Final report

1. Project details

Project title	CO2 Liquid LAboratory Testing (COLLATE)
File no.	64021-2087
Name of the funding scheme	EUDP
Project managing company / institution	IKM Ocean Team Scandinavia
CVR number (central business register)	24320413
Project partners	IKM Ocean Team Scandinavia, EMS, DTU, INEOS, GEUS, Wintershall DEA, Energy Cluster Denmark
Submission date	20/12/2024

2. Summary

Project summary:

2.1.1 Project Summary

Project COLLATE (CO2 Liquid LAboratory TEsting) focused on advancing carbon capture and storage (CCS), a crucial technology for CO2 emission reduction. If the CCUS industry globally grows into a multi-billion DKK/yr. sector, it's crucial for Denmark to play a pivotal role.

2.1.2 Societal Challenge

Geological storage of CO2 poses corrosive conditions, where supercritical CO2 and formation water mix at up to 300 Bar and 100°C, leading to potential severe corrosion without the right steel and cement. Ensuring safe and long-term CO2 storage requires testing well materials under relevant subsurface conditions specific to each site.

2.1.3 Scope and Technology Development

Project COLLATE aimed to develop a testing facility for corrosion testing of materials from wells, metal, and cement under expected subsurface conditions in future CO2 storage sites. In collaboration between GEUS, DTU, and IKM OT, the project optimized material selection for CO2 storage sites, enhancing the quantity and configuration of corrosion tests for informed decision-making.

2.1.4 Innovation

The project was innovative in developing physical equipment and conducting experiments to test experimental procedures, benchmark the performance of IKM OT's reactors, and validate the results. This included outlining test protocols and gaining new insights into cement reactivity and corrosion of different materials.

2.1.5 Results, Conclusions, and Perspective

Important Results:

- Conducted approximately 100 experiments with eight cement types, both historical and state-of-theart.
- Developed a reactive transport model to describe the degradation of Portland cement over time.
- Found that most cement types showed slow degradation, with one type forming cracks.
- Long-term simulations indicated that the cements are highly durable, with lifetimes in wells predicted to exceed 100 years.
- Investigated corrosion behavior in various grades of steel used in CCS infrastructure.
- Found that low alloy steels (L80-1Cr) suffered severe corrosion under all conditions, while high-grade alloys were mostly immune.

Future Use:

- The results will inform material selection and testing protocols for future CO2 storage sites.
- Enhanced understanding of corrosion and cement reactivity will improve the safety and longevity of CCS infrastructure.

Expected Effects:

- Improved safety and efficiency of CO2 storage.
- Contribution to the development of a robust CCUS industry in Denmark.
- Long-term reduction in CO2 emissions through reliable CCS technology.

Projektresumé:

2.1.6 Projektsammendrag

Projekt COLLATE (CO2 Liquid LAboratory TEsting) fokuserede på at fremme kulstoffangst og -lagring (CCS), en vigtig teknologi til reduktion af CO2-udledning. Hvis CCUS-industrien globalt vokser til en sektor med flere milliarder DKK/år, er det afgørende, at Danmark spiller en central rolle.

2.1.7 Samfundsudfordring

Geologisk lagring af CO2 medfører korrosive forhold, hvor superkritisk CO2 og formationsvand blandes ved op til 300 bar og 100°C, hvilket kan føre til alvorlig korrosion uden det rette stål og cement. For at sikre sikker og langsigtet CO2-lagring kræves test af brøndmaterialer under relevante underjordiske forhold specifikke for hvert sted.

2.1.8 Omfang og Teknologiudvikling

Projekt COLLATE havde til formål at udvikle et testanlæg til korrosionstest af materialer fra brønde, metal og cement under forventede underjordiske forhold i fremtidige CO2-lagringssteder. I samarbejde mellem GEUS, DTU og IKM OT optimerede projektet materialevalg til CO2-lagringssteder, hvilket forbedrede mængden og konfigurationen af korrosionstest for at træffe informerede beslutninger.

