and TotalEnergies, and the Norwegian Government. The Northern Lights owners agreed on a conditional Final Investment Decision prior to a so-called State Support Agreement, to contribute to developing a new market for CCS.

The Norwegian Government's commitment was materialized in a Government White Paper submitted in September 2020 proposing to launch a CCS project in Norway, called Longship. The Final Investment Decision was taken by the Norwegian Government with a historic vote in Parliament. 80% of the first phase development of Northern Lights is funded by the Norwegian Government through the State Support Agreement.

Longship reflects the Norwegian Government's ambition to develop a full-scale CCS value chain in Norway, supporting the Government's clear objective of establishing new green industries in Norway. The full CCS value chain approach enables the development of both CO_2 capture and storage projects, demonstrating realistic decarbonisation opportunities for Norwegian and European hard-to-abate industries, and for other projects to follow.

Experience from over 25 years of CO_2 storage on the Norwegian Continental Shelf shows that CO_2 storage is a safe and proven technology. This experience creates trust in CCS as a viable climate solution. Consensus of CCS as a necessary solution to reach net zero emissions across public opinion, policy makers, industry and NGO's enables the successful deployment of CCS projects.

Main barriers

While the state-supported Longship project is enabling the development of a CCS value chain in Norway, the chicken-and-egg dilemma largely remains in establishing a commercial market for CCS services. CCS projects are capital intensive and there is a need to balance the financial risks for both CO_2 emitters and CO_2 transport and storage operators.

Overall, the commerciality of the CCS market and value chain remains a challenge, relying on the ETS for CO_2 abatement and an immature carbon credit market for CO_2 removal. This particularly influences the business case of industrial CO_2 emitters in considering the affordability or future revenue stream for CCS.

In addition, national frameworks need to be adapted to a business that is fundamentally different from conventional oil and gas into a customer driven commercial business that CCS is, enabling the agile and swift development of storage that is necessary to meet the market demands.

Further, there is uncertainty related to financial securities required under national laws and under the CO_2 Storage Directive, putting a significant strain on the business and potentially preventing CO_2 storage operators to enter the business.

What is missing to make it commercial?

The business case for the emitters and potential capture operators needs to be improved, both in terms of incentivizing capture and storage, but also by driving down cost along the value chain. The transport and storage part of the CCS value chain is well defined, and for most part it is a matter of working opportunities to reduce cost and optimize operations. Northern Lights has strong faith in the commerciality of CO_2 transport and storage services, both a as a climate solution and viable business model but recognizes that it takes time to mature projects and develop a new commercial market.

4.2 L10 CCS (The Netherlands)

Key data of the CCS Project	
Project Name	L10 CCS
Location	Netherlands – North Sea
Elements of CCS value chain covered	Transport / Storage
Participants	Neptune Energy, ExxonMobil, EBN Capital, Rosewood Exploration
Status of the project	Early Development
Planned start of operations (date)	2027
CO_2 storage injection capacity at start date (Mtpa)	5
Planned start of expansion (date)	2028
CO_2 storage injection capacity after expansion (Mtpa)	9
Type of CO_2 storage	Offshore – Depleted Gas Fields

Project description

The L10 CCS project aims to safely store large scale CO_2 in the Dutch part of the North Sea. The storage facilities are planned to be built in the depleted gas fields around the Neptune-operated L10-A, B and E areas and aims to store 4 to 5 Mt of CO_2 annually. It represents the first stage in the potential development of the greater L10 area as a collection of large-volume CO_2 storage reservoirs.

The L10 CCS project is a cooperation between Neptune Energy (who kindly provided input to this section), ExxonMobil CCS, Tenaz Energy and EBN. The current project concept is to transport CO_2 from Dutch and international emitters via the port of Rotterdam and the Aramis pipeline to the L10 CCS storage facilities.

Status of the project

The L10 CCS project has completed the concept-select stage and is now entering the Define phase, which will include front-end engineering activities. A storage license application has been submitted to the authorities.

Key enabling factors

A critical enabling factor is the growing interest from industrial CO_2 emitters who face rising costs for their carbon emissions. For many emitters, carbon capture and storage can be the most cost-efficient solution to reduce their carbon footprint. An ever-increasing EU ETS price spurs these emitters to take quick action.

Dutch authorities and industrial CO_2 emitters see CCS as an important pillar in their decarbonization plans to help achieve the Dutch climate goals and stimulate its deployment. The Dutch authorities have designed the SDE++ support scheme for users of renewable energy and decarbonization technologies. Under this scheme, CO_2 emitters could apply for a subsidy/financial support for capturing and storing their emissions. The goal of the scheme is to bridge the gap in costs emitters face between the EU ETS price and the actual capture and storage costs.

The Dutch North Sea has large existing energy infrastructure. Part of it can be repurposed for CO_2 transport and storage enabling the country to become an important hub for CCS. This would give an edge to carbon storage facilities in the Netherlands.

Main barriers

While Dutch authorities and industrial CO_2 emitters see CCS as essential for their climate ambitions and support its development, building a strong business case remains challenging for many emitters and storage providers.

The total costs of capturing and storing CO_2 emissions are higher than would be justified solely via ETS. It does not yet pay off for emitters to choose CCS as an emission reduction solution unless authorities provide additional support schemes or carbon taxes, while maintaining a European level playing field. Locally, in the Netherlands, a minimum carbon tax price is in place, providing some impetus for emitters to consider CCS as a commercially viable emission reduction solution, but more support schemes and alignment across Europe on such mechanisms are still needed.

Furthermore, investments along the entire CCS value chain need a consistent and predictable regulatory framework. This includes clarity on CO_2 quality standards and third-party access with transparent tariffs to CO_2 infrastructure such as pipelines and temporary storage hubs.

Finally, delays in large-scale CO_2 transport infrastructure slow down the deployment of the carbon capture and storage market. This is not in the interest of reducing emissions, nor for participants throughout the value chain as a whole. In the Netherlands, a possible outcome of a legal proceeding at the Council of State on nitrogen emissions resulting from construction activities could jeopardize large-scale CO_2 infrastructure projects.

4.3 Ravenna CCS (Italy)

Key data of the CCS Project	
Project Name	Ravenna CCS
Location	Italy – Adriatic Sea
Elements of CCS value chain covered	Capture / Transport / Storage
Participants	Eni, Snam
Status of the project	Execution (Phase 1) and Definition (Phase 2)
Planned start of operations (date)	2024
CO_2 storage injection capacity at start date (Mtpa)	0.025
Planned start of expansion (date)	2026
CO_2 storage injection capacity after expansion (Mtpa)	4
Type of CO_2 storage	Offshore – Depleted Gas Fields

Project description

Ravenna CCS Phase 1 project aims at storing 25,000 t CO_2 per year and has been authorized and sanctioned. Ravenna CCS Phase 2 aims at storing 4 Mt of CO_2 per year in offshore depleted reservoirs in the Adriatic Sea from 2026 onward. The project is operated by Eni. In December 2022 a Joint Venture was established between Eni and Snam for the joint development of the project. The phase 2 project represents the first large scale CO_2 storage hub in Southern Europe and in the Mediterranean area, providing open access to hard to abate industrial clusters both in Italy and in the Mediterranean European Area. Following the completion of Phase 2, further gradual expansion of the injection capacity of up to 16 Mt CO_2 per year is foreseen, starting from 2030.

