October 2024

Institute for Energy Economics and Financial Analysis

Carbon Capture and Storage: Europe's Climate Gamble

Too Complex, Too Expensive, and Too Late To Support Net-Zero Targets

Andrew Reid, Energy Finance Analyst

Contents

Figures

Key Findings

Europe's bet on carbon capture and storage (CCS) to reach net zero is too reliant upon theoretical and unproven technical solutions.

The technology readiness levels of CCS across sectors targeted for decarbonisation are at the prototype or demonstration phase. This, combined with the trend towards project clusters, increases delivery risk.

CCS costs are prohibitive. Europe's current project pipeline could cost as much as €520 billion and require €140 billion of government support to capture and store a proportion of longer-term targets.

The economic, technical and legislative complexity of CCS is extremely high, which will likely lead to project delays, cancellations and underperformance.

Executive Summary

As countries across the European Union (EU) and the UK race to become carbon neutral by the middle of the century, carbon capture and storage (CCS) has become a core pillar of the largest emitters in the region. The combined official targets of the EU and UK currently aim to capture and store 554 million tonnes of carbon dioxide ($MtCO_2$) per annum by 2050, or 13% of the EU’s total 2022 emissions plus almost a quarter of the UK’s.[1] If these are to be met, the successful implementation and scale-up of CCS is now critical.

While CCS projects have been in operation since 1971, primarily supporting production operations within the oil and gas sector, their application across other industrial sectors is unproven. This presents a major risk to the ambitions of European nations, which are now reliant upon CCS application across multiple emissions-intensive sectors. These proposed uses typically have few or no current projects or test cases, lack supporting legislation or standards and are too expensive to work on a commercial basis. On top of that, they envisage an exceptionally complex value chain that relies on many technically and economically challenging individual projects to work simultaneously in project clusters.

The scale of the technical, economic, legislative and project risks presented by CCS are significant. Our analysis shows that while there are just under 200 potential projects across Europe that aim to capture and store over 150 $MtCO_2$ per annum, over 90% of the proposed emissions capture is from projects that are only at the prototype or demonstration stage.[2]

Costs are also prohibitive. The cost of capture, transportation and storage across European projects averages US$198 per tonne of CO_2 captured, or twice that of forecast carbon prices of US$105 per tonne over the balance of the decade. With insufficient economic incentive to implement CCS, owners of industrial emissions infrastructure will be reliant upon government subsidies to progress potential projects. This could mean as much as €140 billion is required from the taxpayer.

Our concerns about technical feasibility and costs are evidenced by the small number of European projects in operation or under construction. For example, costs at a construction project in the Netherlands have more than doubled, while a carbon capture unit at a cement factory in Norway has had to be postponed because of cost increases. Offshore carbon storage facilities in Norway, often championed as success cases, have been plagued with technical issues that have prevented or delayed storage capacity. What we are currently witnessing across active European CCS projects is that the technical and economic challenges are real.

We are far off the technical, commercial and legislative challenges being addressed successfully. CCS in its present form is not likely to work as hoped, cost more and, importantly, take much longer to implement than planned. The proposed timelines of European projects are already baked with

[1] European Commission Industrial Carbon Management Strategy and the UK Climate Change Committee’s Sixth Carbon Budget.
[2] Using data from the International Energy Agency’s (IEA) CCUS Projects Database and its Energy Technology Perspectives.

optimism despite the obvious challenges and recent history of failures across the smaller, less complex projects in operation and under construction.

This is the biggest risk that championing CCS presents—the likelihood that it may be too late to change track and mitigate or reduce emissions through alternative measures when it is finally realised that the CCS contribution to net-zero targets will fail.

About Carbon Capture and Storage

Carbon capture, utilisation and storage (CCUS) refers to a suite of technologies that capture carbon from large sources, such as power generation facilities or industrial plants that use fossil fuels or biomass as fuel. The captured carbon is then used on-site or at another location—this is the utilisation or the "U".

If the carbon is not utilised, we refer to this as carbon capture and storage (CCS). In this scenario, the carbon is compressed and transported by pipeline, ship or rail to be injected into deep geological formations. These are either depleted oil and gas reservoirs or saline aquifers, which trap the carbon dioxide (CO_2) for permanent storage.[3]

Historically, the economic justification for CCUS has centred around supporting oil and gas operations. Carbon capture is used to aid fossil gas processing by removing CO_2 from gas with relatively high concentrations of CO_2, a requirement to market and sell the gas. The other application is to inject the CO_2 back into oil reservoirs to provide artificial lift to support increased oil production, referred to as enhanced oil recovery (EOR).

