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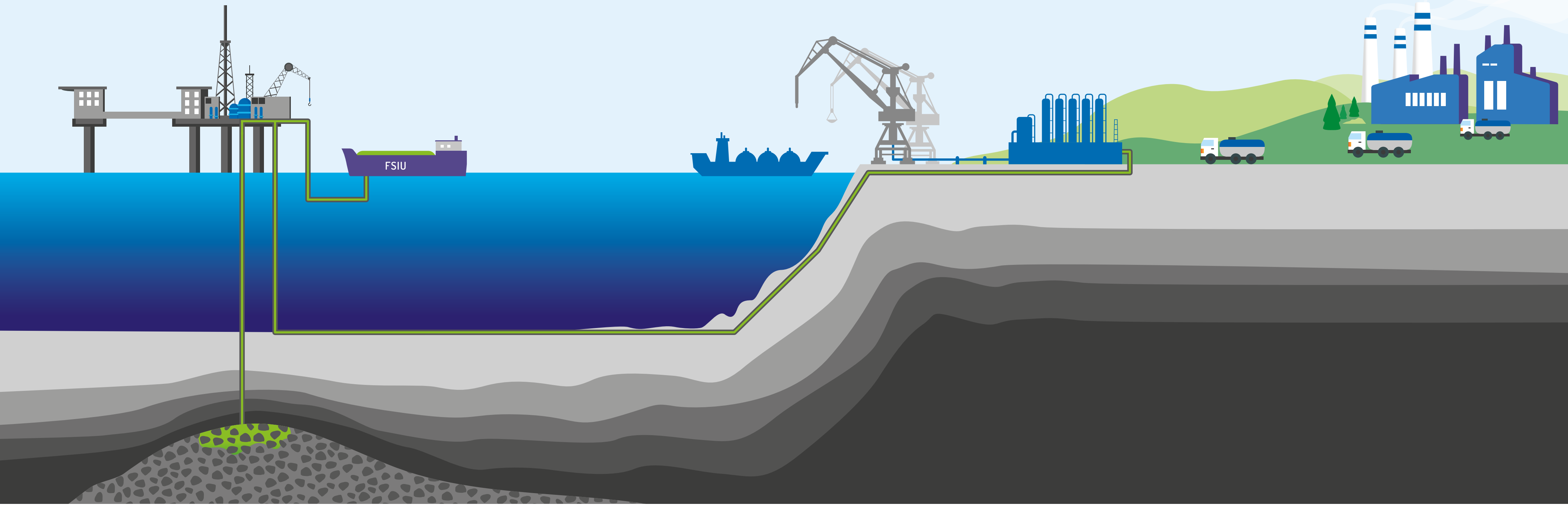


Project Bifrost

Climate change mitigation by geological storage of CO_2 in depleted gas fields

bifrost

CCS – a climate solution for the future

Climate action is urgently needed. CO_2 emissions must be reduced drastically to mitigate climate change in a future with a growing population and high energy demands.

The European Union is committed to a 55% CO_2 emissions reduction in 2030, compared to the 1990 level. The ambitions of the Danish government are even higher, with a target of 70% reduction in 2030, with the aim of being net-zero by 2045 and net-negative by 2050. This challenge calls for significant actions, and one of the most effective technologies to pave the way is Carbon Capture and Storage (CCS).

What is CCS?

CCS is a climate change mitigation technology where CO_2 is captured and stored permanently deep underground in geological formations, instead of being emitted to the atmosphere. Major industrial plants – like steel- and cement factories and bioenergy plants – emit huge amounts of gasses with a high content of CO_2. Rather than releasing the CO_2 into the atmosphere, it is captured from the gaseous emissions at the plants. After purification, the CO_2 is compressed to a liquid-like fluid and transported via pipelines, on trucks, railway or by ships to a geological storage site. Once at the storage site, the CO_2 is injected into a porous rock formation located at 800 to 4,000 metres below the surface. These rocks may be depleted natural gas reservoirs, where CO_2 replaces the gas that previously occupied the pore spaces between the individual sand or chalk grains.

Choosing an appropriate geological storage site is crucial to ensure effective CO_2 containment. The reservoir must be permeable and possess a high porosity, promoting efficient injection rates and a large storage capacity. The rocks immediately above the reservoir must be tight, in order to form an effective seal. Finally, the combined reservoir and seal should form a dome shaped geological structure, ensuring the CO_2 is kept safely and permanently deep underground.

Denmark – the ideal location for CCS

Denmark has the potential to become a major provider of CO_2 transportation and permanent geological storage services in Europe, benefiting from underground storage potential in current and future depleted hydrocarbon fields and saline aquifer structures. Further, Denmark is ideal since it has convertible onshore and offshore hydrocarbon facilities, a strategic location near Europe's main CO_2 sources, and a competent and experienced offshore workforce.

The oil and gas industry in the Danish North Sea has the competencies to make CCS work in practice. This gives the CCS

The oil and gas industry in the Danish North Sea has the competencies to make CCS work in practice.

technology the potential to deliver significant CO_2 reductions within a short timeframe. Therefore, CCS is broadly considered a key solution to meet both the Danish climate ambitions, as well as the goal of the Paris Agreement to keep global warming well below 2°C. This makes CCS an inevitable next chapter in the history of Danish climate change mitigation.

During the past two and a half years, the focus of Project Bifrost has been to develop a concept for permanently storing CO_2 in the underground of the Danish North Sea, turning the nearly depleted Harald fields into a climate solution of the future. With public funding and promising results, Project Bifrost has laid the foundation for Denmark to become a showcase for CCS.

CCS in Denmark – in short

- CCS is a climate mitigation technology where CO_2 is captured and stored permanently deep underground in geological formations.
- Denmark is the ideal provider of permanent geological CO_2 storage due to underground storage potential, onshore and offshore facilities, a strategic position and a competent workforce.