Status of the project

The Ravenna CCS project phase 1 is in execution phase and the Ravenna project phase 2 is entering into the definition phase.

Key driving elements that need to be promptly established:

- A viable business model for all entities along the CCS value chain is required. Government support mechanisms are needed for both, the initial CCS project stage (providing partial coverage of 'first of a kind' commercial risks), and the operational phase of the project. Furthermore, Governments have a role in promoting the development of a capture, transport and storage market at national level. At current CO_2 prices, support mechanisms are necessary and are expected to promote the establishment of a CCS market and to increase investor confidence, similar to support for other decarbonisation solutions, such as renewables, energy efficiency measures, and electric mobility. Support mechanisms are of particular importance for hard-to-abate sectors, for which there are no alternative decarbonisation solution.
- CO_2 transport and leakage monitoring: the codes and standards in place in Italy for the design and operation of pipelines transporting gases are not specific for CO_2. There is a need for a specific technical regulation to facilitate authorization procedures and to define safety and security standards for CO_2 transport through onshore and offshore facilities. In addition, monitoring rules should be put in place building on existing best practices in Italy for the transport of natural gas.
- Enable cross-border transport of CO_2: Ravenna CCS, leveraging on a storage potential estimated at over 500 Mt CO_2, can become the decarbonisation hub not only for the Italian hard-to-abate industries but also for the ones in the Mediterranean area, through the implementation of cross-border projects. To enable cross-border CO_2 transportation, national authorities should de minimis deposit a formal declaration of provisional application of the 2009 amendment to Article 6 of the London Protocol and engage in discussions with other countries in order to enter into the relevant bilateral arrangements on cross-border CO_2 transportation necessary for the purpose of offshore permanent geological storage.

4.4 HyNet CCS (UK)

Key data of the CCS Project	
Project Name	HyNet CCS
Location	UK – Liverpool Bay
Elements of CCS value chain covered	Capture / Transport / Storage
Participants	Eni, Hanson, Viridor, Protos, Buxton Lime, Vertex
Status of the project	Advanced development
Planned start of operations (date)	2027
CO_2 storage injection capacity at start date (Mtpa)	4.5
Planned start of expansion (date)	2030
CO_2 storage injection capacity after expansion (Mtpa)	10
Type of CO_2 storage	Offshore – Depleted Gas Field

Key enabling factors

The following information is kindly based on input from ENI, CO_2 transportation and storage operator. The UK Government is promoting CCS with robust policies and measures. In the Spring Budget 2023 the Government commits to invest 20 B£ to scale-up CCS projects in the UK.

The Government is developing business models to achieve the ambition to capture 20-30 Mt CO_2 annually by 2030. For the transportation and storage part of the CCS value chain, the Government is proposing a regulated business model, while for the emitters the Government proposes an incentive mechanism based on carbon contracts for difference.

The Government should further adopt measures encouraging private companies to invest into CCS projects. In particular, oil & gas companies have capabilities to develop CCS projects and have assets and skills that can be redeployed for CO_2 transport and storage. Incentivizing the reutilization of oil and gas infrastructure helps paving the way for more rapid expansion of new CCS projects.

4.5 Greensand (Denmark)

Key data of the CCS Project	
Project Name	Greensand
Location	Denmark – North Sea
Elements of CCS value chain covered	Transport / Storage
Participants	Consortium of 23 partners among them: Wintershall Dea, Schlumberger New Energy, INEOS, Aker Carbon Capture, Maersk
Status of the project	In operation
Start of operations (date)	2023
CO_2 storage injection capacity at start date (Mtpa)	0.015
Planned start of expansion (dates)	2026 & 2030
CO_2 storage injection capacity after expansion (Mtpa)	1.5 & 8
Type of CO_2 storage	Offshore – Depleted Oil & Gas Field

Project description

Project Greensand ranks among the most advanced CCS projects in the EU. The goal is to establish a value chain for the transportation and geological storage of CO_2, with the aim to store 1.5 Mt of CO_2 as of 2026 and up to 8 Mt of CO_2 as of 2030. Wintershall Dea (who kindly provided input for this section), INEOS Energy and Nordsøfonden work together towards realizing the full-scale development of Greensand (phase 3).

In the ongoing Greensand project phase 2, Wintershall Dea and INEOS Energy are the leading members of the consortium with more than 20 other partners involved - including start-ups, independent institutes and the Geological Survey of Denmark and Greenland (GEUS), an institution within the Danish Ministry of Climate, Energy and Utilities. In this broad consortium each member could focus on its individual strengths, e.g. in areas like materials, logistics, dissemination, monitoring and injection. The Danish Government supported the project with € 26 M public funding.

The depleted Nini West oil field in the Danish North Sea will serve as the storage site. The reservoir offers a favorable geology, with 700 m of tight cap rock, no geo-mechanical problems, and a sandstone reservoir of excellent quality.

Status of the project

The project is at the end of phase 2, which included a pilot injection and seismic surveys. For the purpose of the pilot injection, CO_2 was captured at the INEOS OXIDE facility in Antwerp. The CO_2, which is of food-grade quality (99.9 % CO_2), was filled into insulated ISO tanks and transported in liquid condition to the Nini platform. There, it was injected via a coiled tubing, using an existing wellbore (inactive water injector).

The full-scale development (Nini West/ Main) is expected to start up in 2026 (1.5 million tons), an expansion project (Siri Fairway Expansion) foresees a total storage of up to 8 million tons as early as 2030. The development is crucially based on Denmark awarding a storage license to Wintershall Dea and INEOS Energy in February 2023, and a bilateral agreement concluded between Belgium and Denmark in 2022that allowed cross-border CO_2 transport.

The safe storage of CO_2 is ensured by the presence of tested cap rock and integrity assurance of injection wells and abandoned/to be abandoned wells, ensuring that there is no risk of leakage. A monitoring, measurement and verification concept has been put in place to guarantee adherence to European regulations. The results of the pilot injection and the seismic surveys look promising. Goals were to test reservoir injectivity, to prove that existing infrastructure can be used and to verify applicability of CO_2 monitoring technologies. Further analysis on this is ongoing.

Key enabling factors

- A supportive political and regulatory environment in Denmark: Denmark has become a frontrunner with respect to CCS developments in Europe, already demonstrated in June 2020 by the Climate Agreement on Energy & Industry and the decision to make CCS legal for use in hard-to-abate sectors. That was followed by two agreements on a CCS roadmap (in June and December 2021) with the decision to make import and export of CO_2 legal and the determination to give Geological Survey of Denmark and Greenland (GEUS) funding for the screening of potential storage sites, both on- and offshore. This was accompanied by broad involvement of industry, municipalities, regions and citizens. An agreement on framework conditions for CO_2 storage (in June 2022) established state co-ownership of storage sites at 20 %, thus reducing risks for commercial actors. A "friendly approval process" for storage pilot projects as well as the exemption of storage and transport of CO_2 from the prohibitions of the Marine Environment Act were other decisive enabling factors.
- Broad consortium: the broad consortium participating in the Greensand project certainly was another driver, allowing different actors to contribute with their specific knowledge.
- Knowledge of storage site: the oil production history of the Greensand storage site, with existing reservoir models and 25 years of production history, is another key enabling factor for the project.

What is missing to make it commercial?

