

# End Project report



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## Project Report

### **1/ Introduction**

The European Union is committed to a 55% CO<sub>2</sub> 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<sub>2</sub> 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 massive amounts of gasses with a high content of CO<sub>2</sub>. Rather than releasing the CO<sub>2</sub> into the atmosphere, it is captured from the gaseous emissions at the plants. After purification, the CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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, to form an effective seal. Finally, the combined reservoir and seal should form a dome shaped geological structure, ensuring the CO<sub>2</sub> is kept safely and permanently deep underground.

#### **Denmark – the ideal location for CCS**

Denmark has the potential to become a major provider of CO<sub>2</sub> 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<sub>2</sub> 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 technology the potential to deliver significant CO<sub>2</sub> 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<sub>2</sub> in the underground of the Danish North Sea, turning the 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.

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<sub>2</sub> 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.

#### **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<sub>2</sub> offshore in the future depleted Harald gas fields: The process begins with CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> molecules are replacing the natural gas molecules previously occupying the pore spaces in the reservoir rocks. The

CO<sub>2</sub> 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.



*Figure Intro-1: Harald Platforms*

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<sub>2</sub> emitters. The depleted Harald West sandstone reservoir is targeting in the first phase to store 2–3 million tonnes CO<sub>2</sub> 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 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<sub>2</sub> 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 Blue Nord), 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.

The project structure is organized according work packages, led by one of partners, including different tasks.

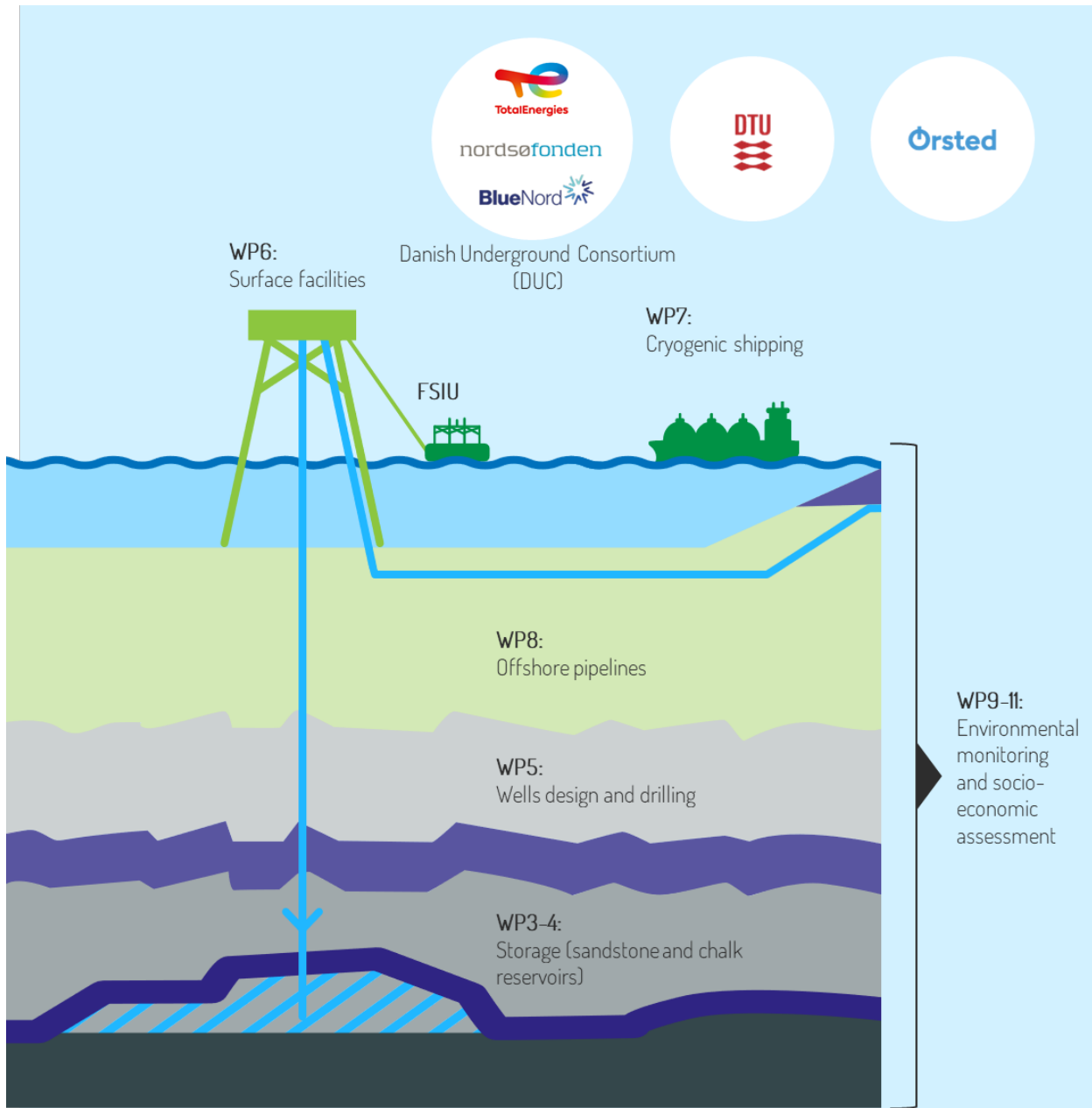


Figure Intro-1: Bifrost Project Work-Packages Structure



**WP2. Communication, Dissemination & Stakeholder Engagement**  
**WP Lead: DUC-TotalEnergies**

### Introduction and objective of this work package

1. To perform communication, dissemination, and exploitation activities for Bifrost, maximizing its visibility and facilitating the uptake of the demonstration results through targeted information to multiple audiences, including consortium members and external parties.
2. To stimulate innovation and cooperation through collaborative tasks that will share findings to scientific and non-scientific groups, commercial partners, policy makers, and society at large. The aim is to disseminate the research results widely among the scientific community and to ultimately encourage a significant acceleration of the development of CCS in Denmark and take-up of the results by commercial partners.

### Key results

With the above two objectives in mind, the communications team focused on two activity tracks to ensure successful outreach and visibility throughout the duration of project:

#### 1. General public and other non-scientific stakeholder groups Communication Track:

This general communication track aimed to build knowledge, foster dialogue and enhance collaboration with policy makers across borders. These dialogues have been instrumental in shaping policies and creating a favourable environment for the adoption of the project's research findings.

We have focused on enhancing our visibility through general events, press releases, media events and the bifrost-ccs.com website. The events have been well-attended by consortium members, commercial partners, and external parties, providing us with a platform to showcase the work and its implications. The press and news releases have been picked up by major news outlets, further increasing our reach. The website served and still serves as a comprehensive resource for all information related to EUDP Project Bifrost, including updates on our progress, upcoming events, and opportunities for collaboration.

Lastly, two videos were produced explaining the project in depth and highlighting the importance of combining academia and industry for such a project has served a purpose of educating and spreading information about the potentials of Denmark becoming a European CCS hub and the benefits of this. In addition, a high-level project brochure has been created to serve as a beacon of information to the general public's interest in CCS. Link to the brochure:

[https://bifrost-ccs.com/wp-content/uploads/2024/06/Bifrost\\_Executive\\_Summary\\_final\\_240613-1.pdf](https://bifrost-ccs.com/wp-content/uploads/2024/06/Bifrost_Executive_Summary_final_240613-1.pdf).

#### 2. Scientific Track:

The scientific track is dedicated to disseminating the research findings to the scientific community. The project has published several research papers in reputed journals, contributing to the body of knowledge in the field of CCS. You can find links to our publications below in the list called 'links to scientific articles'.

The project has also actively participated in various scientific conferences, presenting key findings and studies, and engaging in insightful discussions with other researchers. These conferences have provided the project with the opportunity to learn from others, gain feedback, and establish collaborations for future research. An overview of the conferences is also listed below, called 'overview of conferences/events'.

- We believe that this two-pronged approach of general communication and scientific dissemination has ensured the successful outreach and visibility of EUDP Project Bifrost throughout the duration of the project.

### Links to scientific articles

- Amour F., M.R. Hajjibadi, Hosseinzadehsadati S., and H.M. Nick (under review) What if chalk becomes mechanically weaker during supercritical CO<sub>2</sub> injection in a depleted gas reservoir? *Int. J. Rock Mech. Min. Sc.*
- Amour F., M.R. Hajjibadi, Hosseinzadehsadati S., and H.M. Nick (under review) Impacts of CO<sub>2</sub> Injection on the Compaction Behaviour and Storage Capacity of Chalk Reservoirs. *J. Greenhouse Gas Control.*
- Amour F., M.R. Hajjibadi, Hosseinzadehsadati S., and H.M. Nick (2024) A geomechanical assessment of containment in a depleted gas chalk field: Case study from the Harald East field. *Int. Geomech. Symp. 2024, Kuala Lumpur, Malaysia, Nov. 2024.*
- Amour F., M.R. Hajjibadi, Hosseinzadehsadati S., and H.M. Nick (2024): Well integrity analysis during CO<sub>2</sub> injection in a depleted chalk field. Paper presented at the ARMA24 Conference, Golden, USA, June 2024.
- Amour, F., Hajjibadi, M.R., Hosseinzadehsadati, S. and Nick, H.M. (2024): Thermo-hydro-mechanical simulation of CO<sub>2</sub> storage in a depleted chalk reservoir: Impacts of hydrocarbon production, temperature, injection rate, and rock-fluid interactions on fault reactivation and field deformation. Paper presented at the 17th Greenhouse Gas Control Technologies Conference (GHGT-17), October 2024.
- Amour F., M.R. Hajjibadi, Hosseinzadehsadati S., and H.M. Nick (2023): Shear and Vertical Deformation Behaviour at the Field Scale During CO<sub>2</sub> Storage in a Depleted Chalk Reservoir (Danish North Sea). Paper presented at the ARMA23 Conference, Atlanta, USA, June 2023. Available at <https://doi.org/10.56952/ARMA-2023-0673>
- Amour, F., Hosseinzadehsadati, S. and Nick, H.M. (2023): Viscoplastic Deformation During CO<sub>2</sub> Storage in Danish Chalk Reservoirs: Role of Petrophysical Heterogeneity and Mechanical Alteration. Paper presented at the SPE EuroPEC – Europe Energy Conference featured at the 84th EAGE Annual Conference & Exhibition, Vienna, Austria, June 2023, Paper Number: SPE-214399-MS. Available at <https://doi.org/10.2118/214399-MS>
- Amour, F., Hajjibadi, M.R., Hosseinzadehsadati, S. and Nick, H.M. (2022): Impacts of CO<sub>2</sub> Injection on the Compaction Behaviour of Chalk Reservoirs. *Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022*, Available at <https://ssrn.com/abstract=4286144> or <http://dx.doi.org/10.2139/ssrn.4286144>
- Bonto, M., Jahanbani, M. and Nick, H.M. (2022): Microbial-induced risks associated with CO<sub>2</sub> storage. *Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022*, Available at SSRN: <https://ssrn.com/abstract=4282829> or <http://dx.doi.org/10.2139/ssrn.4282829>
- Ferreira, C. A. S., and Nick, H. M. (2024): Towards a deep learning tool for monitoring the CO<sub>2</sub> plume propagation in carbon storage activities [talk]. *Recent Advances in Geophysical Reservoir Characterization and Monitoring of CO<sub>2</sub> Sequestration in Carbonate Reservoirs Workshop*, May 2024.
- Ferreira, C. A. S., Kadeethum, T., Amour, F., Hosseinzadeh, B., Abdollahi, A., Calvert, A. S., and Nick, H. M. (2024): A deep learning model for CO<sub>2</sub> storage in a depleted gas reservoir using sparse well data. *85th EAGE Annual Conference and Exhibition*, Jun 2024. <https://doi.org/10.3997/2214-4609.2024101572>
- Ferreira, C. A. S., Kadeethum, T., and Nick, H. M. (2023a): Predicting geologic CO<sub>2</sub> storage and plume evolution from sparsely available well data using Barlow Twins. *Third EAGE Digitalization Conference and Exhibition*, March 2023. <https://doi.org/10.3997/2214-4609.202332073>
- Ferreira, C. A. S., Pianos, M., Hosseinzadehsadati, S., Tian, J., Kadeethum, T., and Nick, H. M. (2023b): A predictive DeepONet model of CO<sub>2</sub> plume propagation in geological formations based on sparse well data. *Fourth EAGE Global Energy Transition Conference and Exhibition*, November 2023. <https://doi.org/10.3997/2214-4609.202321097>
- Ferreira, C.A.S., Stepien, M., Hosseinzadehsadati, S., Kadeethum, T. and Nick, H.M. (2022): Predicting the CO<sub>2</sub> propagation in geological formations from sparsely available well data. *Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022*, Available at SSRN: <https://ssrn.com/abstract=4285942> or <http://dx.doi.org/10.2139/ssrn.4285942>


- Hajiabadi, M. R., Amour, F., Hosseinzadehsadati, S. B., and H. M. Nick (2024): Induced Seismicity of CO<sub>2</sub> Injection in a Depleted Chalk Field with a Thermo-Hydro-Mechanical (THM) Model, The 17th Greenhouse Gas Control Technologies Conference (GHGT-17), Calgary, Canada, October 2024
- Hajiabadi, M.R., Amour, F. and Nick, H.M. (2022): Geomechanical Evaluation of a Depleted Chalk Reservoir for CO<sub>2</sub> Storage. Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022, Available at SSRN: <https://ssrn.com/abstract=4284515> or <http://dx.doi.org/10.2139/ssrn.4284515>
- Hosseinzadehsadati, S. B., Amour, F., A. Abdollahi C.C., Hajiabadi, M. R., and H. M. Nick: Is Two-Way Coupled Geomechanical Modeling Essential for CO<sub>2</sub> Storage in Deformable Chalk Reservoirs? The 17th Greenhouse Gas Control Technologies Conference (GHGT-17), Calgary, Canada, October 2024
- Hosseinzadehsadati, S. B., Amour, F., A. Abdollahi C.C., Hajiabadi, M. R., and H. M. Nick: Multi-Physics Simulation of Reactive CO<sub>2</sub> Transport in Chalk Reservoirs: A Case Study. The 17th Greenhouse Gas Control Technologies Conference (GHGT-17), Calgary, Canada, October 2024
- Hosseinzadehsadati, S. B., Amour, F., A. Abdollahi C.C., Hajiabadi, M. R., and H. M. Nick: Multiphysics Modeling for CO<sub>2</sub> Geological Storage in a Depleted Carbonate Reservoir. GeoMontreal Conference, Montreal, Canada, September 2024.
- Hosseinzadeh, B., Amour, F., Abdollahi CC, A., Hajiabadi, M. R., Ferreira, C. A. S., & Nick, H. M. (2024, June). Assessing Caprock Integrity Through Thermo-Hydro-Mechanical Modeling of CO<sub>2</sub> in a Deformable Chalk Depleted Gas Reservoir. In ARMA US Rock Mechanics/Geomechanics Symposium (p. D031S028R002). ARMA. <https://doi.org/10.56952/ARMA-2024-0507>
- Hosseinzadeh, B., Amour, F., Hajiabadi, M. R., Cheriki, A. A. C., & Nick, H. M. (2024, June). Impact of CO<sub>2</sub> Injection on Geomechanical Response in THMC Simulation within the Chalk Reservoir: Thermal Considerations. In 85th EAGE Annual Conference & Exhibition (including the Workshop Programme) (Vol. 2024, No. 1, pp. 1-5). European Association of Geoscientists & Engineers. <https://doi.org/10.3997/2214-4609.202410344>
- Hosseinzadehsadati, S. B., Amour F., Hajiabadi, M. R., and H. M. Nick: Assessment of CO<sub>2</sub> Injectivity in Highly Deformable Chalk Reservoirs: A Thermo-Hydro-Mechanical Analysis. The 57th U.S. Rock Mechanics/Geomechanics Symposium, Atlanta, Georgia, USA, June 2023.
- doi: <https://doi.org/10.56952/ARMA-2023-0646>
- Hosseinzadehsadati, S., Amour, F., Hajiabadi, M.R. and Nick, H.M. (2023): Challenges in Modeling Coupled Thermo-Hydro-Mechanical-Chemical Processes for CO<sub>2</sub> Injection in a North Sea Hydrocarbon Chalk Reservoir. Paper presented at the SPE EuropEC – Europe Energy Conference featured at the 84th EAGE Annual Conference & Exhibition, Vienna, Austria, June 2023, Paper Number: SPE-214449-MS. Available at <https://doi.org/10.2118/214449-MS>
- Hosseinzadehsadati, S., Amour, F., Hajiabadi, M.R. and Nick, H.M. (2022): Hydro-Mechanical-Chemical Modelling of CO<sub>2</sub> storage in a North Sea hydrocarbon chalk reservoir. Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022, Available at SSRN: <https://ssrn.com/abstract=4275914> or <http://dx.doi.org/10.2139/ssrn.4275914>
- Ladenburg, J. and Soytaş, U.: Danskernes accept af grønne energiteknologier – hvor er de lavt hængende frugter (In English: Danish acceptance of green energy technologies – where are the low-hanging fruits). Submitted to Samfundskøkonomien.
- Ladenburg, J., Kim, J., Zuch, M. and Soytaş, U.: Exploring NIMBY and NON-NIMBY climate change mitigation technologies – A Danish national representative study. Submitted to scientific journal.
- Ladenburg, J., Kim, J., Zuch, M., Soytaş, U. (2023) Taking the carbon capture and storage, wind power, PV or other renewable technology path to fight climate change? Exploring the acceptance of climate change mitigation technologies – A Danish national representative study. Available here: <https://www.sciencedirect.com/science/article/pii/S0960148123014970?via%3Dihub>
- Ladenburg, J., Soytaş, U. (2023): Hvor er de lavthængende frugter? social accept af grønne teknologier [in Danish: Where are the low-hanging fruits? Social acceptance of green technologies]. Samfundskøkonomien. 33-40.
- Prevost, M., Genin, A., Ladenburg, J., Frost, J.K., Soytaş, U., Lang, R., Hein, M., Vest, M.R., Andersen, S.I. and Nick, H.M. (2022): Bifrost, An Innovative CO<sub>2</sub> Transportation and Storage Project in Denmark. Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022, Available at SSRN: <https://ssrn.com/abstract=4287094> or <http://dx.doi.org/10.2139/ssrn.4287094>

- Shaheen, S. (2023): Seabed response to potential lateral CO2 plume migration (unpublished master's thesis). Technical University of Denmark, September 2023.
- Stepien, M., Ferreira, C. A. S., Hosseinzadehsadati, S., Kadeethum, T., and Nick, H. M. (2023). Continuous conditional generative adversarial networks for data-driven modelling of geologic CO2 storage and plume evolution. *Gas Science and Engineering*, July 2023. <https://doi.org/10.1016/j.gjsce.2023.204982>
- Torres, L. F. L., Ferreira, C. A. S., Kadeethum, T., Amour, F., Hosseinzadeh, B., Abdollahi, A., Shaheen, S., Calvert, A. S., and Nick, H. M. (2024): Tracking CO2 plume propagation in a depleted gas field using sparse well data and seabed displacement. 17th Greenhouse Gas Control Technologies Conference (GHGT-17), October 2024.
- Zuch, M. and Ladenburg, J.: Information effects on public acceptance of carbon capture and storage: A literature review. Submitted to scientific journal.

### **Overview of conferences/events**

- CCS Conference 2022: CCS and CO2 Management – from Capture to Offshore Storage.
- Technology Conference 2022 – R&D for the Offshore Energy Transition.
- IGS 2022 - International Geomechanics Symposium, (DTU Offshore – technical session presentations).
- GHGT-16: 16th Greenhouse Gas Control Technologies Conference, October, 2022, (TotalEnergies and DTU Offshore – poster presentations, technical session presentations, and conference papers).
- Workshop Directorate-General for Energy, Belgium 2023 - Social acceptance and preference for CCS – the influence of information and knowledge (DTU Management keynote).
- Third EAGE Digitalization Conference and Exhibition, March 2023, oral presentation
- Net Zero Within Reach Conference 2023: Zero Emissions Platform – Bruxelles, Belgium 26 April 2023 (DTU Management presentation on Project Bifrost “Social acceptance and public perception”).
- ICEEEP 2023 - 7th International Conference on Energy Economics and Energy Policy 7th ICEEEP 2023 – Barcelona, Spain, April 28-30, 2023.
- YEEES conference 2023 - 31st Young Energy Economics and Engineers Seminar YEEES 31: Vienna 2023 – YEEES (tu-berlin.de), Vienna, Austria, May 11-12, 2023 (DTU Management: Investigating willingness to pay for Carbon Capture & Storage (CCS) contingent on information, CCS familiarity and scope in Denmark: Double-bounded dichotomous choice contingent valuation approach).
- CO2 Capture, Storage and Reuse 2023 - Fortes Media, CO2 Capture, Storage & Reuse 2023 (fortesmedia.com) Copenhagen, Denmark, 16-17 May 2023 (TotalEnergies presentation on Project Bifrost, CO2 transportation and storage opportunities in Denmark).
- 84th EAGE Annual Conf. & Exhib. SPE EuropeEC – Europe Energy Conference – SPE.org 5 – 8 Jun 2023, Vienna (DTU Offshore – technical presentations and conference papers).
- CCS Conference 2023: Denmark as a CCS hub – a technical view on upscaling, environmental footprint, and monitoring of offshore CO2 storage. DTU Offshore, Copenhagen, Denmark, 6 June 2023 (TotalEnergies keynote on Project Bifrost).
- Energiens Folkemøde 2023 booth for all public to visit and learn more about the project.
- 57th US rock mechanics / geomechanics symposium - American Rock Mechanics Association (ARMA) 2023 Symposium – American Rock Mechanics Association 25-28 June 2023 Atlanta, Georgia (DTU Offshore – technical presentations and conference papers).

