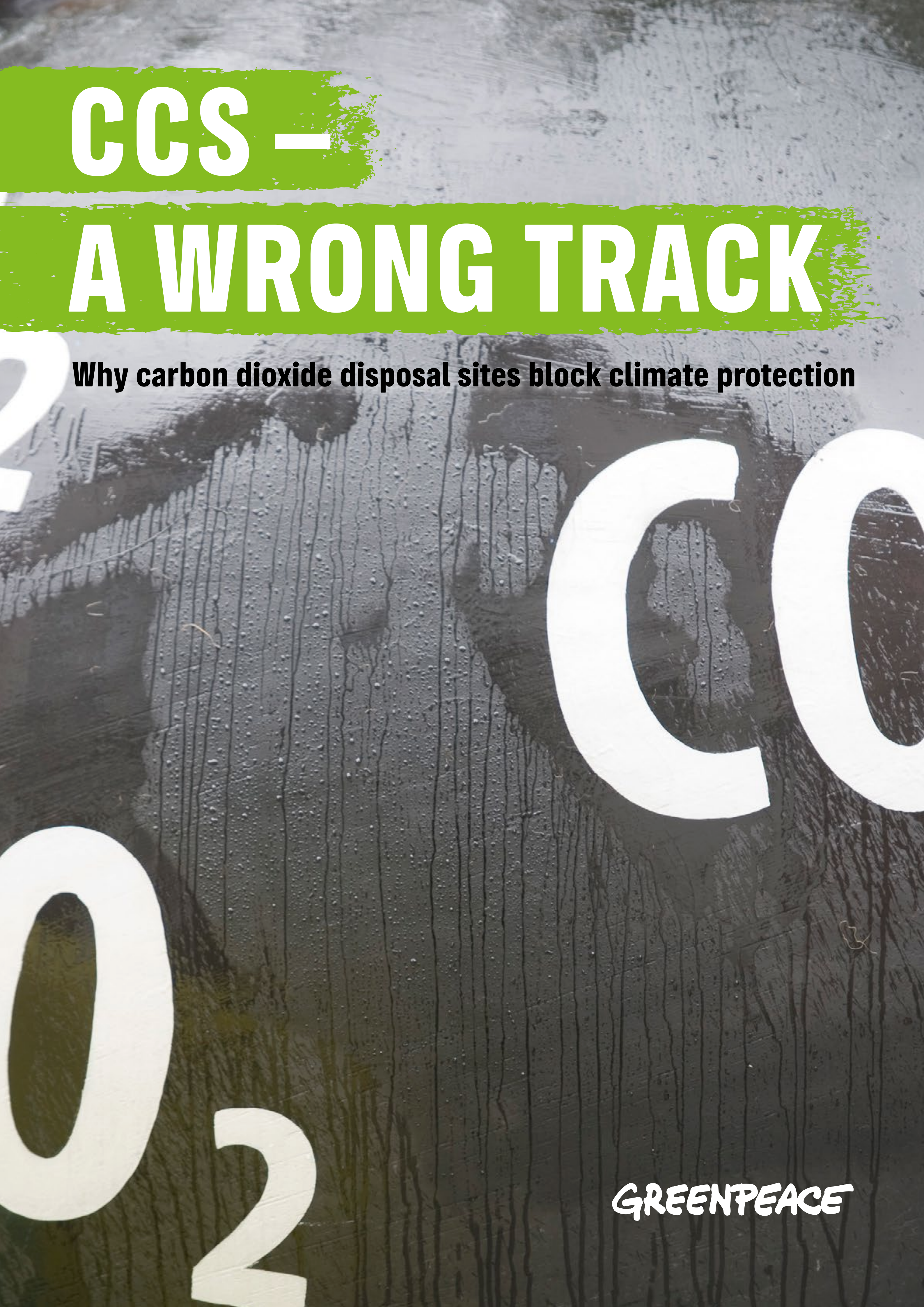

CCS – A WRONG TRACK

Why carbon dioxide disposal sites block climate protection

GREENPEACE

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Why carbon dioxide disposal sites block climate protection

Created by:
Dr. Steffen Bukold, EnergyComment Hamburg
On behalf of Greenpeace Germany

Translated from German to English by:
Julia James, Brandt + Team Communications,
Hamburg Germany

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Greenpeace e.V. Hongkongstraße 10, 20457 Hamburg, T 040 30618-0 **Press office** T 040 30618-340, F 040 30618-340,
presse@greenpeace.de, greenpeace.de **Political Representation Berlin** Marienstraße 19 – 20, 10117 Berlin,
T 030 308899-0 **Responsible for content** Anike Peters **Author** Dr. Steffen Bukold **Photo** Martin Langer (Titel)
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Executive summary

A. Unexpected comeback of the CCS approach

1. CCS — an acronym that has recently been embraced by the industry — stands for **Carbon Capture and Storage**: CO_2 is captured from emitters and then disposed of in underground storage facilities.

Climate policy in Germany is also planning to make CCS a central component, which will involve CO_2 pipelines and tankers to transport the greenhouse gas out of the country, mainly to Norway.

2. This is an unexpected comeback for a hitherto largely unsuccessful technology. Having failed countless times in the past, CCS was not supposed to be more than a stopgap in climate policy, left to deal with residual emissions from sectors with no obvious alternatives. CCS was then finally sidelined by the huge drop in the price of solar and wind energy, as well as many other climate-friendly solutions.

3. But for some industries, notably the oil and gas industry, CCS is now set to become a generously subsidised global lifeline. And that's not all: CCS is set to become a multi-billion-dollar business model over the next few years. Oil and gas companies will be able to make money not only from the sale of oil and gas, but also from the disposal of the resulting emissions.

B. A critical analysis of existing CCS projects

4. Can CCS deliver on these expectations? Little is known about the technical and geological background, and the number of realised CCS projects is surprisingly small. There are only a handful of major plants worldwide, and only two in Europe: Sleipner and Snøhvit. Both are considered best-practice examples of CCS working well. But is this assessment correct?

5. An in-depth analysis of these projects shows that CO_2 storage is associated with considerable risks, geological uncertainties, delays and unexpected project cancellations. Costs remain high and lengthy disruptions are commonplace. There is no progress without large government subsidies.

5.1 In the much-cited **Sleipner** CCS flagship project (Norway) in the southern North Sea, the injected CO_2 migrated to the sea surface much faster than expected and accumulated in a layer that the carefully developed geological models did not predict should exist ('9th layer'). Millions of tonnes of carbon dioxide (nobody knows exactly how much) are now migrating in several directions below the surface, looking for a way up. Fortunately, the injection of CO_2 will stop in a few years, as the neighbouring gas field (the original source of CO_2) is about to run dry.

5.2 Contrary to all predictions, the first attempt at disposal at the **Snøhvit** integrated CCS project (Norway) in the Barents Sea had to be cancelled because the pressure quickly rose to critical levels. So far, only the third attempt appears to be working.

5.3 In a similar geological situation, the CCS project in **In Salah** (Algeria) failed completely. For far too long, the project operators ignored the unexpectedly rapid increase in pressure in the CO_2 disposal site. The ground above the storage site lifted by several centimetres. Only at the last moment was the CO_2 injection stopped and the project cancelled.

5.4 Even after eight years, the huge integrated CCS project **Gorgon** (Australia) is still unable to dispose of the CO_2. In fact, the amount of carbon dioxide disposed of is actually decreasing as salt water and sand keep stopping the injection. If the project is not to fail completely, the oil and gas company Chevron will have to carry out relief and stabilisation wells.

But the real test for all CCS projects is yet to come. Will the CO_2 remain safely in the ground for 100 or 1,000 years?

6. So far, virtually all of the major CCS projects that aim to permanently dump carbon dioxide have only been used to **reduce the unusually high CO_2 content** of certain profitable natural gas reservoirs (Sleipner, Snøhvit, Gorgon, In Salah).

But there are also large low-CO_2 natural gas reservoirs. In other words, CCS only solves **problems that could have been avoided in the first place**. The benefits for climate protection are close to zero.

C. CCS: costly, unrealistic and, above all, too risky in terms of climate policy

7. CCS remains expensive. Without government support, no project could survive the early planning stages. If we go down the CCS route, instead of preventing climate change emissions in the first place, society will have to finance the disposal of those emissions on a permanent basis.

Comparisons with cost developments in the solar and wind industries are inappropriate. There has been no reduction in the cost of CCS projects in recent decades. In particular, CO_2 disposal cannot be standardised. Each project requires a costly analysis of the individual geology of the deposit and the development of a tailor-made solution.

Conversely, an increase in CCS activity is more likely to result in higher prices, given the limited number of specialist companies capable of undertaking these tasks and the lack of significant potential for expansion within a decade. As in other sectors, the gap between costs and prices is likely to persist.

8. The expansion of CCS in Europe, the US and Asia creates new, **risky dependencies for climate protection**, as this technology path allows industry to continue burning large amounts of coal, gas or oil.

It is clear that the CCS chain from industrial plant to CO_2 storage site will be subject to frequent disruptions. In addition to the disposal sites, the capture facilities, which use large amounts of chemicals that are harmful to human health, are considered particularly vulnerable. In addition, the construction of many kilometres of CO_2 pipelines will face considerable opposition, as demonstrated by the Porthos project in the industrial region of Rotterdam and the failed pipeline projects in the US.

Given the significant volumes of CO_2 that need to be transported and disposed of on a daily basis, buffer storage facilities can quickly reach capacity in the event of a disruption. In such cases, emitters are forced to vent the CO_2 into the atmosphere or cease operations.

9. **Unrealistic dimensions**: To store just 10 per cent of the fossil CO_2 emitted globally in 2022, 3,300 functioning Sleipner projects or 670 Northern Lights projects (Phase II) would have to be implemented worldwide.

It is not possible to achieve this scale in the near future, neither technically nor economically. Moreover, the CCS projects planned to date, regardless of their chances of being realised, do not even come close to the volumes that are relevant for climate policy.