2.1.9 Innovation

Projektet var innovativt ved at udvikle fysisk udstyr og udføre eksperimenter for at teste eksperimentelle procedurer, benchmarke ydeevnen af IKM OT's reaktorer og validere resultaterne. Dette omfattede udarbejdelse af testprotokoller og opnåelse af nye indsigter i cementreaktivitet og korrosion af forskellige materialer.

2.1.10 Resultater, Konklusioner og Perspektiv **Vigtige Resultater:**

- Udførte cirka 100 eksperimenter med otte cementtyper, både historiske og moderne.
- Udviklede en reaktiv transportmodel til at beskrive nedbrydningen af Portland cement over tid.
- Fandt, at de fleste cementtyper viste langsom nedbrydning, med én type, der dannede revner.
- Langtidssimuleringer indikerede, at cementerne er meget holdbare, med levetider i brønde forudsagt til at overstige 100 år.
- Undersøgte korrosionsadfærd i forskellige stålkvaliteter brugt i CCS-infrastruktur.
- Fandt, at lavlegerede stål (L80-1Cr) led alvorlig korrosion under alle forhold, mens højlegerede stål var stort set immune.

Fremtidig Brug:

- Resultaterne vil informere materialevalg og testprotokoller for fremtidige CO2-lagringssteder.
- Forbedret forståelse af korrosion og cementreaktivitet vil forbedre sikkerheden og levetiden af CCSinfrastruktur.

Forventede Effekter:

- Forbedret sikkerhed og effektivitet af CO2-lagring.
- Bidrag til udviklingen af en robust CCUS-industri i Danmark.
- Langsigtet reduktion af CO2-udledning gennem pålidelig CCS-teknologi.

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3. Project objectives

3.1 Objective of the project?

The primary objective of the COLLATE project is to advance the development of reactors capable of conducting cost-efficient tests to assess the durability of materials. This initiative is essential to enable the selection of materials that guarantee the long-term safety of Carbon Capture and Storage (CCS). Specifically, the focus is on testing materials like cement and metals within relatively short time frames. However, the significance of these tests lies in their ability to serve as a basis for accurately projecting the durability of materials to match the required lifetime of cement and metals for a storage site. The urgency of this research is evident in its critical need.

In pursuit of this overarching objective, the project outlines several key goals. First and foremost is the imperative to promote project progress and disseminate results effectively. This involves leveraging digital platforms, publications, and presentations through established scientific and industrial channels. The aim is to ensure that the outcomes of the research reach relevant stakeholders and contribute to the broader scientific and industrial discourse.

Moreover, the project seeks to establish and execute exploitation and implementation strategies. This includes coordination of actions and the provision of leadership to steer the project in the right direction. Timely delivery of work packages is emphasized to maintain efficiency and meet project milestones.

A crucial aspect of the project is the monitoring and mitigation of potential risks. This proactive approach is vital to address challenges as they arise and ensure the smooth progression of the research.

Beyond these technical objectives, the COLLATE project has broader aims related to business development. It aims to expand the business area for Danish SMEs participating in the project. This expansion is envisioned through strengthened collaborative relationships between SMEs, universities, state institutes, and major industry operators. Additionally, the project seeks to contribute to the Danish CO_2 reduction goal by developing equipment with market potential within the emerging Carbon Capture, Utilization, and Storage (CCUS) industry. This not only enhances the future export potential for Danish SMEs but also aligns with national environmental sustainability objectives.

3.2 Developed and Demonstrated Energy Technology

Carbon Capture and Storage (CCS) is a technology designed to mitigate climate change by capturing carbon dioxide (CO_2) emissions produced from the use of fossil fuels in electricity generation and industrial processes. The captured CO_2 is then transported and securely stored underground to prevent its release into the atmosphere.

In Denmark, the members of parliament have recently reached an agreement to implement CO_2 capturing and storage on a significant scale. This decision is a strategic response to the pressing need to reduce national CO_2 emissions and combat climate change. By embracing CCS technology, Denmark aims to address the environmental impact of industrial activities and power generation that contribute to the country's carbon footprint.