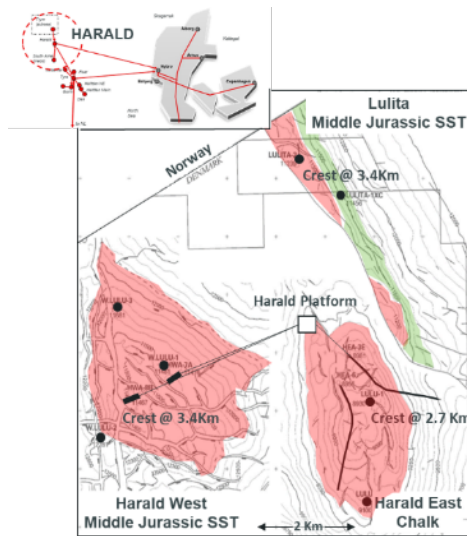
- IAAE European Conference - 18th IAAE European Conference “The Global Energy Transition Toward Decarbonization: a multi-scalar perspective and transformation” IAAE – Conference 2023 (aiee.it) – Milan (Bocconi University), Italy, 24-27 July 2023.
- Danish Offshore Technology Conference 2023: Powering the future – innovating offshore sustainability. DTU Offshore (Bifrost keynotes, presentations, and posters). This year’s Danish Offshore Technology Conference connects the dots between the many initiatives which have been launched: Energy islands, windmill parks, carbon storage, and future technologies such as PtX. There is a need for a systems approach to understanding synergies, possibilities, and environmental impact, and DTU Offshore is looking forward to starting the conversation about this with a mix of keynote speeches and deep dive technology sessions.
- Fourth EAGE Global Energy Transition Conference and Exhibition, November 2023, Paris.
- Informationen og viden om CCS og betydningen for, hvordan vi arbejder med borgerinddragelse. Præsentation i forbindelse med workshop ved ATV Mission Lab 1 WS3.
- Presentation: Carbon Footprint on my doorstep. Presentation of the connection between willingness to pay for offshore CCS and proximity to wind turbines or major CO<sub>2</sub> emitters.
- Presentation: Acceptance of and preferences for CCS: Scale, information, and knowledge effects. Presentation at the Ministry of Climate, Energy and Supply by Jacob Ladenburg.
- Recent Advances in Geophysical Reservoir Characterization and Monitoring of CO<sub>2</sub> Sequestration in Carbonate Reservoirs Workshop, May 2024.
- CCS Conference 2024: CCS Conference/a technical approach to CO<sub>2</sub> storage and the CCS value chain. DTU Offshore, addressing Project Bifrost as case-study.
- 85<sup>th</sup> EAGE Annual Conference and Exhibition, Jun 2024, Oslo – oral presentation
- 58<sup>th</sup> ARMA24 Conference American Rock Mechanics Association, Golden, USA, June 2024 – oral presentation
- Project Bifrost End-Project Conference. The Bifrost consortium has been exploring the prerequisites for establishing efficient transport and storage solutions for a future Danish CCS industry. After extensive effort and collaboration across industries and academia, we look forward to sharing the results, an outlook and the next steps in the Danish CCS development.
- GeoMontreal Conference, Montreal, Canada, September 2024 - Oral presentation.
- The 17th Greenhouse Gas Control Technologies Conference (GHGT-17), Calgary, Canada, October 2024 – several oral presentations from DTU Offshore



**WP3 - Geosciences on Harald West store under continuous injection**  
**WP Lead: DUC-TotalEnergies**

**Introduction and objective of this work package**

Harald West is a gas condensate field in the north-eastern part of the Danish Central Graben, off-shore Denmark (Figure WP3-1).



*Figure WP3-1 showing regional geological map and cross section.*

The field was discovered in 1984 by the West Lulu-1 well encountering gas in a faulted four-way dip structure at a depth of ~3400m. The sediments of the reservoir are Middle Jurassic sandstones and shales deposited in floodplain to shore face marine environments. The seal of the reservoir comprises Late Jurassic marine shales of variable thickness and a Hod Formation chalk layer of uniform thickness of ca. 100m. Above the seal, several porous chalk layers exist, each with their own sealing layers.

WP3 addresses the geology of the Harald West reservoir and its suitability for storing CO<sub>2</sub> in terms of volume capacity and containment confirmation. Existing data from the field was studied in a preliminary and concept phase in pursuit of the below objectives:

Preliminary stage – confirm the storage potential of Harald West (sandstone) including a preliminary evaluation of uncertainties, risks, and opportunities.

Conceptual stage – provide a more comprehensive evaluation of the risks and resources associated to the selected concept and integrate results from WP5 and WP10 in an integrated storage management plan.

**Analysis**

The following work was conducted in the Preliminary Stage analysis:

The geological storage complex was analysed and described, including a well review of current production wells and abandoned exploration wells in the area. The reservoir characterization included analysis of reservoir properties, vertical and lateral boundaries, and properties of the adjacent, hydraulic connected areas. Based on the analysis, the main geological uncertainties could be described qualitatively.

The pre-existing reservoir models were re-calibrated to match the latest historical production and pressure data in the highly depleted middle Jurassic sandstone gas reservoir. Furthermore, the models were converted to thermo-compositional simulation models to evaluate temperature effects and simulate the compositional changes and interactions between reservoir fluids and the injected CO<sub>2</sub>. The storage capacity is constrained by the produced volume, injection rates determined by well design and geomechanical constraints on injection pressure.

Geophysical seismic mapping of the structure, using seismic data from 2011, was conducted as part of the preliminary stage. The detailed mapping and time to depth conversion provided a better understanding of lateral barriers of the field and was a pre-requisite for the high-resolution geological modelling planned for the subsequent Concept study phase.

Based on the important level of depletion, the strong cap rock, an extremely low chance of fault reactivation and line of sight to a manageable injection plan, the preliminary conclusion was that safe and permanent CO<sub>2</sub> injection into the Harald West store can be achieved.

The following work was conducted in the Concept Stage Analysis:

A high-resolution geological model was constructed using input from all wells with new consistent evaluation of bore hole logs and the new geophysical maps interpreted during the feasibility stage. The model flow properties were calibrated to all historical production and well test data during the history match phase. For forecasting the injection performance, compositional and thermal modelling was enabled thanks to the results of a review of thermodynamical data. The modelling work delivered a reference model, based on best technical estimates of each input, as well as a suite of reservoir models each representing other representations (100 models) that also satisfy history matching criteria. The suite of models is a results of a comprehensive uncertainty analysis.

Geochemical reactivity between the pre-existing and injection fluids and the host rock minerals as well as the cap rock was studied using compositions that were described from existing core data. This work was conducted to confirm that the presence of CO<sub>2</sub> would not have detrimental effects on the flow properties of the rocks or the seal.

For 3D geomechanical modelling, the geological model was expanded to include the sequence above the reservoir, all the way to the sea level (See Figure WP3-3). Also, the model was widened to include the graben bounding faults on either side of the Harald Structure. The 3D geomechanical model was populated with reservoir properties in the reservoir zones and with geomechanical parameters (elastic properties) throughout. Stress and deformations (strain) were predicted for the production zone in which significant pressure depletion has occurred. This results in reservoir compaction that was matching the 4D seismic observations made by subtracting a 2011 seismic survey from the 1985 pre-production seismic data. The stress and strain associated with future planned injection was predicted using pressure and temperature input from the high-resolution dynamic model described above. The future stress and strain were analysed to confirm the integrity of the seal.

The assumption that the Harald West is a safe reservoir for storing CO<sub>2</sub> was supported by a comprehensive risk assessment and risk management work scope containment risk workshops were facilitated by third party experts integrating the knowledge and analysis made by the Bifrost teams (wells and subsurface) with company subject matter experts (monitor, CO<sub>2</sub> storage, reservoir management, geomechanics). Risk identification workshops were followed by risk ranking workshops, bow-tie analysis, and application of pre-, during and post injection activities to minimize the residual risks. In the end, after the planning of monitoring and response planning, the plans were evaluated to ensure that the residual risks were As Low As Reasonably Practicable (ALARP).

## Key findings and results

The Harald West CO<sub>2</sub> storage complex comprises the gas filled Middle Jurassic sandstone reservoir currently being produced by the Harald West wells and the caprock interval above as shown in Figure WP3-2. The seal is defined as the Upper Jurassic marine shales and the lowermost very dense chalk of the Hod Formation, being the strongest component of the seal.

The high-resolution reservoir model (Figure WP3-3) predicts the CO<sub>2</sub> to distribute and mix with the remaining gas in the gas cap and stabilize with pressures below the initial reservoir pressure. Satisfactory rates of CO<sub>2</sub> injected per year can be achieved with just one well, being the current producer HWA-07A. The converted well is expected to deliver rates of 2-3 Mtpa for approximately 15 years before the pressure locally near the well is reaching the initial, pre-production reservoir pressure.

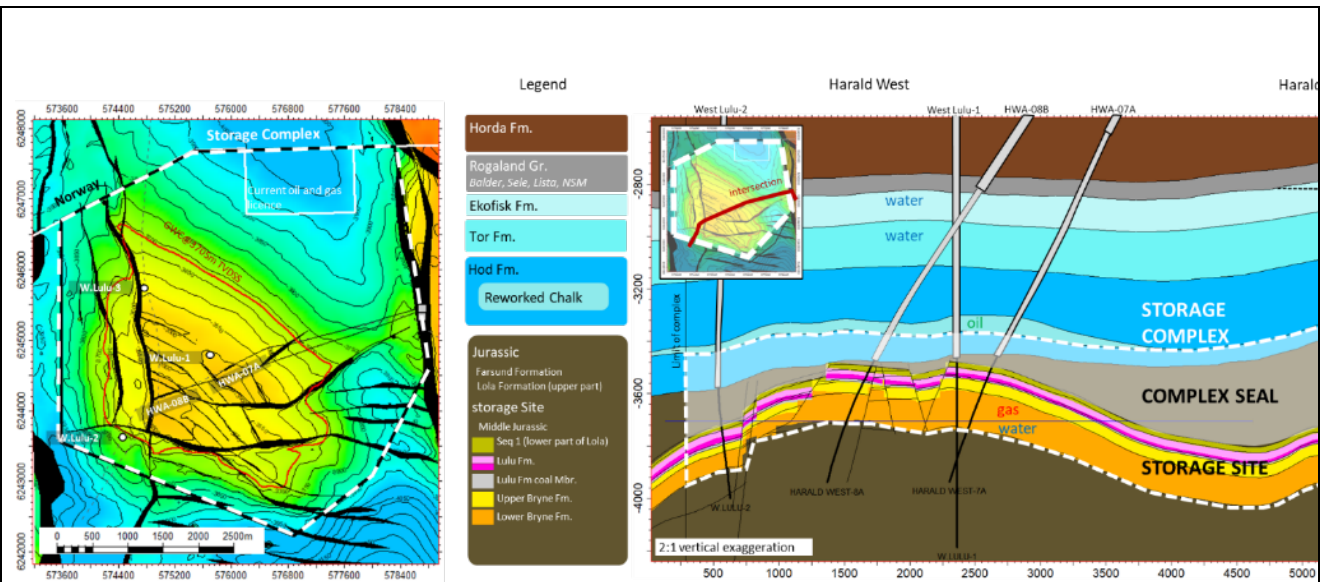


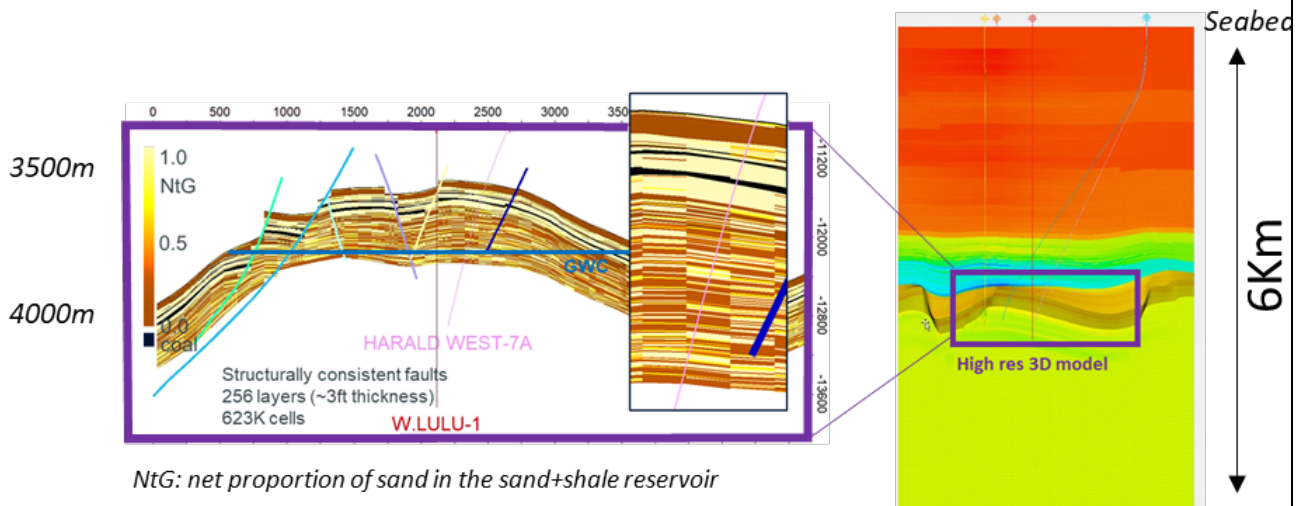
Figure WP3-2: Depth structure map of top of the storage site (Left) and a cross-section view of the storage site, the complex seal that together forms the storage complex.

The seal has been able to trap hydrocarbons for millions of years and the technical work has confirmed that the Harald West will also be a very safe place to store CO<sub>2</sub> permanently. The reservoir simulation predicts temperatures to drop to some 30degC in the vicinity of the injection well. It is in this area that the stresses to the reservoir will be greatest. The geomechanical modelling shows that even if the reservoir layers that will be used for storage are being affected by the imposed stress, the seal will remain unaffected from the stresses and temperatures and will therefore remain intact.

The geochemical analysis shows that there will be no detrimental effect on the flow properties of the reservoir, resulting from the mixed fluids (gas, water, CO<sub>2</sub>, and potential impurities) interacting with the rock minerals in the expected temperature and pressure range.

High resolution 3D reservoir model of the storage site

3D Geomechanical model



NtG: net proportion of sand in the sand+shale reservoir

Figure WP3-3: High resolution 3D reservoir model (Left) and 3D Geomechanical model (Right) developed for the study.

Even though the wells have been drilled through the reservoir seal, history has shown that the barriers between the reservoir and the layers above have remained intact. Studies were conducted in the WP5 of the Bifrost project to support that the barriers will also be effective in the future.

It is the operator’s responsibility to demonstrate that the CO<sub>2</sub> injection progresses as planned and that the CO<sub>2</sub> stays in the geological storage complex. To that end, the Harald West monitor and storage management plans have been established through multi-disciplinary workshops facilitated by third party experts to ensure that the strategy for monitor data collection is optimal.

The overview of monitoring options, the feasibility and limitations of the tools and research for optimized tools were delivered by work package 10. The preliminary selection of monitoring tools for the Harald West storage project includes:

Wells: pressure and temperature gauges at the well head and at the base of the well, injection rate tests, pressure drop-off tests when injection is not ongoing and down hole injection logging is all included for the injection well.

Geophysical monitoring: A 3D seismic survey is included shortly before the injection starts to form a baseline for subsequent repeated seismic surveys designed to detect changes in the reservoir and the overburden in response to the injection. Another 3D seismic survey, with same acquisition parameters and design is included after the injection has ceased, to demonstrate that the CO<sub>2</sub> remains in the reservoir.

Seabed and near seabed environment will be imaged with shallow seismic and scanners as a baseline for repeated surveys to demonstrate that no adverse effects have taken place because of the CO<sub>2</sub> injection. Inspections near the abandoned exploration wells are included with visual data and sediment sampling to demonstrate that CO<sub>2</sub> does not flow along these wells.

**Highlighted interfaces with other work packages**

**WP3, WP4 and WP10 interfaces:**

WP4 is utilizing a reservoir model handed over by TotalEnergies. This model was updated by DTU Offshore to make it suitable for CO<sub>2</sub> storage reservoir simulation in a collaboration between DTU Offshore, TotalEnergies Bifrost team and other chalk modelling experts in TotalEnergies. Thermodynamic and geomechanical simulation was another area of common objectives of WP3 and WP4, and several workshops were arranged to ensure consistency in assumptions and practices. Similarly, workshops were arranged for the evaluation of geochemical reactions lead by DTU Offshore. TotalEnergies R&D and DTU Offshore had several engagements to discuss the laboratory work on core flooding experiments. Results were revied at review meetings concluding the work sub-packages.

WP10 included screening of monitoring tools considering the specific requirements defined in WP3. Feasibility studies were conducted as part of WP10 within TotalEnergies that ensured that critical monitoring tools were feasible, and the cost and constraints were understood. DTU Offshore is besides Bifrost engaged in other seabed and environmental monitoring studies and knowledge sharing sessions were arranged to inform the Bifrost project on research initiatives and ongoing data collection in DK.

An overview of meetings and workshops is provided in Figure WP3-4.

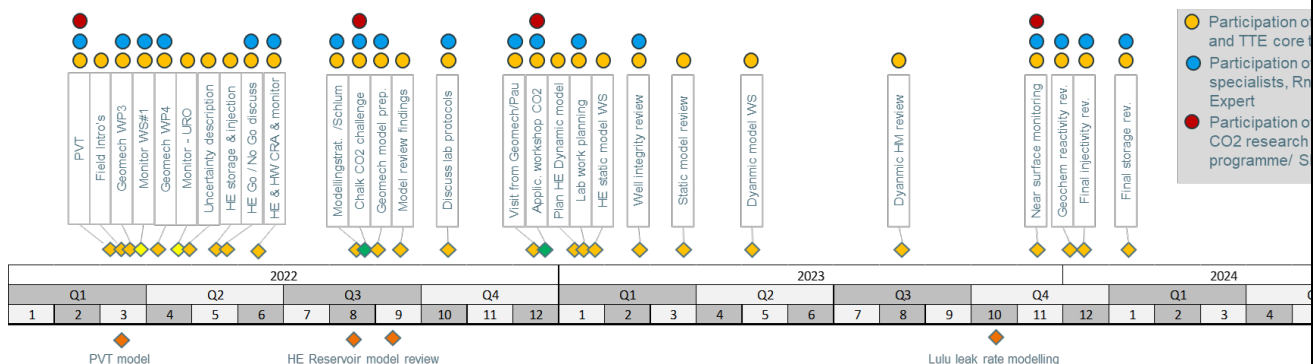


Figure WP3-4: Workshop and review meetings between DTU Offshore and TotalEnergies

**WP3, WP4 and WP5 interfaces:**

WP3 and WP4 work relies heavily on the ability to convert existing production wells to injection wells and the well architecture and completions constraints the options for well related monitoring, hence, relied on the work conducted in WP5. Integrated work between WP3, WP4 and WP5 was required to understand well integrity and to arrive at the integrated monitoring plan.

**WP3, WP4 and WP6 interfaces:**

The transportation of CO<sub>2</sub> and the facilities chosen constraints the pressure and temperature of the inflow to the wells and thereby the rates and volumes of injection that can be achieved.



**WP4 - CO<sub>2</sub> storage in Harald East Chalk – Subsurface Studies**  
**WP Lead: DTU Offshore**

**Introduction and objective of this work package**

Harald East is a gas condensate field in the north-eastern part of the Danish Central Graben (Offshore Denmark) that is producing since 1997 (Figure WP3-1). Discovered in 1980 by the Lulu-1 well, the field is a faulted four-way dip structure at a depth of ~2700m (Figure WP4-1). The sediments of the reservoir are chalk located in the Ekofisk Formation and deposited in a bassinal setting as pelagic rain (Danian age) as well as debris and mud flow, and slumps transporting Maastrichtian age sediment of the Tor Formation from the northeasternward margin of the aborted rifting basin.

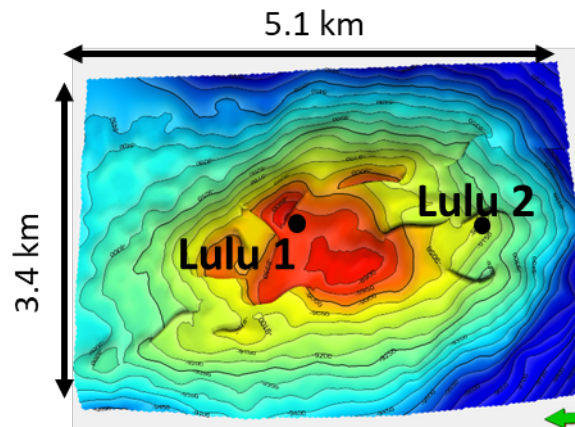


Figure WP4-1: Map view of the Harald East anticline with the two sub-vertical legacy wells Lulu 1 and Lulu 2.

The seal of the reservoir comprises Paleocene marls and mudstone belonging to the Våle and Lista Formations with a uniform thickness of 30 to 40 m. Above the seal, shale, and mudstone interbedded with tuff layers from the Sele and Balder Formations are predominant and show good sealing properties.

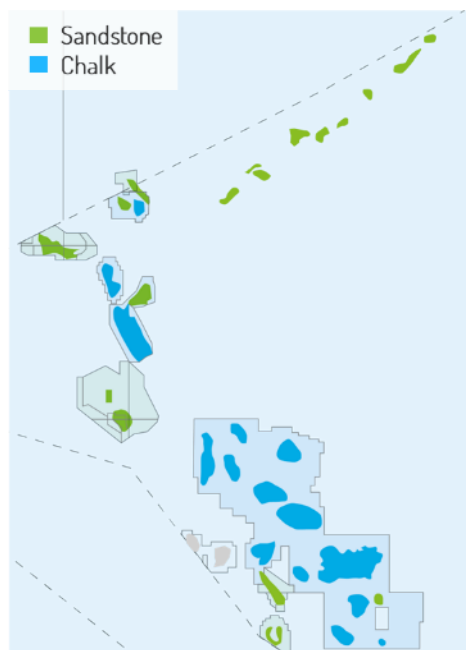


Figure WP4-2: Sand/Chalk reservoirs in Danish North Sea

WP4 addresses the subsurface studies necessary to confirm the potential for CO<sub>2</sub> storage in the Harald East chalk reservoir. Chalk is the predominant lithology for hydrocarbon fields in the Danish North Sea, however for

CO<sub>2</sub> storage purposes, chalk is seen as a less mature lithology. CO<sub>2</sub> storage in Harald East chalk will be an upside to the Harald West CCS project. Additionally, the results can help unlocking CO<sub>2</sub> storage potential in chalk in the broader Danish North Sea area (Figure WP4-2). Existing data from the field was studied in a preliminary and concept phase in pursuit of the below objectives:

The subsurface studies on the Harald East chalk were performed in two stages:

**Stage 1** – Confirmation of the CO<sub>2</sub> storage suitability of the Harald East chalk including the estimation of preliminary storage volumes as well as a high-level risks and uncertainties register.

**Stage 2** - Detailed characterization and derisking of the injectivity, storage volumes and containment of the Harald East storage complex.

## Analysis

The following work was conducted in the Stage 1 analysis:

The suitability of chalk for CO<sub>2</sub> storage was assessed at *in situ* conditions by reviewing literature and in house laboratory (Figure WP4-3) studies on the geomechanical, petrophysical, and chemical alteration of rock exposed to CO<sub>2</sub>. The experimental data included batch and core flooding experiments, triaxial tests, and rock/fluid analyses on subsurface and outcrop chalk samples exposed to brine, carbonated water, and supercritical CO<sub>2</sub>. The capacity of the seal interval to hold CO<sub>2</sub> was also assessed thanks to MICP<sup>1</sup> measurements on Lista Formation from the UK sector of the North Sea.



Figure WP4-3: DTU conducts advanced laboratory tests as part of Project Bifrost.

The geological storage complex was analysed and described using existing data. The reservoir characterization included defining the storage complex (vertical and lateral boundaries) and quantifying the mechanical and petrophysical properties of the storage site and their spatial variability including the seal interval. The seismic data from 1985 was reviewed to analyse the fault distribution and continuity across the seal interval. Based on the study, the main geological uncertainties could be described qualitatively.

The pre-existing reservoir model was calibrated to match the PVT<sup>2</sup> data of CO<sub>2</sub>-reservoir fluids mixture. A geomechanical model of the reservoir and seal were also built based on the pre-existing reservoir model. Then, both the geomechanical and reservoir models were converted into a two-way coupled hydro-mechanical models to assess fault reactivation as well as storage behaviour, capacity, and injectivity in Harald East by considering the pre-injection alteration of the containment during hydrocarbon production and potential CO<sub>2</sub>-induced weakening of chalk. The storage capacity is constrained by the ultimate reservoir pressure (virgin pressure), injection rate and bottom hole pressure.

<sup>1</sup> Mercury Injection Capillary Pressure

<sup>2</sup> Pressure, Volume, Temperature

Coupled simulations included a sensitivity analysis on CGR<sup>3</sup>, injection pressure/rate/index, compaction, porosity, permeability, relative permeability end points, layers' transmissibility,  $K_v/K_h$ , and bottom hole pressure conducted up to 60 years after end of injection. Containment related risks and risks of injectivity loss were evaluated at preliminary level.