CCUS applications have been in existence for many decades, primarily for EOR. The first facility was the Terrell Natural Gas Processing Plant in Texas, U.S., which opened in 1972 to capture and use CO_2 for EOR at a nearby oilfield.[4] There are presently 47 commercial facilities in operation globally, capturing 50 million tonnes of CO_2 ($MtCO_2$) per annum, of which 73% is being used for EOR.[5]

In the days before carbon taxes and climate action, there was little discussion or wider application for CCS across power generation or industrial processes. Put simply, there was no economic or climate incentive to manage or reduce carbon emissions from fossil fuel combustion.

Today, many governments have committed to reducing their carbon emissions, with 196 signatories to the Paris climate accord, a legally binding international treaty on climate change to limit global warming.[6] This, coupled with the introduction of net-zero policies across many governments and the

[3] IEA. Carbon Capture, Utilisation and Storage. October 2022.
[4] National Petroleum Council. Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage. December 2019.
[5] IEA. CCUS Projects Database. 2024.
[6] United Nations. The Paris Agreement: What is the Paris Agreement?

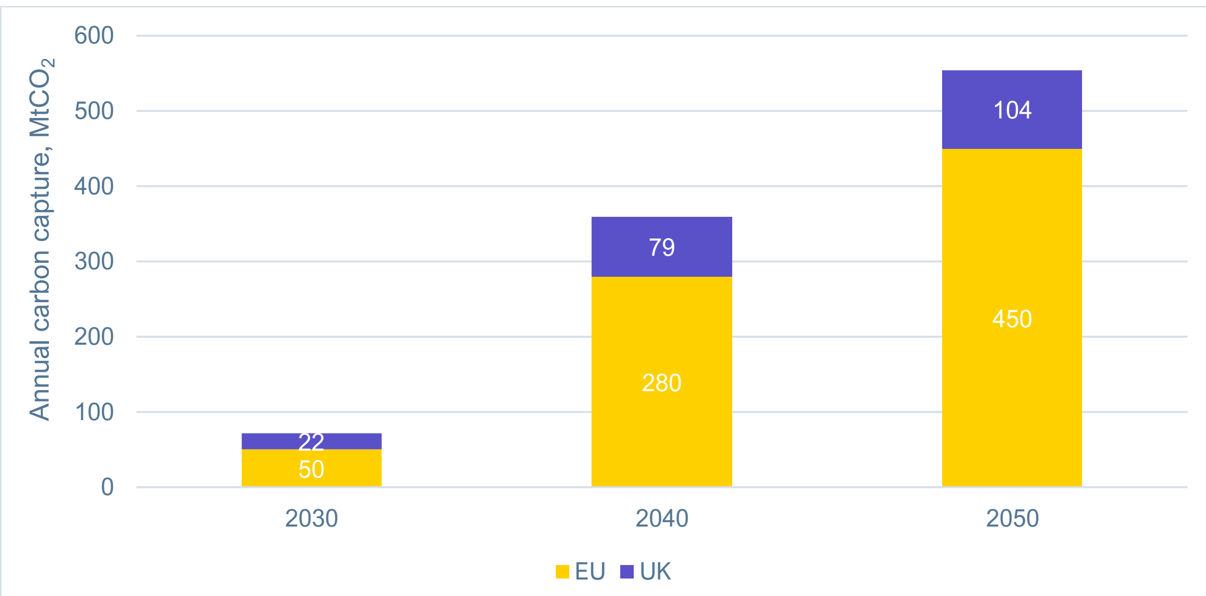
continued and growing use of carbon taxes, now provides political and economic stimulus for increased rollout of carbon capture projects.

Europe's Increasing CCS Reliance

The 27 member states of the European Union (EU) and the UK aim to be net zero by 2050. CCS is being championed as a core pillar of their emissions reduction strategies.

In February 2024, the European Commission introduced the EU's Industrial Carbon Management Strategy, which sets an annual carbon capture target of 450 MtCO_2 by 2050,[7] or 13% of the bloc's 2022 emissions.[8] The UK by comparison is more ambitious. In the Sixth Carbon Budget developed by the Climate Change Committee, the country has a target of 104 MtCO_2 captured per annum by 2050,[9] which accounts for 24% of its 2022 emissions.[10] While EU countries and the UK have significant targets for the middle of the century, it is expected that these will gradually build over the coming 25 years, starting from a shorter-term combined target of 72 MtCO_2 in 2030.

Figure 1: Planned Capture Volumes of European CCS Projects Announced 2016-2024 Year to Date



Source: EU Industrial Carbon Management Strategy and UK Climate Change Committee's Sixth Carbon Budget.