In the current project phase, a final judgment on the economic viability (similar to other CCS projects) is premature. Bilateral agreements governing the import and export of CO_2 for offshore storage are needed, e.g between Germany and Denmark. Subsidies and incentives are equally important at this early project stage, because current CO_2 price levels are not yet sufficiently high to support the establishment of economically viable CCS value chains. Infrastructure (CO_2 pipelines) need to be put in place too.

4.6 Bifrost (Denmark)

Key data of the CCS Project	
Project Name	Bifrost
Location	Denmark – North Sea
Elements of CCS value chain covered	Transport / Storage
Participants	TotalEnergies, Noreco, Nordsøfonden, Ørsted, The Technical University of Denmark (DTU)
Status of the project	Early development
Planned Start of operations (date)	2030
CO_2 storage injection capacity at start date (Mtpa)	3
Planned start of expansion (dates)	2032
CO_2 storage injection capacity after expansion (Mtpa)	16
Type of CO_2 storage	Offshore – Depleted Oil & Gas Field / Saline Aquifer

Project description

Project Bifrost is a cross-border CO_2 transport and storage project aiming to develop open access infrastructure to connect European industrial hubs to offshore storage in the Danish North Sea. The text in this section is based on input from TotalEnergies. The project aims at transporting hard-to-abate CO_2 collected from industrial emitters located inland Denmark and Germany, and with potential for Sweden and Poland, and at permanently storing ultimately up to 10 to 15 Mt of CO_2 annually. With storage operations start-ups scheduled from 2029-2030, the project has the potential to significantly contribute to expanding CO_2 transportation and storage capacities in Europe and make a major contribution towards the EU target of climate neutrality towards 2050.

Project Bifrost will leverage the substantial geological storage potential in the Danish North Sea from both saline aquifer structures and depleted gas reservoirs. The project intends to repurpose existing oil and gas infrastructure where possible, such as offshore facilities (platforms and facilities, pipeline interconnections, etc.) and the offshore gas transportation system in Denmark. Newly built infrastructure will be developed where infrastructure does not exist yet, as well where existing infrastructure cannot be converted for safety and technical reasons or is in use for other purposes. This will encompass new offshore facilities (platforms, wells) for new storage sites, a new pipeline network to connect main emitters clusters in Denmark and from Germany down to Leipzig, and associated compression/pumping stations. The project will also include marine facilities for reception of liquid CO_2 transported by ship from remote locations (such as Poland or Sweden), either located onshore before further transportation offshore (several locations under investigation for such onshore terminal) or located offshore for direct offshore offloading to the storage sites.

The storage part of the CCS value chain developed by project Bifrost rely on one part on two exploration licenses awarded to TotalEnergies and Nordsøfonden, for which an exploration and appraisal campaign is planned to assess and de-risk the storage potential (gas fields and saline aquifer), and also on potential growth. The transportation part of the CCS value chain, connecting emitters to store, will be established through several cooperations between the storage parties and infrastructure providers.

Status of the project

The project is at concept phase, with appraisal of the storage sites and study of development concepts for the transportation. Several options are being investigated and the final concept will eventually be based on market demand.

4.7 MOL CCS project (Hungary)

Key data of the CCS Project	
Project Name	MOL - Hungary CCS project
Location	Hungary
Elements of CCS value chain covered	Transport / Storage
Participants	MOLGROUP
Status of the project	Concept Generation Phase
Planned Start of operations (date)	no data
CO_2 storage injection capacity at start date (Mtpa)	0.7
Planned start of expansion (dates)	No expansion planned
CO_2 storage injection capacity after expansion (Mtpa)	0.7
Type of CO_2 storage	Onshore – Depleted Oil & Gas Field

Project description

This section is based on input from MOL Group. MOL Group's Shape Tomorrow 2030+ Strategy includes the development of carbon capture and storage in Central Eastern Europe. MOL Group has completed the screening of its reservoir-portfolio and assessed its potential CO_2 storage-sites and capacities and has evaluated several options for projects to implement CO_2 injection for the purpose of carbon removal in perpetual storage.

The MOL CCS project aims at the geological storage of biological origin CO_2 emitted into a depleted onshore gas field. The project is planned to be realized in a cooperation between MOL Group and the owner-operator of a Hungarian biorefinery.

The project aims to implement:

- 0.7 Mt CO_2 annual capture and conditioning capacity in a biorefinery;
- transport of the captured CO_2 to an existing MOL gas production site via a new CO_2 pipeline (under 100km);
- corresponding CO_2 reinjection capacity at the gas production site, including the suspension of 24 hydrocarbon production wells and the drilling of up to 8 new CO_2 injection wells, together with 8 new injector lines and associated well-sites.

Project Status

The technical and commercial assessment of the project has been completed, on which basis an initial offer has been made to the biorefinery emitter for CO_2 storage services. The biorefinery operator is not under the EU ETS, therefore is not able to valorize the emission reduction of the captured CO_2 under the EU ETS. MOL Group's offer has not been accepted.

Without a clear revenue stream, the project lacks sufficient commercial value to make it break even. Therefore, no final investment decision has been taken so far. MOL Group is searching for additional sources of value to underpin a positive business case, including attempts to valorize the negative emissions on voluntary markets or to obtain support through government subsidies, such as for potential contract for difference schemes.

Parallel to the work of finding additional commercial value to this specific project, MOL Group repeatedly makes the case both at EU and member state level for the necessity to set up schemes through which it is possible to valorize CO_2 abatement (incl. negative emissions) when the emitter is outside the scope of the EU ETS.

Key Enablers

The project is in line with MOL Group`s 2030+ Strategy that looks for CCS opportunities. It leverages MOL Group's geological knowledge of the Pannonian Basin and sub-surface technological expertise, as well as its status of a leading upstream player in the region. The project utilizes a depleted hydrocarbon reservoir, which creates the benefit that the subsurface is well understood and the reservoir sealing capacity is proven.

The MOL CCS project is also supported by the relatively low-cost technology of on-shore CO_2 storage, the relatively short distance of necessary CO_2 transportation (both compared to far away off-shore sites), and the 95%+ purity of the CO_2 stream, resulting in reasonable capture costs.

For landlocked countries such as in Central and East Europe, smaller-scale onshore CCS projects, including those achieving negative emissions, are necessary to efficiently and sufficiently decarbonize their economies. Such projects are needed also to enable authorized hydrocarbon producers in that region to comply with the CO_2 storage contribution obligation as proposed in the draft EU Net Zero Industry Act.

Main Barriers

There is a general lack of commercial incentives for investors along all segments of the CCS value chain to make projects economic:

- The above mentioned biorefinery is outside the scope of the EU ETS, therefore it has no possibility to monetize its CO_2 abatement on the EU ETS carbon market. There is no transparent voluntary CO_2 abatement market, and project promoters have, so far, experienced no voluntary interest for CO_2 abatement credits from non-obligated parties.
- The MOL CCS project has not received, so far, any external financial support from government sources, and there is no available contract-for-difference scheme in Hungary for CO_2 capture and transmission.
- Carbon capture and sequestration projects, especially if multiple parties are involved, are highly complex. Their planning and development, contracting, permitting, implementation of multiple technologies with long lead-time purchases, and their final testing and commissioning takes many years, even possibly a decade. The time-requirement of such projects might jeopardize the 2030 deadline for them to meet the NZIA's target. Given the time remaining until 2030, and various risk factors outside the control of operators, there is an obvious need for some flexibility in time to meet the NZIA target.