Based on a lack of mechanical weakening of chalk by supercritical CO<sub>2</sub>, a suitable and laterally continuous seal interval, the post-injection storage and CO<sub>2</sub> plume behaviour, a low chance of fault reactivation, and line of sight to a manageable injection plan, the preliminary conclusion was that safe and permanent CO<sub>2</sub> injection into the Harald East store can be achieved. Consequently, embarking on stage 2 of the Bifrost project was supported.

The following work was conducted in the stage 2:

A high-resolution geological model of the Harald East reservoir was constructed using input from all wells with new consistent evaluation of the well, biostratigraphic and seismic data to build the reservoir architecture (Figure WP4-4). The model integrates all detectable faults present in the underburden, reservoir, and overburden intervals of the Harald East area based on interpretations of the 1985 and 2011 seismic cubes. The new reservoir model was calibrated to all production and well test data during the history match phase.

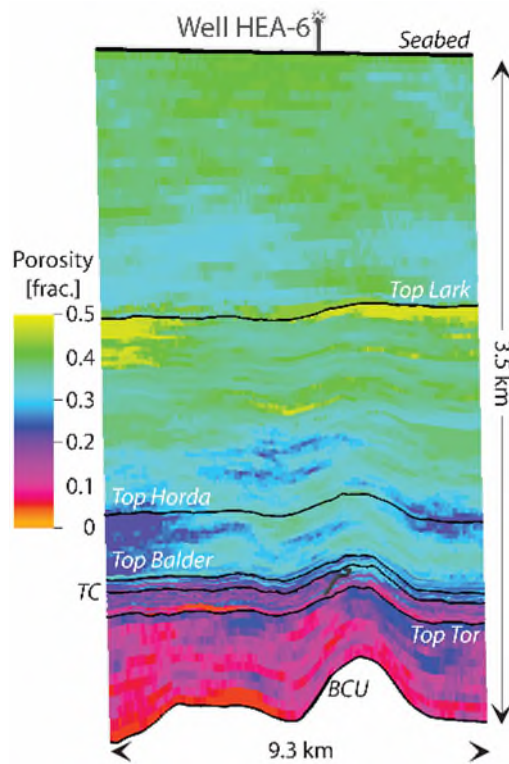


Figure WP4-4: 2-D transect of the 3-D geocellular model showing the total porosity distribution in the under-, side-, and overburden and reservoir. See Figure 1 for the names of formations displayed here. TC = Top chalk corresponding to the top of the Harald East reservoir. BCU = base chalk unconformity.

For forecasting the injection performance, compositional, thermal, geochemical, and geomechanical modelling associated with well stability analysis was enabled thanks to the results of well and new experimental data, and literature review. The modelling work delivered a reference model, based on best technical estimates of each input, as well as a series of realizations carried out during comprehensive sensitivity analyses of key parameters on injection performance, pressure and temperature evolution, storage resource, and CO<sub>2</sub> plume migrations (irreversible rock deformation, fault transmissibility, permeability, relative permeability end points, formation damage, well failure, CGR, layers' connectivity, ultimate reservoir pressure, spill point, and CO<sub>2</sub>-weakening and temperature effects).

<sup>3</sup> Condensate to Gas Ratio

The potential for leakage along mapped faults and wells, and the associated migration pathways in the overburden were analysed up to 1000 years after end of injection utilizing various scenarios regarding fault transmissibility, well permeability, and access of leaked fluids to pore volume in the overburden.

Geochemical reactivity between the pre-existing and injection fluids including impurities in the CO<sub>2</sub> injection stream, and the host rock minerals as well as the cap rock was studied using compositions that were determined experimentally and supported by pre-existing core and well data. The effectiveness of different treatment technologies was compared to identify mitigation procedures in case of injectivity impairment. These experimental and numerical works allowed assessing both reservoir integrity and injectivity and to determine the well operating envelopes.

Coupled 3D thermo-hydro-mechanical modelling of the Harald East region was conducted to predict the subsurface response to CO<sub>2</sub> injection (Figure WP4-5). To this purpose, the geological model was expanded vertically and horizontally to include the stratigraphic succession from Base Cretaceous Unconformity to sea level, the flanks of the Harald East field, and the Harald West area using input from all wells in the Harald East and Harald West fields. The 3D geomechanical model was populated with reservoir properties (including thermal and geomechanical properties) in the reservoir zones and with elastic properties, porosity, permeability, and faults in the underburden, sideburden, and overburden. Temperature, pore pressure, stress, and deformation (strain, shear, tensile) were predicted in the reservoir and the seal interval during past hydrocarbon production as well as during future planned injection including a 150 year-long post-injection phase by using input from the dynamic model described above. The results on reservoir compaction and overburden subsidence were matching *i*) the 4D seismic observations made by subtracting a 2011 seismic survey from the 1985 pre-production seismic data and *ii*) the seafloor subsidence data collected on the Harald East platform between 1996 and 2012.

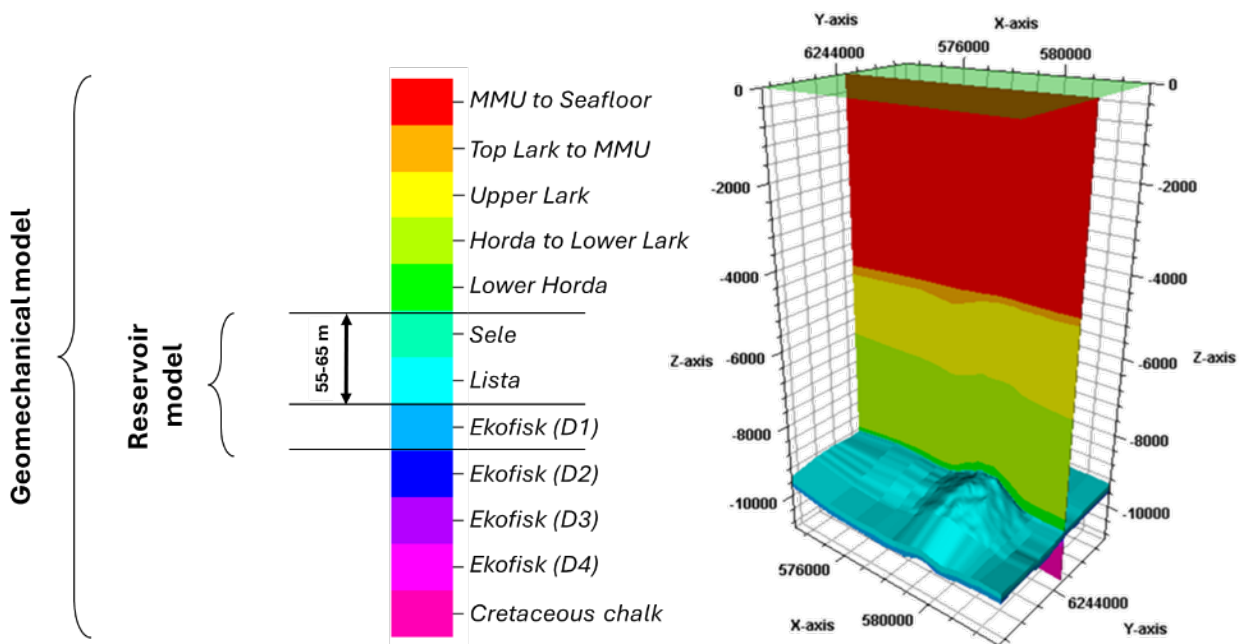


Figure WP4-5: The reservoir and geomechanical model including the underburden, reservoir, sideburden, and overburden of Harald East. MMU = Mid-Miocene Unconformity, BCU = base chalk unconformity.

The predicted stress and strain were used to evaluate the integrity of the reservoir, seal, and the four wells present in Harald East. To this purpose, in addition to Petrel software, DFN<sup>4</sup> generator and a finite element analysis software was employed to assess fault reactivation and well damages, and to predict potential fracture nucleation and propagation, and induced seismicity throughout the model.

<sup>4</sup> Discrete Fracture Network

## Key findings and results

The work has led to the following definition of the Storage Complex for the CO<sub>2</sub>:

A storage definition is required to define the area of focus for monitoring. In the Harald East case, the storage site is defined as the Danian chalk currently being produced by the Harald East wells. There is a safety lateral margin of 500 m outside the gas accumulation area. The primary seal is defined as the Paleocene marine marls and mudstone of the Våle and Lista Formations that are 30 to 40 m thick in total. Besides, above Lista Formation, multiple layers of impermeable clay-dominated rocks up to the base of Lark Formation, can function as secondary seal with a combined thickness over 1000 m.

The high-resolution reservoir model predicts the CO<sub>2</sub> to distribute and mix with the remaining gas and stabilise with pressures below the initial reservoir pressure. The CO<sub>2</sub> plume is expected to remain within the storage unit at a safe distance from spill points. Satisfactory rates of CO<sub>2</sub> injected per year can be achieved by converting one or two of the producers HEA-3E and HEA-6. Each converted well has the potential to deliver CO<sub>2</sub> injection rates of more than 1 Mtpa 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 re-purposed wells.

The risk assessment supported by the technical work suggests that CO<sub>2</sub> can be stored permanently below the pre-production reservoir pressure conditions in the Harald East reservoir. All the high-resolution simulated scenarios (> 50 cases tested for 1000 years after end of injection) suggest that the CO<sub>2</sub> plume remains within the pre-defined storage site away from the spill points.

The experimental studies on supercritical CO<sub>2</sub>-chalk systems at *in situ* conditions highlight a low risk of mechanical instability of the rock's elastic, shear, plastic, and creep properties. Overall plastic and elastic deformation of the storage site predicted by the coupled thermo-hydro-mechanical simulations is thus low and negligible compared to that simulated during the production phase, implying a low risk of damage to the wells during and after CO<sub>2</sub> injection. The DFN generator considering stress induced by pressure and temperature predicts no fracturing and shearing of the reservoir and seal. Induced seismicity is thus unlikely. The few areas predicted to be close to critically stress conditions are located away from the reservoir-caprock interfaces and spatially restricted to small volumes, thereby indicating low risk of seismicity as confirmed by fault analyses and friction models. The faults that are present in the reservoir and extend into the caprock are also therefore not a threat to the seal integrity.

Based on the thermal compositional modelling, a cold zone with temperatures down to some 43 °C (compared to normal temperature of 100 °C) is predicted to form around the injectors within a maximum radius of 200 m. The maximum temperature drop in the caprock close to the injector is predicted to be less than 45 °C. Computed thermal-induced stress does not cause fracturing of the seal and reservoir under these conditions.

The well stability analysis based on the outcomes of the coupled reservoir dynamic and geomechanical simulation shows that the rocks may fracture in the reservoir zone in the cold region near the injection well. If this occurs, fractures that may form at the toe of well HEA-6 in the last years of injection and along well HEA-3E, can facilitate improved injection conditions. This effect is limited to the specific layers in which CO<sub>2</sub> is injected and not in the sealing layers, hence, has no effect on the integrity of the seal.

The geochemical simulation and reservoir simulation considering temperature show that there will be no detrimental effect on the flow properties of the near-wellbore areas and the reservoir, resulting from the mixed fluids (gas, water, CO<sub>2</sub>, and potential impurities) interacting with the rock minerals in the expected temperature and pressure range.

The assumptions on safety of storing CO<sub>2</sub> in the Harald East structure were supported by the multiphysics studies as described above. Thermodynamic simulations looking at potential leakage pathways of CO<sub>2</sub> along pre-existing faults and wells were nevertheless analysed during 1000 years after injection including overburden layers. The simulation outcomes predict that CO<sub>2</sub> remains in the reservoir and the analysis shows that risks of loss of geological containment are negligible thanks to the strength and thickness of the seal.

## Highlighted interfaces with other work packages

### WP3, WP4 and WP10 interfaces:

WP4 is utilizing a reservoir model handed over by TotalEnergies. This model was not fully suited for the advanced reservoir modelling objectives of WP4 and therefore, several workshops were arranged to identify areas of improvement and strategies for the execution integrating recommendations from chalk modelling experts in TotalEnergies. Thermodynamic and geomechanical simulation was another area of common

objectives of WP3 and WP4, and several workshops were arranged to ensure consistency in assumptions and practices. Similarly, workshops were arranged for the evaluation of geochemical reactions led by DTU Offshore. TotalEnergies R&D and DTU Offshore had several engagements to discuss the laboratory work on core flooding experiments. Results were reviewed at review meetings concluding the work sub-packages.

An overview of meetings and workshops is provided in Figure WP3-4.

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WP5 - Well design and drilling  
WP Lead: DUC-TotalEnergies

### Introduction and objective of this work package

The Bifrost project aims to inject CO<sub>2</sub> into the Harald West field, in which there are five existing wells on the structure. This work package focused on the drilling engineering aspects of the project, reviewing the integrity of the existing wells, and optimising the design for the potential new injection wells. The scope of this work package was divided into three distinct areas:

1. **Well Integrity:** Before CO<sub>2</sub> can be injected into the Harald West reservoir, the existing wells must be reviewed to establish whether they pose a leakage risk. There are two types of wells in the field, gas production wells (platform wells currently online) and legacy wells (exploration wells which have since been abandoned). For both well types, the well barriers must be reviewed to establish whether they are sufficient to permit CO<sub>2</sub> storage in the field. For the production wells, an additional well integrity review is conducted, establishing if the wells are robust enough to be converted to CO<sub>2</sub> injection wells.
2. **Well Performance:** This task focused on the injection well's design and operating envelopes, to ensure the target injection rate could be met. The study was premised on the assumption of a continuous, dense stream of CO<sub>2</sub> at the wellhead, with reservoir injectivity constraints established in WP3. The objective of the well performance study was to design an upper and lower completion that would deliver the target injection rate whilst adhering to the input & output constraints.
3. **Well Design:** With the completion design established, the final drilling engineering objective was to design a well that could support this completion. The deliverables of this study were a full well architecture design, and a review of the load cases the well would be subjected to confirm whether the design was sufficiently robust. Two scenarios were considered: repurposing an existing production well and drilling a new well.

### Analysis

The WP5 analysis was conducted as follows:

1. **Well Integrity:** There were several steps to the well integrity study. Firstly, an internal review was conducted by TotalEnergies, comparing the existing well barriers with the company rules for well abandonment. Original drilling reports for the legacy and platform wells were reviewed and cement calculations were performed to establish the exact cement barrier positions, which were in turn compared with the minimum setting depths for these barriers. The barriers were reviewed for each porous / permeable zone and were classed as compliant or non-compliant. The results of this study were independently verified by a well examination consultancy.

To gain a more quantitative understanding of the legacy wells' integrity status, an academic study was commissioned, using a probabilistic method in which the likelihood and potential magnitude of a CO<sub>2</sub> leak can be estimated. This methodology is called a Probabilistic Flow Model; it was initially developed for well abandonment design but has since been refined for Carbon Capture and Storage applications. The methodology considers both the well design itself and the near-well formations through which CO<sub>2</sub> could flow. A grid-based model is created to represent the well architecture, and a series of flow equations is used to model fluid transfer between different zones in the well. Uncertainties such as cement quality are modelled using both deterministic and probabilistic methods.

2. **Well Performance:** The well performance study modelled several different completion design concepts to establish the optimal design for Harald West. One of the key challenges was to achieve sufficient injectivity in both early life and late life, as the reservoir pressure would change significantly. Designs were modelled for both a repurposed well concept and a new well concept.

For the repurposed well concept, the key driver was to avoid negative temperatures. This is because the repurposed well would contain water-based annulus fluid, which could freeze and damage the casing if exposed to low temperatures for extended periods of time. Well performance engineering for this concept focused on a friction-based design, using downhole flow restrictions to ensure the injected CO<sub>2</sub> stream remained in dense state, avoiding the temperature drop associated with low pressure in the well. A key design driver was minimising the number of interventions required as injection pressure rises over the well's lifetime.

For the new well concept, there was no such requirement to avoid low temperatures, as the new well could be designed with freeze-resistant annulus fluids. Well performance engineering focused on creating a simple completion with no intervention requirement and a low energy requirement due to surface compression. Work here was focused on a density-based design, where wellhead choking would allow for a degree of vaporisation of the CO<sub>2</sub> stream, reducing the overall column weight and reducing the pumping energy requirement in early life. It should be noted that the friction-based concept could also be used for a new well.

With the two well performance concepts selected, a second, more detailed study was conducted, seeking to test the design robustness for changes in injectivity, roughness, and impurities. The final design concepts are summarised in the next section of this report. After the concepts were finalised, suitable completion components were identified.

3. **Well Design:** With the completion design confirmed for the two injection concepts (the repurposed well and the new well), the next step was to devise a suitable casing design to provide a safe conduit for the completion.

For the repurposed well, most of the casing is inherited from the existing production well, so drilling engineering was focused on how this casing could be qualified for CCS injection. Detailed casing design modelling was conducted, evaluating the worst-case loads that the well could be exposed to, and establishing if the existing tubulars could cope with these. Contingent designs were also developed in case the existing well architecture requires repair.

For the new well, a full casing architecture was developed. The key technical challenge for the new well was drilling into the now depleted reservoir, and thus the casing design had to be adapted for depletion to deliver the well. Load case modelling was conducted to confirm the new well architecture will be suitable for the planned injection life.

## Key findings and results

The key findings of the WP5 studies were as follows:

1. **Well Integrity:** The internal well integrity study concluded that the Harald West Jurassic sandstone reservoir was suitably isolated for all legacy wells, as per TotalEnergies' company regulations. For each well, a laterally extensive barrier was found to be present across the targeted structure's storage cap rock. There is therefore no requirement to attempt to re-enter these wells for further remedial work.

About the two platform wells, the study found that one well, HWA-07A, was suitable for conversion to a CO<sub>2</sub> injection well, as its reservoir section was robustly isolated with detailed cementing records confirming a competent cement sheath. The second well, HWA-08B, was found to be unsuitable for conversion, and the reservoir will therefore be abandoned more robustly prior to commencement of injection. The findings of this study were supported by an independent well examination review.

The second, and more detailed, aspect of the well integrity scope of work was the probabilistic flow model. A grid-based representation was created for each of the legacy wells, and the risk of leakage was reviewed for a range of potential scenarios. For all the legacy wells on Harald West, the risk of significant leakage was found to be extremely low, with over 99.9% of the planned injection volume expected to be stored for over 3000 years, until all flow was stabilised. The probabilistic study confirmed the findings of the initial TotalEnergies review, by exploring the sensitivity to potential defects in the well barriers and modelling a "worst case scenario," where all cement in the well was defective. Even in this highly conservative case, the risk of significant leakage was extremely low.

- Well Performance:** The well performance study assessed several completion concepts and recommended optimal designs for both the repurposed well and the new well. A range of tubing sizes were modelled for both cases.

For the repurposed well, the optimised friction-based design was found to be a configuration with three downhole chokes, which were designed to ensure any injected flow would remain in dense state, thus preventing expansion and protecting the repurposed well elements from low temperatures. The choke sizes were optimised to minimise the number of well component replacements required, with the final design requiring just three lights well interventions over the fifteen-year injection lifetime. The final design concept is shown in Image WP5-1.

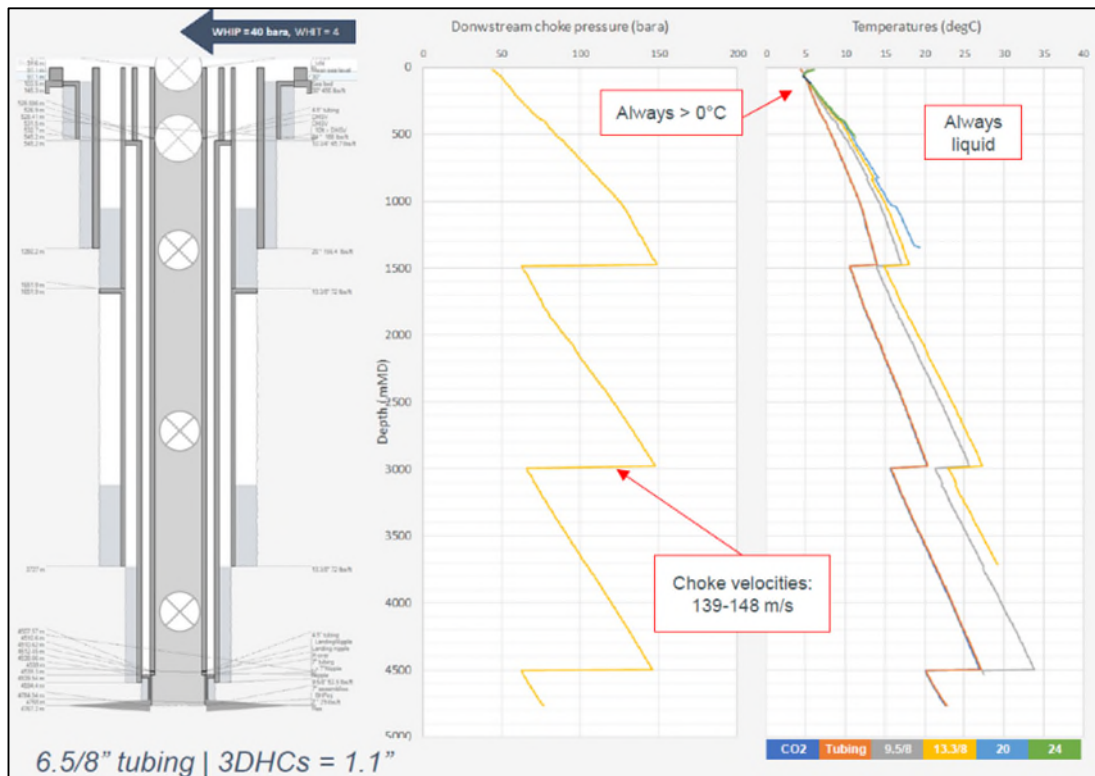


Figure WP5.1: Well Performance Design Output: Friction-Based Concept

For the new well, the design was optimised around a density-based design, where the incoming CO<sub>2</sub> stream is allowed to partially expand at the wellhead, balancing the reservoir pressure. The vapour-liquid equilibrium attained in the column of fluid allows for dampening of surface variations. By removing the downhole chokes from the design, the initial surface pumping requirement is lower and overall energy consumption is reduced.

With the well performance concepts selected, a completion design was then created for both concepts. Completion components were selected, and vendors were contacted to ensure any necessary equipment qualification will be conducted prior to the commencement of workover operations on Harald West. Potential design optimisations using emerging technologies (such as electric flow control valves) were also identified.

- Well Design:** The final scope in this work package was to create designs for the two types of well.

For the repurposed well, an in-depth casing design study was performed of the HWA-07A architecture. All the potential thermal load cases that the well could be exposed to were simulated, and the existing well architecture was found to pass these load cases. It was observed, however, that, should significant casing wear be observed upon re-entry to the well, then the production casing would not comply with the company-mandated safety factors. To ensure this eventuality could be dealt with, a contingent “scab liner” design was devised.

This concept deploys a new tubular inside the base of the existing production casing to isolate any worn or corroded sections and ensure the well design is robust. Deploying a liner in this manner would require a reduction in diameter at the base of the injection tubing, so a well performance sensitivity was run to ensure the required injection rates could still be met. With the base case workover design confirmed compliant, and a contingent option engineered to accommodate potential damage, the repurposed well design is considered feasible.