The parliamentary agreement underscores Denmark's commitment to adopting innovative solutions for sustainable development. Scaling up CO_2 capturing and storage reflects a proactive approach to meeting climate targets and aligning with international efforts to limit global warming. The decision also positions Denmark as a leader in green technology and underscores the government's dedication to reducing the nation's carbon emissions in a meaningful and impactful manner.

4. Project implementation

4.1 Project evolution

Generally, the project has been running as planned with some ongoing alteration along the way. There have been 5 official changes request that all have been approved by EUDP.

4.2 Risk management

Risk	Probability (1 = smallest, 5 = largest)	Impact (1 = smallest, 5 = largest)	Consequence Prob x Impact	Preventive measures (more description in application)
CCS not being implemented as outlined in the Danish Climate Program	1	5	6	Communicate actively about the possible cost reduction by Project COL-LATE
CCS being implemented in a slower pace than outlined	3	2	6	Communicate actively about the possible cost reduction by Project COL-LATE
Project COLLATE cannot realize the desired test capabilities	2	5	10	Ensure that the collaboration between key stakeholders in the project are working as efficiently together during the project as practically possible to increase the chance of success significantly.
Project COLLATE cannot produce a technical setup which can be qualified/verified to deliver commercial	1	5	5	Ensure strong relations between the Operational work and commercial deployment plan of Project COLLATE
Project COLLATE screening capabilities not recognized in the CO_2 Stor-age industry	3	2	6	Actively communicate to different stakeholders in the CCUS value chain about the necessity of the work performed by Project COLLATE
The chamber is leaking, and the test must be interrupted	1	3	3	To ensure that the chamber is tight, NDT (Non-Destructive Testing) and pressure/leak test will be performed
It is not possible to create the same conditions in the test chamber as found in the CO2 storage facility of depleted oil- and gas fields.	1	5	5	Ensure the right operational conditions, requirements, and basis by involving all stakeholders from the beginning in phase 0.

The test chamber becomes too expensive to develop and operate compared to existing solutions in the mar- ket	3	4	12	Make numerous optimizations and tests in Project COLLATE to find the right balance between precision and cost
Test chamber is not functioning	1	5	5	The technology has been tested in a prototype test chamber and no such challenges have emerged.
Getting materials for testing	1	3	3	Ensure that all long lead items are identified already in phase 0, and the procurements are initiated
CO2 Plant is not able to provide the necessary conditions: Temperature, Pressure etc.	1	5	5	The CO2 plant proposed for Project COLLATE was tested in the Feasibility Project

4.3 Project Implementation: Adherence to Plan and Milestones

Yes, the project generally adhered to the envisioned implementation and agreed-upon milestones. However, adaptations were made along the way, necessitating some milestone adjustments to align with evolving requirements or unforeseen challenges.

4.4 Ever changing world

The project encountered unexpected challenges arising from various external factors. The ongoing COVID-19 pandemic disrupted global supply chains, impacting the timely delivery of both basic components and specialized products essenjtial to the project. Additionally, the Suez Canal blockade further prolonged lead times, exacerbating logistical difficulties.

The material selection process proved challenging due to manufacturers' inherent biases and unwarranted confidence in their products. This subjective approach hindered an objective assessment of materials for the project. Furthermore, the manufacturers' limited understanding of the impact from CO2 regarding material compatibility, added complexity to the decision-making process.

The project managers had to navigate uncertainties stemming from these external factors, demonstrating the project's vulnerability to unforeseen global events.

5. Project results

5.1 Scientific and technological results

The COLLATE project's experimental phase focused on the chemical alteration of eight types of cement, including typical Portland cements, in the context of CO2 storage in legacy oil and gas wells. The study aimed to understand how cement, commonly used in these wells, evolves over time when exposed to supercritical

CO_2. The project considered the potential impact on long-term storage safety and aimed to provide a baseline for benchmarking future experiments.

The methodology involved producing cement plugs based on the formulation for a real legacy well or prepared in a manner that made them ready to use in wells, following API Recommended Practices and Specifications. These plugs were then cured at reservoir pressure and temperature before aging in synthetic brines. Subsequent experiments involved exposing the plugs to CO_2 at high pressure and temperature for up to one year, simulating conditions relevant to CO_2 storage.