Despite the large reliance on CCS within Europe, CCS as an emissions reduction solution is very much in its infancy. Of the 50 MtCO_2 captured globally per annum, there are only five operational

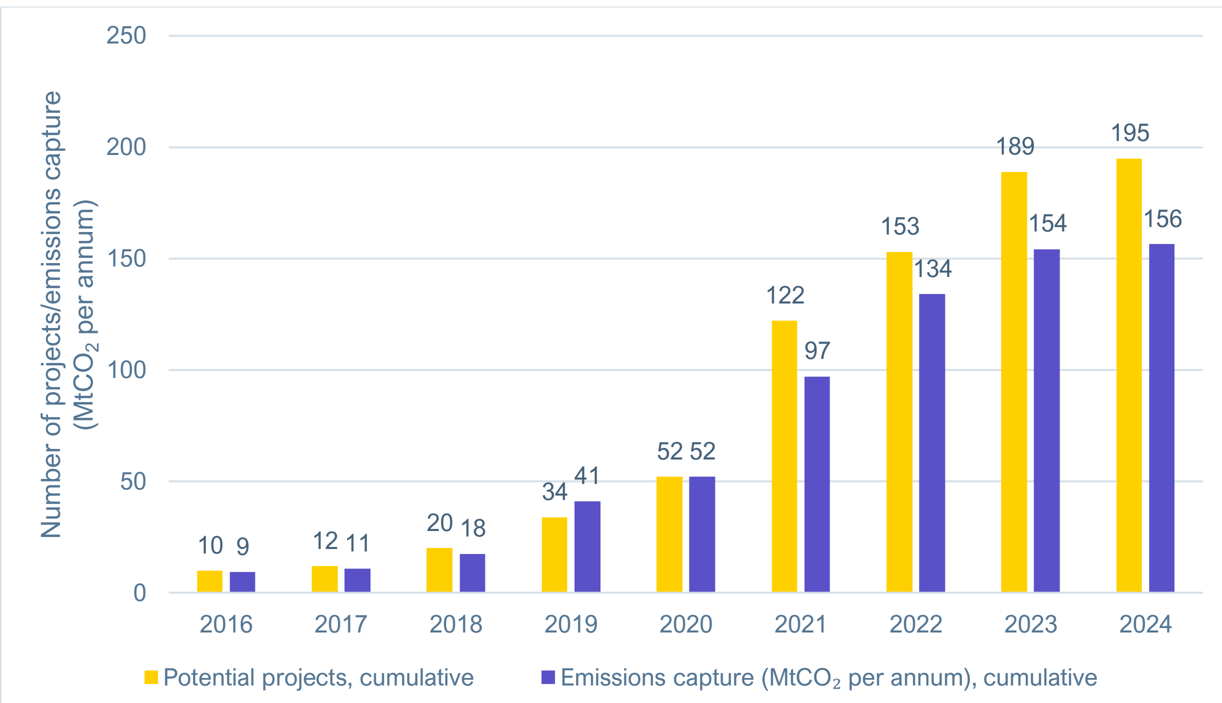
[7] European Commission. Towards an ambitious Industrial Carbon Management for the EU. 6 February 2024.
[8] EDGAR database and IEEFA analysis.
[9] UK Climate Change Committee. Sixth Carbon Budget. 9 December 2020.
[10] EDGAR database and IEEFA analysis.

projects in Europe, which capture a total of 2.7 $MtCO_2$ per annum. Of this, 1.7 $MtCO_2$ (63% of the total) is for natural gas processing in Norway, a country outside of the EU. CCS operations within EU countries amount to 1 $MtCO_2$ across three projects: a refinery in the Netherlands and two very small projects totalling 0.3 $MtCO_2$ in Belgium and Hungary.[11] For the EU and UK to meet their 2030 target of capturing 72 $MtCO_2$ per annum, there is a requirement to add 1.5 times current global capacity from what is effectively a standing start.

Europe's CCS Projects

In parallel with the increased support for CCS as an emissions reduction solution, the number of potential project announcements has also grown over the past eight years. Since 2016, the number of potential projects across the European Economic Area and the UK has increased 20-fold to just under 200, with a total target capture capacity of 156 $MtCO_2$ per annum.[12] Of the 195 projects in the hopper, 11 capture projects are currently under construction, which propose to capture a total of 4.6 $MtCO_2$ per annum.

Figure 2: European CCS Announced Projects 2016-2024 Year to Date



Source: IEA CCUS Projects Database and IEEFA analysis.

[11] IEA. CCUS Projects Database. March 2024.
[12] IEA. CCUS Projects Database. March 2024.

Assuming the projects under construction proceed as planned and successfully capture the emissions they propose, Europe will still rely upon many projects receiving final investment decision and progressing to construction within the next five years to meet the EU and UK's 72 $MtCO_2$ target by 2030. In effect, over half of the proposed projects, or a further 90, will need to proceed and be operational before the end of the decade. This is a massive challenge, especially when considering the technical and economic issues experienced at projects under construction to date.

The Success of Two Storage Projects Is Key

Of the 11 capture projects under construction, two plan to use the CO_2 for industrial applications, one project's CO_2 destination is unknown, while the other eight will be tied to one of two new storage facilities being developed. These two main storage projects will inject the CO_2 captured from several industrial emissions sites across Europe. The first to be completed will be Norway's Northern Lights project, which is due to come onstream in 2025. The second is the Porthos project in the Netherlands, due to be completed in 2026.