The new well design was also fully engineered, to provide a spare well option. A casing architecture was designed which would enable drilling into the depleted reservoir. A drill-in liner was found to be the optimal way to achieve this. A notional target and trajectory were developed, with lower directional requirements than the existing production wells on the platform. Finally, a casing design study was performed to confirm that the well can cope with the cold thermal profile generated by the density-based well performance strategy. Although challenging, the drilling of a new injection well from the Harald West platform is considered feasible.


In summary, both the repurposed well and the new well design are considered feasible. Casing architecture (including contingencies) has been engineered for both well types and has been confirmed adequate by detailed casing design engineering.

#### **Highlighted interfaces with other work packages**

WP5 had significant overlap with WP3. WP3 dealt with validation of the storage potential of the Harald West reservoir. This meant that there were common scopes involving both well integrity and well performance. WP3 describes a Storage Risk Assessment, a technique used to assess the leakage risk of the existing and planned wells in the field. This assessment was conducted with close reference to the well integrity work described in this work package.

#### **References and WP publications**

No publications to date, although the Probabilistic Flow Model used for the Well Integrity studies is planned to be presented in an SPE paper in 2024.

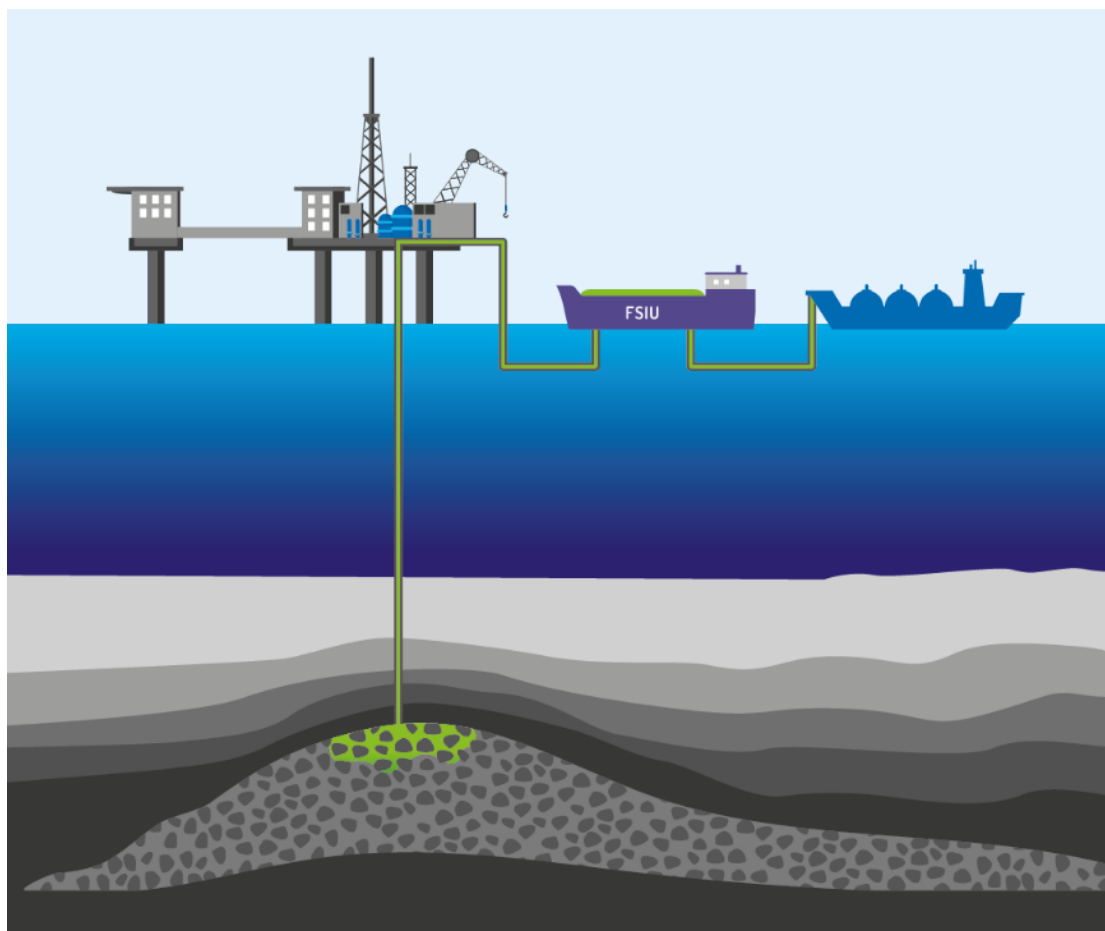
	<p><b>WP6 Surface facilities engineering and operation (Offshore offloading and Harald Platform)</b></p> <p><b>WP Lead: DUC-TotalEnergies</b></p>
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**Introduction and objective of this work package**

This work package addresses two main objectives:

- 1) to assess the Harald facility platform towards its gradual conversion from gas production to CO<sub>2</sub> injection
- 2) to perform preliminary and conceptual designs of a new offshore facility dedicated to the offloading of CO<sub>2</sub> from vessels (Cryogenic CO<sub>2</sub> tankers) and exporting conditioned (treated) CO<sub>2</sub> to the Harald platform.

It is assumed here that injection will be conducted in a “continuous-injection” mode.



*Figure WP6-1: A continuous injection of CO<sub>2</sub> via one platform well into the Harald West reservoir: a fleet of medium pressure cryogenic shuttle tankers for offshore offloading, a Floating Storage and Injection unit (FSIU) for CO<sub>2</sub> buffer storage and conditioning for injection, and integration modifications on the Harald West facilities.*

**Harald facility platform**

**At preliminary study level**

Standards and regulations. List and describe all standards and regulations applicable to the assessment of Harald platform for simultaneous gas production / CO<sub>2</sub> injection, covering:

- Establish the basis for the asset assessment both for its current and future use,
- Identify major equipment upgrade/addition required for CO<sub>2</sub> injection.

a) Establishment of power demand required for CO<sub>2</sub> injection on Harald

- b) Depending on the availability of gas to generate power / heating on Harald, an alternate source of power may be required
- c) The options will be investigated for different ranges of power requirement

#### At conceptual study level

- Asset integrity status. Determination of the actual condition of Harald facility platform, covering Structural - Jackets and topsides; Pressure containing equipment (topside); Pressure systems review
- Pipelines and risers including a review of Risk Based Inspection for Pipelines and a Pipelines Corrosion Structural Assessment.
- Aggregate results and list follow-up actions, including potential modifications. Establish allowance for additional weight, layout sketches for extra equipment, feasibility of additional risers / J-tubes. Quantify impact on structure.
- List Alternate concepts including dedicated metallic structure, direct injection system (single point mooring system), and establish a quantitative screening matrix for the ranking of concepts to be used at Conceptual Study Level (Conceptual screening).
- Screen potential concepts in coordination with Shipping (WP7) and platform allowance from Shipping to Reservoir. Establish pros-and-cons for each concept and rank according to matrix from Task 6.10.
- Recycle of existing feasibility / conceptual studies from engineering contractors. Based on 2020/2021 analysis provided by contractors, update feasibility & design for an FSIU according to project environment and specific requirements.
- Concept select from a limited number of concepts (typically 2), carry a more accurate design and cost estimation, involving flow-assurance, energy balance, operability assessment, OPEX and CAPEX. Material takes off, layout, weight, and class 4 estimates (request Marine engineering contractor budget offers) will be assessed.

#### Analysis

The work program for this package was executed as intended with an initial phase assessing the Offshore offloading solution at a feasibility technical maturity level until May 2022, then moving to a conceptual study comprising a screening phase where multiple concepts were considered and evaluated against quantitative/qualitative ranking criteria. This phase was completed in February 2023 and resulted in the selection of two concepts to be further investigated at conceptual maturity level.

During the feasibility study, the CO<sub>2</sub> transportation and storage chain (Figure WP6-2) proposed in work-program was investigated. Concept optimization was not a driver at this stage and efforts focused on technical maturity, robustness of development and identification of technology gaps to be solved in the next phase of the project. The T&S service considered was directed towards emitters located in Copenhagen and on the east coast of Jutland for total captured CO<sub>2</sub> quantities of 3.0 Mtpa, delivered in MP conditions at two export shipping terminals. As the potential strain of frequent starts and stops of injection equipment has been well identified as threat to the integrity of the well since the beginning of the application, the concepts considered in the Bifrost project were all based on continuous injection. The inherent nature of the shipping transportation solutions investigated leads to potential delays of L-CO<sub>2</sub> deliveries to the FSIU. To avoid well shut-ins due to insufficient L-CO<sub>2</sub> inventory, we have chosen not to overcome those delays with an overdesign of the temporary storage capacity but designing well-envelops which are always able to deliver an injection of 80% or 120% of the nominal average daily rate.

During the conceptual phase, the design of the FSIU and integration on the Harald West platform were further investigated / defined. In addition, a concept relying on a subsea temporary storage system was investigated. This alternate concept, although less mature, represented high potential for cost savings by removing the need for an export pipeline and an onshore terminal. Several technological gaps have been identified. The results will go in further details but one of them is linked with the qualification of the transfer flexible which requires to operate in negative temperatures with the CO<sub>2</sub> as a fluid. However, in this case, the flexible is aerial, and its qualification is deemed easier than in a case of a subsea flexible. More alternate concepts may have been considered but were discarded for the time being in the frame of the EUDP work program. For instance, a concept involving a Single Anchor Loading, seems very promising but contingent to the qualification of cryogenic CO<sub>2</sub>, unbonded polymer flexible lines which qualification time was estimated not be compatible with our intended project execution time.

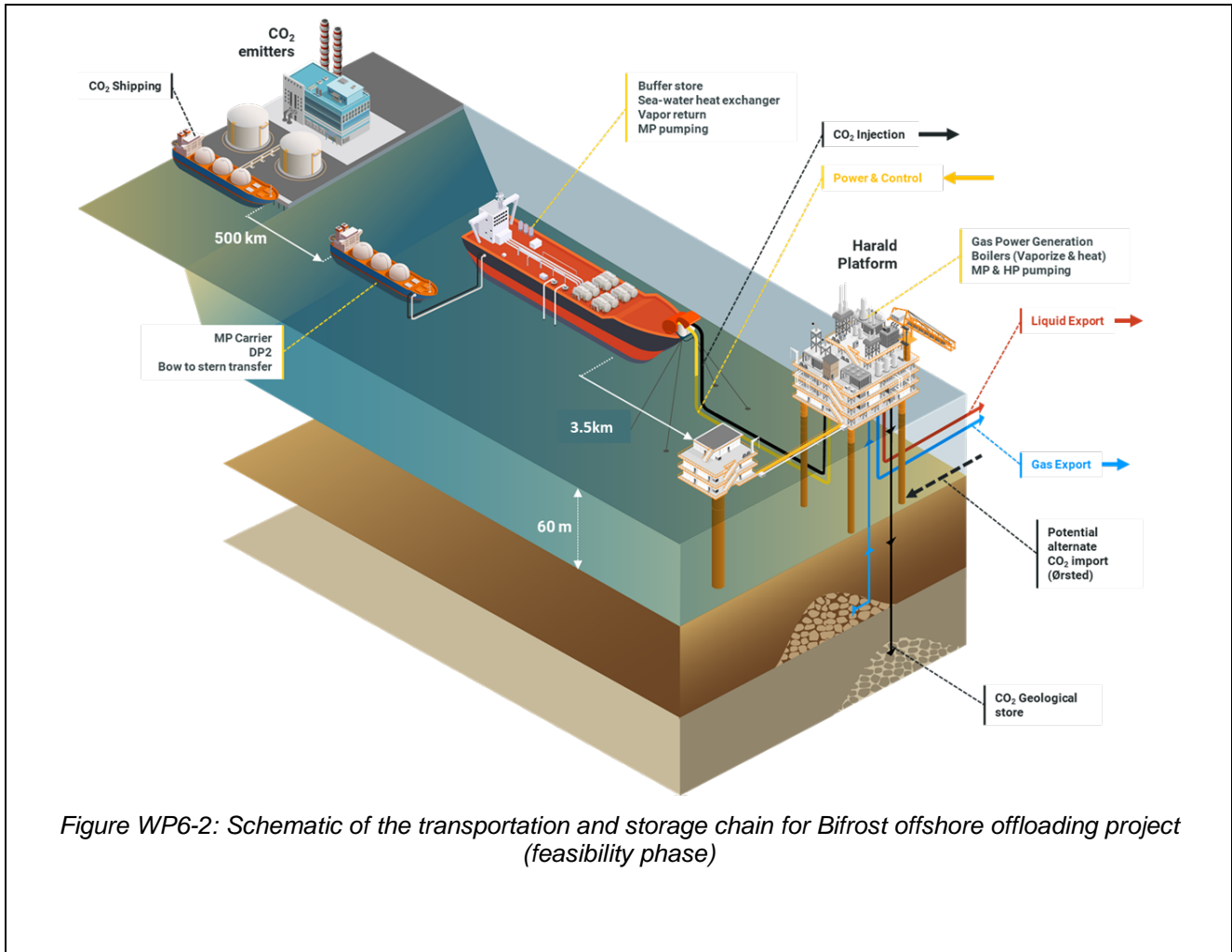


Figure WP6-2: Schematic of the transportation and storage chain for Bifrost offshore offloading project (feasibility phase)

## Key findings and results

### Harald platform:

During the feasibility phase, the deck integration of CCS equipment in Harald West A platform was investigated. Harald West is both the recipient of eight dry wellheads targeting different hydrocarbon bearing reservoirs and the future dedicated CO<sub>2</sub> stores and the process and power generation functions for the facility. Compatibility with a continuation of the O&G activities was enforced. The integration of an additional riser and J-tube connecting to the FSIU export was included. Impact of O&G continuous production on power load, combined with the additional power requirement for FSIU and CO<sub>2</sub> pumping was flagged as a potential bottleneck to be further investigated in conceptual phase.

During the conceptual phase, a cost optimization was conducted to minimize the impact of long offshore integration work. A CCS module was designed to reduce offshore work and allow for additional power generation in the event of a period of “dual operation mode” during the possible continuation of O&G activities on the platform in the early phase of CO<sub>2</sub> injection. Three integration cases were therefore investigated: the “in-deck integration” of CCS equipment (only suitable for CCS only operation mode of the facility), the “One additional deck” CCS module concept which hosts CO<sub>2</sub> pumps and metering and the “Two additional decks” CCS module concept which also includes the siting of one additional gas turbine driven generator in order to preserve the full redundancy of power generation dedicated to the O&G asset. This concept also requires heavier work on the platform including a crane extension to accommodate the second additional deck height.

### Rigid Riser and J-tube

A new riser and J-tube caisson will be installed on the Harald West A jacket structure. The preferred location is on the North face of the jacket as this will reduce the number of pipeline crossings between the FSIU and the platform. An alternative location for the riser caisson is on the East face of the jacket. Both locations are considered feasible. An emergency shut down valve (ESDV) will be located on the CO<sub>2</sub> import riser.

A flexible subsea line from the FSU will be connected to the riser base for CO<sub>2</sub> import and a power/control umbilical to the FSU will be pulled to the platform via the J-tube. (Figure WP6-3)

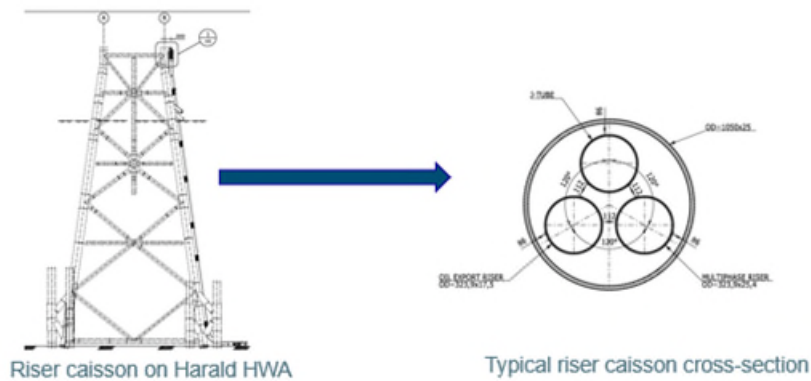


Figure WP6-3: Riser/J-tube caisson

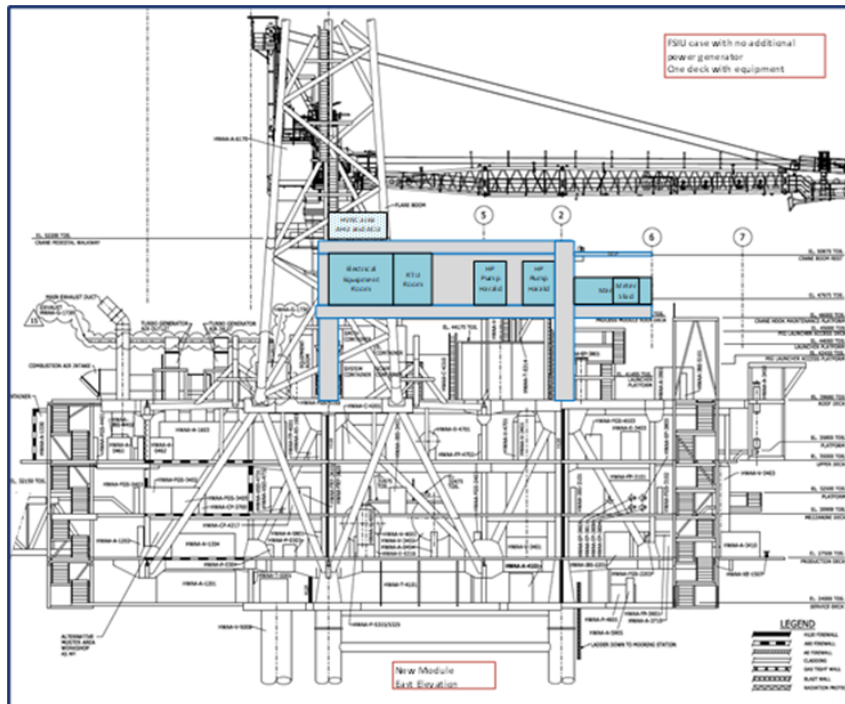
“One additional deck” CCS module

The CO<sub>2</sub> imported from the FSU is conditioned and pressurized for transfer to the Harald platform. The CO<sub>2</sub> will arrive at the Harald platform with a minimum temperature of 0 DegC to 5 DegC and a pressure up to a maximum of 150 barg.

Additional pressure boosting is required at Harald. A set of High Pressure (HP) pumps will be required on Harald to increase the injection pressure to some 350 barg. The CO<sub>2</sub> is then routed from the HP pumps to an injection manifold for distribution to any of the two Harald West wells.

A meter system is envisaged on the Harald platform for allocation metering.

An Electrical room will be provided to accommodate the required local switchboards and Variable Speed Drives (VSD) for the HP pumps. An instrument room will be provided for meter panels and ESD, control & communication cabinets. A step-up transformer for the power supply to the FSU will be provided (Figure WP6-4)



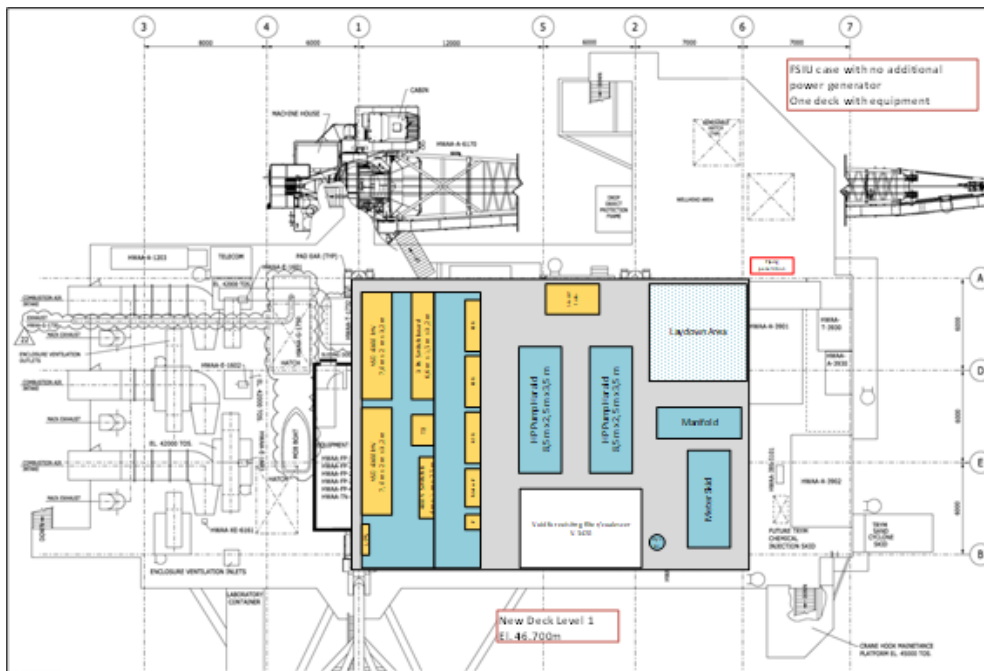


Figure WP6-4: Layout of One-deck CCS module.

**Control**

A control and communication fibre optical cable will be combined with the power cable in an umbilical connecting the Harald platform with the FSIU. This will allow data transfer between the two installations for both control and emergency shut down purposes.

Currently the Harald West B platform host a Central Control Room (CCR) from which the Harald operation can be monitored and controlled. It is also possible to control Harald remotely from the Tyra field CCR. This could be extended also to some control and shut down actions on the FSIU.

**Structural capacity for additional facilities**

A structural analysis of the Harald WA jacket has been performed with the objective to evaluate the impact of adding the CO<sub>2</sub> facilities to the platform. The basis was installation of a 1050 mm OD riser/J-tube caisson and a topside module and brownfield modifications of approximately 2000 ton taken as a conservative approach.

The study concluded that some reinforcement of the jacket is required to sustain the extreme wave and wind load cases. The jacket reinforcement solution was identified in the study. The impact on extreme wave and wind load on the topside will be evaluated in the next phase of the study.

**Design life and life extension.**

The Harald platforms were installed in 1996 and started production in 1997, with an initial design life of 25 years. Harald has not produced hydrocarbons since shutdown of Tyra in 2019 and until April 2024 after restart of the Tyra. During this non-producing period, the Harald platforms have been manned, operated and maintained.

Harald integrity was reviewed to identify any potential showstoppers for a life extension of the Harald West A platform including providing a scope for the life extension activities. No showstoppers were identified.

**Power Supply**

The base case assumes that electrical power for the FSIU is supplied from the Harald platform. The current assumption on power required for the FSIU is some 4 MW.

The Harald platform has 3 main turbine driven generators installed (2 duty/1 stand-by) each 4,2 MW. For short term, the backup gas turbine may be used as addition power source.

Without hydrocarbon production on Harald around 6 MW is available for the CO<sub>2</sub> injection. The baseload on the Harald is assumed to be around 1-2 MW without O&G production. The FSIU processing as described in

the process capture used 3-4 MW to heat and pressure increase for an injection of 2.5 Mtpa. Late in the injection period higher power demand on Harald is foreseen as the reservoir pressure increases.

The base case for the conceptual study, fuel gas for power generation can be supplied from Tyra via pipeline to Harald.

In the next phase of the project, alternate and low GHG footprint power generation solutions will be further investigated.