Over-optimism about CCS will therefore lead to a climate policy trap. The development of CCS infrastructure, CO_2 disposal sites and capture facilities will be so slow and fragile that the fossil economy will not be able to reduce its emissions and will be far too slow to invest in low-emission production methods and products.

10. **Environmental risks**: The German government's recent assessment report on CCS lists numerous environmental risks posed by CCS for which no safe solution is in sight, ranging from hazardous chemicals used in capture facilities to potential leaks in CO_2 pipelines. Carbon dioxide can also cause damage to the marine environment. Biodiversity in affected areas is declining rapidly.

Another factor is that the risk of earthquakes increases when very large amounts of CO_2 are injected - a phenomenon that has been occurring regularly in the US for years when water is injected into reservoirs. The quakes can cause cracks in the cap rock of the CO_2 reservoirs, opening the way to the surface. It is not at all clear how the operators of CO_2 repositories will be able to deal with such problems.

Major earthquakes can also put CO_2 disposal sites at risk. Since 1900, there have been 79 earthquakes in Norway with magnitudes between 4.0 and 6.1, some of which have occurred in the immediate vicinity of existing or planned CO_2 storage sites. Last year alone, four major earthquakes occurred off the Norwegian coast.

11. **Conclusion**: There is no place for CCS in today's energy world. Solar and wind power, electromobility and batteries, green hydrogen and other electrolytically produced raw materials now offer more attractive alternatives for almost all industries.

The CCS route is too expensive, too slow and technologically immature. Above all, it is too risky. Without being able to mitigate it in terms of climate policy, it wants to extend the fossil path far into the future.

This reversal of roles is also evident in the few CCS flagship projects that have gone into operation: Sleipner (Norway), Snøhvit (Norway) and Gorgon (Australia).

In all three cases, the commercially attractive resource is natural gas with an unusually high CO_2 content. Until now, this carbon dioxide has simply been released into the atmosphere, where it damages the climate. In Norway alone, 124 oil and gas fields release 5.3 million tonnes of CO_2 each year.[Q20 — see list of sources in appendix].

Now companies are being celebrated and subsidised for capturing the greenhouse gas on site and dumping it in CO_2 disposal sites. In other words, they are solving problems of their own making by opting for particularly climate-damaging gas deposits. The climate benefit is close to zero, as only the CO_2 that was previously extracted from the ground is disposed of. The (cleaned) natural gas is then sold and produces just as many emissions as before.

The fossil fuel industry is in unanimous agreement that CCS has no future without massive state subsidies. In contrast to photovoltaics, wind power and batteries, CCS has remained expensive in recent decades.

As a result, the industry's message to the media is contradictory: on the one hand, CCS is presented as an attractive, low-risk climate solution that is technically feasible. On the other hand, government should bear most of the costs and provide guarantees because the technical challenges and economic risks are said to be incalculable.

This report

Assuming that government support is provided, can CCS ever meet expectations? So far, the number of CCS projects that have been realised is surprisingly small. Details are scarce in Germany.

So, what is the bottom line so far for the Norwegian showcase projects Sleipner and Snøhvit, and for projects outside Europe? Can CCS become a mainstream climate policy strategy?

This report presents the main CCS projects in detail, with a focus on projects in Norway. To date, Sleipner and Snøhvit are the only CCS projects in Europe.[2] Moreover, Norway is also at the centre of Germany's CCS hopes, with plans for Northern Lights or Smeaheia.

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[2] Germany has not yet seen any major CCS projects. The only project currently underway is a pilot project in Ketzin/Havel, where the disposal of CO_2 is being investigated. Around 67,000 tonnes of CO_2 were injected here by 2013. The project seems to have been forgotten about, as the site has not been monitored since 2017. It is therefore not possible to make any statements about the tightness.[Q42][Q67]

1. CCS: an overview

1.1 The current debate

What is CCS?

The acronym CCS (Carbon Capture and Storage) has recently become a topic of considerable debate within the fossil fuel industry, as well as in the political arenas of Berlin and Brussels. CCS encompasses two distinct processes: the separation and capture of CO_2 in industrial facilities or power stations and the subsequent disposal of the greenhouse gas in underground reservoirs (carbon storage).[1]

At first, the idea seems plausible: the climate crisis is primarily caused by CO_2 emissions from fossil fuels. So why not just capture the greenhouse gas and inject it back into the ground? That is, after all, where we got oil, gas and coal from. Then we could save ourselves the trouble of converting our industry, electricity, heating and vehicles. However, this superficial logic overlooks the huge effort and risks involved in the CCS route.

Political momentum

In earlier IPCC reports and climate protection scenarios, CCS was only a last resort for climate policy and the technology was to be reserved for industries that had no other way of becoming carbon neutral. But now it is about to become a lifeline for the fossil economy. At the last United Nations Climate Change Conference (COP 28), almost all oil and gas multinationals put CCS at the heart of their climate strategies. So, it's business like usual, with CCS soon to follow. However, the financing is to come largely from taxpayers' money.

CCS is currently being welcomed as a fundamental component of climate policy in both Brussels and Berlin. Even the Green party, which has been unequivocally opposed to CO_2 disposal sites, now wishes to support the technology. CO_2 pipelines to Denmark and, above all, Norway are to be used to transport the greenhouse gas out of the country. At the end of May 2024, the cabinet discussed a draft of the German carbon management strategy and an amendment to the Carbon Storage Act (KSpG) to pave the way for this.

Problem or solution?

Countries like Norway and oil companies like Equinor or ExxonMobil view the technology as a means of generating additional profits. The workbench is being extended to encompass not only the sale of oil and gas, but also the disposal of emissions generated by them.

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[1] Not to be confused with DAC, which stands for Direct Air Capture. This involves filtering CO_2 from the ambient air. Since CO_2 is only present in low concentrations in the atmosphere, the energy and engineering requirements for DAC are very high and have been extremely expensive to date. Furthermore, sufficient green electricity must be available at the site for the DAC system to generate a net benefit for climate policy.

1.2 Basic information: geology and CCS

Oil and gas production

It is a common misconception that oil and natural gas accumulate in underground lakes or caves. In fact, they are found in rock pores, which also contain salt water, sand or other gases such as CO_2. These pores are often interconnected in particularly permeable rock types (e. g. sandstone), allowing gases or liquids to migrate over long distances.

After drilling, the high temperatures and enormous pressures at great depths force these substances out of the pores of the rock and up to the surface. The pressure in the reservoir then drops and the pores are then filled with salt water or other substances from the surrounding rock regions.

CO_2 depositing and the supercritical state

For CO_2 injection (carbon storage), this process is reversed. First, high energy is used to compress the carbon dioxide into a supercritical state for transport and storage. In this state, CO_2 resembles a gel and has the properties of both a gas and a liquid, making it easier to transport or pump through a borehole.

For the greenhouse gas to remain in this compressed state, it must be stored at least 800 metres underground, where the temperature and pressure conditions are right to keep CO_2 in a supercritical state. Above these 800 metres, CO_2 can become a volatile gas that seeks its way to the surface at high speed.

In old gas fields or, more often, in saline aquifers that are highly permeable and contain large amounts of saline groundwater, the aim is to displace the water and other substances with the CO_2 that is injected at high pressure. This causes the pressure to rise, first around the borehole and then over a wider area.

This CO_2 mixes with the existing substances and some of it is gradually and permanently trapped in the pores of the rock by various forces (trapping forces). Over the centuries, the amount of immobile carbon dioxide increases. The rate at which this happens is unclear and varies from place to place.

However, significant amounts of CO_2 remain mobile for a long time and continue to migrate, generally upwards, as it is lighter than salt water. It is therefore necessary that the chosen disposal site has a completely impermeable cap rock to block the path of the gas to the surface.

Rock layers are usually not completely homogeneous. Their properties, such as pore size or permeability, can vary within a few metres. CO_2 disposal projects are therefore always likely to throw up unpleasant surprises.

If the rock is able to absorb and distribute significantly less CO_2 than expected, the pressure can rise above critical limits.

The stability of the cap rock determines how quickly and how much CO_2 can be injected. If the pressure becomes too high, the cap rock will crack, and the gas may be able to reach the surface.

In this case, the repository is no longer sealed, and CO_2 injection must be stopped. Additional wells can help by extracting water from the deepest layer of the repository and injecting it above the cap rock, reducing the pressure in the repository and improving the stability of the cap rock.

The way ahead looks black

Even today, geological analyses are little more than blind guesswork.

Drilling with sensors allows only selective measurements, while large-scale seismic surveys can only provide rough data. The old miner's saying, ‘It’s dark before the pickaxe’, applies equally to deep drilling.

In addition, any investigation is only a snapshot of a subsurface that is constantly in motion — especially when drilling or oil/gas extraction is taking place in the immediate vicinity of a proposed CO_2 disposal site. What appears to be a perfect seal today may show cracks a few years later. However, CO_2 disposal sites must remain stable for thousands of years to fulfil their purpose.

Even the most advanced methods have their shortcomings, as evidenced by the fact that the expensive exploration wells drilled by multinational oil companies often turn out to be dry holes after years of preliminary research, failing to find the large oil or gas reserves hoped for.

And the same applies vice versa: in a region off the coast of southern Norway that was considered to have been thoroughly explored, the third largest oil field in Norwegian history was discovered in 2010, completely unexpectedly: Johan Sverdrup. Today, it supplies almost 40 per cent of Norway's oil.

Seismic analyses: expensive and complex

Geological surveys are not only time-consuming but also very expensive. Only a handful of highly specialised companies in the world can collect the data and analyse it in painstaking detail, often over a period of years.

Modern exploration vessels cost hundreds of millions of dollars. Pulling kilometres of cable behind them, they use artificially generated detonations to gather as much information as possible from the reflection waves of the different layers of rock.

There are only a few dozen ships in the world capable of collecting data of the quality required for CO_2 disposal. As soon as larger regions need to be surveyed, the cost of these preliminary studies alone can be in the hundreds of millions.