The Northern Lights project plans to inject CO_2 into a depleted oil and gas reservoir 100 kilometres offshore. The CO_2 will be captured from industrial sites, liquefied and transported by custom-designed ships and stored temporarily at the receiving terminal, before being piped to the storage site offshore.[13] The project is presently in its first phase and aims to store 1.5 $MtCO_2$ per annum, initially from two industrial sites within the Oslo-fjord region, as part of the Longship project.[14]

While Northern Lights has yet to be completed, it has already run into issues at the capture sites and timing delays. Initially, the project was due to be completed in late 2024, but this has been pushed back to 2025. Economic issues have plagued the Celsio waste incineration plant at Klemetsrud, which had planned to capture 400,000 tonnes of CO_2 per annum. The project is currently on hold due to "a sharp increase in the price of equipment deliveries, geopolitical instability, and a reduced exchange rate".[15] This has forced a budget and cost review, with no indications of when it may resume or be completed.

This is a concern given the already huge cost of the Northern Lights and Longship projects. According to research firm Wood Makenzie, the expected capture, transportation and storage costs of both projects are estimated to be US$253 per $MtCO_2$. Capture costs alone are estimated to be US$108 per $MtCO_2$, while transport costs are US$87 $MtCO_2$ and storage US$58 per $MtCO_2$.[16] Total capital expenditure is expected to be US$1.9 billion, with running costs of US$93 million per annum, to effectively capture and store 2% of Norway's 2022 emissions. With European carbon pricing

[13] Northern Lights. What we do.
[14] Northern Lights. About the Longship project.
[15] Hafslund Oslo Celsio. Karbonfangstprosjektet på Klemetsrud gjennomfører en kostnadsreduserende fase. 26 April 2024.
[16] Wood Mackenzie. 2023 CCUS Cost Update: factors affecting levelised cost (LCOCCUS) to 2030 and beyond. 29 March 2023.

expected to average €95 per tonne over 2021-2030,[17] the Northern Lights project is uneconomic and relies heavily on government support for ~80% of the costs associated with it.[18]

The Porthos project in the Netherlands is also beset with issues. Porthos plans to transport some 2.5 $MtCO_2$ from the Port of Rotterdam by pipeline each year, to be stored in an empty gas field 20 kilometres off the coast.[19] The carbon is intended to be captured across several industrial sites around the Rotterdam area. While costs were expected to be around half that of the Northern Lights project at €500 million for transport and storage, they have risen to €1.3 billion over the past five years[20] due to inflation and material price rises.

The CCS Pipeline's Technical and Economic Risk

As CCS application within the oil and gas industry has existed for many decades, the capture technology is relatively mature for natural gas processing and some chemical applications. This historic use for these applications should not be confused with CCS technology readiness more generally. The technology readiness level (TRL) of carbon capture across other industries, transportation and storage is much less mature.

The International Energy Agency (IEA) uses a scoring system from one to 11 to determine the TRL status, where one is at the concept stage and initial idea and 11 is a mature technology with proof of stability. A review published in September 2020 identified that most CCS applications have a TRL status of nine or lower.[21] At the higher end of the scale, hydrogen and ammonia production have a TRL of nine, are in the early adoption phase and are commercially available, although requiring improvement to stay competitive. While hydrogen projects make up around a quarter of CO_2 to be captured by proposed European projects, other large industrial sectors—namely cement, and power and heat—have much lower TRLs.

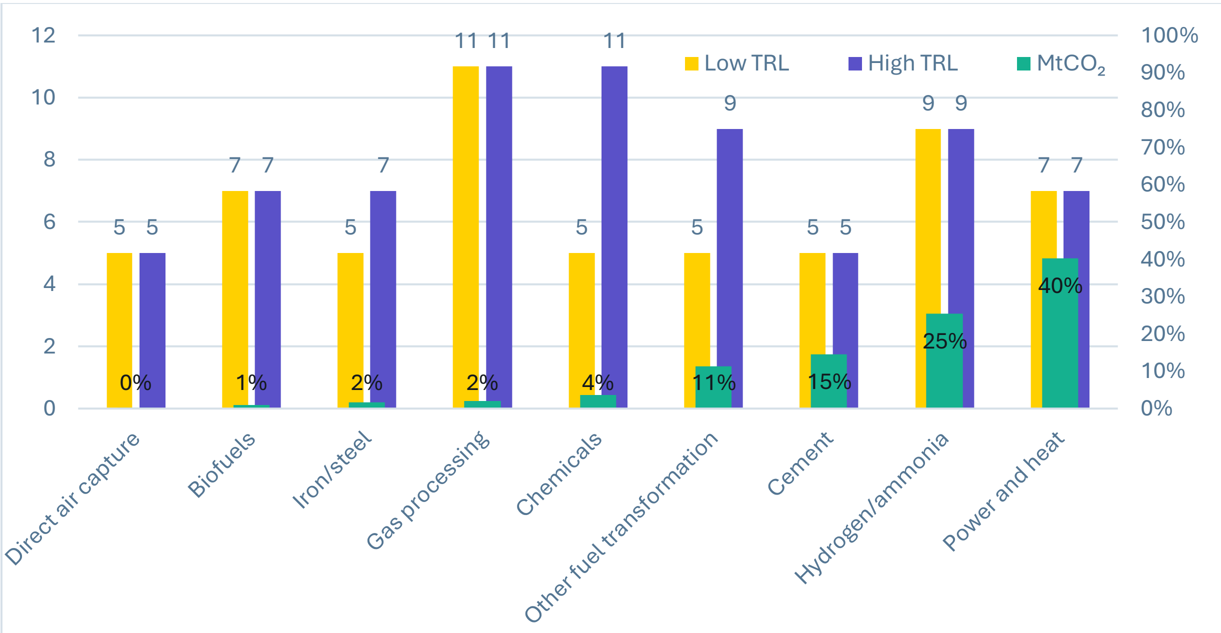
> **Put simply, most potential carbon capture applications within Europe are nowhere near being technology-ready.**