#### Power demand

In a dual operation mode (CCS and O&G), power generation for O&G process, and hydrocarbon export to shore must be maintained and constitute a specific O&G load. Platform base load is expected not be affected by CCS activities. On the other hand, CCS specific load comprises the following items:

- Power generation for the FSUI, (including, baseload for living quarters, process equipment including vapor condensers, vaporizers, water lift-pumps for heat exchangers and export pumping unit).
- Power generation for CO<sub>2</sub> booster pumping. To be able to maintain a yearly injection rate of 2.5 Mtpa, additional pumping capacity is required on the platform. It is estimated that a maximum pressure of 344b is sufficient to maximize the storage capacity of the store. Optimized design may consider arbitrating marginal resources against pumping costs (CAPEX and OPEX)

#### **Interface with loading and conditioning system**

A feasibility level, a first estimate of CO<sub>2</sub> containers, process and topside layout were devised. Functions of the FSUI include:

- The temporary storage of MP CO<sub>2</sub> (cryogenic) with a capacity of 30,000 m<sup>3</sup>.
- The pre-pumping and heating of the CO<sub>2</sub> to 50b and 0°C using seawater thermal exchangers.
- The pressurized dense phase CO<sub>2</sub> export system that allowed to ensure 150b export pressure and pressure maintenance in the CO<sub>2</sub> tanks via on-site vapor generation.

This phase concluded on the feasibility of such floating facility. The loading system and definition of process equipment for the handling of vapor CO<sub>2</sub> expelled during loading operations were identified for the conceptual phase of the project.

During the conceptual phase, it was decided to investigate both a “nearshore” FSUI concept that could benefit from side-by-side loading and an “offshore FSUI” which corresponded to the concept studied during feasibility. The interest for the “nearshore” FSUI was motivated by the removal of specific requirements on the fleet of CO<sub>2</sub> tankers, the increased efficiency of the handling of vapor expelled from the FSUI tanks during loading operations, the lower costs for facility operations and more favourable footprint of the power sourcing, resorting to onshore grid rather than offshore fuel gas consumption.

In addition to those two FSUI concept, an opportunity to investigate a subsea system for storing the CO<sub>2</sub>.

Results on FSUI design can be found in WP07 Report.

#### FSUI location

Apart from providing access to the reservoir via the existing wells, the Harald platform will interface with the Floating Storage and Injection Unit (FSUI) from which the CO<sub>2</sub> is imported. The CO<sub>2</sub> will be imported to the Harald platform via a flexible pipeline from the FSUI moored nearby Harald. The Harald platform will furthermore interface with the FSUI via a combined power cable and optical fibre umbilical.

Preliminary location of the FSUI relative to the Harald West facilities follows the following principles to be refined at pre-FEED stage: A 3km approach radius was used in addition to a 500m safety distance that allows tanker to approach offloading area without the need to coordinate with Harald facility.

#### Alternate concept: the Tower Loading Unit

The Tower Loading Unit concept has previously been studied by other companies. Transport pressure was around 40barg, allowing operating with CO<sub>2</sub> at positive temperatures close to the seabed ones. CO<sub>2</sub> injection was performed in batches.

With Bifrost Basis of Design, the concept consists in offloading CO<sub>2</sub> from the Medium Pressure carriers offshore, use an offshore pipeline as a buffer storage between the CO<sub>2</sub> carriers and the Harald West reinjection platform and take advantage of the sea temperature to heat the CO<sub>2</sub>. Injection is continuous.

In more details, the liquid CO<sub>2</sub> is discharged from the ships at a purpose-built offloading tower at the shallowest end of the pipeline. At the deepest point, a pump sends liquid CO<sub>2</sub> to the Harald platform where further boosting can be used depending on the reservoir pressure and injection requirements.

To use the pipeline as a storage, it requires to be operated around the saturation pressure of CO<sub>2</sub>. The vapour/liquid interface localization varies, depending on offloading/refilling operation and pumping for injection.

The study has concluded that there is not a single vapour-liquid interface in the pipeline. Instead, due to the geometry and multiple local high and low points, there are a multitude of interfaces. Gas pockets are distributed along the pipeline as gradual vaporization occurs. Indeed, during an offloading, CO<sub>2</sub> vapor condensation is not instantaneous. The dynamics of the system pushes the vapour bubbles toward the subsea pump and may result in vapour being entrained in the pump.

In addition, the following points would need to be addressed:

- Qualification of flexibles for the minimum design temperature (negative) during steady and transient conditions, in a CO<sub>2</sub> service
- The acceptability of the stresses induced to the pipeline when operating in negative temperatures in the seawater.
- Availability of the system

For all these reasons, the alternate concept of the Tower Loading Unit will not be further pursued.

### Highlighted interfaces with other work packages

#### **During feasibility phase**

WP07 provided logistic studies for the joint dimensioning of the export terminal, ship sizing and FSIU buffer storage. WP07 provided the costs and feasibility assessment of MP 12,000 m<sup>3</sup> L-CO<sub>2</sub> tankers with bow-loading system and dynamic positioning systems.

#### **During conceptual phase**

WP07 provided data relative to the FSIU interface with the platform. This included power demand and pressure estimate for the CO<sub>2</sub> at the platform.

WP05 provided well operating envelopes for the 2 injection wells, impacting the power requirements.



**WP7 - Cryogenic CO<sub>2</sub> Shipping**  
**WP Led: DUC-TotalEnergies**

### Introduction and objective of this work package

The objectives were first to determine the ships and floating unit capacity via logistic study and then to develop the Floating Storage Injection Unit (FSIU) for both nearshore and offshore solutions.

TotalEnergies has been actively considering the use of a floating storage & injection unit (FSIU) to develop a portfolio of solutions for CCS chains. TotalEnergies has extensive experience operating offshore floating units to built-in an appropriate level of confidence in this concept and considers it is a viable alternative to pipeline transport from shore.

A naval designer company was engaged to develop the preliminary design of the FSIU for nearshore unit from which the offshore unit can be derived. The deliverables are general arrangement, layout, hull scantling, weight report, electrical and heat balance, process preliminary design and cost estimate for new built unit.

### Analysis

The development of FSIU concept has allowed to highlight technical challenges on the process. To solve these challenges, optimized solution for boil off gas management (under patent) was developed to improve reliability and reduce power need.

### Key findings and results

#### Logistic study

Shipping simulations have been conducted and have determined that three (3) Liquid CO<sub>2</sub> (L-CO<sub>2</sub>) carriers of 12,000 m<sup>3</sup> capacity are required to allow injection of 3 Mtpa from Danish emitters from greater Copenhagen area in the reservoir.

The corresponding required capacity for the FSIU was established at 30,000 m<sup>3</sup>.

A dynamic model was used to ensure buffer storage at CO<sub>2</sub> emitters terminals does not reach tank top and considering limit weather conditions for offshore transfer operations.

#### Floating Storage Injection Unit

##### General

The FSIU is a permanently moored unpropelled offshore floating unit, designed to received liquid CO<sub>2</sub> from L-CO<sub>2</sub> carriers, store the product, re-heat and pressurize it for final transfer to the injection location.

The study focused on a 30,000 m<sup>3</sup> capacity unit fitted with type-C storage tank and operating under MP condition (13 to 18 barg, -22°C to -30°C).

The unit is designed to remain on site for 20 years without dry-docking.

Two different concepts are possible: nearshore unit moored inside a protected area or a port (concept F3) or offshore unit moored close to the well (concept F1).

To reduce GHG emissions, the unit is powered from shore in concept F3 and from the platform in concept F1. Thus, only essential power needs to be installed onboard to ensure safety of the unit in case of power disruption.

The unit has been designed to:

- ensure continuous injection with sufficient redundancy installed to allow maintenance and provide availability greater than 98%.
- Target zero CO<sub>2</sub> venting in normal operation
- Provide metering and quality control of the product transferred.
- Lower complexity and cost of the facility without impacting safety and availability via minimalistic equipment and personal approach in design.

**Main characteristics**

Length Over All abt = 182.4 m (for near shore unit)

Depth (moulded) = 15.9 m

Breadth (moulded) =31.5 m

Design draft = 8.80 m

Deadweight about 32 000 t.

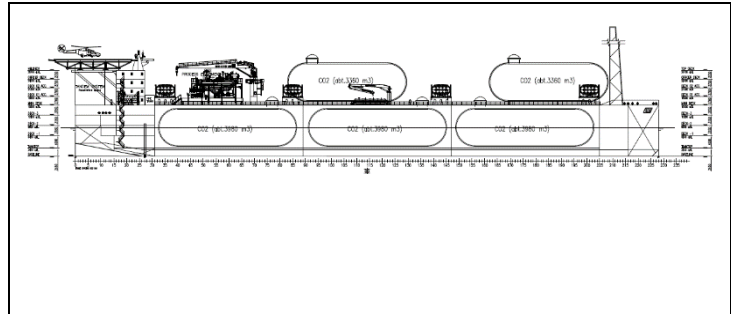


Figure WP7-1: General arrangement (near shore unit)

The FSIU presents a complete double hull with L-shape ballast tanks. The cargo tanks are accommodated in three compartments on two rows inside the hull with two additional tanks on the deck.

The main machinery is accommodated below the living quarter on the aft of the unit. The offshore unit is fitted with loading hose stored on a reel on the aft deck.

The unit is provided with a helideck for logistics (crew, spares and consumables transfer).

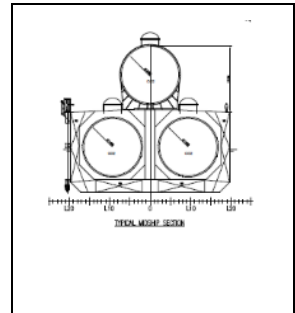


Figure WP7-2: Midship section

**Cargo containment system**

The liquid CO<sub>2</sub> is stored in independent IMO<sup>5</sup> Type C tanks (Internal diameter 11.40m, 6 x 3,974 m<sup>3</sup> (internal length 42.80 m) inside the hull and 2 x 3,351 m<sup>3</sup> (internal length 36.70 m) on the deck). The cargo system is provided by TGE Marine. The minimum cargo temperature is -35°C, design vapour pressure is 19 barg, max cargo density is 1,170 kg/m<sup>3</sup>. Tank material is VLF550 and insulation via PU spray foam.

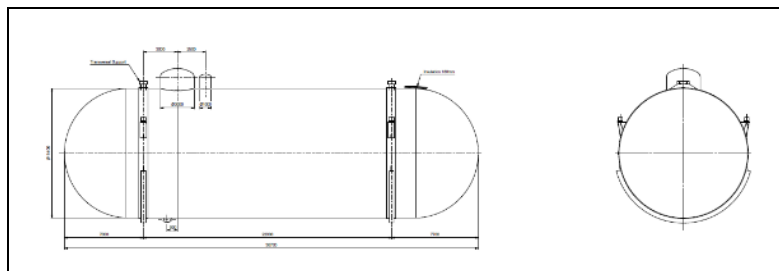


Figure WP7-3: Cargo tank Principal Arrangement (side and front view)

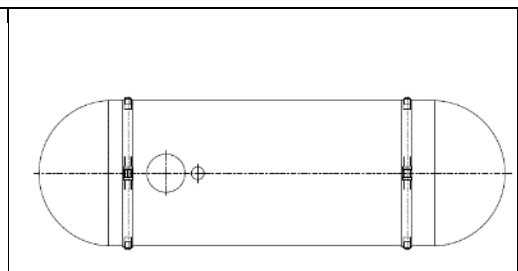


Figure WP7-4: Cargo tank Principal Arrangement (top)

**Loading system**

**Near Shore unit**

<sup>5</sup> IMO = International Maritime Organisation

The near shore unit (concept F3) will be loaded in side by side via flexible lines accommodated on saddles between both ship and FSIU midship manifold. This is allowing to connect the vapour return line and enhance the delivery flow rate from the ship.

**Offshore unit**

Due to harsh environment conditions, the offshore FSIU (concept F1) will be loaded in tandem by L-CO<sub>2</sub> carrier fitted with Dynamic Positioning System (DP2) and a bow transfer manifold. This is widespread practice to offload oil FPSO in North Sea.

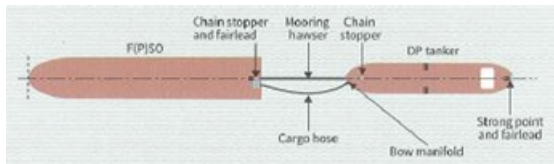
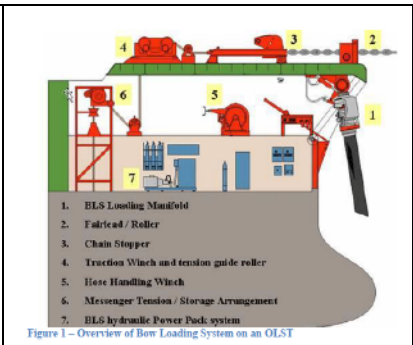


Figure WP7-5: Tandem cargo transfer configuration for a DP Shuttle tanker (OCIMF Guidelines for Offshore Tanker Operations)

Right: Figure WP7-6: Overview of Bow Loading System (Norsk olje&gass 140-Norwegian Oil and Gas recommended guidelines for Offshore Loading Shuttle Tankers).



This solution presents several challenges and require still the fill qualification of BLS (bow loading system) for use with cryogenic CO<sub>2</sub> and of the flexible line. These works are ongoing.

Existing tandem transfer system are accommodating a single line, then, it is not possible to connect vapour return line towards the L-CO<sub>2</sub>-carrier and enhanced BOG management system is required on FSIU.

**Process**

**General**

For the process facilities design, operation modes on the FSIU must be identified. For the Offshore FISU concept, there is no vapor return line during ship transfer to the tanks. This means that the extra vapor due to liquid level increase in the storage tanks needs to be handled. In the following table, need of Vapor management for different scenarios during loading off-loading tank operations are evaluated. The estimated operation time for each mode is given assuming that a 99.5% availability for CO<sub>2</sub> injection.

Case Name	Ship off-loading	CO <sub>2</sub> export	Vapor management	Estimated operation time (%)
Ship + CO <sub>2</sub> export	X	X	Offshore (no vapor return line): Management of vapor in the storage tank (ship off-loading flow rate higher than export CO <sub>2</sub> flowrate) (sizing case)  Onshore: no need of vapor management	34,90%
No ship + CO <sub>2</sub> export		X	CO <sub>2</sub> vaporizer to maintain pressure.	64,60%
Ship + no CO <sub>2</sub> export	X		Management of vapor in the storage tank: Degraded situation	0,17%
Maintenance			Management of vapor in the storage tank: Degraded situation	0,50%

Process design is sized for the first two operation modes.

**LMG proposed process system:**

The below PFD shows the process design proposed by LMG/ARAGON

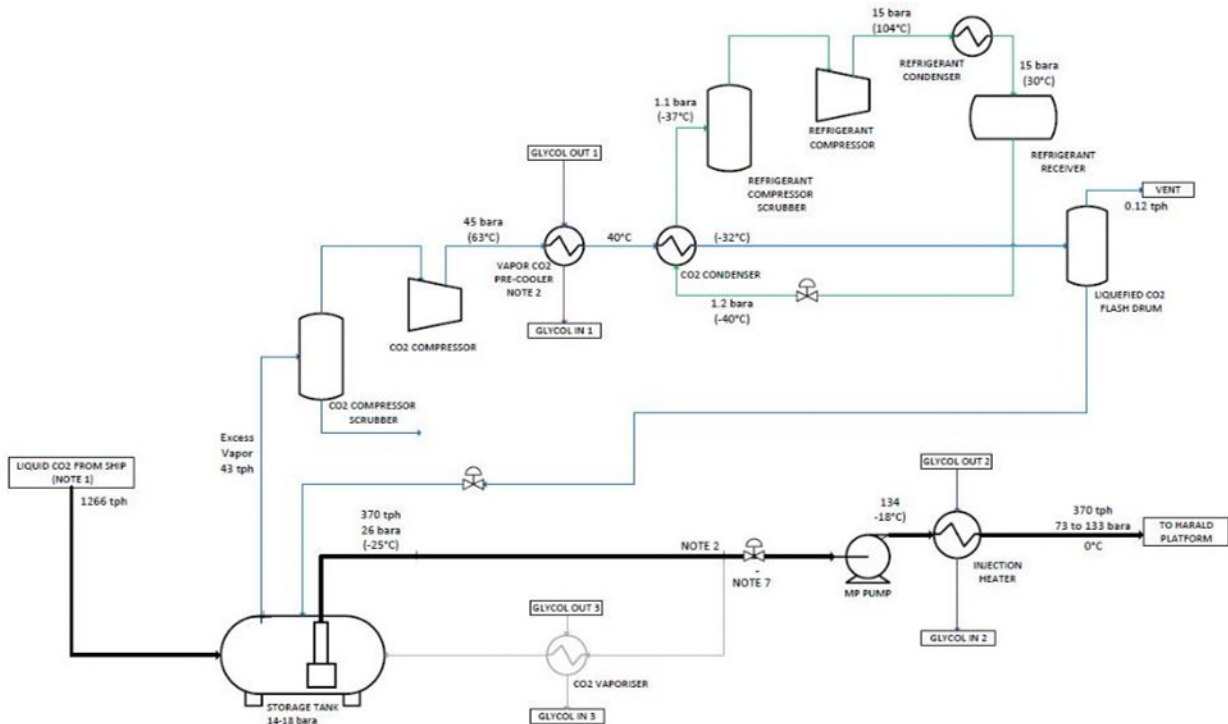


Figure WP7-7 process design proposed by LMG/ARAGON

A brief description of the main process facilities on the FSIU is given hereafter:

**Deep-well cargo pumps**

Liquid CO<sub>2</sub> will be provided from the storage tanks via in-tank deepwell pumps. These pumps must be designed to supply CO<sub>2</sub> to the topside at a sufficient pressure, regardless of the current liquid level in the CO<sub>2</sub> storage tanks. The rated design capacity of the deep well is determined by the maximum required flow rate and the lowest tank level.

**Injection pump**

The Injection Pump take suction directly from the deepwell pumps via and injection pump suction vessel. Based on preliminary input from vendors there are available pump models that will fit this application based on the suction pressure and the low temperature (-34 °C) delivered from the deepwell pumps.

**CO<sub>2</sub> Injection Heater**

The CO<sub>2</sub> Injection Heater is located downstream the injection pump and shall heat the CO<sub>2</sub> to the required injection temperature of 0 °C through heat exchange with glycol/water heating medium. Accounting for the temperature rise over the injection pump, the heater will heat the CO<sub>2</sub> from around -28 °C to 0 °C. Printed circuit heat exchangers are used to reduce footprint and weight requirements.

**CO<sub>2</sub> Vaporiser**

During the injection of CO<sub>2</sub> when there is no ship, the level in the storage tanks will gradually be reduced. A CO<sub>2</sub> vaporiser maintains a constant pressure in the storage tanks during emptying. A slipstream of CO<sub>2</sub> is taken from upstream the injection pump and routed to the vaporiser, where the CO<sub>2</sub> is heat exchanged with glycol/water. The vaporised CO<sub>2</sub> is routed back to the storage tanks.

**Vapor management system:**

Vapor management system handles displaced vapor due to level increase in the FSIU cargo tanks during loading of Liquid CO<sub>2</sub>

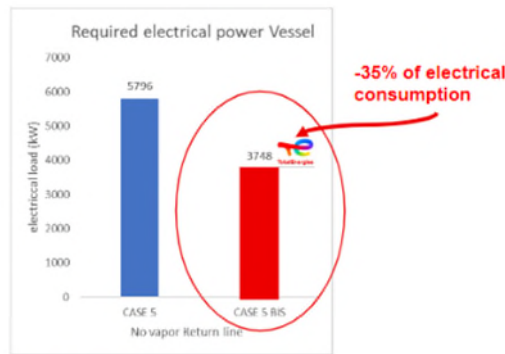
The base case vapor management system consists of the following main equipment items:

- Compressor: compressing Vapor CO<sub>2</sub> to maintain a constant pressure in the cargo tank vapor header. The compressor is protected from liquid carryover by an upstream suction scrubber.
- compressor aftercooler, to reduce the outlet temperature from the compressor using glycol/water as the cooling medium.
- condenser, which cools and condenses the compressed CO<sub>2</sub>.
- Liquefied CO<sub>2</sub> flash drum, receiving liquefied CO<sub>2</sub> from the condenser and separating the non-condensed components (if present).
- condenser uses a synthetic refrigerant (R-449A) to cool the compressed CO<sub>2</sub> to -32 °C. The mechanical refrigeration system consists of:
  - Refrigerant compressor scrubber
  - Refrigerant compressor, protected by an upstream suction scrubber.
  - Refrigerant condenser, using glycol/water as the cooling medium.
  - Refrigerant receiver to function as a surge drum for the refrigerant.

The main drawback of this process is the high energy requirement for the refrigerant loop to condensate excess vapor CO<sub>2</sub>.

**Enhanced Boil of Gas Management system (TotalEnergies patent ongoing)**

An optimization of LMG process design was studied. The aim is to remove refrigerant loop and perform thermal integration with available cool streams on the platform. Optimized design potentially allows saving about 2 MW of electrical consumption when compared to LMG process design:



Ship + CO<sub>2</sub> export case

Figure WP7-8: Improvement of required electrical power vessel.

**Mooring system**

**Nearshore unit (concept F3)**

The nearshore unit can be permanently moored inside a port along a quay or in a protected area (benign weather area) using TotalEnergies patented Asymmetric Spread Mooring Solution allowing side-by-side loading.

	 <p><b>Acknowledgement of receipt</b></p> <p>We hereby acknowledge receipt of your request for the processing of an international application according to the Patent Cooperation Treaty as follows:</p>
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	Approval in Principle by Bureau Veritas, qualified internally by TotalEnergies Proqual process to TRL 6 – ready for project.
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*Figure WP7-9: Asymmetric Spread Mooring Solution*

**Offshore unit (concept F1)**


The offshore unit will be moored using an internal turret system allowing the connection of the mooring system while accommodating the export line and the power line from the nearby platform.

**Highlighted interfaces with other work packages**

Close collaboration with WP06 for offshore unit (F1), the platform will provide the power to the FSIU.

**References and WP publications**

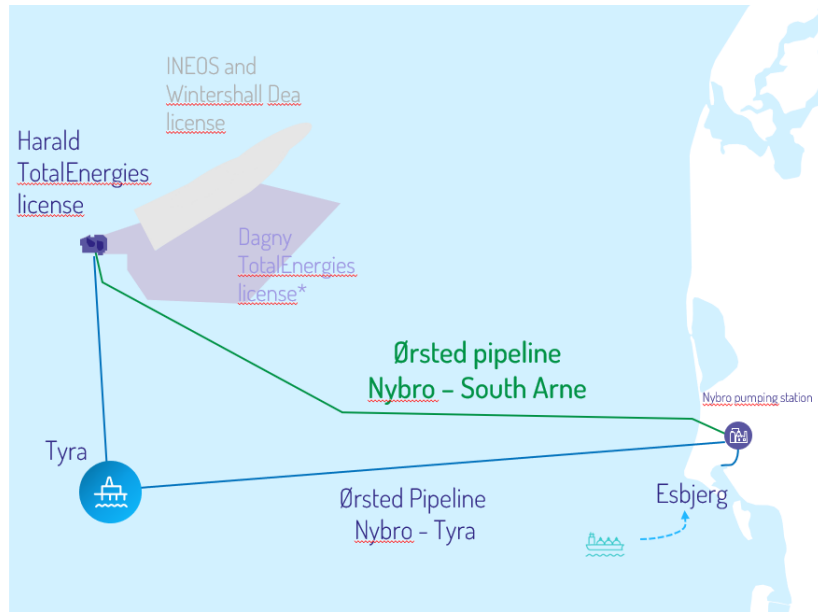
INTERNAL: LMG Marin project number 439014 “BIFROST L-CO<sub>2</sub>”



**WP8 - Offshore pipelines**  
**WP Lead: Ørsted**

**Introduction and objective of this work package**

The objective of WP8 is to investigate the feasibility of existing infrastructure and conversion from transporting hydrocarbons to transporting CO<sub>2</sub>. The feasibility study both includes capacity assessment, fitness for purpose assessments and evaluate risks associated with transporting dense CO<sub>2</sub>.