Carbon capture — the separation of CO_2

Carbon capture in industrial plants or power stations is almost always carried out by amine scrubbing. These highly alkaline and extremely harmful substances absorb the CO_2 at low temperatures (around 40 degrees) and release it after heating (around 150 degrees). The amines can be reused after extensive treatment.

Throughout the CCS process (capture, compression, transport, disposal), capture typically accounts for the largest proportion of costs and the highest energy losses. CO_2 compression is also very energy intensive.[Q41]

The higher the CO_2 content of the flue gas, the easier it is to capture the carbon. This is why almost all CCS projects for gas and coal-fired power plants have failed: the CO_2 content of flue gas is particularly low. Capture is extremely expensive, and the plants often break down.

In other projects, too, the capture rate — the proportion of CO_2 that is captured — is regularly well below expectations.

But this does not have to be the case. Capture rates of over 90 per cent can be achieved with very high financial and energy input and under favourable conditions at the emission source (constant, high CO_2 content).

1.3 CCS projects worldwide

Development of the CCS technology path can be roughly divided into three phases.

(1) Originally, CCS was supposed to enable the decarbonisation of power plants. Coal would suddenly have become climate-friendly, and natural gas could have extended its path as a “bridge technology” indefinitely into the future. But CCS failed on all fronts. Almost all projects were abandoned due to technical or economic problems, or never got beyond the planning stage.

(2) CCS only gained momentum as the climate crisis worsened. However, CO_2 disposal was only intended as a solution for the “last mile”, i. e. for industries where low-emission technology paths were not in sight.

(3) In recent years, however, the fossil fuel lobby has managed to turn this stopgap measure of climate policy into a supposed lifeline for the oil and gas industry.

Faced with the pressure of the climate crisis and growing international competition in clean technology markets, the US, Europe, Australia, Japan and China are now offering industry huge subsidies.

At the United Nations Climate Change Conference (COP 28) in 2023, chaired, fittingly, by an oil executive, the motto was no longer ‘phasing out fossil fuels’ but ‘phasing out fossil emissions’. The business model of the oil, gas and coal industry is therefore to remain stable even after 2050. To achieve this, more than 10 billion tonnes of CO_2 would have to be stored each year. CCS could thus become the world's largest industry by volume and a huge new business for the fossil fuel industry.

One thing is already clear: CCS will go far beyond its original role as a niche solution. From the oil sands industry in Canada [Q50] to oil refineries, LNG projects and petrochemicals in the US, Europe and Japan, companies are taking action. And other sectors are jumping on the bandwagon: from the fertiliser industry (ammonia/urea) to waste incineration, CCS is being touted as a climate solution. CCS is now high on the agenda in most sustainability reports and long-term climate strategies.

Project overview

The project database of the International Energy Agency (IEA) from spring 2024 (15 March 2024) now lists 844 CCS projects of all kinds.[Q6] However, this number quickly shrinks on closer inspection:

1. Most of them are vague project proposals with no clear investment decision.

2. In terms of climate policy, many projects are irrelevant or even harmful, particularly those that use CO_2 only for enhanced oil recovery (EOR), in which CO_2 is pumped into an oil reservoir to force the raw materials to the surface. A significant proportion of the CO_2 is released again during production.[Q40] In many cases, the CO_2 used for EOR comes from natural sources, so it would never have reached the surface without oil production. In addition, transporting and compressing the CO_2 requires large amounts of energy, most of which comes from fossil fuels.

3. Another group of projects uses CO_2 for chemical processes (Carbon Capture an Utilisation, CCU). In most cases, the release of the greenhouse gas is only delayed and not prevented.

Once these categories are excluded, there are only nine projects already in operation that aim to permanently dispose of CO_2.[3] Two of these nine CCS projects are located in Europe (Sleipner, Snøhvit). Almost all of the large projects in this group are aimed at natural gas processing, i. e. cleaning CO_2-rich natural gas deposits. At the point of consumption (power plants, heating, etc.), the natural gas then generates just as many emissions as other natural gas supplies. This is where the gas industry creates the problem in the first place, i. e. by exploiting CO_2-rich gas deposits instead of concentrating on low-CO_2 gas deposits from the outset.

According to the IEA, this poor record is unlikely to improve by 2030. Much is being planned, but little is yet being implemented. Even major projects currently under construction, such as Northern Lights (Norway), will make little difference to the global emissions balance, with their small storage capacity of 1.5 million tonnes of CO_2 per year initially and 5 million tonnes of CO_2 per year planned later.[Q6]

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[3] The small-scale project Climeworks Orca (Iceland) is not included here due to its very small capacity of 0.004 million tonnes of CO_2 per year and its different technological approach (direct air capture from ambient air).

Table: Active CCS projects with CO2 disposal worldwide (IEA database)

Project name	Country	Partners	Start of Trade Fair	Capacity (Mt CO_2 per year)	Sector
Sleipner	Norway	Equinor, Eni	1996	1	Natural gas processing/ LNG
Snøhvit	Norway	Equinor, Petoro, TotalEnergies, Eni, Wintershall	2008	0.7	Natural gas processing/ LNG
Quest	Canada	CNRL, Shell, Chevron	2015	1 - 1.2	Other fuel transformation
Illinois Industrial CCS	United States	ADM	2017	0.5 - 1.1	Biofuels
Gorgon CCS	Australia	Chevron, Shell, ExxonMobil, Osaka Gas, Tokyo Gas, Chubu Electric Power	2019	3.4 - 4	Natural gas processing/ LNG
Qatar LNG	Qatar	QatarEnergy LNG, ExxonMobil	2019	1.23 - 2.1	Natural gas processing/ LNG
Red Trail Energy BECCS	United States	Plains CO_2 Reduction Partnership, Energy & Environmental Research Centre, Red Trail Energy	2022	0.18	Biofuels
CNOOC Enping offshore CCS	China	CNOOC	2023	0.3	Other fuel transformation
Midwest AgEnergy Blue Flint Ethanol	United States	Blue Flint Sequester Company LLC, Harvestone Low Carbon Partners, Ag Energy Group LLC	2023	0.2	Biofuels

Source: IEA [Q6]. Only realised projects that aim for permanent CO_2 disposal.

Planned sites and the race for subsidies

But it does not have to stay that way. Many countries and the EU are prepared to subsidise new CCS projects to the tune of billions of euros.[Q005] In Europe, CO_2 is mainly to be stored in saline aquifers or in old gas and oil fields in the North Sea.

The IEA database (*https://www.iea.org/data-and-statistics/data-tools/ccus-projects- explorer*) and CATF *(https://www.catf.us/ccsmapeurope/)* provide detailed information on all major projects.

In the UK, however, concerns are already growing. Subsidies for some major projects are to be stopped for the time being because the costs are too high.[Q42] In the Netherlands, too, the situation is unclear following the change of government.

2. CCS projects in Norway and worldwide

2.1 Sleipner — issues with CO_2 migration

In the CCS debate, one Norwegian project is repeatedly highlighted as the industry's gold standard: the Sleipner project in the southern North Sea. This project has even become the blueprint for the EU's CCS Directive (2009/31/EC), which relies heavily on its findings.[Q46]

Norway introduced high CO_2 taxes back in 1991. At the same time, Statoil (now Equinor) was developing the Sleipner gas field group, located 250 kilometres off the coast of southern Norway in the North Sea. Even then, Statoil was one of the leading companies in the offshore oil and gas industry. The company had more than 20 years' experience with the geological conditions in the North Sea.

Sleipner's gas reserves have an above-average carbon dioxide content of over 5 per cent. In order to be marketed to customers, this content had to be significantly reduced.

Until then, it had been common practice to separate the CO_2 and simply let it escape into the atmosphere. However, the new CO_2 tax made CO_2 disposal an attractive alternative. From 1996, almost 1 million tonnes of carbon dioxide per year were to be captured on site, compressed and dumped around 1,000 metres below the seabed.

Before the project began, extensive geological analysis was carried out: drilling, seismic surveys (artificial explosions that cause waves that the layers of rock reflect in different ways) or conclusions drawn from neighbouring regions.

In particular, the extensive seismic surveys refined the 3D models of the region. In the end, part of the large Utsira rock formation was selected as the best place to dump the CO_2. The formation is located 850 to 1050 metres below the sea surface and, according to the results of the analyses, consists of 8 layers.[Q1] It was therefore deep enough to keep the CO_2 in supercritical form thanks to the high pressure and suitable temperatures found there (see Chapter 1.2).

There are several layers of highly porous sandstone, each about 30 metres thick, separated by thin, more or less impermeable layers of shale (1 to 2 metres). On top of this is a very thick layer, which is thought to be impermeable, and which is supposed to block the rise of CO_2 to the sea surface.[Q35]

Drilling went from the sea surface to the Utsira formation at a depth of 1050 metres. From there, the borehole continued horizontally to create as much storage space as possible.

Despite initial problems, the capture technology, i. e. the separation of CO_2 from the extracted natural gas, worked quite reliably. The process is complex but relatively straightforward for this type of emission source and has been tried and tested in the natural gas industry for many decades. As a result, the amount of CO_2 that was not stored and emitted into the atmosphere remained relatively low over time (see table below).

Table: Amount of CO_2 released to the atmosphere (vented) from the Sleipner West CO_2 injection facility, 1996-2022

Year	Tonnes of CO_2	Year	Tonnes of CO_2	Year	Tonnes of CO_2
1996	81,000	**2005**	6,200	**2014**	5,400
1997	29,000	**2006**	2,500	**2015**	800
1998	4,200	**2007**	6,400	**2016**	4,600
1999	9,100	**2008**	13,600	**2017**	800
2000	8,300	**2009**	4,600	**2018**	1,600
2001	3,100	**2010**	900	**2019**	100
2002	87,600	**2011**	2,400	**2020**	1,200
2003	23,900	**2012**	5,900	**2021**	2,100
2004	21,400	**2013**	5,000	**2022**	300

Source: Norwegian Environment Agency [Q37]

What proved problematic, however, was the injection of CO_2 underground. A further 3D seismic survey in 1999, just three years into the project, revealed the first problems. The behaviour of the CO_2, which had been injected at high pressure, was apparently not as expected.