Some 40% of European projects' emissions will come from the power and heat sector, which has a TRL of seven and remains in the demonstration phase and pre-commercial. A further 15% of emissions are expected to come from the cement sector, which has a TRL of five, or the large prototype stage. The "other fuel transformation" category, which includes refineries, will account for 11% of emissions. It has a TRL between five and nine, depending upon the specific application. In total, over 90% of proposed project emissions are expected from sectors where technology and

[17] BloombergNEF. EU ETS Market Outlook 1H 2024: Prices Valley Before Rally. 1 May 2024.
[18] Gassnova. The Norwegian Full-scale CCS project.
[19] Porthos. Project.
[20] Dutch News. Dutch carbon capture project Porthos soars in price. 8 March 2024.
[21] IEA. Energy Technology Perspectives 2020.

commercial applications remain at the prototype or demonstration phase. 66% of the proposed emissions capture is in sectors with a low TRL of seven or below. Put simply, most potential carbon capture applications within Europe are nowhere near being technology-ready.

Figure 3: European CCS Project Emissions by Sector and Technology Readiness Level



Source: IEA and IEEFA analysis.

Technical and commercial risk surrounds most carbon capture applications. The same is true for transport and storage. A TRL of 11—where a technology is mature and has proof of stability—exists for CO_2 pipeline transportation and for storage in EOR operations. As we have noted, however, the future of CCS is for applications outside the oil and gas sector. As such, the technological readiness of the proposed European project pipeline is much lower.

In terms of transport, many of the proposed European projects such as Northern Lights plan to use ships to transport CO_2 from ports or directly to offshore storage projects. The TRL for these operations ranges from five to seven presently. On the storage front, injection into depleted oil and gas reservoirs, which makes up most of the proposed projects across Europe, has a TRL of seven, the pre-commercial demonstration phase.

There is the added uncertainty that projects fail to deliver on their expected emissions capture. Across industrial sectors, it is often expected that capture will be 90-95% effective, albeit this has often not been the case. In a previous IEEFA study of 13 projects across natural gas processing, power and the industrial sector, only three performed to capacity, with the highest capture rate being

83%. Three projects failed outright, five underperformed materially to their own targets and two refused to publish any data.[22]

Project performance across storage is also worrisome. Both of Europe's operational offshore storage projects, the Equinor-owned and -operated Sleipner and Snøhvit facilities offshore Norway, have had their technical challenges.

At Sleipner, large quantities of CO_2 unexpectedly migrated upwards from the reservoir, which was fortunate to be geologically bounded—had it not, there was a risk the CO_2 could have escaped. At Snøhvit, the targeted formation within the reservoir was supposed to have 18 years of planned capacity. However, 18 months into operations, pressure rose unexpectedly. Storage was suspended while an alternative storage site had to be drilled,[23] effectively forcing the operator to create a new storage area.

These projects are often championed as proof of offshore storage and will factor in the IEA's upper 11 TRL. While the oil and gas sector has over a century of experience extracting fossil fuels from high-pressure and high-temperature reservoirs, reinjecting gases for permanent storage is still very much in its infancy and will remain so for some time.

Every oil and gas reservoir is different, with unique characteristics that change with intervention. Learnings from one project will not necessarily be relevant for the next. Despite Equinor's extensive oil and gas sector experience, at Sleipner it was lucky, while Snøhvit's additional well would have cost tens of millions of dollars. Considering these operational sites total only 1.7 $MtCO_2$, or 2% of Europe's proposed 2030 storage ambitions, there are likely to be many more technical challenges and cost increases to come.