Various characterization techniques, including X-ray computerized tomography and scanning electron microscopy, were employed to analyze the plugs at different stages. Notably, many of the aged cement exhibited reduced porosity and altered diffusion rates, slowing CO_2 penetration.

The study found that after prolonged experimentation, CO_2-induced reactions affected the cement to a depth of 1-3 mm from the surface for typical cement. This alteration manifested as two layers: an outer layer with low porosity rich in calcium carbonate and an inner layer with higher porosity where calcium-bearing oxides and hydroxides had dissolved. For other cement types, the penetration was deeper, but with little impact on the cement composition and structure.

Contrary to some reported experiments, significant macroscopic fracturing of the cement was not observed for the historically used portland cement. However, microfractures were identified in the portland cement, particularly in samples exposed solely to the supercritical CO_2 phase. The presence of water seemed to inhibit deep penetration of CO_2 into microfracture networks.

In summary, the COLLATE project's experiments indicated slow alteration of both the historically used portland cement and new, state-of-the-art cementtypes in conditions simulating CO_2 storage. Major fracturing did not occur for most types, and the results are poised to serve as a benchmark for comparing future experiments conducted by IKM OT.

DTU:

The study focused on the investigation of corrosion behavior in various grades of steel (materials with varying chromium contents:1%, 13%, 25%, 29%, and 32%) used in CCS infrastructure. To achieve this, corrosion tests were conducted in two different environments: impure dense phase supercritical CO_2 and aqueous CO_2-saturated brine with impurities. The steels were exposed to CO_2 streams mixed with varying concentrations of oxygen, nitrogen dioxide, and sulfur dioxide. The study employed conventional electrochemical techniques such as DC polarization and AC impedance spectroscopy for monitoring corrosion. Additionally, the nature and composition of corrosion products were analyzed using Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD), respectively. The research further utilized X-ray (micro-) computed tomography (CT) to examine the surface morphology beneath the corrosion scale and to obtain a 3D visualization of the scale structure.

Analysis of the short-term experiments revealed that low-grade steels exhibited higher corrosion rates than high-grade steels, with the presence of HNO_3 endorsing the corrosion rates. Quantitative analysis indicated that corrosion in low-grade steels worsened with increasing temperature, while high-grade steels displayed a stable passive layer. The presence of SO_2 led to an enhanced corrosion rate compared to NO_x concentration under same condition as shown in the Figure.