What is missing to make it commercial?

Investors need a transparent and clear legal framework both at EU and member state level to underpin positive business cases for all participants of a CCS project, i.e. all segments of a CCS value chain: including capture, transportation, injection and storage operation. The inherent risks, including financial, technological and even geological risks need to be appropriately rewarded for all investors to engage across the value chain.

Long term liabilities for the integrity of the CO_2 storage site after the completion of the injection and after regulatory verification needs to be taken over by the state.

4.8 Prinos CCS (Greece)

Key data of the CCS Project	
Project Name	Prinos CCS
Location	Greece, Northern Aegean Sea
Elements of CCS value chain covered	Transport / Storage
Participants	Energean
Status of the project	Early development
Planned Start of operations (date)	2025
CO_2 storage injection capacity at start date (Mtpa)	1
Planned start of expansion (dates)	2027
CO_2 storage injection capacity after expansion (Mtpa)	3
Type of CO_2 storage	Depleted Oil Field / Saline Aquifer

Project description and participants

The Prinos Carbon Capture and Storage is a scalable project that leverages existing onshore and offshore infrastructure. The project is carried out by Energean (who kindly provided the input for this section) and involves the development of an offshore CO_2 storage site and related pipeline infrastructure in the North of Greece for the purpose of storing emissions of hard-to-abate domestic industries, as well as industrial emissions of surrounding countries such as Bulgaria, Italy, Croatia, Cyprus, and Slovenia. DESFA, Greece's natural gas TSO, supports with the development of an entire CO_2 transport chain to collect CO_2 from the facilities of emitters and transport these quantities into storage..

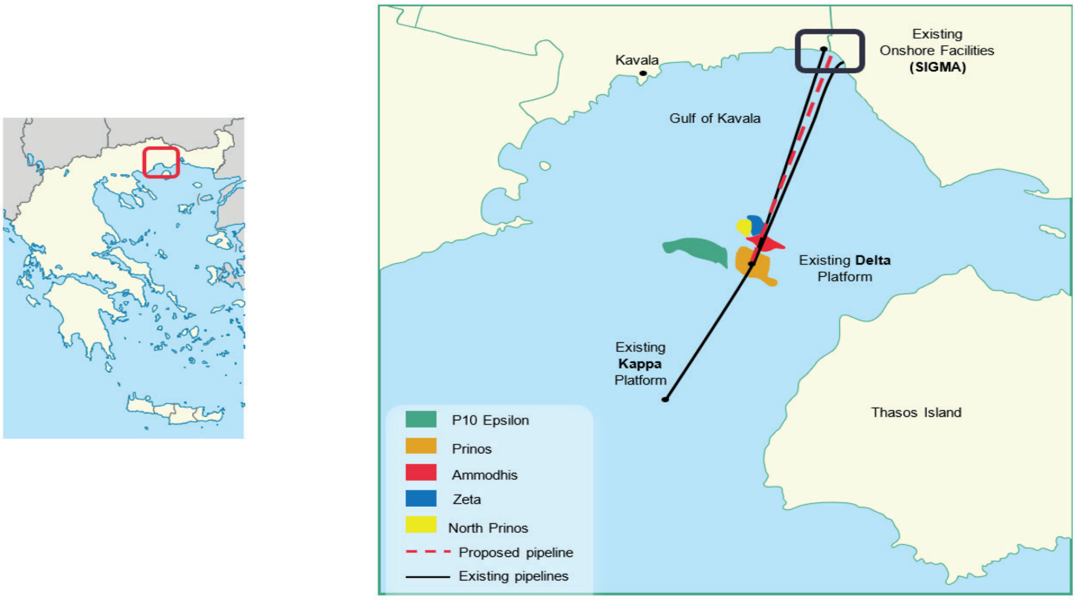


Figure 4-2: Location of Prinos CCS project

Status of the project

In October 2022, Energean was granted a 22-month licence by the Hellenic Hydrocarbons and Energy Resources Management Company to explore the Prinos field as a location to store CO_2. Following a subsurface study by Halliburton, the suitability of the field for geological storage of CO_2 has been confirmed. Two project stages have been identified, subject to refinement and optimization: a small-scale project with a capacity of up to 1Mt of CO_2 annually, operational from Q4 2025, and an option to increase the capacity to up to 3Mt of CO_2 annually as of Q4 2027.

In addition, Wood plc has completed a pre-FEED study regarding the onshore storage of 1 to 2 Mt CO_2 annually based on a Well Head Platform developed with wide and coarse subsurface assumptions.

The EU has endorsed Greece's Recovery and Resilience Plan that includes CO_2 storage in Prinos. Also, an application for the inclusion of the project in the 1st Union list of Projects of Common Interest and Projects of Mutual Interest under the revised TEN-E Regulation has been submitted. Prinos CCS has successfully passed a technical assessment, making the project eligible for inclusion on a preliminary list that is expected to be finalized in November. Regarding the capture of CO_2 emissions, Energean has signed with industrial emitters from Greece and abroad 8 non-binding MoUs.

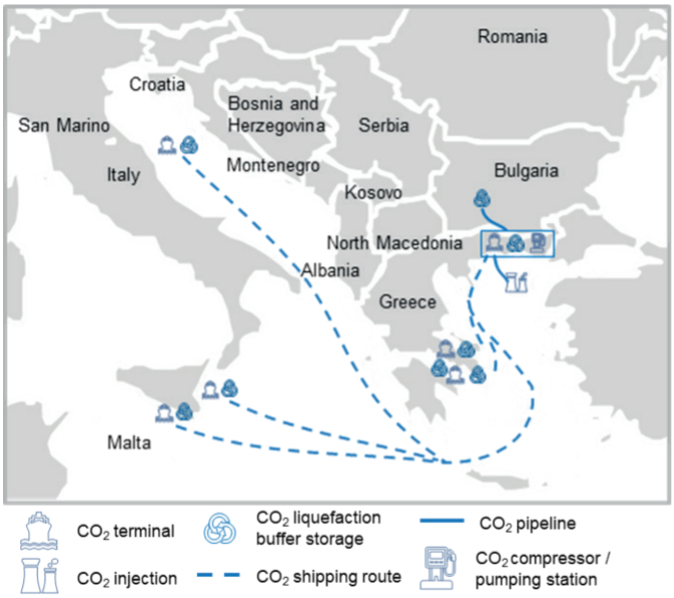


Figure 4-3: CO_2 Transport and Storage at the Prinos CCS project

What are the key enabling factors of the project?

- Prinos is strategically located to serve large emitters of the region
- Energean is an experienced offshore project developer and operator
- Deep knowledge of a reservoir that has been producing hydrocarbons for more than 40 years and has been assessed to be suitable for CO_2 storage
- Utilization of existing onshore and offshore infrastructure
- The EU has endorsed Greece's Recovery and Resilience Plan that includes CO_2 storage in Prinos.
- The Greek industry produces about 9 Mt of CO_2 emissions annually and additional emitters are in the neighbouring countries
- The energy group Motor Oil and the cement producer TITAN have been recently selected for EU Innovation Fund grants, supporting innovative low-carbon technologies, for respective carbon capture and storage (CCS) initiatives taken by the two corporations. Their selection promises to create opportunities for synergies and the development of a domestic value chain in the CCS sector

What are the barriers?