The Economics of CCS

Actual cost estimates for CCS projects vary considerably, and most are unavailable in the public domain. By referencing the National Petroleum Council, the IEA and Wood Mackenzie, we have created an average expected cost per tonne of CO_2 across each industrial sector for capture and average costs for offshore transport and storage.

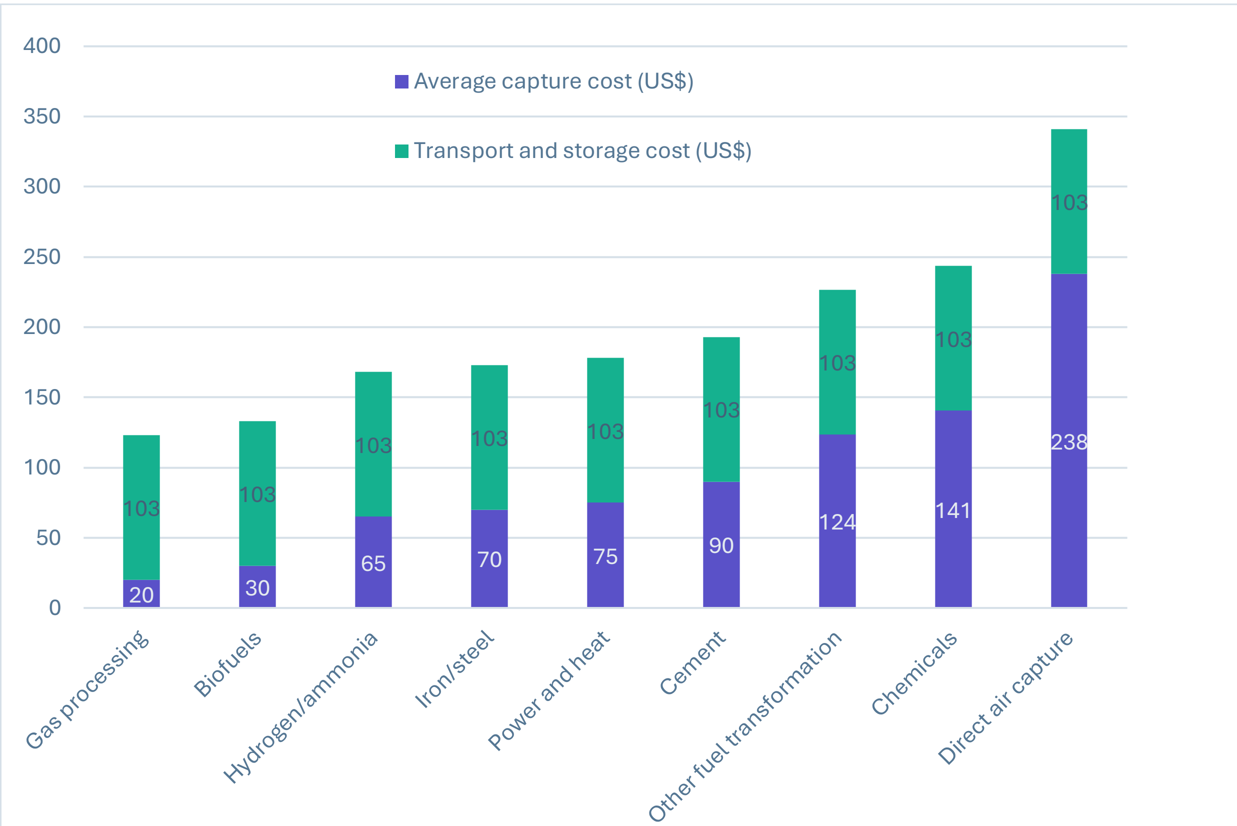
Even if we were to bullishly assume that capture will be effective and reach the 90-95% rates proposed by most projects, the total cost of capture, transport and storage is high. Capture costs vary due to the percentage of CO_2 contained in the exhaust gases post-combustion. For natural gas processing, ammonia and ethanol production, the average CO_2 exhaust percentage is 98%, which makes it less intensive and lower cost to capture. Other sectors such as cement, power generation

[22] IEEFA. Fact Sheet: Carbon Capture and Storage (CCS) has a poor track record.
[23] Ibid.

and refining have rates below 20%,[24] making it more technically challenging, energy intensive and costly to abate.

In relation to transport and storage, Europe's reliance on depleted offshore oil and gas reservoirs will be expensive. Due to the logistical and technical challenges of creating and operating infrastructure in a marine environment, costs are on average 294% higher than onshore.[25] When the average costs of capture, offshore transportation and storage are combined, the cost of CCS per tonne ranges from US$123-341. Lower capture costs of US$30 per tonne or below are in evidence across gas processing and biofuels. At the other end of the scale, direct air capture averages US$238 per tonne due to the difficulty of processing CO_2 from air and the energy intensity required.

Figure 4: Average Capture, Transport and Storage Cost per Tonne of CO_2



Source: National Petroleum Council, IEA, Wood Mackenzie and IEEFA analysis.