*WP8-1: Offshore gas pipeline repurposing for CO<sub>2</sub> service*

In the WP8 additional assessments of the value chain has been assessed, that includes design of a harbour terminal for receiving shipped dense CO<sub>2</sub>, and a new pipeline connecting the existing offshore pipeline with the receiving terminal. Port of Esbjerg has been screened for a base case for a location of the terminal, where other locations have been identified and screened for synergies. The option for connecting the offshore pipeline to a pipeline network is included, where the tie-in considered is in the vicinity of Egtved Jutland

**Analysis**

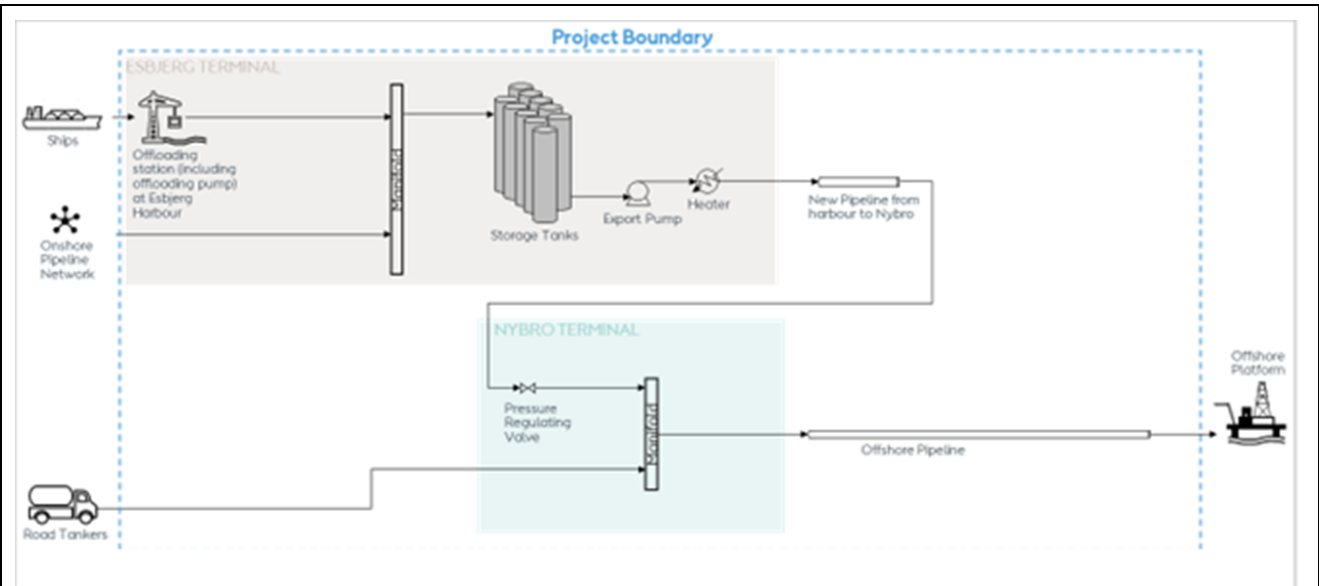
WP8 has been divided into workstreams for analysis of different solutions and screening of opportunities. The work package is divided into four streams each controlled through the interface, to ensure a combined workable solution:

- Generic Design of Receiving terminal,
- On-shore pipeline connecting harbour terminal with Offshore pipeline,
- Feasibility studies of offshore pipeline for operating in dense CO<sub>2</sub> (capacities, flow assurance, dispersion modelling, etc.),
- Fitness for service evaluation on non-metallic materials in existing components,
- Due diligence of South Arne Gas pipeline for conversion to operate dense CO<sub>2</sub>.

The expected CO<sub>2</sub> feed stream composition during the project is expected to be within the below defined composition. The composition is found to be comparable with other projects using shipping as the mode of transportation from emitters. The composition can be challenged during later project stages, subject to experimental studies and risk analysis.

Component	Mole Fraction
CO <sub>2</sub>	0.995483
Nitrogen	0.000801
Argon	0.000801
Hydrogen	0.000801
Methane	0.000801
CO	0.000200
Oxygen	0.000010
Ethane	0.001001
H <sub>2</sub> O	0.000050
H <sub>2</sub> S	0.000010
SO <sub>2</sub>	0.000010
diM-Sulphide	0.000000
NO <sub>2</sub>	0.000010
Ammonia	0.000003
Methanol	0.000020
Benzene	0.000000
TEGlycol	0.000000
MEAmine	0.000000

It has been investigated if it is feasible to deliver CO<sub>2</sub> via ships to a harbour, intermediate storage of CO<sub>2</sub> at a Harbor, transport of CO<sub>2</sub> from intermediate storage to Nybro via a new onshore pipeline, and transport of CO<sub>2</sub> from Nybro to offshore (Harald) via the existing 24" Nybro to South Arne / Harald pipeline, making the boundary for a detailed analysis.



WP8-2: Project WP8 (CO<sub>2</sub> transportation infrastructure) battery limits

The illustration is a simplified overview of the project boundaries. The boundary of the project includes:

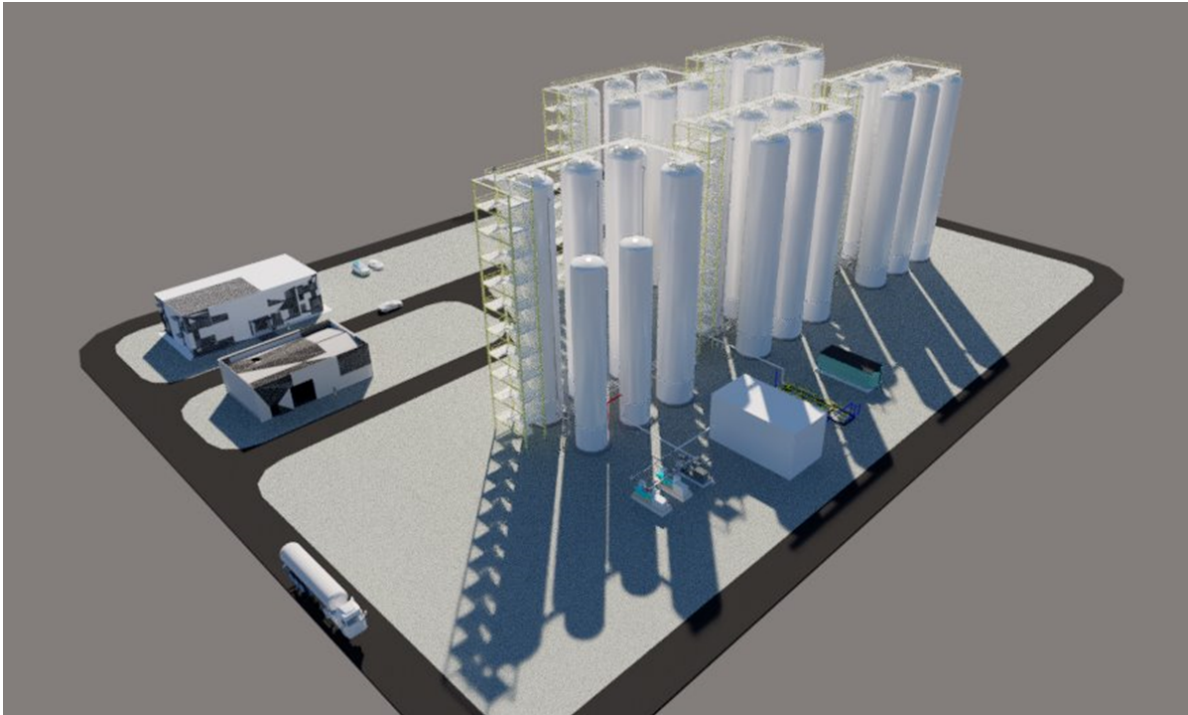
1. Transportation of CO<sub>2</sub> to harbour via ships
2. Intermediate storage of CO<sub>2</sub> at harbour
3. Transportation of CO<sub>2</sub> to Nybro via a new onshore pipeline
4. Export of CO<sub>2</sub> to Harald via existing offshore pipeline, up until the riser at Harald

The capacity of the Ørsted owned and operated pipelines is evaluated for transport of liquid CO<sub>2</sub>, and the 24" South Arne pipeline system connecting Harald to Nybro may be made available for transport of CO<sub>2</sub>, within the timeframe for the first CO<sub>2</sub> injection. Therefore, it was decided to make a more comprehensive due diligence on the South Arne Pipeline for a requalification considering change in product properties from natural gas to dense CO<sub>2</sub>, and the change in flow direction and temperatures.

**Key findings and results**

The basis of design for the generic onshore terminal, is considering 3 Mtpa, which is the target rate for the first phase of the project. Options to upscale to 16 Mtpa is investigated as part of the studies.

The generic harbour design is found to contain Harbor quay side, where ships will be offloading CO<sub>2</sub> into a receiving terminal consisting of several temporary storage vessels (Figure WP8-3), build near the harbour. During offloading of CO<sub>2</sub> into the temporary storage vessel, a vapor return line back to the ship is required. A new pipeline will be installed from the harbour to Nybro. Finally, the CO<sub>2</sub> flowrate will be fiscally measured, and its composition analysed to guarantee specifications are met.



*Figure WP8-3: onshore CO<sub>2</sub> storage buffer tanks.*

For optimization purposes of the temporary storage capacity, an ESSOR (Emitters Shipping Scheme & Onshore Receival) model has been developed. This gives an estimate of the number of storage tanks required to keep a steady flow to the offshore storage. The model is incorporating the number and size of ships, and size of pumps required for the entire value chain, from CO<sub>2</sub> emitters to onshore receival storage plants, able to optimize the cost in the hole value chain.

The pressurized liquid CO<sub>2</sub> will be exported to the offshore facilities using the existing Ørsted owned offshore pipeline (24" Natural Gas Pipeline between Nybro and South Arne / Harald offshore platform). Prior to export offshore, the liquid CO<sub>2</sub> will be pressured up to maximum 138 bara (pipeline operating pressure) at the harbour. The liquid CO<sub>2</sub> will also be heated to above zero degrees to ensure that ice does not form around the offshore sections of the 24" Nybro to South Arne / Harald pipeline.

### **Process Safety**

A high-level dispersion and risk model has been prepared to evaluate the extent of the CO<sub>2</sub> releases. An inherent safety design workshop and a preliminary hazard and operability study on the conceptual process design has also been conducted. All these analyses combined are to ensure that considerations are made in the early design phases for safe CO<sub>2</sub> operations.

A preliminary flow assurance analysis for the 24" offshore pipeline was conducted to assess offshore arrival pressure under different transport/injection rates, considering fill up, blowdown and packing/unpacking of the pipeline. With a minimum arrival pressure of 80 barg to stay in the dense phase region and avoid multiphase flow, the maximum transport rate is around 13 Mtpa.

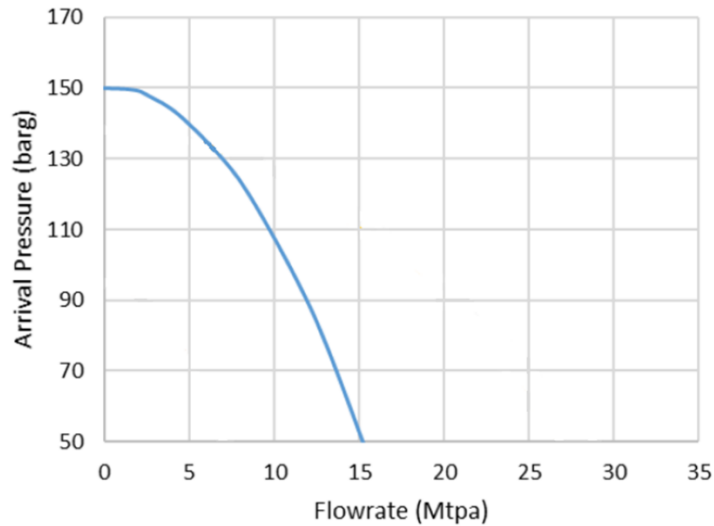


Figure WP8-4: Flowrate vs Arrival pressure for the offshore South Arne/Nybro pipeline.

During commissioning and start-up of the pipeline, filling up the pipelines and pressurize it to 80 barg after vacuum drying is required. In the study, the inflow of CO<sub>2</sub> is taken from either road tankers or ships. It can be seen how shipping would allow to bring the pipeline to pressure much faster than with road tankers.

Fill-Up Time from 1 mbar to 80 bar (no backbone)						
Inflow Mass Rate (ton/h)	Time (hours)	Time (days)	Truck /day	Truck Frequency (hours)	Ship /month	Ship Frequency (days)
<b>1</b>	70270	2928	1	24.0	0.1	250
<b>5</b>	14054	586	5	4.8	0.5	50
<b>10</b>	7027	293	10	2.4	1.0	25
<b>15</b>	4685	195	15	1.6	1.4	17
<b>20</b>	3514	146	20	1.2	1.9	13
<b>30</b>	2342	98	30	0.8	2.9	8
<b>40</b>	1757	73	40	0.6	3.8	6
<b>50</b>	1405	59	50	0.5	4.8	5
<b>100</b>	703	29	100	0.2	9.6	3
<b>150</b>	468	20	150	0.2	14.4	2

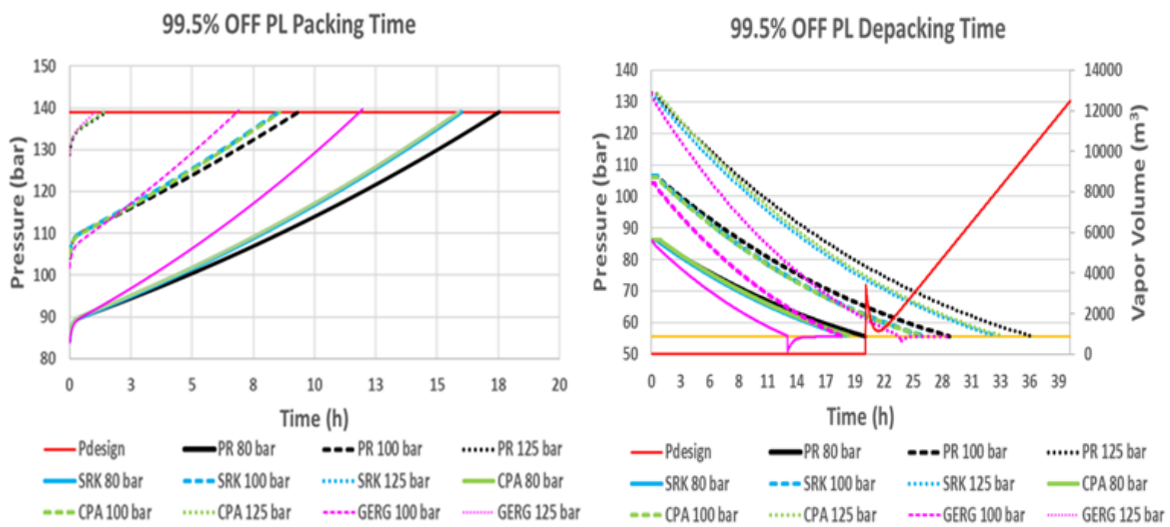
Figure WP8-5: Shipping vs road tankers to pressure the pipeline.

The Controlled blowdown release of the pipeline in case of a depressurization caused by an emergency ore for maintenance purposes is considered done through different orifice size. The size of the orifice, for a controlled blowdown was investigated, with the conclusion that a smaller orifice than 4" is required, to secure no material failure due to low temperatures.

Blowdown Time		
Orifice (in)	Time (hours)	Time (days)
4	281	11.7
8	230	9.5
12	216	9

Figure WP8-6: Controlled blowdown release of the pipeline in case of a depressurization.

In case of any planned or unforeseen event in the supply chain of CO<sub>2</sub>, causing stop of pumping to offshore, or if the injection to the well requires a stop, the packing and de-packing of the pipeline could provide operator to react before a complete shutdown of the entire system. By packing and de-packing, the pipeline, it is used as a storage, and calculations shows the time to react for operation in different scenarios.



Figures WP8-7&8: time to react for offshore pipeline operation.

**General offshore pipeline Capacities**

The capacities for transporting liquid CO<sub>2</sub> in the, by Ørsted owned three offshore pipelines is investigated. The operating window is depended on the CO<sub>2</sub> specification as two-phase flow should be avoided. Boil-off which could occur at the platform end of the pipeline should be avoided to avoid handling of two-phase flow at the platform but also due to the lower solubility of water in the CO<sub>2</sub> gas phase which could result in free water drop out and associated internal corrosion risk. The Combined capacities in especially the gas pipelines is high and should be sufficient to support most of the depleted wells in the North Sea.

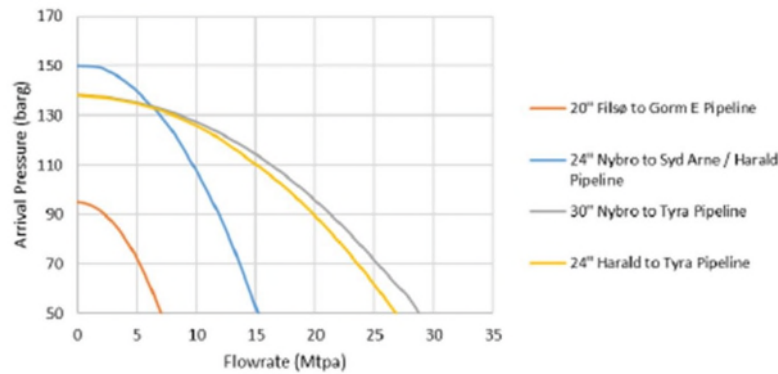


Figure WP8-9: Offshore pipeline capacities vs arrival pressure.

Investigations of the gas flow in the South Arne pipeline, can be rerouted, making the South Arne available much earlier, meeting the timeline for first CO<sub>2</sub> injection in the depleted oil fields.

### Due diligence of the South Arne Pipeline

The current South Arne – Nybro pipeline condition is considered fit for the re-qualification. No deviations critical for the re-qualification has been identified. From the available monitoring, inspection and experience records, there are no indications that the South Arne – Nybro pipeline has been exposed to excessive loads or degradation that may have significantly reduced the initial capacity of the pipeline.

Non-metallic materials found in the existing subsea ball valves have been testing in supercritical CO<sub>2</sub> and the ball valves are found to be compatible with CO<sub>2</sub> transport.

The seals tested are PTFE lip seals used on the stem and seat, and NBR (nitrile) and FKM (Viton) O-rings used as sea water seals. The mechanisms evaluated for non-metallic seals in CO<sub>2</sub> are chemical degradation by contaminants, swelling/extraction, rapid gas decompression (RGD) damage and low temperature effects. Degradation by exposure to contaminants is not expected due the limited concentration of potentially harmful contaminants in the CO<sub>2</sub>-stream combined with the low ambient temperature. CO<sub>2</sub> itself will not cause chemical degradation of the non-metallics but may cause swelling (or extraction of material ingredients) and RGD damage of the seals. Low temperatures are not expected to cause leakage. PTFE has sealing ability to cryogenic temperatures. The static O-rings may stiffen, particularly the FKM's, but no damage is expected, and the seals will recover once temperature increases. The PTFE has not been affected by exposure to dense CO<sub>2</sub>. RGD-damage of a PTFE seal cross section is not likely. Some swelling in CO<sub>2</sub> may be expected, but the lip seal design will tolerate such volume increase. PTFE lip seals are frequently used for liquid CO<sub>2</sub> applications. Some damage has been observed on FKM O-rings and NBR seals in the event of an RGD. However, FKM O-rings are used as sea water seals, therefore with functioning primary seals, these seals will not be directly exposed to CO<sub>2</sub>. In case the seals are exposed to CO<sub>2</sub>, an RGD event is not likely to cause damage to such an extent that the seals may leak.

The pipeline is during installation provided with internal coating, to reduce the drag in the gas flow. The internal flow coating in dense CO<sub>2</sub> has been evaluated by performing blistering tests. Cyclic decompression showed blistering, with blisters forming between steel and coating. However, the selected decompression rate has been assessed being too high to be relevant for normal pipeline operation. Long term exposure autoclave test has shown that the flow coating has acceptable blistering resistance to one decompression cycles at a realistic decompression rate. Further testing is being performed with relevant decompression scenarios for the pipeline.

An assessment of the risk of running ductile fracture has been performed according to DNV-RP-F104. The assessment is taking pipeline dimensions and material properties such as yield strength and Charpy value into account.

The DNV assessment can be used to calculate the maximum length that a crack may be able to propagate in case of a crack initiation for different saturation pressures of the CO<sub>2</sub> transported in the pipeline. The analysis shows that if the saturation pressure is below 64.5 barg the maximum propagation of a crack is 97 m before the crack will reach a section on the pipeline with sufficiently toughness to arrest further propagation.

As a repair of a damage of 97m is considered feasible utilising normal pipeline repair methods and the rupture of 97 m of pipeline does not affect the dispersion of the CO<sub>2</sub> significantly compared to a localised rupture this is found acceptable.

Based on this it is concluded that CO<sub>2</sub> with a saturation pressure up to 64.5 barg can be transported in the pipeline with regards to the risk associated with running ductile fracture. The saturation pressure of the Ørsted proposed specification at 20 degrees is well below the allowable value at 59 barg and CO<sub>2</sub> mixed with 2% N<sub>2</sub> is at the limit with a saturation pressure of approximately 65 barg at 20 degrees.

Internal corrosion can be prevented provided no acid aqueous phase is formed. When the final CO<sub>2</sub> specification has been defined a comprehensive test program is expected to be required as it is anticipated that only testing can confirm the interplay between the different impurities and the CO<sub>2</sub> will not lead to material cracking or internal corrosion.

Brittle fracture and weld defects have been considered and are no expected to be a showstopper, but more detailed analysis shall be conducted in the next phase of the project.



WP9 - Health Safety Environment and societal. Stakeholder management

WP Lead: DUC-TotalEnergies

### Introduction and objective of this work package

- Defining permit and consent register in compliance with regulations in place. The objective of the Permits and Consents Register is to identify and maintain a register of applicable health, safety and environmental consents and permits for project-related activities. The register will identify expected permits and consents and the related legislation, the approval process and timelines, relevant regulatory bodies, and stakeholders.
- Performing Environmental and Societal desktop study and SENVID study to identify social and environmental potential impact. The original scope of work has been changed and stakeholders' management and engagement and societal have been spread out onto several work packages, including WP2 and WP11. The objective of the desktop study is the Environmental Baseline Study (EBS) and a preliminary stakeholder mapping to be deepened as part of the future EIA process.

### Analysis

- **Permit and Consent (P&C) register.**

The P&C register report includes a list of the permits and consents required for pre-investigations, which are needed before installation can begin (marine surveys, geophysical surveys, archaeological control, exploration of wells etc.), installation, operation (injection and storage), and closure including plugging of wells and decommissioning of installations. This 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 since they use similar installations (platforms, pipelines, wells etc.) as those considered for the Bifrost concept.

- **the Environmental Baseline Study (EBS)**

The EBS provides an overview of the environmental existing data and current knowledge of the surrounding environment from the TEPDK monitoring program as well as the protected areas network.