Project Bifrost: Bridging the present and the future

The project name “Bifrost” originates from Norse mythology, referring to a rainbow bridge connecting Asgard (the world of Gods) to Midgard (the world of humans). Project Bifrost connects onshore and offshore: CO_2 is captured onshore and led offshore to be injected and stored underground in a sustainable way. This makes Project Bifrost a bridge of transition – a solution that bridges the present-day use of traditional energy forms with the low-carbon energy forms of the future.

Project Bifrost is partly funded by the Danish state through the Energy Technology Development and Demonstration Programme – EUDP. The two and a half year study has been carried out in 2022–2024 in two project phases, starting with a preliminary phase of 6 months followed by a conceptual phase.

The Harald fields – the perfect destination for the Danish CCS adventure to take off

Project Bifrost has performed the research and groundwork necessary for transporting and storing CO_2 offshore in the future depleted Harald gas fields: The process begins with CO_2 being captured on land, then transported offshore via specialised shipping or existing pipelines to the Harald platform, which is 250 kilometres off the west coast of Denmark. Finally, the CO_2 is injected into the depleted gas reservoirs that are deeply seated in the subsurface. Here – more than 2.5 kilometres below the seabed – the CO_2 molecules are replacing the natural gas molecules previously occupying the pore spaces in the reservoir rocks. The CO_2 is trapped below seals of tight rocks – seals that trapped the natural gas in the reservoirs for millions of years without leakage, proving them to be highly effective.

The Harald fields have been chosen for the project because of the existing infrastructure, the well-known and suitable geology, the shallow sea water depth, and the central location for major national and European CO_2 emitters. The depleted Harald West sandstone reservoir is targeting in the first phase to store 2–3 million tonnes CO_2 yearly. By adding the Harald East chalk reservoir as an upside, the injection capacity may be increased significantly. Chalk is the main reservoir type of

The Harald fields: A particularly suitable destination for developing CCS-solutions.

DTU carries out advanced laboratory tests as part of Project Bifrost.

the oil and gas fields in the Danish North Sea. Accordingly, the success of Harald East could serve as an important stepstone in the efforts to store CO_2 in offshore Denmark.

With a storage capacity of several million tonnes per year, the Harald fields are the perfect destination for the Danish CCS-adventure to take off at scale.

Partnering for CCS

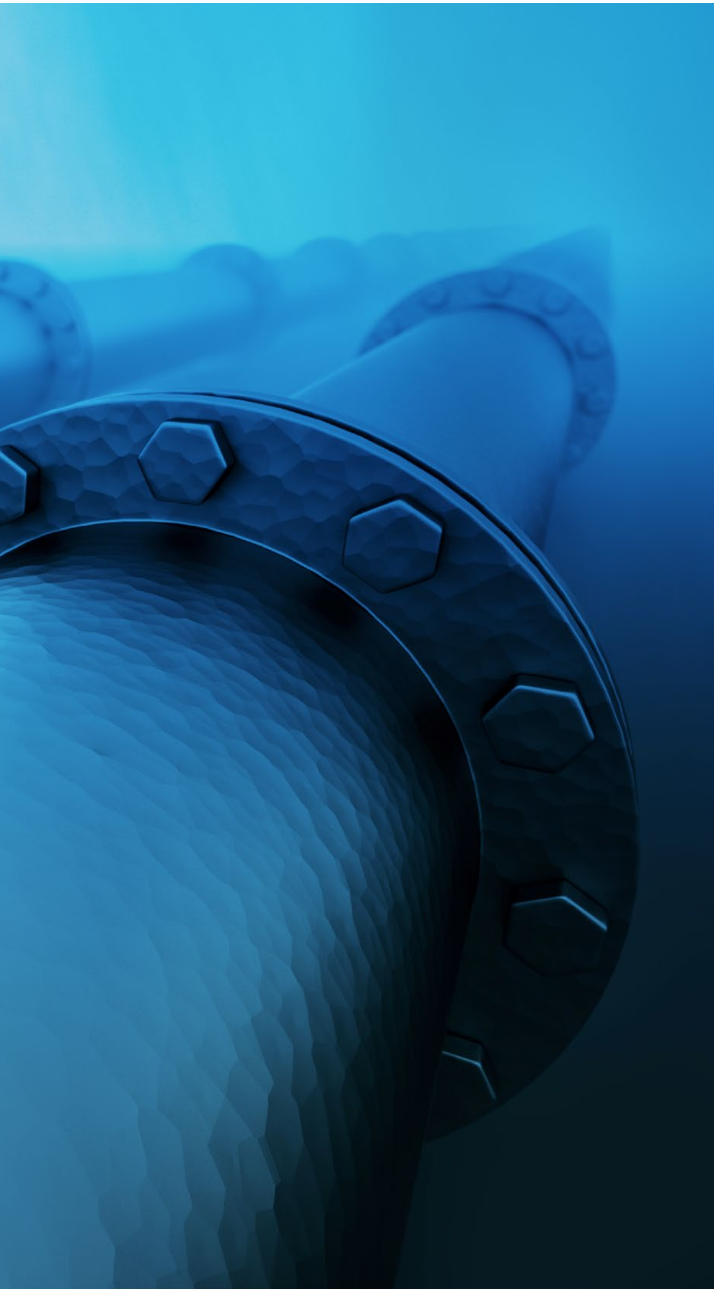
With Project Bifrost, the industry and the academic world are on a shared mission: Unlocking the CCS potential in Denmark and advancing state-of-the-art research and development of CCS. The Danish Underground Consortium – DUC (TotalEnergies, Nordsøfonden and BlueNord), Ørsted and the Technical University of Denmark - DTU, are all partners in the Project Bifrost and committed to finding CCS solutions in Denmark.

The oil and gas industry's solid offshore experience provides the knowledge necessary to ensure that establishing CCS-solutions in the Danish North Sea is safe for both the environment and people. With DTU as a strong academic force, Project Bifrost gives insights into the technical, operational, and socioeconomic dimensions of implementing CCS development in Denmark.