- Regulations and legislations allow room for interpretation, creating uncertainty potentially delaying the project
- Lack of standardized risk register designed for CCS and a lack of industry standards
- Long-term political consent and support is required for the implementation of the CCS value chains
- Clarity in sharing of responsibilities between authorities in Greece: HEREMA is responsible for granting the exploration and storage permits, but who is responsible for the rest of the permitting procedure?
- Clarity in cross-border CO_2 transport: Greece is not yet a signatory to the London Protocol amendments. Work is needed between EU member states on a bilateral basis.
- Uncertainties regarding the business cases due to current commercial viability

What is missing to make it commercial?

- Sufficient funding, from any available source
- State (and the European Commission) should draw on experience from RES support schemes: grants, tax exemptions, feed in tariffs/feed in premiums, quota obligations, long term uptake contracts with State guarantee, fast track licencing, One-Stop Shops

5. What is missing to create sustainable business cases for CCS projects?

5.1 Tools to de-risk project revenue streams

One of the key barriers for the development of CCS projects in Europe is uncertainty about future revenue streams for investors along the value chain. Without some degree of certainty, investors don't commit the significant amounts of capital needed for CCS related investments. In addition to uncertainties related to revenue streams, investors are also faced with uncertainties about project related CAPEX and OPEX, project implementation and permitting complexities, public acceptance exposures, and an immature legal framework. However, these are not discussed in this section. While revenue stream uncertainties are normal for any business, they can be a barrier to market development where a market is in a nascent stage and where business models are capital intensive with a certain risk of stranded investments. Risks include:

- Emitters (who contemplate investing into capturing the CO_2 instead of paying for ETS allowances) are faced with uncertainties about the ability to timely and in a firm manner dispose the captured emissions. They are also exposed to uncertainties about the future value of ETS allowances (should they rather just pay the for ETS allowances?).
- CO_2 transportation and shipping companies are faced with uncertainties about future transportation capacity needs, its build-up over time, the location of storage sites (i.e. where to build the pipelines end-points), and tariff levels.
- CO_2 storage companies are faced with uncertainties about demand for storage services at a particular location, the ability of storage customers to commit long term, and the timely establishment of the needed connecting infrastructure. They will also be faced with competition amongst storage service providers and uncertainty about achievable tariffs for storage services.

There are market based tools to reduce project uncertainties: Long-term (10-15 years) contracts between the multiple entities along the value chain, with clear terms on tariff levels and booked capacities and take or pay provisions providing certainty about future revenue streams. Such contracts balance risks and rewards along the value chain and should generally be negotiated between the market parties resulting in back-to back chains of contracts from the emitter to the storage service operators. Such long-term contractual relationships typically need to be in place before investors take final investment decisions. A fit for purpose legal framework should facilitate the establishment of such back-to-back contractual chains.

CCS projects should start developing around clusters of emitters, where multiple emitters can contribute to a common infrastructure for the transportation and storage of CO_2. Building such clusters generates economies of scale in construction and operations, resulting in lower unit costs, reduced risk, and the ability to standardize and scale up quickly.

However, during the CCS market built up phase, while ETS allowance prices are insufficient to incentivize CCS related investments, and where long-term contracts are not sufficient to underpin the needed investments, the EU and member state governments have a role to support and enable market establishment. Tools to do so are visualized in **Figure 5-1** below and include:

- Carbon Contracts for Difference (CCfDs) for entities investing into CO_2 capture;
- Public-private partnerships and guarantees for transportation infrastructure;
- Targeted public funding of investments along the CCS value chain;
- CO_2 aggregators with public backing;
- Regulated tariffs for onshore transaction infrastructure where they facilitate investment.

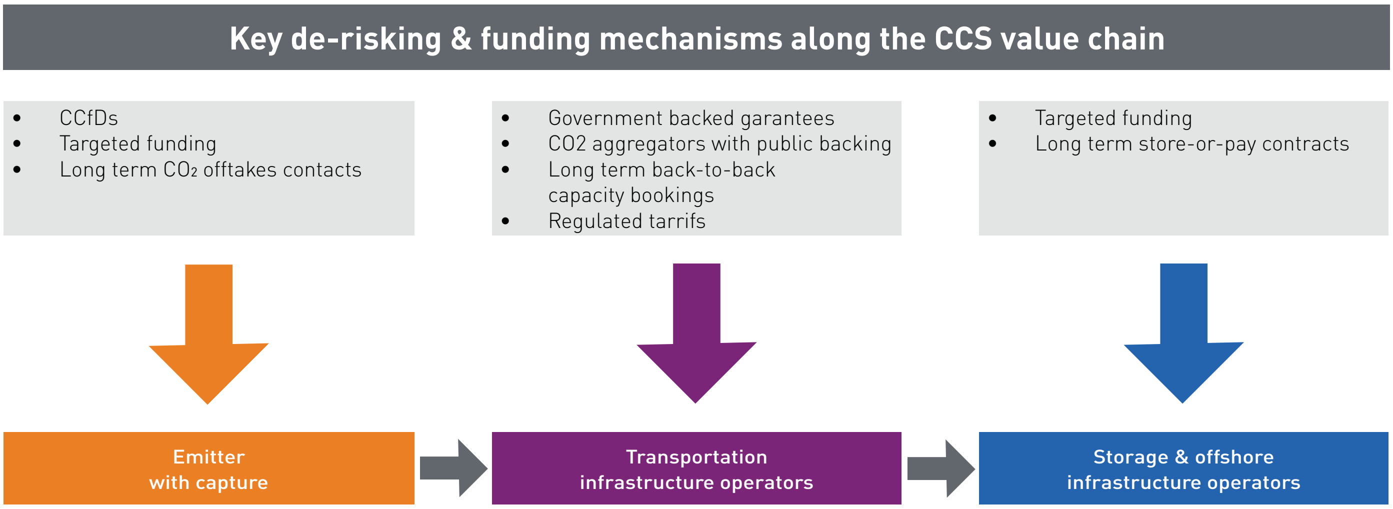


Figure 5-1: Selected tools to derisk CCS project related revenue stream uncertainties

Carbon Contracts for Difference for entities investing into CO_2 capture:

Emitters are exposed to fluctuations in the price of EU ETS allowances. To mitigate this risks, 'carbon contracts for difference' can provide assurance to the emitter of a certain ETS allowance level by compensating the emitter for the delta between the needed allowance level to make a capture investment (and the payment obligation associated with the disposal) economic (also referred to as 'strike price') and the prevailing ETS allowance market price at a given point in time. **Figure 5-2** below illustrates the functioning of a CCfD.

CCfDs can be awarded e.g. by a government-backed body through competitive tenders where emitters would submit bids for CCfDs. The bidding criteria could be the strike price over a certain period and for a certain volume of CO_2 captured and disposed of where CCfDs are granted by member states authorities, they may be considered as state aid under EU rules and therefore would require approval from the European Commission.