While the oil and gas industry is used to extracting oil and gas from a reservoir to the surface and lowering the pressure in the reservoir, the reverse was now required: increasing the pressure in the reservoir by injecting CO_2 and requiring a stable ultimate storage solution that would last for centuries. It quickly became apparent that the industry's existing modelling methods were not up to the task.

The graphs suggested an increasing accumulation of CO_2 in a layer of rock that had escaped previous investigation. Contrary to predictions, the gas appeared to have migrated very rapidly up 250 metres through all the sandstone layers and was now only 800 metres below the sea surface. Although an ascent was considered possible at the start of the project, it was thought to be much slower and in small amounts.[Q1]

The carbon dioxide had now reached a critical depth, just above which the gas would have left the supercritical state, causing the gas volume to increase significantly. The migration could have accelerated considerably.

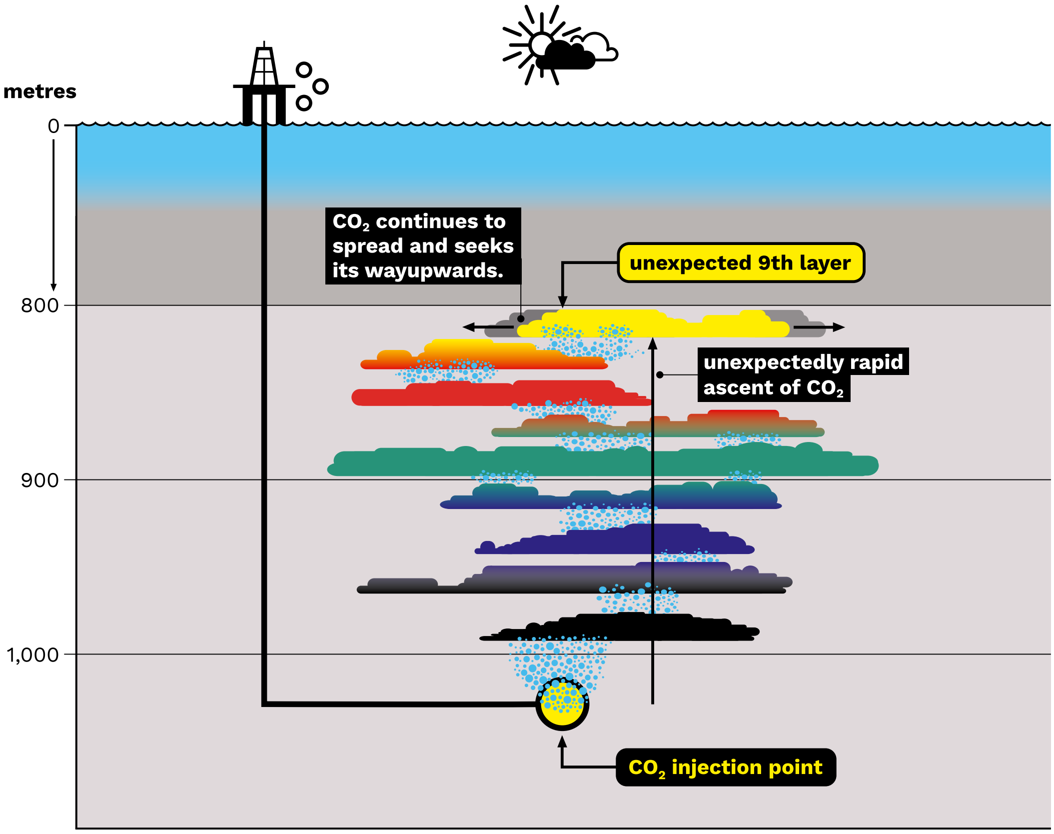
CO_2 levels in this area, known as ‘Layer 9’, appeared to be rising rapidly. In the years that followed, numerous studies and additional geological analyses were carried out as the risks became apparent.

First, the CO_2 had moved much faster than expected because the layers were unexpectedly permeable and heterogeneous. Second, there were more layers in the rock formation than previously thought.[Q44]

The cap rock, the impermeable layer above the entire Utsira formation, has so far been able to prevent CO_2 from rising to the surface. However, previous detailed analyses of the cap rock were limited to a relatively small area. It was unclear how far it extended horizontally, how homogeneous it was further away and how dense it could remain in the long term as increasing amounts of CO_2 accumulated.

Data from 2016 show that the carbon dioxide bubble is moving about 3 kilometres, mostly to the north-east, and has reached an area of 4.8 square kilometres. However, there is also movement to the west — a direction that could cause problems as the Sleipner gas field, with its still-active wells, lies in that direction.[Q35][Q38]

Sleipner CO_2 disposal site



Complex and expensive 3D seismic analysis is now required at regular intervals to track the movement of the CO_2 masses. Statoil/Equinor makes the data available worldwide and ensures a high level of transparency to receive additional suggestions and interpretations (the 'Sleipner benchmark', see [Q22]).

Models and analyses must break new ground again and again because there is no comparable research to guide them. Temperatures and pressures must be estimated because there were initially no, and now only a few, sensors on site to provide real-time data on the behaviour of the 'CO_2 bubble'.

There is still no clarity about the geological risks in the coming decades. So far, the cap rock has remained impermeable. However, there are still no reliable models and predictions on whether CO_2 could find a way through or around the cap rock. Equinor expects that most of the CO_2 will dissolve in the long term — but only after 5,000 to 50,000 years.[Q38]

Most of the gas reserves in the neighbouring Sleipner fields have now been depleted. This means that the source of new CO_2 injections is gradually drying up. However, the next steps are not yet entirely clear. Equinor could accelerate gas production there by drilling additional wells.[Q39]

The following table shows the amounts of CO_2 injected from the Sleipner gas field and disposed of in the Utsira formation for the period 1992-2022.

Table: Amount of CO2 injected in the Sleipner CCS project (tonnes)

Year	Tonnes of CO_2	Year	Tonnes of CO_2	Year	Tonnes of CO_2
1996	70,000	**2005**	858,000	**2014**	658,000
1997	665,000	**2006**	820,000	**2015**	707,000
1998	842,000	**2007**	921,000	**2016**	632,000
1999	971,000	**2008**	814,000	**2017**	557,000
2000	933,000	**2009**	860,000	**2018**	509,000
2001	1,009,000	**2010**	743,000	**2019**	482,000
2002	955,000	**2011**	929,000	**2020**	506,000
2003	914,000	**2012**	842,000	**2021**	322,000
2004	750,000	**2013**	702,000	**2022**	115,000

Source: Equinor/Norwegian Environment Agency [Q37][4]

There are different assessments of the current situation: the Norwegian authority responsible (NPD) sees no clear signs of CO_2 migration from the designated region. However, they believe that an imminent eruption in a westerly direction is possible. The seismic contractor (PGS), on the other hand, has detected migration from the original target region (storage anticline).[Q21]

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[4] The values in the table have been revised downwards, especially for 2020, after Equinor initially reported higher CO_2 injection rates.[Q71]

Conclusion: None of the world's leading exploration and production companies, nor the international expertise in geophysics and reservoir engineering, were able to foresee or solve the problems in what is probably the world's longest-prepared CCS project.

It is easy to imagine the risks associated with CCS projects, where the scale is much larger, and the focus is on profit. They will be much less careful, much faster and with less competent oversight than in the model country of Norway.

2.2 Snøhvit: tough start north of the Arctic Circle

Norway's Snøhvit gas field is located in the harsh Barents Sea north of the Arctic Circle. This is not an ideal location in the event of a crisis, as major interventions are only possible for a few months of the year. All the production facilities had to be located on the seabed at a depth of 300 metres, from where the gas is pumped to the distant coast.

Once on land, the gas is cleaned of its very high CO_2 content (5 to 8 per cent) and other unwanted gases and liquids. The end product, which is then almost entirely methane, is then liquefied into LNG and exported by tanker.

Europe's only LNG export terminal, the Snøhvit/Hammerfest LNG complex, is a multi-billion investment. For Statoil (Equinor), it was therefore a high-risk venture from the outset.

Once captured, the CO_2 is energy-intensively compressed onshore and then piped back to the gas field region. Since 2008, it has been stored in a repository beneath the seabed.

After much consideration and analysis, Statoil chose the deep Tubåen rock formation as a disposal site for the CO_2 because it is 2600 metres below the sea surface, much deeper than the relatively shallow Utsira formation that caused major problems in the Sleipner project.

Geophysical analyses have shown that the Tubåen rock formation has an 80-metre-thick layer that is sufficiently porous to store the desired amount of CO_2 for about 18 years. The aim is to find other storage sites for the period after that.

But even this project soon ran into problems. During the initial drilling, it was discovered that the porous layer was only 30 metres thick, rather than 80 metres. Although this reduced the storage capacity, it was not initially considered a major obstacle.[Q1]

Two years later, however, the pressure in the drilling area unexpectedly increased. Initial calculations showed that Tubåen could only withstand another six months of CO_2 injection before the pressure in the deposit would exceed critical levels. The entire Snøhvit project, including the LNG terminal, was suddenly at risk.

A number of emergency measures were in place by the companies in an attempt to relieve the pressure, but to no avail.

The cause could only be speculated about, as there was no other information available at short notice apart from data from a few pressure sensors. In the end, there was only one explanation: the rock layer was simply not permeable or porous enough to absorb large amounts of CO_2. The extensive geological analyses carried out beforehand had obviously been wrong. At least the pressure increase was detected in time. [Q1]

Injections stopped in 2011 because the project companies had to seal the well. Equinor began looking for a new deposit. The next attempt targeted the neighbouring Stø formation at a depth of 2,460 metres. Caution was needed because gas was being produced nearby at a depth of 2,435 metres.

While the first test injections failed, the operators became more confident, and Statoil began injecting CO_2 into the Stø formation. However, it soon became clear that the region could only store a limited amount of CO_2. There was a constant risk that the CO_2 would migrate to the active gas field above and cause problems there.

This meant that a new, larger storage site had to be found to accommodate the large volumes of CO_2 being piped in from the coast.