Together, the Project Bifrost partners have the CCS expertise needed to uncover the fundamentals of CCS development in Denmark: TotalEnergies, the operator of DUC, brings experience as partner of the CCS projects Northern Lights (Norway) and Aramis (The Netherlands), Ørsted as the owner and operator of the existing upstream offshore pipeline system in the Danish North Sea, BlueNord as part of CarbonCuts' onshore CCS project in Rødby (Denmark), and DTU as an academic frontrunner in CCS research. Nordsøfonden participates on behalf of the Danish state.

Project Bifrost – in short

- Project Bifrost is partly funded by the Danish state through the Energy Technology Development and Demonstration Programme (EUDP).
- Project Bifrost has developed a concept for transporting and storing CO_2 offshore in the future depleted Harald gas fields.
- The Harald fields have a storage capacity of several million tonnes per year.



From source to sink – modes of transporting CO_2

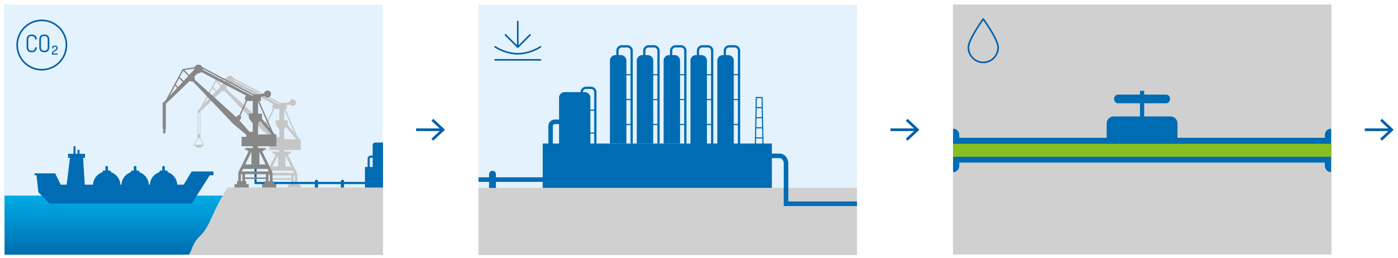
CO_2 can be captured at the major sources – heavy industry or power and heat production plants – by utilising present-day technologies. From the emitters, the CO_2 may be transported by road tankers, pipelines or by ships to an intermediate storage plant. Project Bifrost has evaluated two alternative transportation solutions from the storage plant on land to the offshore Harald fields: A pipeline solution and a shipping solution.

Pipeline solution

Project Bifrost has investigated the offloading of CO_2 from ships to a receiving terminal and intermediate storage in the harbour of Esbjerg, transportation of CO_2 to Nybro at the west coast of Jutland through a new onshore pipeline and further transportation to the offshore Harald fields via an existing natural gas pipeline.

The intermediate storage is designed to provide a steady flow towards the Harald fields. The intermediate storage can cover all phases from the startup phase of 3 million tonnes CO_2 annually to 16 million tonnes CO_2 annually. The CO_2 will be pressurised to 138 bars, heated, and transformed into a liquid phase in the storage tanks prior to transportation through

Transport of CO_2 through pipelines



CO_2 offload from ships to a receiving terminal at the harbour.

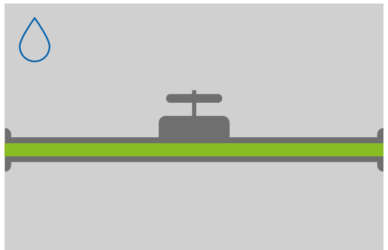
CO_2 pumped to an intermediate storage at the harbour and transformed into a liquid.

Liquid CO_2 transportation through a new onshore pipeline to Nybro.

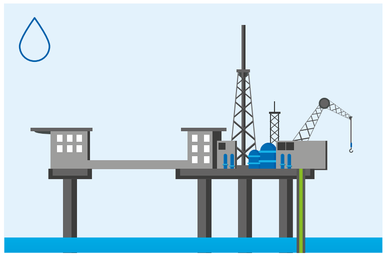
the new onshore pipeline to Nybro where the CO_2 will be redirected offshore via an existing natural gas transmission pipeline to the Harald platforms.

The existing offshore pipelines, owned and operated by Ørsted, have been evaluated for CO_2 transportation. All pipelines are found suitable for transportation of CO_2.
The evaluation shows that the maximum transport rate is approximately 25 million tonnes annually for the pipeline from Nybro to the Tyra field and 13 million tonnes annually for the pipeline from Nybro to the Harald fields. Investigations show that the pipeline from Nybro, connecting to the Harald fields, can be made available in an early stage, meeting the timeline for the first CO_2 injection in the depleted hydrocarbon fields.

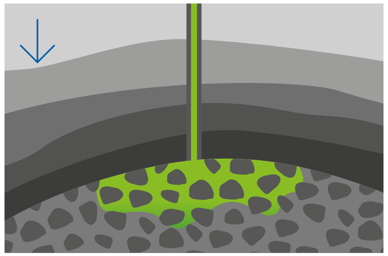
An assessment of the risk of chemical degradation and corrosion indicates that neither the metallic pipeline nor non-metallic seals or the inner coating of the pipeline will be affected by the CO_2 and associated low-concentration contaminants. A fracture assessment indicates that normal pipeline repair methods can be applied in the unlikely event of a fracture formation.



Liquid CO_2 transportation through repurposed offshore Ørsted pipeline.



Arriving offshore at the Harald platforms.