The implications here are significant. With such high costs, there is insufficient economic incentive for firms to decarbonise without further government support. EU carbon prices are expected to average €95 or $103 over 2021-2030,[26] much lower than the average cost of CCS across all

[24] National Petroleum Council. Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage. 12 March 2021.
[25] Wood Mackenzie. What's shaping CCUS project costs? 2 May 2023.
[26] BloombergNEF. EU ETS Market Outlook 1H 2024: Prices Valley Before Rally. 1 May 2024.

industrial sectors. Arguments are often made that the average cost of CCS will reduce over time because of scale, improved financeability, and better engineering designs and performance.[27] While this may be the case, the relative infancy of CCS and the technical immaturity and challenges that plague current projects point to increased costs in the short term. Efficiencies will not be easy to achieve. As we have seen, the cost of CCS is more likely to remain high, if not increase, in the short to medium term.

For the UK and other European countries to ensure CCS projects are progressed in the short to medium term, additional subsidies and financial support will likely be required. Our high-level analysis of the potential cost of the current European project hopper is €520 billion.[28] This figure is based on the average cost per tonne of CO_2 captured, transported and stored within each sector over a 20-year project life. Assuming financial incentives in the form of reduced emissions trading system (ETS) payments support investment in projects, this would cover 73% of the expenditure. This suggests the balance of €140 billion would need to be some form of financial support mechanism provided by governments or other stakeholders.[29]

A Lack of Supporting Legislation and Complex Project Risk

In addition to the clear technical and commercial challenges that surround CCS, there are also insufficient industry standards, policies and legislation in place to guide and manage the numerous project interactions and technical and safety requirements required for a functioning CCS capability. This is especially the case within the EU where CCS development lags that of Norway and the UK.

The European Commission's Industrial Carbon Management Strategy, released in February 2024, concludes that presently:

- There is a lack of comprehensive regulatory framework across the entire value chain, notably for industrial carbon removals and certain CO_2 uses.
- The first businesses involved in building carbon value chains also face CO_2-specific cross-value chain risks, such as liability for leakages or the unavailability of transport or storage infrastructure.
- There is insufficient coordination and planning, especially in cross-border contexts.

[27] UK CCS Cost Reduction Task Force. The potential for reducing the costs of CCS in the UK. November 2012.
[28] Figure derived by applying the average cost of CO_2 capture, transport and storage across each industrial sector's proposed emissions capture over a 20-year project lifespan.
[29] ETS values are calculated using the S&P EU ETS real annual forecast price from 2024 to 2043. The 20-year capture, transportation and storage cost of €520 billion minus the potential ETS value assumes the €140 billion gap will require support to make projects economically viable.

On the first point relating to legislation, the report highlights that CO_2 emitters will need to rely on a functioning cross-border, open-access CO_2 network. Such a network currently isn't regulated by the EU, nor are there established accounting and liability rules in place. As CO_2 will be captured from different sources, there will also be a requirement for a quality standard. The report finds that overall, "a dedicated policy and regulatory framework will be necessary" to optimise the development of the carbon management market.[30] Given the early stage of CCS in the EU, the technology's complexity and the requirement to gain cross-border support for new policies, agreeing and implementing legislation will take time.

Perhaps the most challenging component of the infant CCS industry relates to the required value chain interactions. The complexity of solving these issues should not be underestimated. Most full-cycle CCS projects—those that capture CO_2 from various industrial sites and then transport it to a port or pipeline to be injected and stored subsurface—will involve many interactions. There will be capture sites in different locations, across different industrial sectors, using different technologies and involving many project owners. As we have noted, these technologies will be applied at varying costs, will have varied TRL levels and most likely will not capture the proposed CO_2 levels.

The challenge of establishing commercial models and legislation to manage these interactions is enormous, while also adding to the already high risk of any single project. A CCS cluster reliant upon a certain volume of CO_2 being captured daily, weekly or annually from various sites—each with different CO_2 quality streams, reliability levels, and financial and operational strengths—substantially increases the risk that capture volumes will not be as intended.

Lower volumes will in turn impact the economics and commercial viability of transport and storage operators. Similarly, a failure or outage at the transport or the storage site, as we have seen at the Sleipner and Snøhvit facilities, would effectively render the capture obsolete. With nowhere to store the captured CO_2 and with no alternative options, what will effectively happen is eye-wateringly expensive emissions releases.