The following table summarises the amounts of CO_2 injected and vented to the atmosphere for the years 2007 to 2022. From September 2020 to May 2022, the entire LNG plant had to be shut down and repaired due to a major fire, which explains the low values in these years.

Table: Amount of CO2 injected and vented in the Snøhvit CCS project, 2007-2022

Year	Injected t CO_2	Vented t CO_2	Year	Injected t CO_2	Vented t CO_2
2007	0	71,000	**2015**	679,000	39,000
2008	197,000	93,000	**2016**	750,000	4,000
2009	308,000	50,000	**2017**	680,000	4,000
2010	460,000	93,000	**2018**	758,000	11,000
2011	403,000	87,000	**2019**	721,000	9,000
2012	490,000	55,000	**2020**	422,000	1,000
2013	469,000	27,000	**2021**	0	0
2014	587,000	37,000	**2022**	402,000	11,000

Source: Equinor/Norwegian Environment Agency [Q37]

Until 2015, Equinor carried out further seismic studies and eventually found a region behind a fault line in another part of the Stø formation. It is close to the Snøhvit gas field, which means that new production wells have been drilled in the gas field not far from the new CO_2 injection well. Caution is therefore still required.

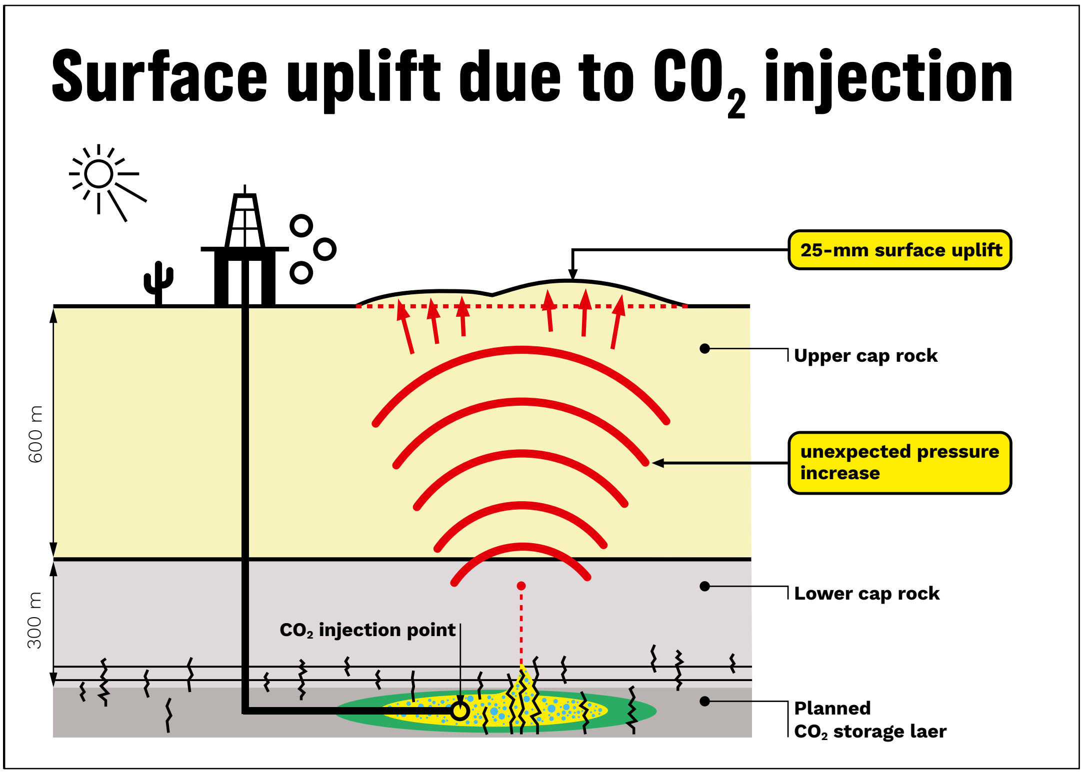
By the end of 2022, 1.1 million tonnes of CO_2 had been pumped into the Tubeån formation and 6.2 million tonnes into the Stø formation. Almost 0.6 million tonnes of carbon dioxide were released into the atmosphere — still almost 10 per cent of the CO_2 volumes extracted. This indicates a number of technical problems, although these have been reduced in recent years.

2.3 Failures overseas: In Salah, Gorgon, Quest

2.3.1 In Salah (Algeria): surface uplift and project cancellation

Another CCS project was carried out next to the In Salah gas field in the Algerian desert. As with Sleipner and Snøhvit, the natural gas had a very high CO_2 content, which the project partners BP, Equinor and the Algerian state company Sonatrach (operator) wanted to capture and inject into an older gas field in the ground.

The geological conditions were considered simple and manageable. A common fold in the rock layers (anticline) had formed a geological saddle with a very thick impermeable layer (950 metres). The chosen disposal site (Krechba formation) was at a more than adequate depth of 1900 metres.[Q49]



Source: Greenpeace Germany

There was an excellent match between the 3D seismic data and existing geological knowledge from gas production. The remaining risks were considered to be “minimal”. CO_2 injection began in 2004 with the aim of injecting 1 million tonnes of CO_2 per year.

It did not take long for both the Intergovernmental Panel on Climate Change (IPCC) and the industry to regard the In Salah project as a model for the successful application of CCS.[Q48]

From 2009, however, the CO_2 pressure in the deposit began to rise unexpectedly rapidly. Despite this, the operators did not react and continued to inject CO_2 until 2011, nor did they drill a relief well to extract water and reduce the pressure.

As a result, the pressure became so high that it caused the first cracks to appear in the cap rock, which is supposed to prevent the CO_2 from reaching the surface.[Q1] As this layer was very thick, no CO_2 was able to escape, but the ground in the region above the deposit lifted by several centimetres. As the region is uninhabited, no buildings or people were affected.

But the project companies realised that the risks had become too great. Despite the thick cap rock, there was still a risk of further cracks and uncontrolled CO_2 leakage. The project was halted and eventually terminated. In total, only 3.8 million tonnes of CO_2 could be stored. After 2011, the CO_2 from the gas field was vented directly into the atmosphere [Q3].

2.3.2 Gorgon (Australia): no success in eight years

Gorgon is one of the world's largest industrial fossil fuel complexes. Operated by Chevron, the project in Western Australia includes gas extraction, gas processing, LNG liquefaction and LNG loading. The total investment to date is a staggering US$55 billion. About US$2 billion has been spent on CCS facilities so far.[Q17][Q49]

A high proportion of the gas, up to 15 per cent, is CO_2. The Australian authorities made the grant of the production licence conditional on 80 per cent of the CO_2 being captured and safely disposed of underground each year from the originally planned start of operations (2016).

But that only addresses part of the environmental impact. Chevron is allowed to vent all of the high emissions from the energy-intensive, natural gas-fired LNG plants into the atmosphere. So even with the best use of CCS, the Gorgon integrated project will only reduce emissions by about 40 per cent. But even that is not nearly enough.

Chevron's plan was to inject the CO_2 into the Dupuy formation, from where it would migrate upwards over time and be stopped by a thick cap rock at a depth of 2300 metres.

However, the project faced problems from the outset.[Q16][Q28][Q1] Most of these were related to the injection process, rather than the capture of CO_2, which has been standard practice in natural gas production for decades. The injection process, on the other hand, is subject to different geological and technical problems in each project.

Even the start of operations was delayed by three years. Sand and water kept getting into the pipelines and pumping systems, preventing the disposal of CO_2. Large amounts of carbonic acid formed which attacked the metal in the wells. The plant repeatedly had to be partially or completely shut down for months at a time.

It was not until August 2019 that the CCS plants began operating. But even then, the agreed reduction in CO_2 emissions of 4 million tonnes per year was not achieved. As mentioned above, this target represents 80 per cent of the CO_2 that is brought to the surface from the gas fields in use.

In fact, CO_2 injections have continued to fall since the first year of operation in 2019/2020: initial injections totalled 2.7 million tonnes of CO_2 per year, which has since fallen to just 1.6 million tonnes.

Corrosive salt water and carbon dioxide continue to enter the CO_2 pipelines. Meanwhile, the pressure in the repository rises because the injected CO_2 only distributes poorly.

Chevron is now drilling more and more wells to lower the pressure in the CO_2 disposal site by withdrawing water and to raise the pressure above the vulnerable cap rock by injecting water. But new problems keep arising.[Q49]

For eight years, the second largest oil company in the US has been unable to cope with CCS technology. At the same time, however, Chevron has been expanding its industrial operations. The resulting CO_2 emissions jumped to 8.3 million tonnes of CO_2 in 2022.[Q16] This makes the site the largest industrial emitter in Australia. Chevron plans to continue producing and exporting natural gas in the region until 2060.

Yet the group's management is relaxed and sees no reason to hurry: “We're getting terrific insights ... In a couple of years, we'll have that constraint removed.”[Q17]

Although Chevron now must pay CO_2 taxes in Australia for some of its emissions, these are only a fraction of the profits the company has made in recent years from LNG exports from the Gorgon plant.

Political resistance is growing, however. The eastern Australian state of Queensland plans to issue a general ban on CO_2 disposal sites this year.[Q69]

2.3.3 Quest (Canada): carbon capture for oil sands

Shell's Quest CCS project in Canada aims to decarbonise the production of hydrogen (blue hydrogen) at the Scotford steam cracker. The hydrogen is used to process Canadian oil sands into synthetic crude oil.

After the plant began operations in 2015, an average of 1 million tonnes of CO_2 per year was stored in a sandstone formation, rising to 7.7 million tonnes by the end of 2022. But that was only about 50 per cent of the CO_2 emissions from the Scotford plants. Shell usually talked about 90 per cent.[Q24]

According to external analyses, the CCS system captured almost 80 percent of the emissions from the stream cracker processes, but the same amount of emissions from the process energy and CO_2 compression equipment was released into the atmosphere. In 2022, the power requirements of the capture processes totalled 32.6 GWh, supplied initially by the regional power grid and then by a dedicated gas-fired power plant.