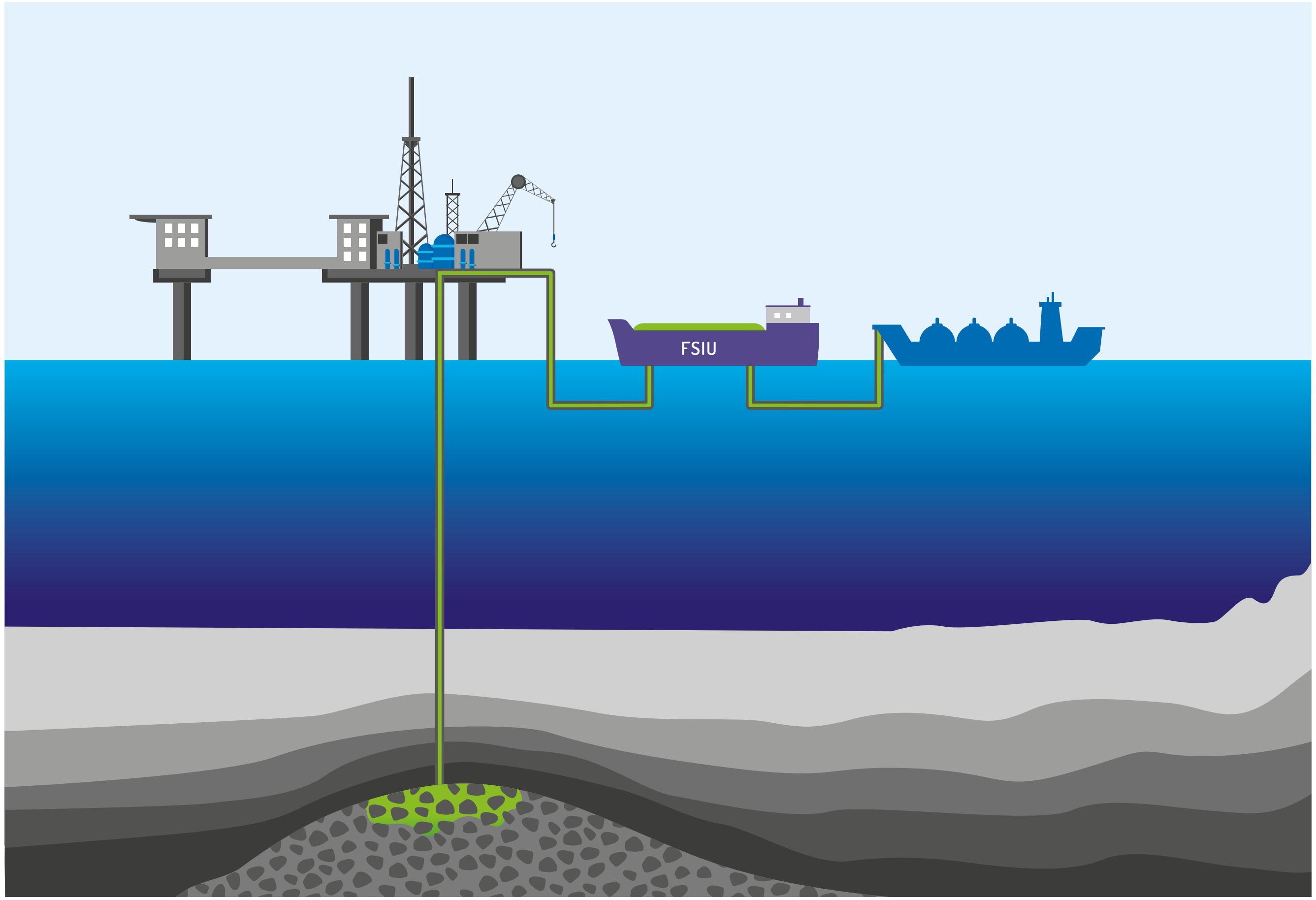
CO_2 injection into depleted reservoirs in the Harald fields.

Shipping solution

Project Bifrost has also investigated the transportation of CO_2 by ships to the platform at the Harald fields instead of using a pipeline. In the shipping solution, the CO_2 is cooled to a cryogenic state (-30°C to -20°C) and loaded onto liquid CO_2 tankers. The CO_2 is then shipped offshore and loaded onto a Floating Storage & Injection Unit (FSIU) connected to the Harald platform. To allow injection at the target rate of 3 million tonnes CO_2 annually, shipping simulations have determined that three liquid CO_2 tankers of 12,000 m^3 capacity each are required. The corresponding capacity required for the FSIU is 30,000 m^3.

The CO_2 will be imported through a flexible pipeline from the FSIU to the Harald platform. The FSIU will furthermore interface with the Harald platform through a combined power cable and optical fibre connection. The CO_2 will be heated and pressurised at the FSIU and will arrive at the Harald platform with a minimum temperature of 0°C and a pressure up to a maximum of 150 bars. At the platform, a set of high-pressure pumps will increase the pressure to 350 bars needed for the injection into the geological reservoirs.

Shipping CO_2 to a Floating Storage & Injection Unit (FSIU) and injection via the Harald platform.



From source to sink – in short

- The CO_2 may be transported offshore by a former natural gas pipeline.
- Transporting CO_2 by ship to the Harald fields is also a viable solution.

A pathway to the storage – wells at Harald West

Project Bifrost aims at injecting CO_2 into the Harald West sandstone reservoir and the Harald East chalk reservoir. A comprehensive study has been made on existing wells and a proposed new injection well at Harald West. This work focused on an integrity study of existing wells, a modelling of well performance, and the creation of well designs.