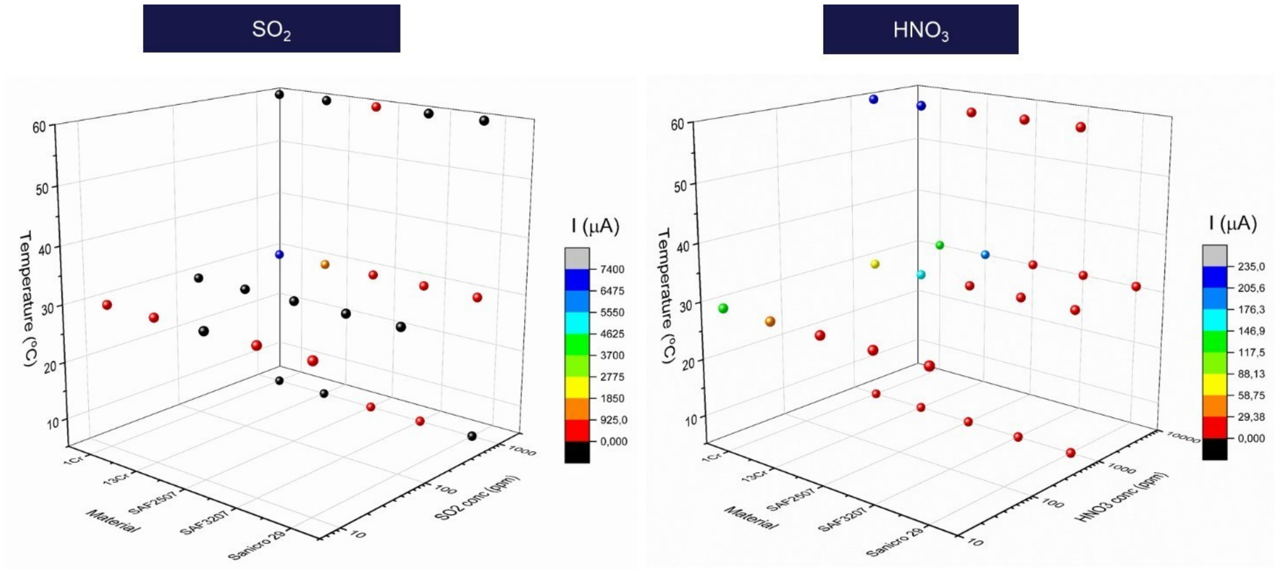

Figure-1: Impact of impurity concentration and temperature on the corrosion current for different materials. Higher corrosion currents corresponds to higher corrosion rate.

Long-term experiments were conducted to assess material performance over extended exposure times. EIS and LPR measurements were performed, and subsequent characterization of the samples included LEXT, SEM, EDS, and XRD analyses. The results confirmed the rapid corrosion rates observed in the short-term analysis for low-grade steels. The morphology and protective nature of the corrosion products varied with temperature and time. High-grade steels exhibited minimal corrosion and consistently low corrosion rates below 15 µm/y.

Additionally, SECM was employed to investigate localized corrosion phenomena. The findings indicated uniform corrosion for 1Cr samples, while 13Cr showed preferential corrosion sites, potentially due to pitting. SAF3207 and Sanicro 29 showed negligible corrosion, even at a localized scale.

Further, the experimental work conducted with supercritical CO2 with varying impurity content also pointed out similar corrosion behaviour as shown in the following table. Autoclaves designed at IKM-OTS (as shown in Fig.2a) were employed to inject CO2 at 200 bar pressure with varying impurity types and content. The results clearly showed under non-aggressive conditions, low alloy steel showed corrosion while other alloys were immune to corrosion as shown in Fig. 2b. On the other hand, as the aggresivity of the captured CO2 stream increased with higher impurity content, even L80-13Cr stainless steel corroded heavily and and pitting corrosion was observed. However, high alloyed steel were still immune from corrosion under those conditions.

Supercritical CO2 with 2000 ppm H_2O

Sample	Initial	Final	Weight change
L80-1Cr	4,1081	4,1075	0,0006
L80-13Cr	5,3483	5,3483	0
SAF 3207	5,2445	5,2444	0,0001
Sanicro 29	4,753	4,7531	-1E-04

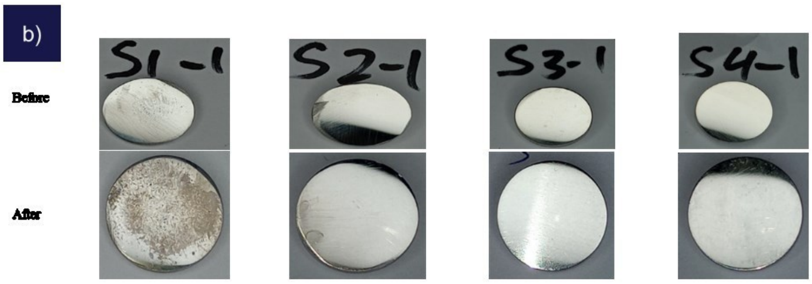

Figure 2: Exposure studies of different materials under impure CO2 conditions using a) Autoclaves at IKMOTS b) subsequent surface analysis of different materials before and after exposure to CO2 with 2000 ppm of water at 200 bar pressure.

Further, the test rig developed as a part of this project was employed to simulate insitu corrosion of different materials under varying levels of CO2 injection as shown in Fig.3. The Aqeous phase and Thinfilm phase corrosion studies were also measured electrochemically in the benchmarking test where the setup showed good calibration and similar behaviour from the lab scale results.