But the CO_2 savings for the steam cracker also fell short of expectations. In the years 2020 to 2022, the capture rate was 76.8 to 78.2 percent. Shell blames this mainly on technical failures of the capture equipment.

The total cost (CapEx+OpEx) in 2022 was CA\$168 per tonne of CO_2 (CO_2 avoided). This is equivalent to about €120 per tonne of CO_2.[Q24][Q25][Q26]

2.4 Big plans for Europe: Longship/Northern Lights, Smeaheia, Greensand and Porthos

2.4.1 Longship & Northern Lights (Norway)

CCS is also set to become big business in Europe. Norway is leading the way, followed by the UK, the Netherlands and Denmark.

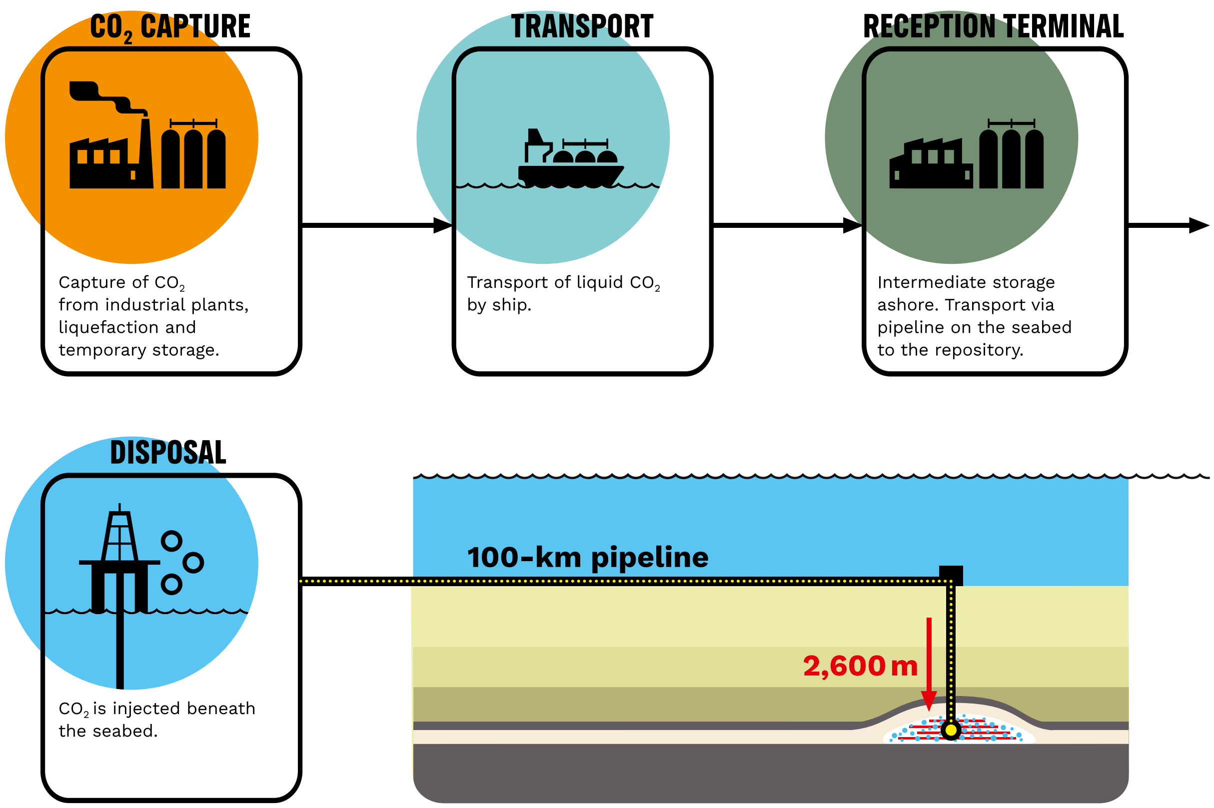
Funded largely by the public purse, the Longship CCS project, which in Phase I also launches the Northern Lights project, provides the overarching framework for Norway's current CCS strategy.[Q7]

Both Sleipner and Snøhvit were CCS projects for adjacent gas fields that supply CO_2-rich natural gas. The Northern Lights repositories will be available for all CO_2 supplies, initially only from Norway (Phase I), but then also from other countries (Phase II). Control will then be in the hands of the oil and gas companies Equinor, Shell and TotalEnergies.

Initial planning for Longship began in 2005 as part of the government's CLIMIT programme. The newly established Norwegian state company Gassnova took over operational management in 2007. The search for suitable sites and the mapping of the seabed took until 2014. The Smeaheia area (to the east of the large Troll gas field), the Heimdal area and the large Utsira formation, already known from the Sleipner project, were selected as the best locations.

Plans originally envisaged the first storage sites receiving CO_2 from the Mongstad refinery (Equinor), but this plan was abandoned in 2013 due to excessive costs. And Oslo already had more far-reaching plans: the country now wanted to store CO_2 from all over Europe.

Three years later, Equinor, Shell and TotalEnergies formed the Northern Lights joint venture. Once again, the plan changed. The Johansen formation (south of the Troll gas field) was now identified as the preferred CO_2 disposal site. In 2019, Equinor received the necessary licences, and the first well was drilled a year later. Northern Lights then submitted a development plan. Shortly afterwards, Equinor and the Norwegian government approved the first investments.



CO_2 dispoal infrastructure Northern Lights

Source: Greenpeace Germany

In Phase I, Northern Lights is building an annual storage capacity of 1.5 million tonnes of CO_2 per year for two industrial plants in Norway: a cement plant owned by Heidelberg Materials in Brevik and a waste incineration plant owned by Celsio in Oslo (Hafslund).[Q8]

The captured and compressed gas will be transported by ship to a terminal at Øygarden on the west coast of Norway. From there it will be piped about 100 kilometres across the ocean to the 2,600-metre-deep CO_2 storage site in the southern North Sea.

Disposal was supposed to start in 2024, but there are problems:

- Work on the capture facility for Celsio's waste incineration plant in Hafslund has been put on hold in 2023, as the expected costs have been much higher than originally planned. A decision on whether to continue with the project will be made at a later date.[Q9][Q10]
- The cement plant in Brevik does not expect to complete its capture facilities until the end of 2024. Even then, it will only be able to capture a maximum of 50 per cent of the plant's emissions.[Q11]

In Phase II, Northern Lights' disposal capacity for supplies from other European countries will be expanded, probably to 5 million tonnes of CO_2 per year. If the model proves successful, Northern Lights intends to market much larger CO_2 capacities in the longer term.

The first customers are already in sight: Norwegian fertiliser giant Yara wants to dispose of CO_2 from its ammonia plant in the Netherlands, and Danish energy company Ørsted is also interested.

Subsidies for Longship/Northern Lights
The Norwegian government will subsidise most of Longship's investment and operating costs for a period of ten years.[Q12] The two Phase I CO_2 emitters (Heidelberg Materials, Celsio) will not have to pay for the transport and storage of CO_2 for a period of ten years.

In addition, the Northern Lights consortium (Equinor, Shell, TotalEnergies), Heidelberg Materials and Celsio will save on the cost of emission allowances (ETS, the Norwegian combustion tax). Oslo will also permanently waive VAT on cross-border CO_2 transport and CO_2 disposal activities off the Norwegian coast. Most of the expenditure in Phase I is for the capture facilities of the two industrial customers. The subsidies for Northern Lights (transport and storage of CO_2) are expected to amount to around €600 million.[Q14]

Depending on how the costs are defined, the Norwegian tax authorities will cover 70 to 80 per cent of the total costs, which are estimated to be US$2.5 billion (NOK25.1 billion) based on an estimate from 2020. The final amount is still unclear because, as mentioned above, the project is not yet in regular operation.[Q18] The remaining costs will also be partly financed by the Norwegian state, as the project company Equinor is majority-owned by the state.[Q14]

2.4.2 Smeaheia (Norway)

Norwegian oil and gas company Equinor is pursuing a project similar to Northern Lights on its own: Smeaheia. It is named after the location of the proposed CO_2 repository off the coast of Norway, to the east of the large Troll gas field.

From 2028, Equinor plans to store up to 5 million tonnes of CO_2 per year from across Europe, rising to 30 to 50 million tonnes from 2035. The greenhouse gas will be pumped directly to the deposit by pipeline from Germany (from Wilhelmshaven), the Netherlands (from Eemshaven), Belgium (from Zeebrugge) and France (from Dunkirk). Alternatively, it can be transported by CO_2 feeder tanker to a land terminal on the Norwegian coast.

Smeaheia will be an important part of a wider collaboration between European industry and Norwegian oil and gas company Equinor. However, the first investment decisions are not expected before 2026. Equinor hopes to start CO_2 deliveries from 2029.[Q70]

2.4.3 Greensand (Denmark)

Also, Denmark is planning a large CO_2 disposal site in an old oil field (Nini West, Frigg Sandstone) in the Danish North Sea. Similar to Northern Lights, the Greensand project is intended to offer international services: the transport and disposal of CO_2 emissions from European industry, including from Germany.[Q52]

However, with little information being released, the status of the project is currently unclear.

Compared to the Norwegian projects, Greensand has been developed at a rapid pace. Project leader Ineos (a British chemical company) and Wintershall Dea, Germany's largest oil and gas company (currently being taken over by the UK's Harbour Energy), point out that the old oil field has already been well explored and that the cap rock has been shown to be impermeable.[Q32]

In early 2023, the two project companies carried out the first CO_2 injection test. In a presentation, it was reported that the pressure in the repository rose to 260 bar after injection and then fell rapidly as the CO_2 spread. As the estimated limit pressure for the safety of the cap rock is only slightly higher (280 bar), this was a critically high value.

However, from 2025, the rate of injection is expected to increase tenfold from the test project in 2023, to up to 10,000 tonnes of CO_2 per day. This would be three times more than the Norwegian Sleipner project. Further enquiries with the project leader, Ineos, appear to indicate that more precise results of the test injection will be published later.[Q32]

Since then, no new information has been published on the quality of the test injection or the subsequent findings for the disposal site. There has also been no new press release on the project website since February 2023.