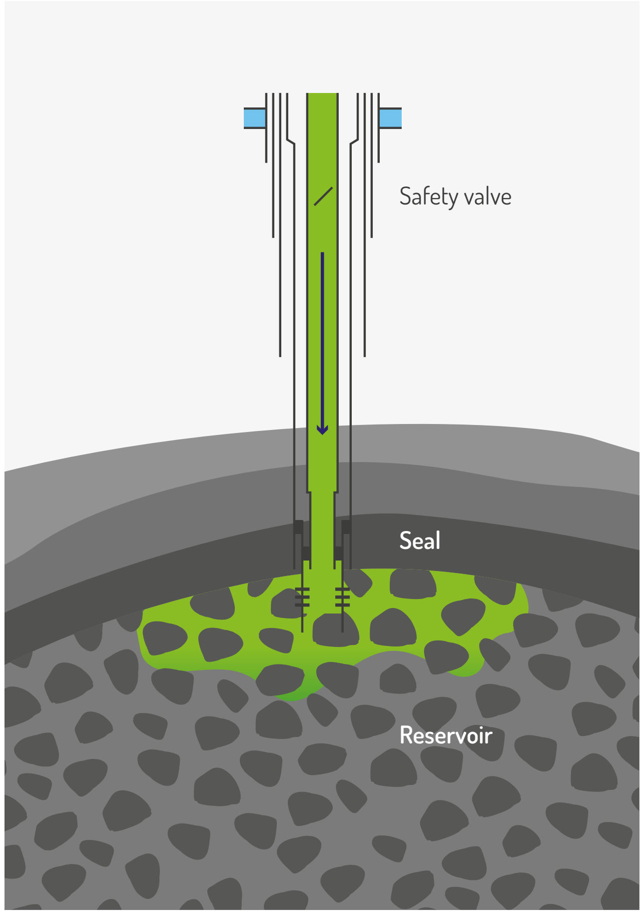
Harald West has a total of five existing wells – two gas production wells and three abandoned exploration wells. The integrity of these wells has been reviewed to establish whether they pose a leakage risk when injecting CO_2 into the reservoir. The review showed that all abandoned wells are equipped with sufficient barriers to permit permanent CO_2 storage with minimal risk of leakage. One of the gas production wells was found suitable for conversion to a CO_2 injection well, whereas the other gas production well was deemed unsuitable for conversion and will thus be abandoned robustly prior to commencing the injection.

Performance concepts and well designs were created for two types of CO_2 injection wells – the converted former gas production well and a new injection well. For the converted well, a new inner liner was designed in order to isolate any worn or corroded sections and to ensure a robust well design. The new well was designed to provide a spare well option. Studies of drilling conditions concluded that it is feasible to drill the new well into the depleted gas reservoir.

A pathway to the storage – in short

- Abandoned wells possess minimal risk of leakage.
- Both converted gas production wells and new injection wells are suitable for CO_2 injection.

Two types of injection wells have been designed: a converted former gas production well and a new injection well.



The CO_2 storage – safe geological conditions

Harald West and Harald East both exhibit a combination of a porous reservoir unit overlain by a tight sealing rock and a geological structure with dome shaped geometry. Together these features define the two fields as geological traps from which the CO_2 cannot escape after injection into the reservoir units. As part of Project Bifrost, the geological characteristics of the Harald West sandstone reservoir and the Harald East chalk reservoir have been addressed for the suitability of permanently storing CO_2 in terms of volume capacity and containment confirmation.

Laboratory tests of rock samples indicate safe storage of CO_2 in the Harald fields.

The analysis has involved a number of studies, including seismic mapping of the geological structures, high-resolution numerical reservoir models, geochemical reactivity studies, geomechanical numerical modelling and in-depth risk assessment.

Harald West sandstone storage complex

The Harald West CO_2 storage complex comprises the gas filled Middle Jurassic sandstone reservoir currently being produced by the Harald West wells and the seal interval above. The more than 100 metres thick seal is defined as Upper Jurassic shales and the lowermost very dense chalk of Cretaceous age. The reservoir is situated at a depth of approximately 3,400 metres.

The assessment of Harald West indicates that after termination of gas production and commencement of CO_2 injection the CO_2 will distribute and mix with the remaining gas and stabilise with pressures below the initial reservoir pressure, i.e. the pressure measured before hydrocarbon production commenced. Satisfactory rates of CO_2 injection can be achieved for the initial phase with just one well, being the current gas production well. The converted well is expected to deliver rates of 2–3 million tonnes CO_2 per year for approximately 15 years before the pressure locally near the well is reaching the initial, pre-production reservoir pressure. The CO_2 plume is expected to remain within the storage unit at a safe distance from spill points. Geochemical analyses show that there will be no detrimental effect on the flow properties of the reservoir or the integrity of the seal, resulting from the mixed fluids (gas, water, CO_2, and potential impurities) interacting with the rock minerals.

The seal has been able to trap natural gas for millions of years, and the technical work has confirmed that it will also be able to enclose the CO_2 safely for a permanent storage. In addition, this seal is just one of many seals that exists between the storage complex and the seabed.

Harald East chalk storage complex

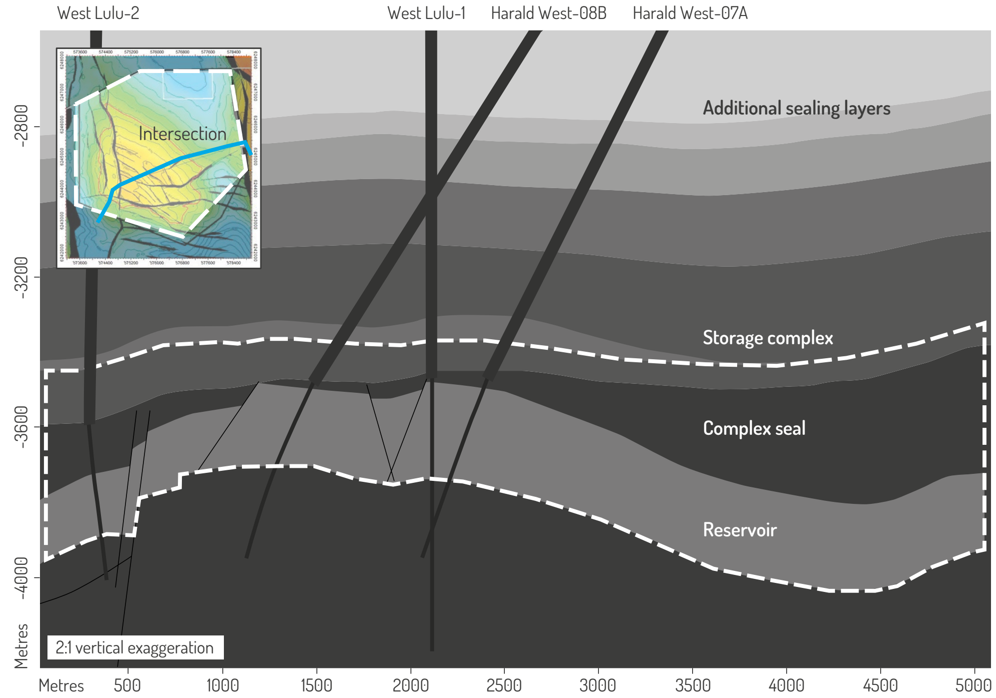
The Harald East storage site is comprised by the Danian chalk reservoir currently being produced by the Harald East wells and the 30–40 metres thick seal composed of Paleocene marl and mudstone. Above this primary seal there are multiple layers of impermeable clay-dominated rocks that form secondary seals with a combined thickness of more than 1,000 metres. The reservoir is situated at a depth of approximately 2,700 metres.