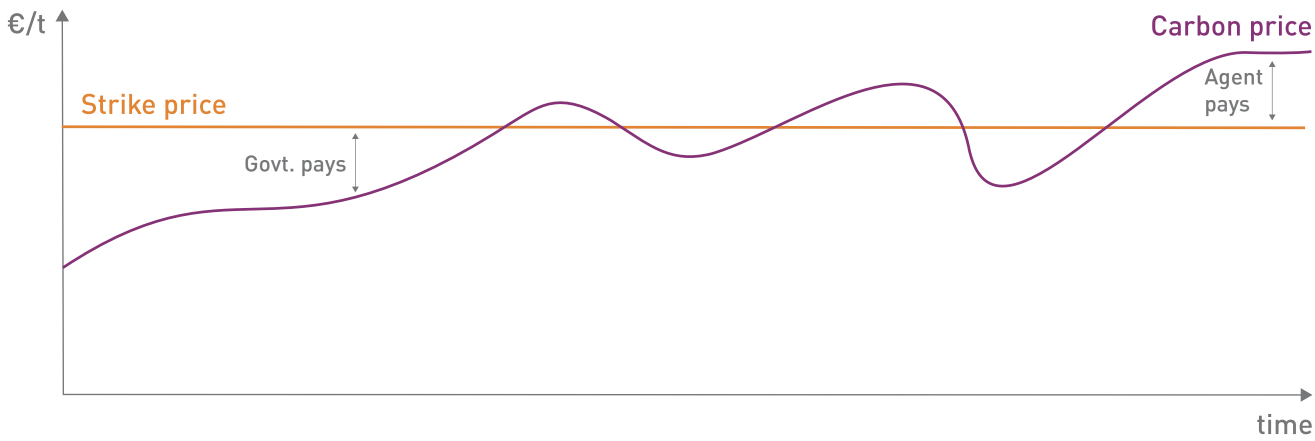


Figure 5-2: Illustration of the functioning of a carbon contract for difference

Public-private partnerships and guarantees for transportation infrastructure:

Transmissions system operators for onshore transport of natural gas today are publicly or privately owned but their revenues are generally regulated under EU rules. Currently, their role with regard to the transport of hydrogen is being discussed in the context of the EU Hydrogen & Decarbonized gas market package. Lessons should be learned, and rules for the transport of CO_2 may be adopted from the rules currently being established for hydrogen.

State ownership, state financing / grants, or state backed loan guarantees can be used to support investments into CO_2 transportation infrastructure needed to connect emitters with storage sites. In the case of loan guarantees, the government would offer guarantees to private investors or lenders, assuring that they will be repaid even if the project doesn't generate sufficient revenue.

Targeted public funding of investments along the CCS value chain:

Public funding is needed in particular in the early years of the establishment of a CCS industry in Europe and for initial phases of projects, given the so far insufficient EU ETS allowance price levels. When designing funding schemes, it is essential to consider both, initial capital expenditures (CAPEX) and longer-term operating expenditures (OPEX).

Public funds can come from various sources: in additional to EU funds available, national governments and can allocate funds from their budgets to support CCS projects. These funds might be used for research and development, pilot projects, infrastructure development, and regulatory framework establishment. The mix of funding sources will likely vary from project to project and from country to country, depending on local priorities, regulatory frameworks, and financial capabilities. Public funding encourages private investors and other stakeholders to engage, as they are more likely to participate when they see a stable and supportive funding environment.

Cross-border CCS projects are with increased complexity due to different legislation across jurisdictions. Funding becomes especially important in these cases as it can support joint development activities, feasibility studies, and pilot projects that capitalize on shared resources and costs. By pooling financial resources, cross-border projects can achieve economies of scale and optimize the utilization of assets, making CCS more economically viable.

CO_2 aggregators with public backing:

Please refer to section 5.2 below, dedicated to CO_2 aggregators.

Regulated tariffs for onshore transportation infrastructure:

Reducing revenue stream uncertainties for investors into CO_2 onshore pipeline infrastructure can be facilitated by fit-for-purpose tariff regulation if they facilitate investments. However, regulation should provide for exemptions to allow flexible solutions where stakeholders can build needed infrastructure connecting emitter and storage sites without a regulated regime.

Offshore pipelines in many cases are an integral part of CO_2 storage projects. In general, tariffs for offshore infrastructure should not be based on regulated regimes but be based on commercial negotiations as they form part of the cost to develop offshore storages competing with other projects. Access to offshore infrastructure should be based on 'light-touch' non-discriminatory and transparent access conditions as provided for by Article 19 of the CCS Directive.

Other transportation modes such as barges/ships or via rail should not be regulated but operate under market-based commercial arrangements. This allows for flexibility when agreements are negotiated between transportation system operators and emitters or aggregators. Commercial arrangements can be tailored to local circumstances and market dynamics, enabling the most suitable and economically viable solutions for CO_2 transportation.

5.2 A possible role for CO_2 aggregators?

Figure 5-3 below illustrates the many business activities/entities likely involved along a CCS value chain from CO_2 capture to storage. In this business someone needs to contract with the transportation infrastructure operators (e.g. gathering pipeline operators, trunk-line operators, processing operators, interim storage operators, shipping companies, and ultimately storage operators) and it may create a barrier to capture project developers if they need to also negotiate and conclude all these contracts. The same may apply to storage project developers. In such a case, a CO_2 aggregator can have a role in concluding contracts with multiple emitters, multiple transportation infrastructure operators, and one or several storage operators. ACO2 aggregator would contractually 'glue together' a CCS value chain and act comparable to a natural gas supply company.

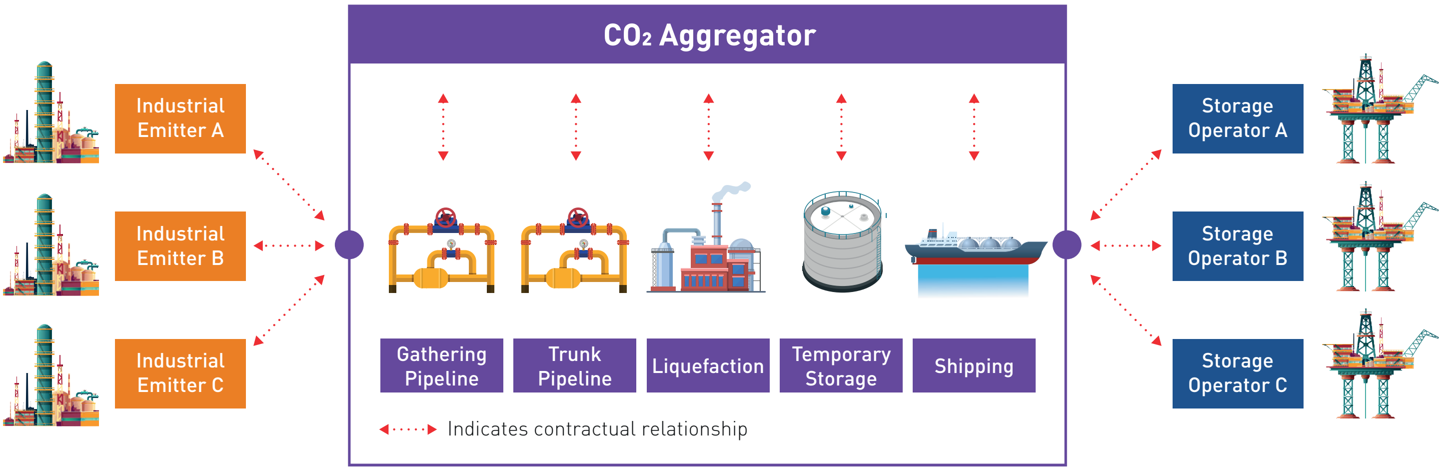


Figure 5-3: A possible role for a CO_2 Aggregator

A CO_2 aggregator could possibly more effectively manage ('de-risk') business risks than individual contractual chains would do. A CO_2 aggregator could:

- Contract with (multiple) emitters to take their captured CO_2 thereby giving them CO_2 disposal certainty. Separately, a CO_2 aggregator can contract for CO_2 storage with (multiple) storage operators, thereby de-complexifying the back-to-back contractual chain (the 'chicken-and-egg issue' from emitter to storage operator) for CCS project developers.
- Contract with emitters to take their captured CO_2 over a different period (e.g. 10 years) than it contracts with transportation infrastructure operators or storage operators (e.g. 15 years. The aggregator thus would assume some contra duration risks.
- Contract with emitters to take their captured CO_2 for a tariff which provides the needed long-term revenues to pay for transport and storage capacity bookings.
- Contract with multiple transportation infrastructure operators connecting the many emitter sites with (multiple) storage sites. The aggregator could likely more effectively and in an optimized manner enter into the long-term infrastructure capacity bookings needed by investors.