The reasons are unclear. They may be related to the proposed acquisition of Wintershall Dea by Harbour Energy, as it is currently an open question whether Harbour Energy is interested in continuing the project. A final investment decision on the next phase of the Greensand project was expected to be made in the course of this year (2024).

2.4.4 Porthos (Netherlands)

Another large-scale CCS project is being implemented in the Rotterdam region. The 'Port of Rotterdam CO_2 Transport Hub and Offshore Storage' (Porthos) project includes an integrated CCS infrastructure with CO_2 capture from various industrial facilities in the region, transport and storage. The project is supported by EU funding and financial support from Dutch climate protection programmes.

However, costs are already rising dramatically in the early stages of the project. For example, instead of €0.5 billion, it will cost at least €1.3 billion to inject the CO_2 captured from Rotterdam refineries and industrial plants in Phase I into an old gas field a few kilometres off the Dutch coast. This is apparently due to rising material costs and delays caused by legal disputes.[Q53]

From 2026, the project is expected to dispose of around 2.5 million tonnes of CO_2 per year. After 16 years and a total of 37 million tonnes of CO_2, the gas field will reach its capacity limit. Construction of the 50-kilometre pipeline from the port of Rotterdam to the disposal site, an old gas field, began in April 2024.[Q54]

Porthos' main customer is the oil industry. Shell alone wants to use it to dispose of 1 million tonnes of CO_2 a year from its large Pernis refinery, equivalent to a quarter of the plant's emissions.

For the Netherlands, Porthos will only be the starting point for much larger CCS projects. Shell and TotalEnergies' Aramis project is expected to be about ten times larger.

3. The risks of CCS

What conclusions can be drawn from the case studies and the rest of the CCS literature? The following pages outline the main risks and uncertainties of this technology pathway.

3.1 The disillusioning results of CCS projects to date

Despite 50 years of experimentation with CCS technologies, the technology still seems to be in its infancy. Costs remain high and disruptions are commonplace. Without huge government subsidies, almost nothing is happening.

And it's not just the capture systems (separation of CO_2), which remain expensive, prone to failure and extremely energy intensive. There is still no major industrial plant in the world that is fully decarbonised with CCS. Reports of high capture rates regularly refer only to specific sub-processes of the plant or to short periods of time.

The record on CO_2 storage is even worse. There are still only a handful of projects. Even the best-prepared projects (Sleipner, Snøhvit) quickly ran into difficulties.

- After only a few years, the elaborate geological models for the flagship **Sleipner** project (Norway/Equinor) had to be revised. The injected CO_2 found its way to the surface much faster than expected and accumulated in a layer that was not supposed to exist (the ‘9th layer’). Now, millions of tonnes of CO_2 (nobody knows the exact amount) are migrating in several directions under the cap rock, looking for a way to the sea surface. Eventually, the CO_2 injection will stop in a few years because the adjacent gas field (the original source of CO_2) will dry up.

- Contrary to all predictions, the dumping at Snøhvit (Norway/Equinor) had to be stopped after the first attempt. The pressure quickly reached critical levels. So far, only the third attempt seems to be working.

- A geologically similar CCS project In Salah (Algeria/BP) failed completely. The geological models used were apparently flawed. The project operators ignored the rapidly increasing pressure in the CO_2 repository for too long, causing the ground above the repository to uplift by several centimetres. Only at the last minute was the CO_2 injection stopped, and the project terminated.

- Even after eight years, the giant integrated project Gorgon (Australia/Chevron) still cannot get CO_2 dumping under control. In fact, the amounts injected are decreasing from year to year as salt water and sand repeatedly disrupt the injection process. Chevron must continuously carry out relief and stabilisation drilling to prevent the project from failing completely.

As the projects are only a few years old, the real test has yet to come: Will the greenhouse gas still be in the ground after 100 or 1,000 years?

3.2 Where to put it? Old oil and gas fields or saline aquifers?

The carbon dioxide will be stored in old oil/gas fields or in saline aquifers. Both options have their advantages and disadvantages.

a) Aquifers are found almost everywhere and usually have a large storage capacity. But little is known about these formations, especially those under the North Sea.

The permanent and safe disposal of CO_2 therefore requires many years of extensive analysis. Its large and complex scale makes it difficult to assess. If very large amounts of CO_2 are injected, it could spread more quickly than expected to regions where the quality of the cap rock is inadequate.

b) Much more information is available about old, depleted oil and gas fields. In particular, the original cap rock appears to have worked in the past. On the other hand, these fields have a limited absorption capacity. In addition, the cap rock has already been perforated during the long years of oil or gas production, and this is often the case in old or complex fields. The quality of the cap rock has been compromised by these wells and any additional damage caused by rapid changes in reservoir pressure and is more prone to leakage.[Q56]

The same applies to the North Sea, where countless gas leaks have been discovered in old wells. According to the German Federal Institute for Geosciences and Natural Resources (BGR), CO_2 could also escape from these wells if they leak.[Q55]

c) The BGR is therefore recommending previously undisturbed red sandstone formations for CO_2 storage. However, there is little data on their exact geological composition, and it is unclear whether they are suitable for long-term storage. 3D modelling is expensive and time consuming. The cost is expected to be between €100m and €200m for each disposal site.[Q55][Q57]

d) In oil and gas production, the risks often decrease over time as the pressure decreases. When CO_2 is injected, the opposite is true: the pressure rises and can even rise sharply because other substances (salt water, etc.) have to be constantly displaced. In addition, the injection is intermittent and not regular. And all this in an environment characterised by very high pressures and temperatures.[Q001][Q56]

Carbon dioxide disposal is therefore different from oil and gas production. The decades of experience in the oil and gas industry are of limited use here, especially if the injection is to take place not in old oil and gas fields, but in saline aquifers that have hardly been explored.[Q002][Q56]

e) Like coal mines or nuclear waste repositories, CCS sites are a permanent regulatory and financial liability if they are to fulfil their climate policy purpose. In many regions of the world, it is unclear who can take responsibility for this.

3.3 Consequences for climate protection: risky dependencies

Expanding CCS in Europe, the US or Asia will create new, risky dependencies for climate protection, as industry will continue to be allowed to burn large amounts of coal, gas or oil.

If unexpected disruptions occur, for example at a large CO_2 site, in a pipeline or at a port, which will be the order of the day given the state of development of the industry, the entire CO_2 chain will come to a standstill.

> In particular, the capture processes, which involve energy-intensive processes and the continuous, costly recycling of chemical solvents, are considered to be prone to failure.
>
> Other processes, such as long-distance CO_2 transport by ship or pipeline, are considered technically simpler, but there is a lack of experience, particularly in Europe.
>
> In the Midwestern US, major CO_2 pipeline projects are currently failing due to local opposition (Heartland Greenway Project). However, the US Department of Energy estimates that 150,000 kilometres of new CO_2 pipelines will have to be built in the coming decades to reach CO_2 storage sites, some of which are far from the emitters.[Q65]
>
> A study by the German Cement Works Association (VDZ) has shown that 4,800 kilometres of new CO_2 pipelines will be needed in Germany for cement and lime production and waste incineration alone, at a cost of €14 billion. According to the study, capture alone will cost €80 to €110 per tonne of CO_2, excluding transport and storage.[Q66]

Given the huge amount of CO_2 that has to be disposed of every day, the buffer storage tanks will quickly fill up if there is a malfunction. After a short time, emitters will have to release all of their CO_2 emissions back into the atmosphere.

Disruption to underground repositories can even cause long-term problems if, for example, displaced salt water or sand finds its way back into the well, damaging equipment and causing lengthy downtime.

Similar facilities, such as LNG export terminals, are prone to technical failures that can last for months. But these only interrupt gas exports, unlike CCS, where CO_2 emissions cause irreparable climate damage after a short time.

Due to the high subsidies that have been maintained over a long period, CCS could also become a risk for climate policy: should countries stop funding for political or financial reasons, it is unclear who would be responsible for the safety of the existing sites and for the disposal of the ever-increasing amounts of CO_2.

The hundreds of thousands of abandoned oil and gas wells in the US, Nigeria and the North Sea, which continue to release methane into the atmosphere, are already evidence of this problem.

3.4 Upstream CCS: a zero-sum game for climate protection

Perfectly functioning CCS technology will still result in climate-damaging emissions from the fossil fuel sector. Most of the planned capture systems and CO_2 repositories for industry do not come into play until after fossil fuels have been burned or transformed.

Upstream emissions from oil, gas and coal extraction remain high and are only reduced in exceptional cases, such as CO_2-rich natural gas deposits.

Most of the large CCS projects that have already been implemented (Sleipner, Snøhvit, Gorgon) are developing natural gas fields with extremely high levels of CO_2 in the reservoir. However, this is not necessary as there are also fields with a low CO_2 content in the natural gas mixture.

In other words, CCS, supported by government subsidies, solves problems that could also have been avoided by the fossil gas industry. There is virtually no benefit for climate protection, especially since this natural gas will ultimately be burned, generating CO_2 emissions.

Nor will CCS solve the problem of upstream methane emissions. Depending on the definition of the upstream sector and the temporal impact of methane emissions (GWP20/GWP100), oil and gas extraction alone currently emits 3 to 7 gigatonnes of carbon dioxide equivalent [Q64], which is 10 to 20 per cent of the CO_2 emissions currently affecting the climate from the burning of oil, gas and coal worldwide.

3.5 CCS remains expensive

CCS projects are expensive and receive large government subsidies. In fact, without this support, few projects would survive the early planning stages. After half a century, there is still no viable business model for CCS that does not require massive government subsidies.[Q59]

Instead of preventing emissions, the public would have to finance the disposal of climate emissions on a long-term basis.[Q19]

There is little hope that these costs will come down in the future. Any comparisons with the solar or wind industries miss the point. There has been no cost reduction in CCS projects over the past few decades [Q60] and WoodMackenzie's analysis suggests that investment costs will improve slightly by 2050, but operating project costs will rise.[Q62]

While there are economies of scale in large CCS hubs at seaports, in bundling CO_2 streams in large pipelines or in large CO_2 tankers, this infrastructure accounts for only a small proportion of the costs.