Modelling work predicts the CO_2 to distribute and mix with the remaining gas, stabilise with pressures below the initial reservoir pressure, and to stay at a safe distance from spill points. Satisfactory rates of CO_2 injection can be achieved by converting one or two of the gas production wells. Each of these converted wells has the potential to deliver CO_2 injection rates of more than 1 million tonnes per year before the pressure locally near the well is reaching the initial, pre-production reservoir pressure after some 8–16 years depending on rates and number of converted wells. The results of geochemical simulations indicate no detrimental effect on the flow properties of the reservoir or the integrity of the seal, resulting from the mixed fluids interacting with the rock minerals.

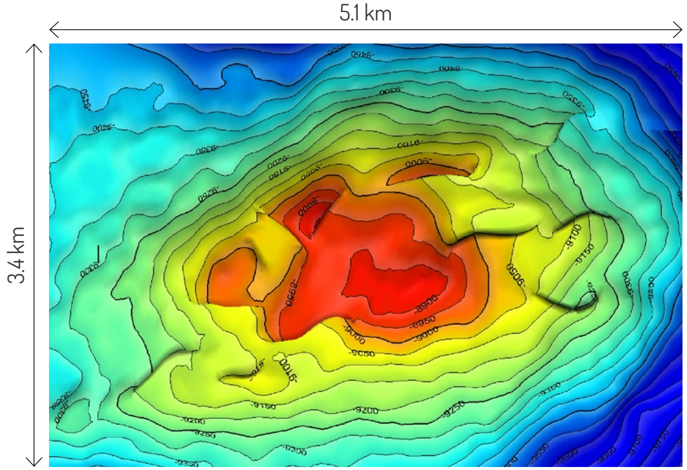
Risk assessment supported by the technical work indicates that the seal will trap the CO_2 safely for permanent storage in the chalk reservoir. Experimental studies demonstrate a very low risk of mechanical instability of the reservoir rock properties after CO_2 injection. Thermodynamic simulations looking at potential leakage pathways of CO_2 along pre-existing faults and wells were analysed for a 1,000-year period after termination of injection. These simulations predict that CO_2 remains in the reservoir with negligible risks of loss of geological containment thanks to the strength and thickness of the seal.

The CO_2 storage – in short

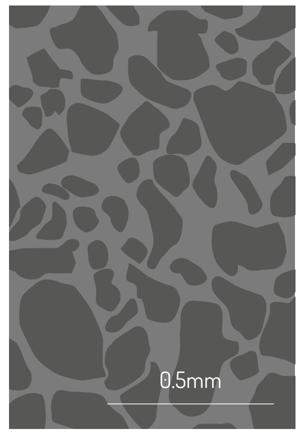
- The Harald West storage complex comprises a sandstone reservoir.
- The Harald East storage complex comprises a chalk reservoir.
- Both types of storage complexes are suitable for permanent CO_2 storage.



Geological cross-section of Harald West showing the upside-down bowl shape of the geological structure. Existing wells are indicated.



The upside-down bowl shape of Harald East as shown on the depth map of the reservoir surface. Two abandoned exploration wells are indicated.



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The pore spaces between sediment grains in the reservoirs will be filled with CO_2.

Impact studies and monitoring

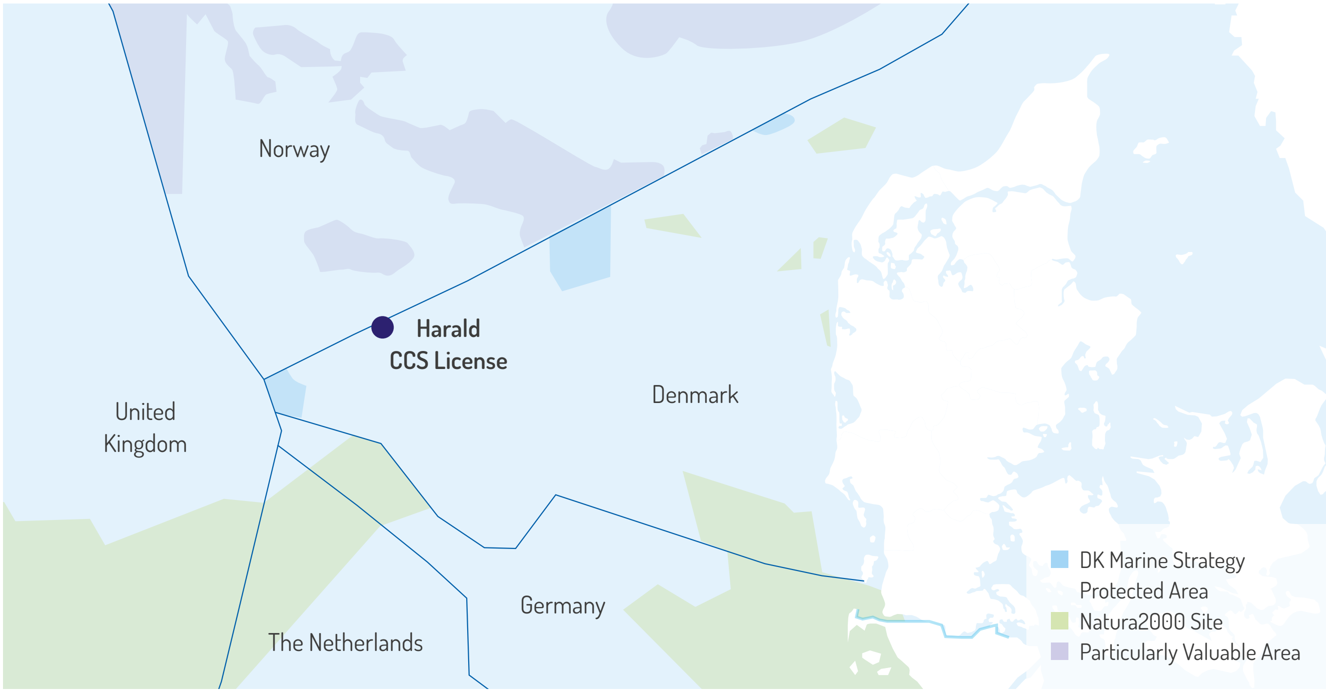
Project Bifrost is not affecting any protected areas in the North Sea region.