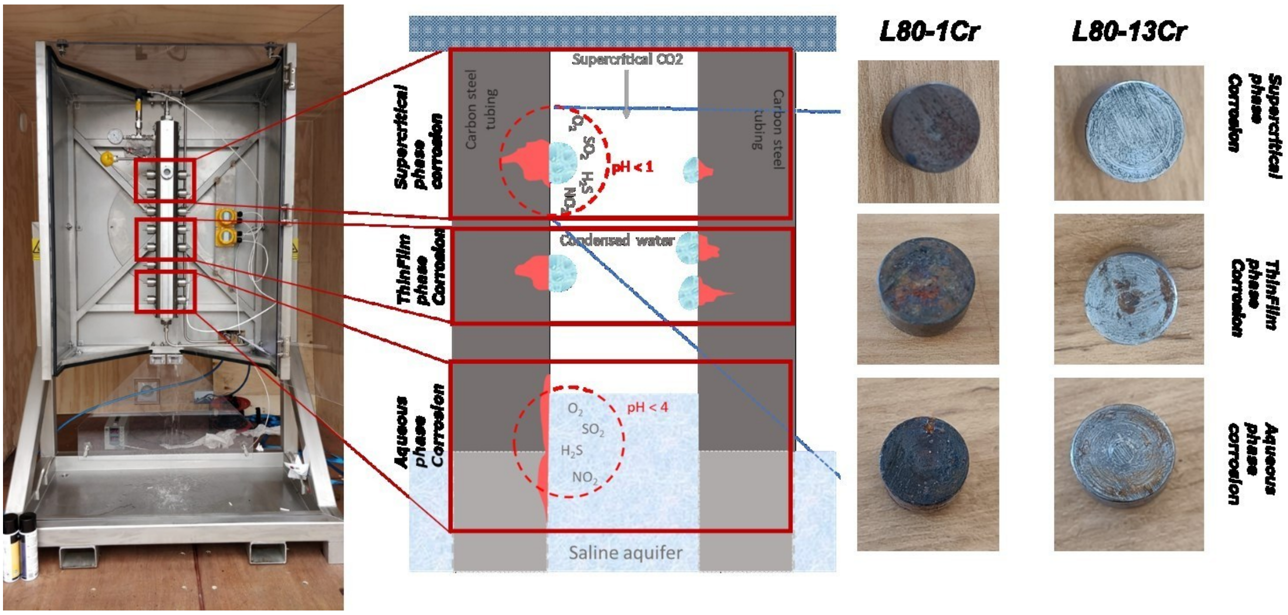

Figure 3: Benchmarking test of the reactor developed as a part of COLLATE project and ideology to use different sections of reactor to simulate different zones of corrosion in the CCS injection pipeline.

5.2 Commercial results

IKM OT, in collaboration with other project partners, has successfully developed two innovative reactors as part of the project. The first is an electrochemical reactor designed for testing metals and conducting real-time corrosion analysis in environments characterized by high pressure and high temperature. This state-of-the-art equipment represents a significant advancement, providing unprecedented accuracy and generating highvalue data. The enhanced precision allows for data-driven decision-making when selecting materials for Carbon Capture, Utilization, and Storage (CCUS) equipment, contributing to the optimization of material choices for enhanced performance and longevity.

The second reactor developed within the project serves a dual purpose. It can function as an autoclave, providing a controlled environment for exposure tests, and it is also adaptable for flow-through tests involving various materials and test conditions. This reactor's versatility makes it a valuable tool for evaluating the performance and durability of materials under different scenarios, further enhancing the project's capability to assess and select materials for CCUS applications.

Both reactors contribute to the project's overall goal of advancing the understanding of material behavior in CCUS environments. The electrochemical reactor specifically offers real-time insights into corrosion processes, while the exposure test reactor provides a flexible platform for assessing materials in diverse conditions. These developments mark significant progress in the field, offering the potential for more informed decision-making in the selection of materials for CCUS equipment.

The facility, in conjunction with IKM OT's flow loops and advanced gas dosing and analysis capabilities, has successfully recreated realistic operational conditions across the Carbon Capture, Utilization, and Storage (CCUS) value chain. This includes dynamic and static scenarios, incorporating customized variations in chemical composition, temperature, pressure, and flow. The comprehensive capabilities of the facility enable precise replication of the diverse conditions encountered in CCUS processes.