The CO_2 aggregator could employ tender procedures to identify cost-effective carbon capture options as well as, separately, tender procedures to identify cost-effective storage options. Through these tenders, the aggregator can solicit proposals from various emitters who plan to capture CO_2 and separately from CO_2 storage service providers and select solutions that offer the lowest cost per unit of carbon captured or stored. Such competitive processes ensure efficient allocation of resources thereby likely reducing overall CCS value chain cost.

A CO_2 aggregator could be as a separate legal entity dedicated to aggregating captured CO_2 emissions and concluding contracts along the value chain. The aggregator would assume risks associated with CO_2 management, acting as a central point of responsibility. The CO_2 aggregator could receive support from public entities through public-private partnerships or loan-guarantees, further enhancing its ability to facilitate the commercial viability of CCS projects and promote the development of sustainable revenue streams.

The decision to establish a CO_2 aggregator in the CCS value chain depends on several factors. If there are multiple emission sources that individually cannot achieve the economies of scale needed for a cost-effective CCS implementation, a CO_2 aggregator can consolidate these emissions and achieve efficiency and cost savings. When it comes to CO_2 transport, a centralized approach facilitated by an aggregator can optimize the utilization of transportation infrastructure. Instead of each emission source building and managing their own transport network, the aggregator can with its capacity bookings underpin the timely development of the needed pipeline or shipping systems, minimizing redundancies and reducing overall infrastructure costs. On the other hand, for instance in the case of large industrial emitters with substantial resources and capabilities, it may be feasible for themto implement CCS projects independently without the need for an aggregator. They can manage agreements along the entire value chain, including capture, transport, and storage, using their own expertise and infrastructure.

It therefore depends on the specific circumstances in a country or region, the scale of emissions, and complexity of CCS projects to determine whether the involvement of a CO_2 aggregator is beneficial or necessary.

5.3 Clear rules on liabilities / CO_2 accounting

Consistent implementation of EU CO_2 Storage Directive 2009/31/EC

Before liabilities for stored CO_2 are transferred from a storage operator to a competent authority, the EU CO_2 Storage Directive 2009/31/EC – amongst others - requires the monitoring and verification of a storage sites for a minimum of 20 years after closure. However, member state legislation implementing the Directive resulted in inconsistent implementation across different jurisdictions. This creates issues and uncertainties for project developers. Member states should more consistently implement the Directive and thereby better take into account the four Guidance Documents under the Directive. These Guidance Documents include guidance on liability transfer to competent authorities post closure, on CO_2 accounting and liability management, criteria to be taken into account when setting the amount of financial security, and require operators to set aside funds to cover potential leakages.

CO_2 accounting

Clarity is needed regarding liabilities and accounting rules for CO_2 emissions/leakages and related financial or liability exposures for operators along CCS value chains. Clear rules on who in a CCS value chain is liable for possible leaks at each stage of the value chain provide certainty for operators and facilitate risk management. The EU ETS requires detailed accounting between operators of CO_2 volumes captured, transported and stored. Operators are accountable for any leaks and are required to surrender EUAs under the ETS for leaked volumes. Such clarity must also be established where CO_2 is exported to third countries (outside the EU/EEA).

The London Protocol

The London Protocol to the Convention on the Prevention of Maritime Pollution established by the UN International Maritime Organization (IMO) establishes rules regarding the dumping of waste in the sea and is thereby restricting cross-border CO_2 trade. A 2009 amendment to the London Protocol allows CO_2 cross-border transport between countries who ratify the London Protocol with its amendment. However, the London Protocol is not yet ratified by many countries including several EU member states. The amendment will enter into force only once two thirds of the London Protocol contracting parties ratify the amendment. The Commission recently clarified[10] the application of London Protocol between the EU and EEA countries confirming that the EU legal framework (the EU ETS Directive and the CO_2 Storage Directive) and the EEA Treaty can act as an arrangement under the meaning of Article 6 of the London Protocol and that the amendment does not need to be ratified under those jurisdictions. Nonetheless countries in the EEA that are parties to the London Protocol need to: deposit a formal declaration of provisional application to the IMO and notify the IMO that they are part of the arrangement. Furthermore, the Commission's interpreting document is not well known to all projects developers and members states. This creates legal uncertainties impacting project viabilities. With the aim to mitigate the aforementioned uncertainties the European Commission should insist on the ratification of the London Protocol by all EU member states, or at least encourage corresponding bilateral agreements between EU member states and/or EEA countries.

Financial securities to cover for potential leakages

Financial securities to be established by operators to cover for possible leakages can create significant cost to CCS projects and thus possibly constituting project barriers. Competent authorities should therefore apply a reasonable, predictable, and risk-based approach when determining financial securities needed from CO_2 storage operators. For example, financial securities needed should be based on the price of EUAs at the time storage injection (and not at a future point in time for which the EUA price is unknown) to create certainty about the security amounts.

10 European Commission, 2022, The EU legal framework for cross border CO_2 transport and storage in the context of the London Protocol.