Comprehensive work has been carried out through Project Bifrost documenting that CCS in the Harald fields has limited impact on health, safety, environment and society.

Health, safety, environment, and societal implications

A permit and consent register has been established in compliance with regulations in place. The register includes specification of the responsible authorities, description of relevant regulations, challenges, and the expected timeline for each permit/consent. The register draws upon experience from existing oil and gas projects in the Danish sector of the North Sea.

A desktop study has been carried out in order to identify potential impact on environment and society. The assessment of existing monitoring data around the Harald platforms indicated only negligible impact on the seabed conditions and the benthic fauna communities around the platform. Analysis also showed contaminant concentrations below the Effects Range Low (ERL) as defined by OSPAR (Oslo-Paris Convention) and developed by US National Ocean and atmospheric Administration (NOAA). Three species of marine mammals (strictly protected under the Habitats Directive Annex IV and the Danish legislation) are potentially present

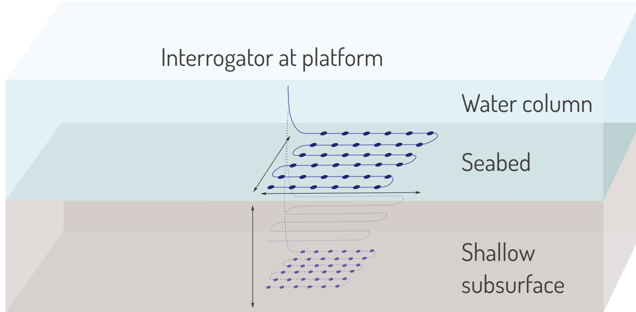


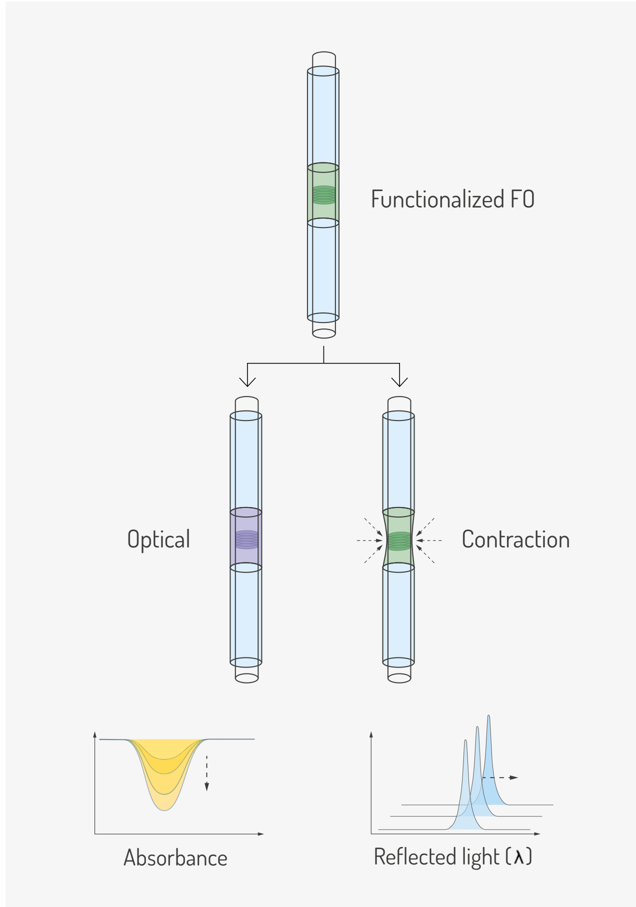
in the area: harbour porpoise (the most abundant with a density of about 1 animal/km²), white beaked dolphin and minke whale. The study also shows that Project Bifrost is not affecting any protected areas in the North Sea region.

Monitoring for safety

Monitoring of geological storage facilities, from pre-injection baseline surveys to final handover of the facility to authorities, is central to demonstrating safe and permanent containment

Fibre optical CO_2 monitoring concept.





of the CO_2, to prevent and mitigate potential leakage, and to build public acceptance. Identifying the right monitoring technologies is therefore key to the success of any CCS project.

A worldwide review of monitoring, measurement and verification plans for offshore CO_2 storage projects was performed. The review maps out the existing and readily available monitoring technologies, with focus on offshore storage in depleted hydrocarbon fields. The review also provides a view on recent advances that could play a key role in future long-term monitoring of storage sites.