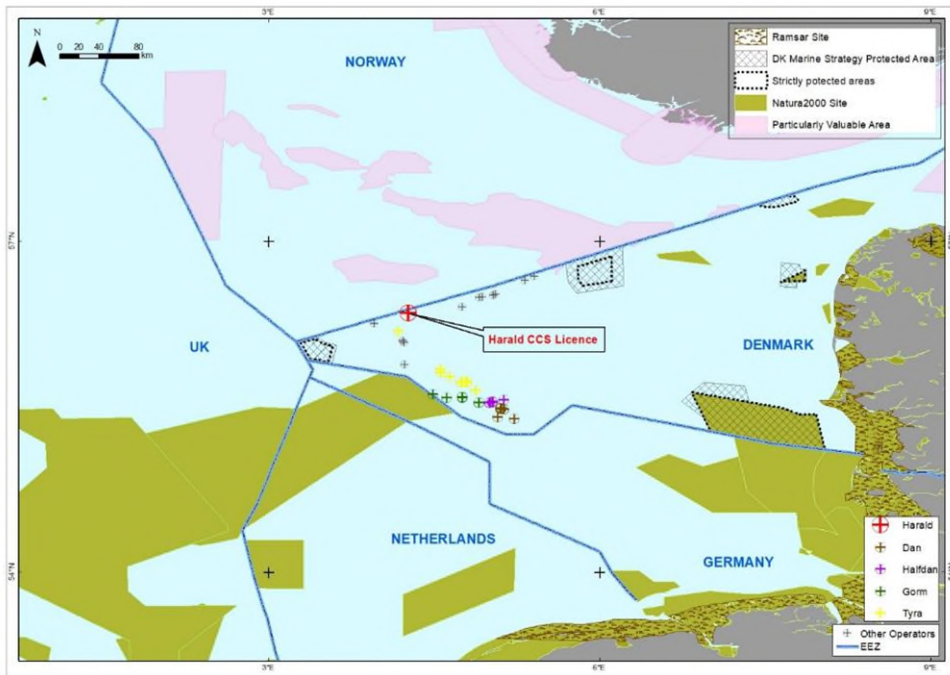


Figure WP9-1: Overview of the protected areas network.

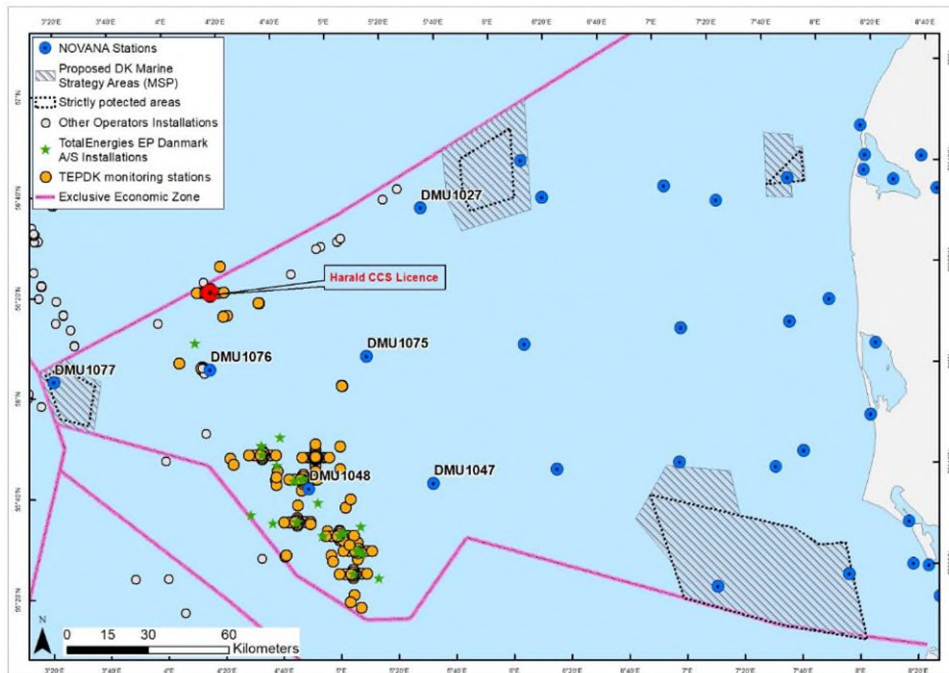


Figure WP9-2: Overview of the TEPDK monitoring plan and NOVANA stations.

**Key findings and results**

- **Permit and Consent (P&C) register.**

The following figure provides an overview of the permit and consent procedure covering 1) permits for marine surveys (pre-project phase), 2) construction permit (EIA permit) and storage permit (project phase), 3) permits related to operation of the facility (operation phase) and 4) closure. The figure highlights the major phases with indication of the legal requirements.

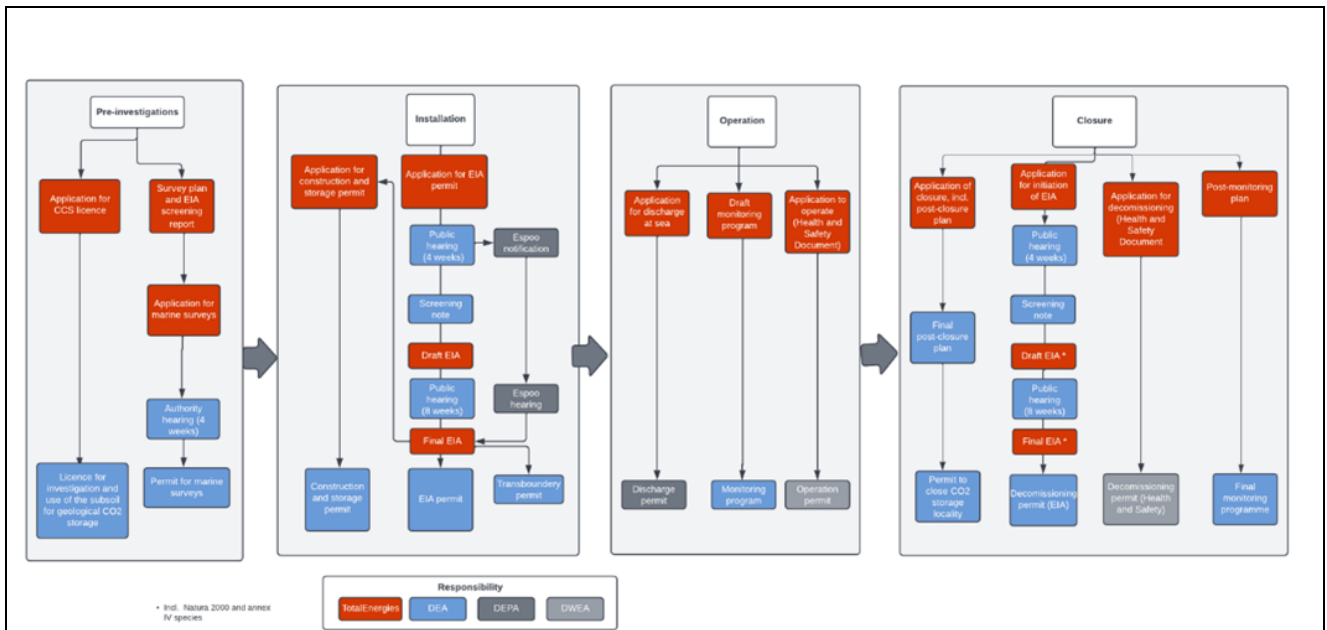


Figure WP9-3: Overview of the permitting process for investigation, installation, operation, closure of project Bifrost.

A list of local Authorities stakeholders relevant for the offshore part of the Bifrost project is provided below:

- Danish Energy Agency, DEA: Authority for EIA and overall licenses
- Danish Environmental Protection Agency, DEPA: Authority on EIA of land facilities, Espoo consultation and discharge permit.
- Danish Coastal Authority, DCA: Construction permit in Danish territorial waters. Coastal Protection under the Nature Conservation act (beach protection line and dune protection line).
- Danish Energy Board of Appeal (EKN)

**The Environmental Baseline Study (EBS).**

The protected areas network is not affected by the proposed project, since:

- The Doggerbank is the closest protected area, and it is about 60km away. This is an IUCN cat IV protected area, Natura 2000 site and OSPAR zone (Convention for the Protection of the Marine Environment of the North-East Atlantic)
- Marine Strategy Area H as (part of the MSFD implementation) is about 50 km away.
- Marine Strategy Area G (part of the MSFD implementation) is about 90 km away.
- Particularly valuable and vulnerable areas (SVO) in the Norwegian North Sea is about 25 km away.
- No KBAs are around the project area.
- No IFC (International Finance Corporation) “Likely” or “Critical” habitat nor marine sensitivities are around the project area.

The assessment of the environmental status of the seabed around, from the existing monitoring data around the Harald platform, is based on the approach developed for the descriptors and indicators prescribed within the Marine Strategy Framework Directive (MSFD). Results show for all stations that there is only negligible impact on the seabed conditions and the benthic fauna communities around Harald. Analysis also shows a spatial gradient around the platform and all contaminant concentrations below the Effects Range Low (ERL) as defined by OSPAR and developed by NOAA.

Three species of marine mammals (strictly protected under the Habitats Directive Annex IV and the Danish legislation) are potentially present in the area, based on the estimates of the cetacean abundance in the North Sea from the SCANS-IV aerial and shipboard surveys of September 2022. They are *Harbour porpoise* (the most abundant with a density of about 1 animal/km<sup>2</sup>), *White beaked dolphin* and *Minke whale*.

**Highlighted interfaces with other work packages**

Several coordination meetings have been organized at the initiative of WP9 with the various workstreams in charge of the communications and engagements with Project stakeholders. Updates and documents from WP2, WP9 and WP11 were shared during those meetings.

**References and WP publications**

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EU Habitats Directive 92/43/EEC

EU Birds Directive 2009/147/EC

EU Marine Strategy Framework Directive (MSFD), 2008/56/EC

Danish Subsoil Act, Consolidation Act No. 1461, 29/11/2023

Danish EIA Act, Consolidation Act No. 4, 03/01/2023

Danish Offshore Habitat Order, BEK No. 786, 14/06/2023

Danish Marine Strategy Act, LBK No. 123, 01/02/2024



WP10 - Monitoring Plan  
WP Lead: DTU Offshore

### Introduction and objective of this work package

Measurement, Monitoring and Verification (hereafter 'MMV') of geological CO<sub>2</sub> storage, from pre-injection baseline surveys to final handover to authorities, is central to demonstrate safe containment, to prevent and mitigate potential leakage, and to build public acceptance. It is therefore central to the success of any carbon capture and storage (CCS) project to identify the most suitable and cost-effective MMV technologies.

WP10 includes three main tasks:

- 1) A review of public MMV plans to discuss options and recommend the best tools for cost efficient monitoring of the Harald Fields
- 2) Feasibility studies including numerical simulations to assess the suitability of specific technologies to monitor CO<sub>2</sub> injection in the Harald fields and to understand the limitations of the methods.
- 3) Advancing the efficiency of tools and methods for improved monitoring through research and development.

The work was effectively carried out between DTU Offshore, leading the work for objectives 1 and 3 and TotalEnergies responsible for objective 2.

### Analysis

#### Review of MMV plans:

The review work done at DTU Offshore in spring 2022 was performed to establish the 'State of the Art' within monitoring, measurement, and verification (MMV) of offshore CO<sub>2</sub> storage. The main objectives of the review were to:

- Describe and classify available MMV plans for offshore CO<sub>2</sub> storage projects (existing and planned).
- Review the 'State of the Art' in monitoring for offshore CO<sub>2</sub> storage projects.
- Provide an inventory of currently available monitoring methods and technologies.
- Propose emerging/future technologies that could be relevant for offshore storage sites.
- Identify the best analogue projects from an MMV perspective for offshore CO<sub>2</sub> storage in Denmark (with special focus on reuse of depleted hydrocarbon fields).

As offshore CO<sub>2</sub> storage projects vary significantly, the reviewed projects were categorized by geological setting, previous history of the storage site, and business model. Offshore CCS projects worldwide differ from each other in several keyways that affect monitoring programs. The storage reservoir may be sited in open saline aquifers at shallow and intermediate depths (ca 1,000-2,500 m), such as Sleipner in Norway and Gorgon in Australia, or alternatively in deeper depleted gas fields (ca 2,500-4,000 m) with existing infrastructure from hydrocarbon exploitation, such as planned projects Porthos and Aramis in the Netherlands and the Harald Fields in Denmark.

#### Feasibility studies:

Numerical simulations were conducted to assess the feasibility of 1) detection of CO<sub>2</sub> in the subsurface using seismic methods and 2) evaluating the efficiency of detecting rock deformations using seismometers, also known as micro-seismic methods. The simulations were building on results of WP3 analysis.

A seismic survey relies on detection of sound waves that are reflected from geological layers deep below the seabed, in this case 3-4km. Sensors are towed behind acquisition boats that also source the sound waves.

The received waves are analysed to construct a three-dimensional image of the subsurface including the reservoir. By repetition of the seismic acquisitions, changes in the subsurface can be mapped and attributed to changes in pressure, temperature, or the presence of CO<sub>2</sub>, all of which can change the way the waves are reflected. When such 3D surveys are repeated, it is called 4D seismic. The main limitation of this method is that the acquisition environment is noisy, and the emitted wave energy dissipates across the long distances weakening the signal. Small variations in the reservoir, deep below sea-level, can therefore not be detected. TotalEnergies simulated the acoustic properties of the reservoir under the relevant conditions to evaluate when the effects of pressure, temperature and fluid changes would be sufficient to be detectable using 4D seismic. The study focused on the feasibility of detecting the CO<sub>2</sub> in the gas cap of the reservoir and detectability of CO<sub>2</sub> in the chalk layers above the reservoir. The optimal 4D data acquisition strategy was also analysed.

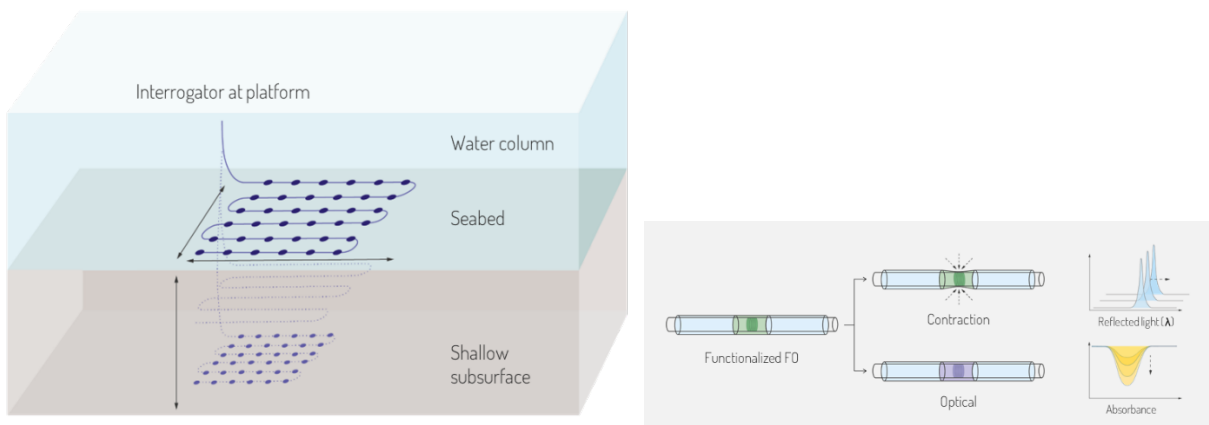
The rocks of the reservoir are elastic but may in theory deform under extreme stress. Deformations may be detectable using the same technology that is used to detect earthquakes in seismic active regions of the world. In case geophones are deployed in the wells and on the seabed and are constantly “listening,” then it is in theory possible to detect rock deformations in the reservoir (which can be tolerated) and distinguish these from deformations of the sealing layers (which is not tolerated). The technology was considered for the Bifrost project since it can be a good method to demonstrate that the seal remains intact during the injection, i.e. to verify that there are no new paths for CO<sub>2</sub> to escape. The detectability of deformations and the optimal geophone deployment was analysed by TotalEnergies to understand if this method could be useful for verification purposes.

**Research and development:**

Research work includes 1) development of sensors for detecting changes in the near seabed environment and 2) Maturation of a digital twin concept utilizing an advanced machine learning method to optimize prediction of CO<sub>2</sub> subsurface behaviour.

The development of overly sensitive, stationary fibre-optics-based chemical sensor for sea-bed monitoring can be a cost-effective technology for offshore CO<sub>2</sub> storage monitoring (Figure WP10-1) that can provide more efficient sampling and at a lower cost, compared to physical inspections at water depths of 65m. The elements of the study include:

- Adsorption study to understand the CO<sub>2</sub> uptake of the metal-organic framework from seawater (mass capacity, kinetics)
- Systematic evaluation of how to chemically functionalize the fibre optics to grow mechanically stable films, preliminary results show that pre-functionalization before MOF growth is needed, and the exact conditions is being determined now.



*Figure WP10-1: Development of cost-effective sensors for detecting changes in the near seabed environment.*

Another key point of the research work is the development of a machine learning (ML) model for a digital twin concept of CO<sub>2</sub> subsurface behaviour that works with balanced accuracy and computational cost. ML was demonstrated to predict CO<sub>2</sub> subsurface behaviour accurately by leveraging the existing strong correlation with field porosity/permeability. However, estimating these properties from 3D seismic and well logs is time-

consuming and introduces uncertainties. Hence, efforts have been made to develop a model that uses readily available data inputs in CCS projects, such as well logs, injection history, and seismic data (Figure WP10-2).

An additional input data that could contribute to a digital twin concept is the seabed displacement. As previously mentioned, CO<sub>2</sub> injection can induce rock deformation, potentially resulting in seabed uplift. It is essential to determine if this uplift is detectable and if there is a correlation between it and the lateral CO<sub>2</sub> plume movement. Further investigation is needed to explore these relationships. Therefore, the development of the ML model for a digital twin concept includes:

- Testing different ML architectures to determine the best candidate for a digital twin concept for CO<sub>2</sub> storage in terms of accuracy, flexibility, and efficiency.
- Investigation of the potential amount of seabed uplift and the existence of a correlation between uplift and lateral CO<sub>2</sub> plume movement.
- Assessment of the ML model accuracy and efficiency using well logs, seabed displacement, and seismic data.

### Key findings and results

The review of public available MMV strategies resulted in a report by DTU Offshore. This report maps out the existing and readily available monitoring technologies, with focus on offshore storage in depleted hydrocarbon fields, and provides a view on recent advances that could play a key role in future long-term monitoring of storage sites. There appears to be a trend for modern MMV plans to be leaner than plans proposed 10 or 15 years ago, reflecting the change in financial drivers and an increased focus on cost. Additionally, there are some country specific trends with for example MMV plans in the Netherlands paying more attention to induced seismicity as compared to projects in the neighbouring UK, which focus more on environmental and seabed monitoring. Hence geology, history of the storage site, business model, national politics & regulations, and societal risk perceptions all play a role in MMV planning for geological CO<sub>2</sub> storage.

The numerical feasibility simulations showed that the combined effect of fluid changes, pressure and temperature changes in the gas cap that will host the CO<sub>2</sub> will be detectable using 4D seismic if a seismic baseline is acquired before the injection starts and another is acquired after the injection, enabling the comparisons. Due to the small contrasts between gas and gas mixed with CO<sub>2</sub> it will however not be possible to reliably detect the CO<sub>2</sub> explicitly, in isolation from the other effects of pressure and temperature.

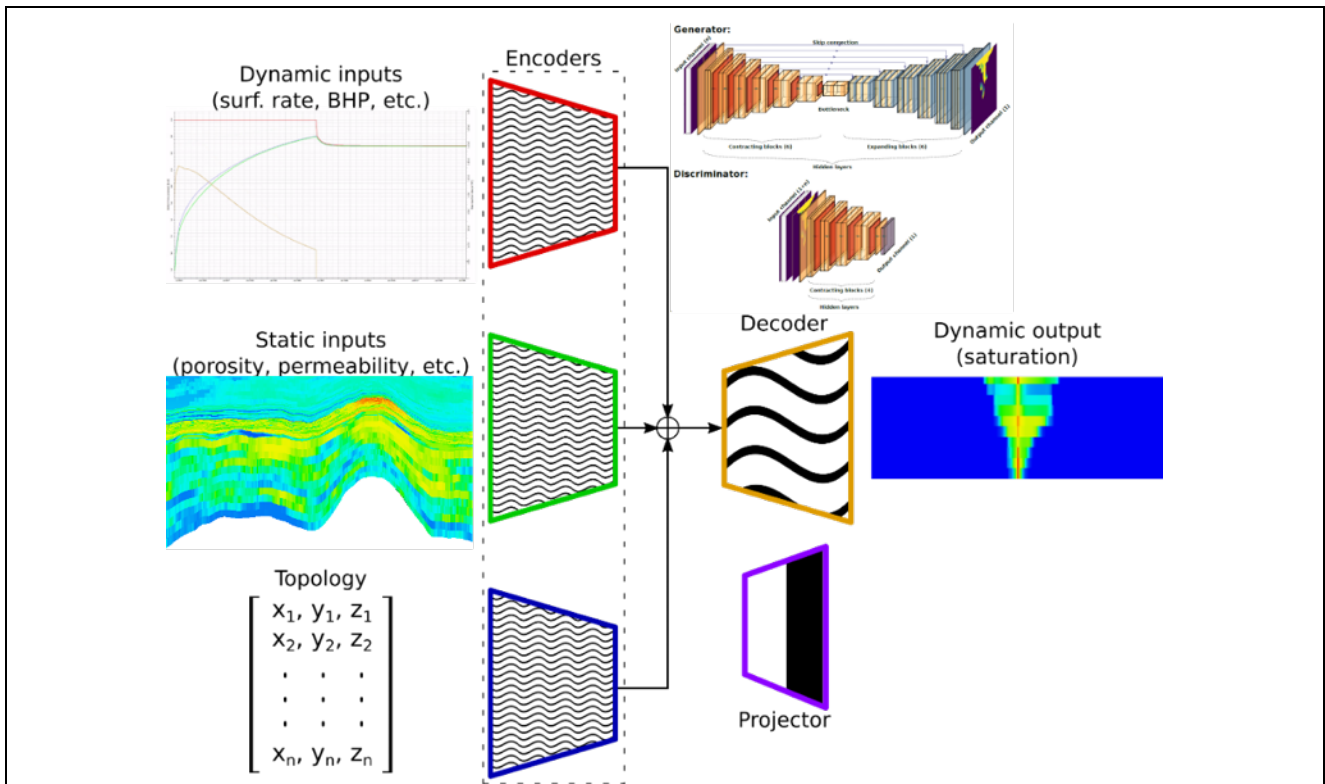


Figure WP10-2: Machine Learning application for monitoring and prediction of the CO<sub>2</sub> plume.

The chalk intervals above the gas reservoir are in the Harald West area water filled. Should CO<sub>2</sub> leak into the chalk from beneath, then the fluid change will be detectable using 4D seismic. This means that if no changes are detected in the chalk between the baseline and the final seismic acquisitions, it has been demonstrated that the CO<sub>2</sub> has not leaked, and containment is thereby verified. For this reason, 4D seismic will be an integral part of the monitor plan for Harald West.

The micro seismic feasibility study indicated that should rock deformations occur, then it will be possible to distinguish deformations in the reservoir from extremely unlikely deformations in the seal. Next step will be to identify the most cost-efficient method to deploy the geophones.