6. Conclusions and policy recommendations

- CCS value chains are long, complex, and involve investments and operations by multiple business entities: emitters capturing CO_2, entities transporting and processing CO_2, and CO_2 storage operators. These entities need to put in place commercial solutions based on long-term contracts balancing risks and rewards along the CCS value chain thereby underpinning and de-risking the financing for the needed investments.
- The development of CO_2 storage projects takes between 5 and 13 years to complete. Each project development phases can be supported and facilitated through a fit for purpose and stable regulatory framework. Effective measures include:
  - In the screening phase, existing hydrocarbon licenses should be transferrable from oil & gas operations to CO_2 storage operations;
  - In the characterization and appraisal phase, it is important that non-ambiguous terms and clearly stipulated rights and obligations exist for competent authorities and applicants with regard to the issuing of permits;
  - In the design, appraisal & contracting phase, a clear and stable framework and the existence of fit for purpose CO_2 standards facilitate the design phase of FEED studies.
- Based on Rystad Energy data and a set of scenarios, levelized costs of CCS value chains vary from about 130 to 230 €/tCO2. This contrasts with recent CO_2 emissions allowance prices at levels between 80 and 100 €/t CO_2. The establishment of CCS value chains, at least during current ETS price levels, is therefore not sufficiently incentivized through the ETS.
- Experience in project developments shows that some of the most advanced projects are taking place in countries where supporting policy mechanisms for CCS have been established. Lack of business case and of adequate support remain a major obstacle for project developments at large scale even in regious where geology for CO_2 storage sites has been identified.
- A variety of policy mechanisms are available to de-risk CCS value chains, both at EU and member states level. They can take form of funding mechanisms or policy incentives (revenue support or a price of carbon emitted). It is important that EU and Member States establish and maintain a fit for purpose level of support to complement private investments in particular during the initial phase of the CCS industry. More funding schemes and alignment between Member States is needed.
- To enable commercial development of CCS projects, EU and member states have a role in reducing revenue stream risks for CCS value chains, especially during the take-off phase of CCS development. Adequate policy tools include:
  - Carbon Contracts for Difference (CCfDs) for entities investing into CO_2 capture;
  - public-private partnerships and guarantees for transportation infrastructure;
  - targeted public funding of investments along the CCS value chain;
  - CO_2 aggregators with public backing;
  - regulated tariffs for onshore transportation infrastructure where they facilitate investment.
- It should be noted that – as EUA prices can be expected to increase – needed policy and funding support can likely reduce over time and – depending on the design of a CCfD mechanism, - can even provide revenues to Governments. This can make CCfDs a particularly valuable mechanism for Member States.
- EU and Member State rules on liabilities and CO_2 accounting need to be clear and predictable to provide certainty to project developers in particular in the case of cross-border projects. The ongoing review of CCS Directive Guidance Documents offers opportunities to clarify aspects related to post-closure liabilities and financial mechanisms. Moreover, the Europe Commission should encourage ratification of the London Protocol or the establishment of bilateral agreements among Member States to facilitate cross-border projects.

Annexes

Annex 1: Assumptions made to calculate CCS value chain costs

CCS value chain segment	Assumptions
General	**Variables set by IOGP** • Discount rate (%): 10 • Exchange rate of 1.1 $/€ • FID taken at: 2027 (We assume capture technology to be of the year 2027 which results in better economics due to technology improvements & energy efficiency) • Operations start at: 2030 with power price (USD/kWh): 0.08 (according to Rystad Energy's assumptions, average power price in Europe for 2030 will be 0.08 $ / kWh)
Capture	**Variables set by IOGP** • CAPEX Overrun (%): 25 • Emissions Capture (Mtpa): 1 • Capture efficiency (%): 90 • Lifetime of Capture equipment (years): 20 • Capture technology: Amine-Based Chemical Absorption (2027)
Transport	**Variable Values set by IOGP** • Lifetime of pipelines (years): 25 • Lifetime of ships (years): 25 • Steel Price (USD/kg): 1.23 • Fuel Cost (USD/MWh): 50
	Values set by Rystad Energy • Temporary onshore storage required: 120% total ship capacity • CO_2 is liquefied for transport • CO_2 is transported in liquid form (1060 kg/m3) • CO_2 returned to gas state during unloading • Other OPEX & CAPEX include loading, gasification, harbour fees & terminal costs • Ship speed: 22 km/hr • Ship availability: 90% (proportion of time ship not undergoing maintenance)
Storage	**Variable values set by IOGP** • Lifetime of storage infrastructure (years): 20 • Well Reuse (%): 0 • Include Permit Cost: YES • Contingency (%): 25 • Include EOR: NO

Annex 2: Overview of CO_2 concentrations in the exhaust gases for different industrial processes

Table 1: CO_2 concentrations in the exhaust gases for different industrial processes[11]

Industrial Process	CO_2 Concentration (mol%)
Aluminium Production	1-2
Natural Gas Combined Cycle	3-4
Conventional Coal fired Power Generation	13-15
Cement Production	14-33
Steel Production (blast furnace)	20-27
Hydrogen Production	15-20
Integrated Gasification Combined Cycle	8-20
Natural Gas Processing	2-65

Table 2: CO_2 concentrations in the exhaust gases for different industrial processes assumed in calculations in this paper

Industrial Process	CO_2 Concentration (mol%)
Gas Processing	60
Chemicals	10
Power Coal	14
Refining	10
Iron Steel	26
BECCS	11
Waste	11
Cement	20
Blue H2	15
Power Gas	4

11 Source: Techno economic evaluation of amine based CO_2 capture: impact of CO_2 concentration and steam supply - Energy Procedia (2012)

Annex 3: Sensitivity Analysis

Impact of **Power Prices** ($/KWh), **Discount Rate** (%), **Capture Capacity** (Mtpa), **Capture Efficiency** (%), **Capture Technology Status** (Year), **Capex Overrun** (%), and **Project Lifetime** (Years) on the Levelized Cost of Capture (when all other parameters presented in Table 1 remain the same).

CO_2 Capture costs ($/t CO_2)	Power Prices ($/KWh)			Discount Rate (%)			Capture Capacity (Mtpa)		
	0.04	0.08	0.12	5	10	15	0.1	1	5
Gas Processing	35.35	64.24	93.13	62.71	64.24	65.98	66.4	64.24	63.06
Chemicals	63.08	102.82	142.56	97.3	102.82	109.09	110.61	102.82	98.57
Power Coal	76.7	114.13	151.56	104.85	114.13	124.68	127.23	114.13	106.98
Refining	76.39	116.13	155.87	107.47	116.13	125.98	128.35	116.13	109.45
Iron Steel	86.31	119.83	153.36	107.36	119.83	134.02	137.44	119.83	110.21
Beccs	81.91	120.98	160.05	110.85	120.98	132.49	135.27	120.98	113.17
Waste	95.01	134.08	173.15	120.86	134.08	149.11	152.74	134.08	123.89
Cement	100.67	135.79	170.92	120.3	135.79	153.4	157.65	135.79	123.85
Blue H2	102.51	139.48	176.46	123.99	139.48	157.09	161.34	139.48	127.54
Power Gas	97.3	144.07	190.85	132.13	144.07	157.64	160.92	144.07	134.87

CO_2 Capture costs ($/t CO_2)	Capture Efficiency (%)			FID taken (Year)			CAPEX Overrun (%)			Project Lifetime (Years)		
	85	90	95	2024	2027	2030	10	25	40	15	20	25
Gas Processing	64.62	64.24	63.9	65.16	64.24	63.12	63.46	64.24	65.02	64.82	64.24	63.94
Chemicals	104.19	102.82	101.59	113.12	102.82	96.22	100.02	102.82	105.62	104.9	102.82	101.74
Power Coal	116.44	114.13	112.07	129.04	114.13	107.81	109.42	114.13	118.85	117.63	114.13	112.31
Refining	118.28	116.13	114.2	119.18	116.13	112.14	111.73	116.13	120.53	119.39	116.13	114.43
Iron Steel	122.94	119.83	117.06	128.1	119.83	113.3	113.5	119.83	126.17	124.53	119.83	117.39
Beccs	123.5	120.98	118.73	127.12	120.98	117.96	115.84	120.98	126.12	124.79	120.98	119
Waste	137.38	134.08	131.14	146.09	134.08	128.46	127.37	134.08	140.8	139.06	134.08	131.49
Cement	139.65	135.79	132.34	146.2	135.79	127.57	127.93	135.79	143.66	141.62	135.79	132.76
Blue H2	143.34	139.48	136.03	149.89	139.48	131.27	131.62	139.48	147.35	145.32	139.48	136.45
Power Gas	147.04	144.07	141.41	161.74	144.07	136.45	138.01	144.07	150.14	148.57	144.07	141.73

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