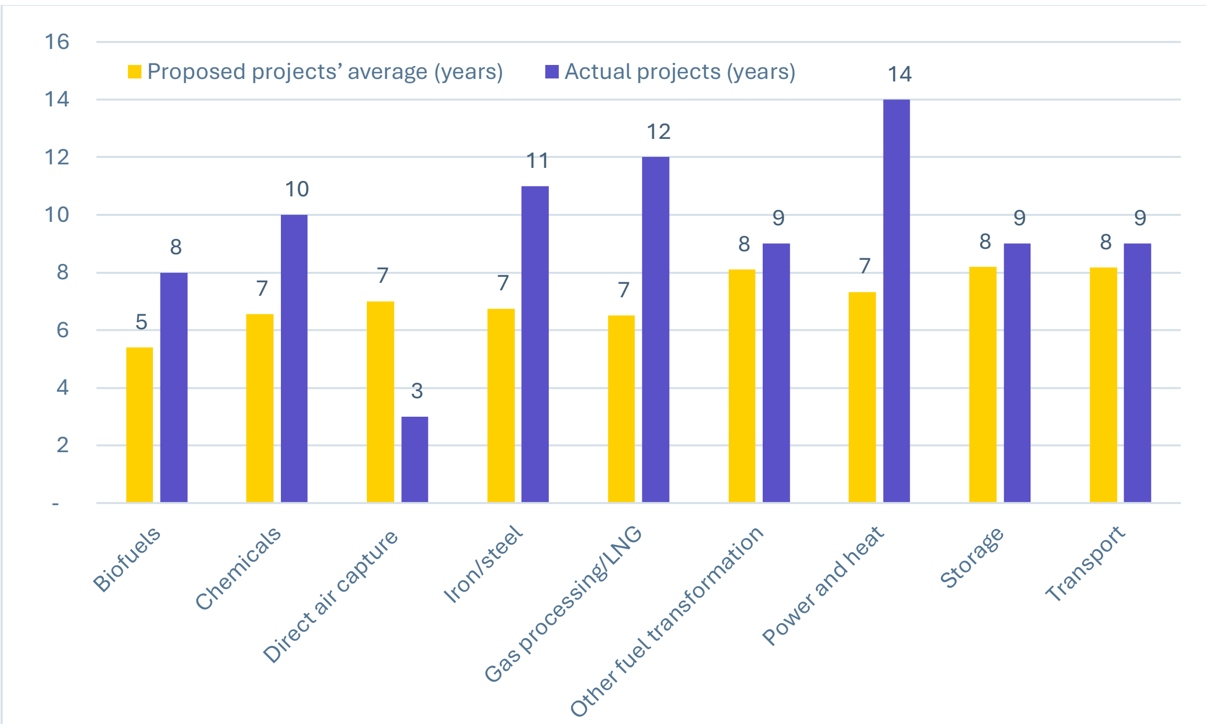
Do We Have the Time?

A paper produced by the NASA Ames Research Center concluded that it would take over 20 years and cost an estimated US$500 billion to achieve the first human mission to the planet Mars.[31] If there's enough money and enough time, then theoretically anything is possible. In the real world, however, we are far off CCS's technical, commercial and legislative challenges being addressed successfully. In its present form, CCS is not likely to work as hoped and is likely to cost more and, importantly, take longer to implement than expected.

[30] European Commission. Towards an ambitious Industrial Carbon Management for the EU. 6 February 2024.
[31] NASA Ames Research Center. Humans to Mars Will Cost About "Half a Trillion Dollars" and Life Support Roughly Two Billion Dollars. July 2016.

The proposed timelines of European projects are already baked with optimism despite the obvious challenges and recent history of failures across the smaller, less complex projects in operation or under construction. The IEA database reveals that across industrial sectors, proposed CO_2 transport and storage projects are expected to reduce their development and construction timelines by 28% on average compared with operational projects, excluding direct air capture. We understand that project managers at the start of an endeavour are full of optimism. However, can we really believe that CCS will deliver in a faster timeline? Clearly not.

Figure 5: European Proposed Project Timelines Versus Historical Projects



Source: IEA CCUS Projects Database and IEEFA analysis.

This is the biggest risk that championing CCS presents—the likelihood that it may be too late to change track and mitigate or reduce emissions through alternative measures when net-zero targets and the CCS contribution are realised to be at risk. Emissions reduction targets for 2030, 2035, 2040 and 2050 are at most only 26 years away. It also looks likely that EU and UK 2030 ambitions will not be met. Ideally, this should be enough for policymakers to realise that CCS is highly unlikely to meet its obligations as a pillar of net zero and begin working urgently to put alternatives in place.

About IEEFA

The Institute for Energy Economics and Financial Analysis (IEEFA) examines issues related to energy markets, trends and policies. The Institute's mission is to accelerate the transition to a diverse, sustainable and profitable energy economy. www.ieefa.org

About the Author

Andrew Reid

Andrew Reid is a partner at NorthStone Advisers and a guest contributor at IEEFA Europe, providing research and editorial support to offshore related topics and reports. Andrew has worked for over two decades across the global upstream industry in research and consulting roles with a leading investment bank, a big four advisory firm, and an independent boutique.

A graduate of both Aberdeen universities, Andrew holds an MA (hons) in Economics from the University of Aberdeen and an MBA from the Aberdeen Business School.