The monitoring of CO<sub>2</sub> by physical measurements and deployment of sensing systems at the seabed is based on the concept of distributed chemical sensing targeting variations in CO<sub>2</sub> concentration just add the surface or by trenching just below surface. Measurements at natural CO<sub>2</sub> seepage sites reported in literature have shown that only a few meters above seabed surface, the CO<sub>2</sub> signal is easily diluted to zero, supporting the conceptual strategy taken Sensors spots are grown on the surface of the fibre optic cable to make distributed sensors along the length of the fibre. Only one spot fibres are so far being analysed. A material has been found that responds reversible to changes in CO<sub>2</sub> in water, and work is ongoing to create robust multilayer deposits. Further, the impact of temperature variations on the optical/strain signal measured, needs to be assessed.

On the development of a digital twin concept, three machine learning architectures were assessed: conditional generative adversarial networks – CcGANs (Ferreira et al., 2022; Stepien et al., 2023), Barlow Twins autoencoders – BT-AEs (Ferreira et al., 2023a), and Barlow Twins deep operator networks – BT-DeepONets (Ferreira et al., 2023b). The first attempt to work only with well logs as inputs was using CcGANs. Despite not leveraging the strong correlation between field porosity/permeability and the CO<sub>2</sub> subsurface behaviour, the CcGANs were able to predict the CO<sub>2</sub> plume propagation with 90% of accuracy. This type of ML architecture lacks flexibility though, in terms of input data. The next attempts were made towards more flexible ML architectures, which are the BT-AEs and the BT-DeepONets. Both performed with the same level of accuracy of the CcGANs but presenting flexibility in terms of data processing. The BT-DeepONets presented a higher efficiency, which makes this architecture a potentially suitable candidate for monitoring the CO<sub>2</sub> plume movement. In terms of inputs, the model based on BT-DeepONets considered injection history and well logs,

whereas the models based on CcGANs and BT-AEs only considered well logs. Monitoring the CO<sub>2</sub> plume propagation considering also seismic data is currently under development.

Numerical simulations of CO<sub>2</sub> injection were conducted to explore any potential correlation between the lateral movement of the CO<sub>2</sub> plume and seabed uplift, revealing a positive correlation (Shaheen, 2023). However, the vertical displacement appears smoothed, making difficult the precise identification of migration pathways using seabed uplift data alone in real-world applications. Combining seabed displacement monitoring with seismic data and well logs may provide an improved accuracy in the monitoring of the CO<sub>2</sub> subsurface behaviour. Such combination along with BT-DeepONets is currently being explored (Ferreira et al., 2024b) and compared to monitoring based on well logs and seismic data (Ferreira and Nick, 2024; Ferreira et al., 2024a).

### Highlighted interfaces with other work packages

The monitor and injection strategies for Harald East (WP4) and West (WP3) are heavily influenced by the results of the WP10 work. This is further described in the WP3 and WP4 chapters of this report. The monitoring plan is described in WP3

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- Ferreira, C. A. S., and Nick, H. M. (2024): Towards a deep learning tool for monitoring the CO<sub>2</sub> plume propagation in carbon storage activities [talk]. Recent Advances in Geophysical Reservoir Characterization and Monitoring of CO<sub>2</sub> Sequestration in Carbonate Reservoirs Workshop, May 2024.
- Ferreira, C. A. S., Kadeethum, T., Amour, F., Hosseinzadeh, B., Abdollahi, A., Calvert, A. S., and Nick, H. M. (2024): A deep learning model for CO<sub>2</sub> storage in a depleted gas reservoir using sparse well data. 85th EAGE Annual Conference and Exhibition, Jun 2024. <https://doi.org/10.3997/2214-4609.2024101572>
- Ferreira, C. A. S., Kadeethum, T., and Nick, H. M. (2023a): Predicting geologic CO<sub>2</sub> storage and plume evolution from sparsely available well data using Barlow Twins. Third EAGE Digitalization Conference and Exhibition, March 2023. <https://doi.org/10.3997/2214-4609.202332073>
- Ferreira, C. A. S., Pianos, M., Hosseinzadehsadati, S., Tian, J., Kadeethum, T., and Nick, H. M. (2023b): A predictive DeepONet model of CO<sub>2</sub> plume propagation in geological formations based on sparse well data. Fourth EAGE Global Energy Transition Conference and Exhibition, November 2023. <https://doi.org/10.3997/2214-4609.202321097>
- Ferreira, C.A.S., Stepien, M., Hosseinzadehsadati, S., Kadeethum, T. and Nick, H.M. (2022): Predicting the CO<sub>2</sub> propagation in geological formations from sparsely available well data. Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022, Available at SSRN: <https://ssrn.com/abstract=4285942> or <http://dx.doi.org/10.2139/ssrn.4285942>
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- Stepien, M., Ferreira, C. A. S., Hosseinzadehsadati, S., Kadeethum, T., and Nick, H. M. (2023). Continuous conditional generative adversarial networks for data-driven modelling of geologic CO<sub>2</sub> storage and plume evolution. Gas Science and Engineering, July 2023. <https://doi.org/10.1016/j.jgsce.2023.204982>
- Torres, L. F. L., Ferreira, C. A. S., Kadeethum, T., Amour, F., Hosseinzadeh, B., Abdollahi, A., Shaheen, S., Calvert, A. S., and Nick, H. M. (2024): Tracking CO<sub>2</sub> plume propagation in a depleted gas field using sparse well data and seabed displacement.



WP11 - Socioeconomic assessment

WP Lead: DTU University

**Introduction and objective of this work package**

Understanding the economic impacts, stakeholder perceptions and social acceptability are three cornerstones for the successful rollout of CCS. Considering both the technical, commercial, and social barriers that still exist for CCS deployment, the groundwork developed by this project will advance the understanding of the potential of the Danish sector of the North Sea for CO<sub>2</sub> storage. With the completion of these objectives, we will be able to define value propositions throughout the CCS value chain and kick-start the development of CCS in Denmark. The scope of this work package was divided into three distinct areas:

The objectives of this work package include:

- 1) Estimate the economic effects of CO<sub>2</sub> storage on the Danish economy.
- 2) Gather and analyse perceptions and acceptance of carbon storage among key stakeholders.
- 3) Gather and analyse perceptions, acceptance of – and preferences for CO<sub>2</sub> storage among the Danish population in general and targeted groups.

**Analysis**

- 1) Estimate the economic effects of CO<sub>2</sub> storage on the Danish economy.

We use a bottom-up approach to estimate the costs under different technological and economic assumptions, then use these expenses as an injection vector in multiregional input-output models to compute the direct and indirect economic impacts of offshore CCS.

- 2) Gather and analyse perceptions and acceptance of carbon storage among key stakeholders.

The research is based on a qualitative methodology involving in-depth semi-structured interviews with 18 key stakeholders, including Green NGOs, industry/emitters, trade and interest organisations, authorities, and climate experts. These interviews were conducted between 2022 and early 2023 to capture diverse perspectives and interests within the CCS domain. The interviews were recorded, and notes were taken during the interviews, which were subsequently analysed relative to specific themes (Figure WP11-1).



*Figure WP11-1: Data collection process and analysis for stakeholder study.*

- 3) Gather and analyse perceptions, acceptance of – and preferences for CO<sub>2</sub> storage among the Danish population in general and targeted groups.

The data on CCS acceptance and preferences were collected via three surveys (co-financed by other projects) in the summer 2022, 2023 and autumn of 2023. The surveys were developed through iterative processes of literature review, interviews with regulation and energy experts, individual survey tests and interviews, and pilot tests. Jointly with the survey development, we applied to the Danish Health Data Authority for permission to randomly draw samples of 55,000 individuals based on their personal identification numbers. The respondents were invited to participate in the surveys in their digital mailbox, "E-boks". Reminders were sent out via E-boks to individuals who had not answered the surveys. The survey response rates are between 15%- 22%.

As a central part of the survey, we asked questions about CCS knowledge, and we conducted three randomised information experiments to test how information impacts the acceptance of CCS and the willingness to pay for CCS, see below.

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#### Baseline information

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CO<sub>2</sub> capture and storage (CCS) is a technology where CO<sub>2</sub> is captured at power plants or industries. The CO<sub>2</sub> is transported via pipes/ships to the storage site and pumped deep into the subsoil, where nature itself ensures that the CO<sub>2</sub> stays there. In Denmark, we are already testing the possibilities of capturing CO<sub>2</sub> and storing it in two large old oil/gas fields in the North Sea.

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#### Information A : Baseline + Global CCU Usage

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CO<sub>2</sub> capture and storage (CCS) is a technology where CO<sub>2</sub> is captured at power plants or industries. The CO<sub>2</sub> is transported via pipes/ships to the storage site and pumped deep into the subsoil, where nature itself ensures that the CO<sub>2</sub> stays there. **The technology has been used abroad for almost 40 years**, and in Denmark, the possibilities of capturing CO<sub>2</sub> and storing it in two large old oil/gas fields in the North Sea are being tested.

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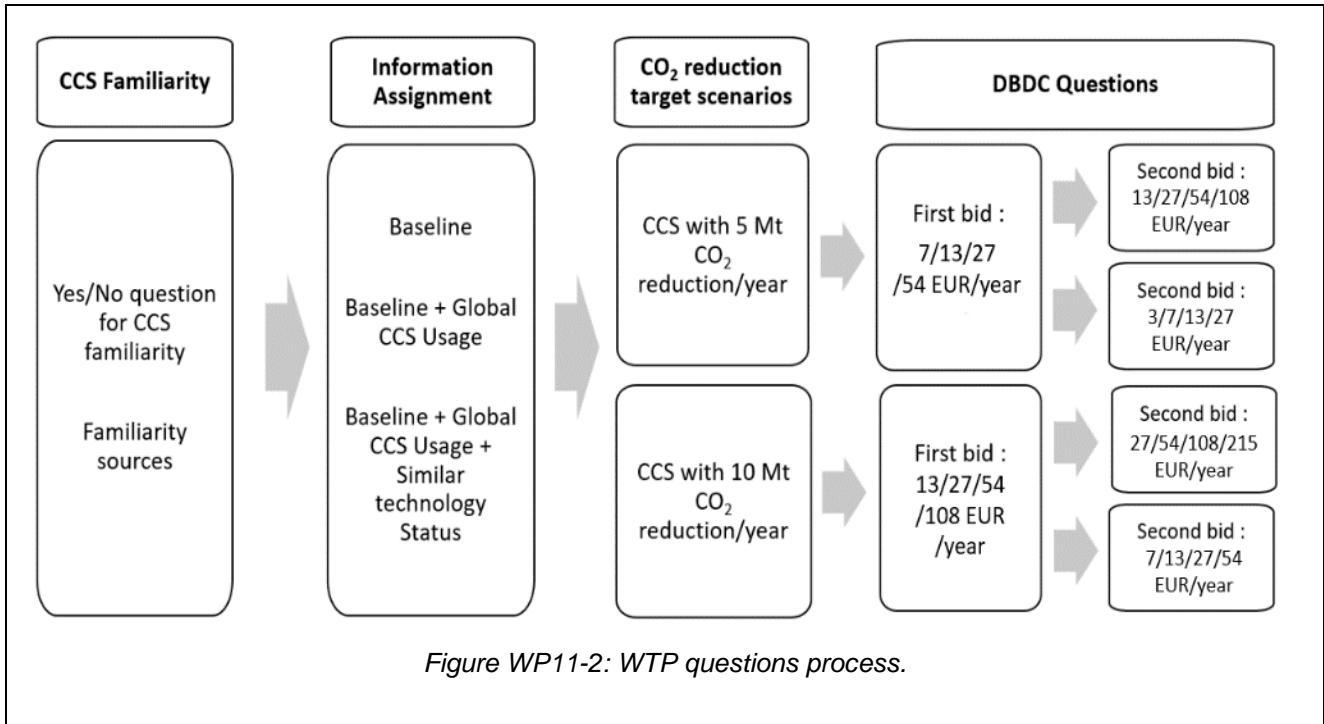
#### Information B: Baseline + Global CCU Usage + Similar National Technology Status

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CO<sub>2</sub> capture and storage (CCS) is a technology where CO<sub>2</sub> is captured at power plants or industries. The CO<sub>2</sub> is transported via pipes/ships to the storage site and pumped deep into the subsoil, where nature itself ensures that the CO<sub>2</sub> stays there. **The technology has been used abroad for almost 40 years** and in Denmark the possibilities of capturing CO<sub>2</sub> and storing it in two large old oil/gas fields in the North Sea are being tested. **Gas storage is not a recent technology in Denmark. Since the mid-80s and 90s, millions of cubic meters of natural gas have been stored and extracted annually underground in Jutland (Lille Torup) and Zealand (Stenlille).**

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In the preferences questions, we also tested if the preferences and WTP for CCS are sensitive to the scope of the CCS scale. Half of the respondents were told that CCS can capture and store 5 Mtpa from 2030. The other half of the respondents were told that the CCS can capture and store 10 Mtpa from 2030. Each respondent was presented with a randomised amount representing a household CCS tax and asked if the respondent's household was willing to pay the amount for CCS. If the respondents answered yes, they got a new and higher amount. If the respondents answered no, they got a new and lower amount. See the Figure WP11-2 for the CCS WTP questionnaire process.



**Key findings and results**

**1) Estimate the economic effects of CO<sub>2</sub> storage on the Danish economy.**

This research examines the macroeconomic impact of offshore CCS technology, focusing on the BIFROST project in Denmark using existing natural gas pipelines. Using cost estimates and input-output models, it finds positive value-added and employment impacts over 30 years. Two scenarios are considered based on pipeline operational timing, with early use maximising benefits. Recommendations include the early adoption of pipeline transportation and the maintenance of CO<sub>2</sub> storage and loading activities within Denmark for maximum impact.

**2) Gather and analyse perceptions and acceptance of carbon storage among key stakeholders.**

This qualitative study offers insights into implementing Carbon Capture and Storage (CCS). Stakeholders trust CCS but stress its use when no alternatives exist, integration with green tech, and offshore advantages. The value chain's coordination is crucial, as is creating an international market and CO<sub>2</sub> import for economic viability. Urgent regulations are needed for infrastructure, certification, and democratic involvement. CCS is vital for carbon emission reduction but should not prolong fossil fuel use or hinder renewables. Denmark aims to be a European storage hub, focusing on environmental impact assessments, safety (favouring offshore storage), and regulatory frameworks. Social acceptance and stakeholder engagement are vital, emphasising CCS as a climate solution and building trust through comprehensive information.

**3) Gather and analyse perceptions, acceptance of – and preferences for CO<sub>2</sub> storage among the Danish population in general and targeted groups.**

We find broad support for CCS, but the support also increases in the more "distant" locations. CCS support ordering is thus  $CCS_{\text{offshore}} > CCS_{\text{nearshore}} > CCS_{\text{onshore rural}} > CCS_{\text{onshore}}$ . The support correlates with CCS familiarity and is affected by our information experiment. CCS familiarity significantly increases the support for offshore, nearshore, and onshore rural CCS. Information A: Baseline + Global CCU Usage does not significantly affect offshore and onshore urban CCS acceptance. Information B: Baseline + Global CCU Usage + Similar National Technology Status significantly increases the acceptance of nearshore CCS and onshore rural and urban CCS (Figure WP11-3). We furthermore find that peoples' personal risk profile (risk averse vs. risk seeking) is correlated with acceptance. particularly risk averse people have a lower CCS acceptance, independent on CCS locations.

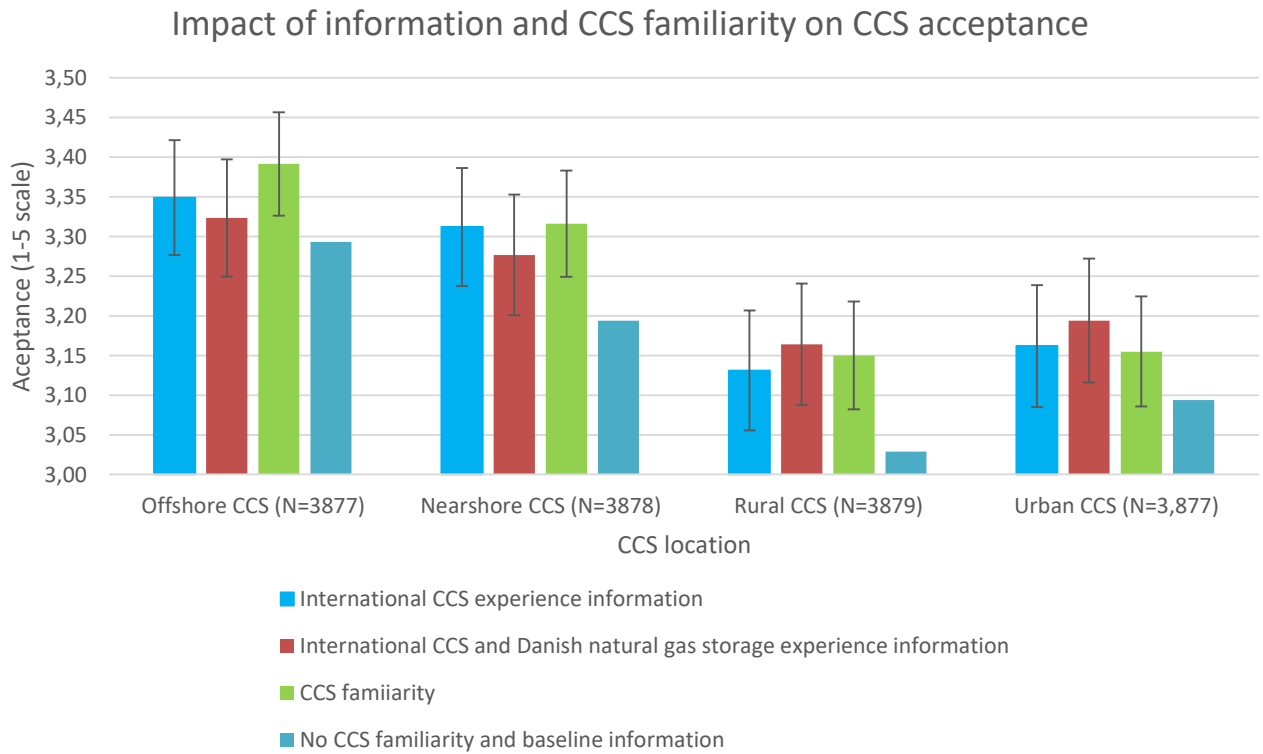


Figure WP11-3: CCS acceptance, information, and CCS familiarity.

The results related to the WTP questions reveal positive WTPs that increase with the scope of the CCS capacity (5 Mtpa and 10 Mtpa). Respondents with no CCS familiarity are willing to pay 47€ and 78€/year/household for the 5 Mtpa and 10 Mtpa CCS, respectively. Information A: Baseline + Global CCU Usage does not affect willingness to pay significantly, while Information B: Baseline + Global CCU Usage + Similar National Technology Status increases the WTP for the 5 Mtpa scenario with 8€/year. Respondents familiar with CCS are willing to pay 11€ and 16€ more for the 5 Mtpa and 10 Mtpa of CO<sub>2</sub> CCS, respectively (Figure WP11-4)

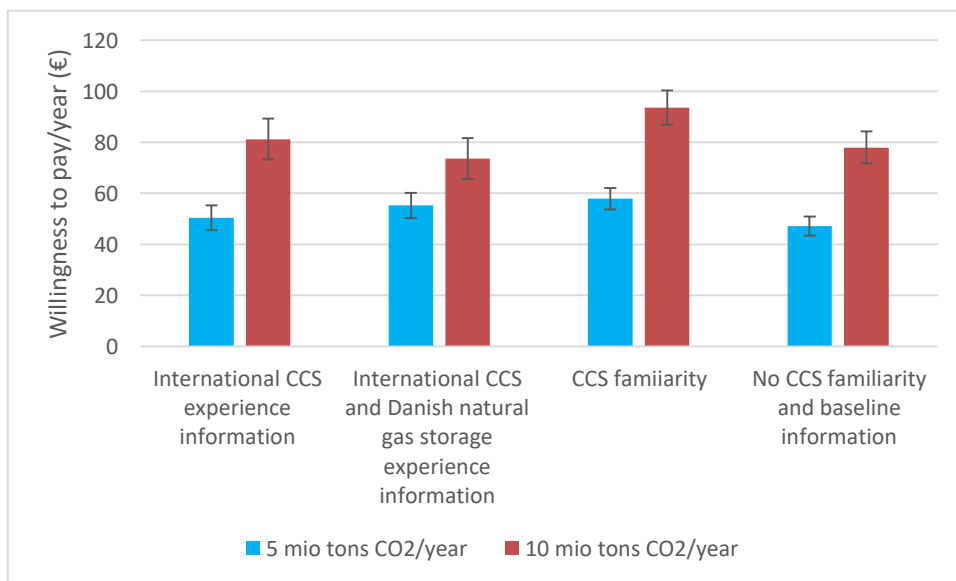


Figure WP11-4: Willingness to pay for 5 Mtpa and 10 Mtpa CO<sub>2</sub> CCS, information, and CCS familiarity.

We furthermore find that peoples' personal risk profile (risk averse vs. risk seeking) is correlated with the WTP. Particularly risk averse people have a lower WTP for CCS.

## References and WP publications

### Two papers are published:

- Ladenburg, J., Kim, J., Zuch, M., Soytaş, U. (2024). Taking the carbon capture and storage, wind power, PV or other renewable technology path to fight climate change? Exploring the acceptance of climate change mitigation technologies – A Danish national representative study. *Renewable Energy*. Vol. 220, pp: 119582.
- Ladenburg, J., Soytaş, U. (2023) Where are the low-hanging fruit? social acceptance of green technologies (In Danish: Hvor er de lavthængende frugter? social accept af grønne teknologier), (3), 31-40.
- **One paper has been submitted, received major revision, revised and is currently in the second review:**
- Tolstrup, S., Ladenburg, J., (Resubmitted after revision): A qualitative analysis of key stakeholders' perception of CCS and its value chain in a Danish North Sea storage context – through a socio-economic lens, *International Journal of Green House Gas Control*.
- **One paper has been submitted, received major revision and is under revision by the authors:**
- Kim, J., and Ladenburg, J. (major revisions). Breaking Barriers to Carbon Capture and Storage: An Integrated Analysis of Scope, Information and Familiarity Effects on Willingness to Pay, *Communications Earth & Environment*.

### Papers in preparation

- Ladenburg, J., Zuch, M., Kim, J. Information effects and familiarity effects and CCS acceptance.
- Berthet, E., Soytaş, U., Ladenburg, J. The value-added and employment impacts of an offshore CCS System in Denmark
- McBride, P., Morrissey, K., Ladenburg, J. Risk perception and the acceptance and willingness to pay for offshore carbon capture and storage.
- Kim, J. Unveiling Cognitive factor dynamics: How Ordering, Prior familiarity, and information shape public preferences for CO<sub>2</sub> mitigation strategies.
- Zuch, M. Carbon Footprints on my Doorstep: Investigating the relationship between scope, spatial characteristics, and willingness to pay for carbon capture and storage in Denmark.



## Conclusion:

**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<sub>2</sub> in a safe and cost-effective way.

Project Bifrost is thus key for Denmark to unlock its CCS potential; meet its CO<sub>2</sub> 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<sub>2</sub> in the Harald fields on commercial terms with the storage exploration license, awarded in February 2023; and BlueNord is involved in CO<sub>2</sub> storage studies through CarbonCuts.

For Denmark to become the European hub for CO<sub>2</sub> storage, additional partnerships are required from the full CCS value chain to develop solutions for transporting the CO<sub>2</sub> from emitters to the Harald facilities.