Numerical feasibility simulations showed that the combined effects of fluid changes, pressure and temperature changes in the gas cap that will host the CO_2 will be detectable using 4D seismic. This requires a seismic baseline survey acquired before the injection starts and another survey acquired after the injection, enabling comparisons of the two surveys. Should CO_2 leak from the sandstone reservoir in Harald West into the chalk at shallower depths, the fluid change will also be detectable using 4D seismic. A micro seismic feasibility study indicated that if rock deformations occur, it will be possible to distinguish deformations in the reservoir (which can be tolerated) from extremely unlikely deformations in the seal (which is not tolerated).

Long-term monitoring of CO_2 by physical measurements and deployment of sensing systems at the seabed has been investigated for CO_2 seepage detection. A fibre optical technology is under development, where the sensors themselves consist of a micrometre-thin CO_2-sensitive coating reacting by contraction and thus affecting the light flux through the fibre optical cable. The plan is to place sensor networks at the seabed across the entire CO_2 storage area.

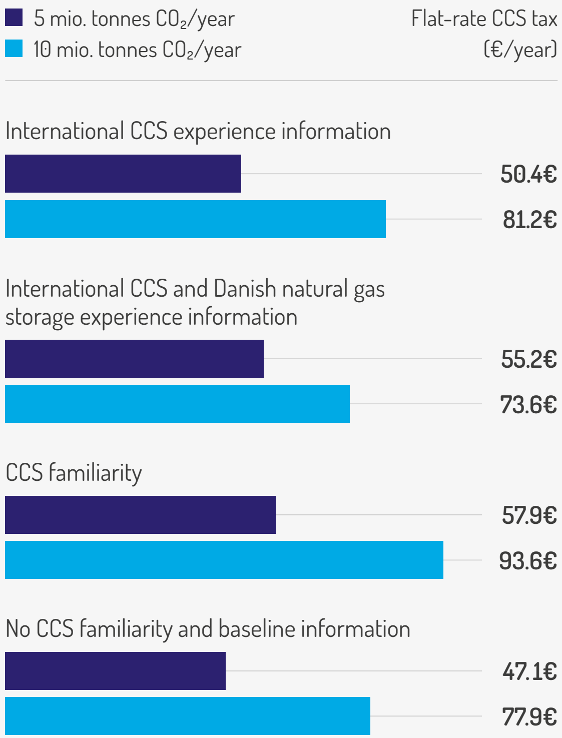
Machine learning may be used to constantly analyse the stream of data that will be provided from monitoring tools. Three machine learning models for monitoring of CO_2 plume movements were tested. The tests resulted in promising results supporting further research on the topic.

CO_2 in depleted hydrocarbon fields – in short

- CCS in the Harald fields has limited impact on health, safety, environment and society.
- Project Bifrost is not affecting any protected areas in the North Sea region.

Social acceptance – cornerstone in a successful rollout of CCS

The willingness to pay is higher if the CO_2 storage rate is higher



The acceptance and preferences among the Danish population were analysed based on surveys among 55,000 individuals. The survey response rates were between 15%–22%. The results indicated a general support for CCS. The analysis also showed that the citizens were more positive to a CO_2 storage site if it was placed at some distance to the individual citizens compared to storage sites nearby. The degree of general familiarity and the information about CCS offered to the individual citizen also had positive impacts on the acceptance. In addition, a positive relationship between the yearly amount of CO_2 to be stored and the willingness to pay also existed, irrespective of familiarity and information level.

The stakeholder analysis showed a trust in the CCS technology, however, mainly if no alternatives for CO_2 emission reduction exists. In addition, the key stakeholders stressed that CCS should not prolong fossil fuel use or hinder renewables. The stakeholders were aware of the need for urgent regulations for infrastructure and certification and for democratic involvement.

The macroeconomic impact of offshore CCS technology for Denmark, focusing on Project Bifrost, has been explored when utilising the existing natural gas pipeline for CO_2 transportation. The study showed a positive impact over a 30-year period for both economy and employment. The benefits are highest in the case of early pipeline conversion and intermediate CO_2 storage and loading occurring in Denmark.

Social acceptance – in short

- A survey among 55,000 individuals indicated a general support for CCS.
- A stakeholder analysis showed a trust in the CCS technology.
- A macroeconomic study showed a positive impact over a 30-year period for both economy and employment.

Project Bifrost – key to unlock Denmark's CCS potential

Project Bifrost has successfully demonstrated that a long-term solution for CCS in Denmark is possible by using existing infrastructure in the Danish North Sea. The two natural gas reservoirs of the Harald fields are highly suited for permanent storage of CO_2 in a safe and cost-effective way.

Project Bifrost is thus key for Denmark to unlock its CCS potential, meet its CO_2 neutrality targets and to provide employment alternatives to the workforce currently related to oil and gas production.

Forward focus

Project Bifrost is at the appraisal phase – and the start of a journey. Further development is needed to make CCS a commercial and industrial reality, and all participants in EUDP Project Bifrost will continue to engage in this development: DTU continues working on innovative monitoring technologies; Ørsted will launch technical studies for repurposing of the offshore gas pipeline and onshore facilities in Nybro; TotalEnergies and Nordsøfonden continue to work towards storing CO_2 in the Harald fields on commercial terms with the storage exploration license, awarded in February 2023; and BlueNord is involved in CO_2 storage studies through CarbonCuts.

For Denmark to become the European hub for CO_2 storage, additional partnerships are required from the full CCS value chain to develop solutions for transporting the CO_2 from emitters to the Harald facilities.

Project Bifrost results – in short

- Project Bifrost is key for Denmark to unlock its CCS potential.
- The Harald fields are highly suited for permanent storage of CO_2 in a safe and cost-effective way.
- A long-term solution for CCS is possible by using existing infrastructure in the Danish North Sea.

Links and contact details
For more information:
https://bifrost-ccs.com/
https://eudp.dk/en/node/16469

If you have any questions or comments, feel free to contact Project Manager of Project Bifrost, David Nevicato:
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