Most of the costs are associated with capturing CO_2, for which no significant cost reductions or technological advances are expected.

The second largest cost factor is the CO_2 deposits, and the outlook here is even worse as each project presents different challenges.

CCS projects cannot be standardised. Each project requires a great deal of effort to analyse the geology of the deposit and develop a tailored technical solution. At any time, problems can (and will) arise because the behaviour of rock formations cannot be predicted when large amounts of CO_2 are injected.

On the contrary, if CCS were to boom, prices would tend to rise because the number of companies specialising in these tasks is limited and is unlikely to increase significantly within a decade. Geological expertise, exploration vessels, drilling technology and reservoir engineers will become scarce and therefore more expensive.

As in other industries, the gap between costs and prices will continue to widen. Actual market prices will be significantly higher than the cost of CCS, especially if the price of CO_2 allowances rises, as seems likely from today's perspective. Site operators will then be able to command a price in the market that is at least close to their customers' expected or actual CO_2 costs.

Even the Energy Transitions Commission (ETC), an influential industrial and banking think-tank, warns against relying on falling costs and rapid deployment of CCS projects. The industry's progress to date has been “very disappointing”.[Q61]

3.6 Unrealistic dimensions

Together, the Norwegian projects Sleipner and Snøhvit disposed of a maximum of 2 million tonnes of CO_2 per year, but for several years now, only half of that amount has been disposed of. The large-scale Northern Lights project is expected to dispose of 1.5 million tonnes in Phase I, and up to 5 million tonnes of CO_2 from Phase II onwards. The failed Gorgon project was supposed to dump 4 million tonnes of CO_2 per year but is only managing 1.6 million tonnes of CO_2 per year.

If CCS is to be a relevant part of climate protection, as the oil and gas industry claims, then these volumes are almost irrelevant.

The burning of oil and gas produces 18.5 billion tonnes of CO_2 each year, and the burning of coal is responsible for another 15 billion tonnes of CO_2.[Q58]

Depositing just 10 per cent of this fossil CO_2 would therefore require 3,300 functioning Sleipner projects or 670 Northern Lights projects (Phase II).

These are dimensions that we will not even be able to come close to managing in the coming decades, either technically or economically. And that's not even mentioning the foreseeable delays in building hundreds of thousands of kilometres of CO_2 pipelines, ports and tankers.

Disposing of CO_2 would require resources on a scale far beyond the industry's capacity for accurate preliminary geological studies and careful project implementation. At the same time, the risks of failure or accident increase.

There is therefore a real danger that over-optimism about CCS will lead to a climate policy impasse: the development of CCS infrastructure, CO_2 storage sites and capture facilities is likely to be so slow and fragile that the fossil fuel industry will not be able to reduce its emissions and will be far too slow to invest in low-emission production methods and products.

3.7 The unsolvable problem of control

The flagship projects in Norway (Sleipner, Snøhvit) have been carried out over a long period by technically advanced, financially strong and experienced oil companies. All processes have (so far) been regulated and supervised by the Norwegian state.

It is easy to imagine the problems that will arise in less well-resourced states and regions, and in many other CCS projects, project companies will be primarily concerned with saving time and money and maximising profits.

In normal oil and gas production, a field is exploited for a number of years before the wells are sealed with concrete. Even with these relatively simple processes, many things do not go as planned. There are countless abandoned leaky wells, where methane escapes, or leaky pipelines, where oil spills into the environment. Poor regulation, too few or no controls, overburdened authorities or political disinterest are the causes.

It is hard to imagine that the implementation of CCS projects around the world will suddenly turn hitherto negligent regions and states into models of climate and environmental policy.

3.8 Environmental risks

At the end of 2022, the German government published its second detailed evaluation report on the progress of CCS in Germany and worldwide.[Q43] It lists numerous environmental risks associated with CCS technologies for which no technically safe solution is in sight, especially if CCS is deployed on a large scale:

- One of the risks highlighted in the report is that carbon capture equipment could leak hazardous chemicals, gases or fuels.

- Pipeline leaks or shipping accidents can suddenly release large amounts of CO_2, threatening human health.

- The emissions and energy consumption associated with the transport and injection of several million tonnes of CO_2 per year must also be taken into account.

- CO_2 or saline formation water from the reservoir rock can escape from underground storage sites and contaminate or salinate shallow groundwater or drinking water by migrating upward or displacing saline water. The same is true of soils, which may suffer a change in pH.

Carbon dioxide released from leaks can also cause damage in the sea, as can be seen today in natural sources of carbon dioxide in the Mediterranean. The pH drops and biodiversity declines rapidly. Few species survive.[Q63]

3.9 Seismic risks

The injection of large volumes of CO_2 increases the risk of earthquakes — a phenomenon that has been occurring regularly in the US for years as a result of the injection of reservoir water following fracking.

The earthquakes can cause fissures in the cap rock of CO_2 storage sites, opening a path for the CO_2 to reach the surface. It is unclear how operators of CO_2 disposal sites can technically solve such problems.

Norway and its continental shelf are also repeatedly hit by strong earthquakes: since 1900, there have been 79 quakes with magnitudes between 4.0 and 6.1. In 2023 alone, there were four earthquakes with magnitudes above 4.0. Numerous earthquakes have occurred in the vicinity of planned or existing CO_2 storage sites, including in the immediate vicinity of the Utsira formation (21 March 2022, magnitude 5.2).[Q31]

3.10 Closing words

There is no place in today's energy world for the global deployment of CCS. Solar and wind power, electric vehicles and batteries, green hydrogen and other electrolytically produced raw materials now offer more attractive alternatives for almost all industries.

Many expensive CCS projects are already nothing more than a zero-sum game in climate policy, as they are intended to serve the exploitation of climate-damaging oil and gas deposits, including CO_2-rich natural gas fields or Canadian oil sands.

And the CCS pathway is too expensive, too slow, technologically immature and, above all, too risky for widespread industrial use. It is designed to extend the fossil fuel pathway far into the future without being able to mitigate it in terms of climate policy.

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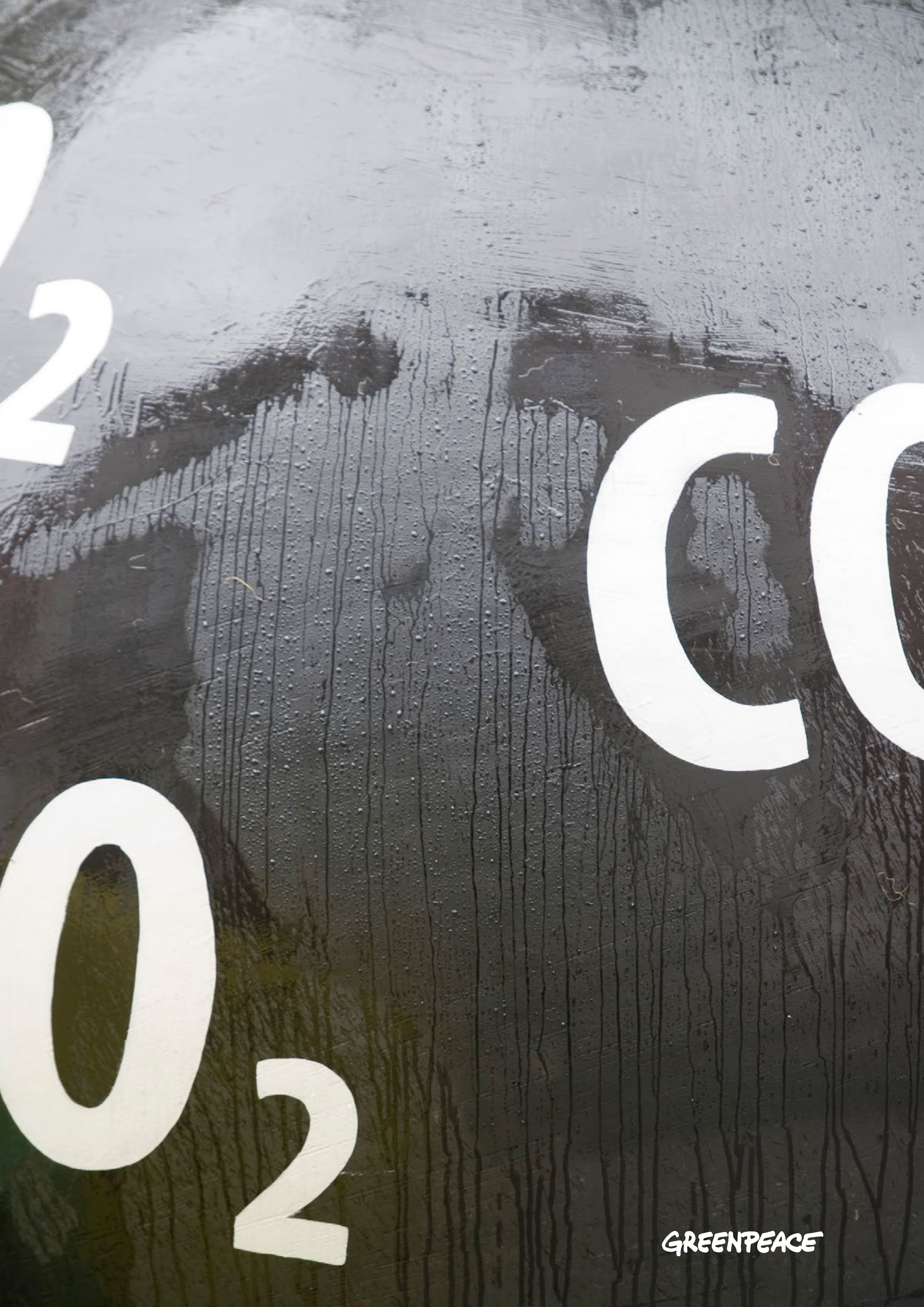

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