Key components of the facility include advanced 3D printed holders, accommodating specimens ranging from small coupons and plugs to actual valves or other process equipment. This versatility allows for a wide range of materials and components to be tested, contributing significantly to understanding chemical reactions, determining corrosion rates, and generating valuable data for selecting appropriate sealing materials. The inclusion of actual valves and process equipment enhances the facility's applicability to real-world scenarios, providing insights into the performance of materials under conditions closely resembling practical CCUS operations.

In essence, the facility's integration of flow loops, gas dosing, and advanced 3D printed holders establishes a sophisticated testing environment. This enables researchers to explore and analyze the behavior of materials across different facets of the CCUS value chain, facilitating informed decision-making and optimization of materials for enhanced performance and reliability in CCUS applications.

5.3 Target group and added value for users

The primary target groups for the solutions and technologies developed through Project COLLATE are:

1) CO2 Transport and Storage Stakeholders:

Suppliers to wells for CO2 storage, including drilling companies and material providers, stand to benefit significantly. The project outcomes directly impact their operations and contribute to the optimization of material choices for CO2 storage.

2) Utility Companies and Industries:

Large utility companies and industries involved in capturing CO2 are key beneficiaries. The technologies and solutions developed by COLLATE enhance their ability to make informed decisions regarding material selection for Carbon Capture and Storage (CCS), ultimately contributing to the efficiency and effectiveness of their CO2 capture initiatives.

3) Climate:

While not a direct target group, the ultimate beneficiary of the project is the climate. By improving the understanding of material behavior in CO2 storage environments, COLLATE contributes to the broader goal of mitigating climate change through effective and secure CCS practices.

4) Scientific Community:

For scientific publications, the target audience is a broader community with an interest in long-term material durability in the subsurface. This includes stakeholders involved in CCS, geothermal operations, and radioactive waste disposal. Disseminating findings to this community ensures knowledge exchange and contributes to advancements in related fields.

5) Major Operators and Industry Developers in CCUS:

The main target group comprises major operators and industry developers shifting their focus toward Carbon Capture, Utilization, and Storage (CCUS). As the market evolves, these entities will play a pivotal role, and the COLLATE project provides valuable tools and insights for their operations.

6) Sub-Suppliers and Related Services:

There is a market share for sub-suppliers and various related services in the evolving landscape of CCUS. Companies providing complementary services and materials can find opportunities in supporting the needs of major operators and industry developers.

7) Research and Development (R&D) Institutes:

R&D institutes engaged in projects related to the CCUS industry represent another target group. These institutes may require the facilities and competencies developed in the COLLATE project to advance their own research initiatives.

By targeting these diverse groups, Project COLLATE aims to maximize the impact of its outcomes across the entire CCUS value chain and contribute to the broader scientific and industrial community involved in sustainable energy and environmental practices.

8) Dissemination

The results of Project COLLATE have been widely disseminated through various platforms and media to reach both technical and non-technical audiences.

LinkedIn:

- COLLATE ECD Website
- LinkedIn: Multiple posts, including "Fremtidens materialer til CO2-lagring testes i Danmark" and "INNOVATIONSPROJEKT: CO2-LAGRING UDFORDRES AF KORROSION"
- Project Description and Final Video: The COLLATE project description and a concluding film has been taped and will be shared in Q1 2025, summarizing the project's scope, innovations, and results.

Media Coverage:

- Press Releases: Articles in CleanTechWatch and EnergiWatch highlighted the testing of new materials for CO2 storage by an Esbjerg-based company.

- IT-Kanalen.dk: Featured an article on the new opportunities for IKM Ocean Team based on their CO2 competencies.

Innovation Series:

- Få hjælp til innovation: This series included episodes like "IKM Ocean Team" and "Intro til serien," which discussed the project's contributions and the involvement of IKM Ocean Team in the energy cluster.

Interviews and Stories:

- Result Story: A comprehensive result story was shared, detailing the project's achievements and future implications.
- Interviews: Interviews with IKM Ocean Team members provided personal insights into their engagement and contributions to the project.

Conferences and Journals:

Furthermore, three manuscripts are in preparation at GEUS. The first and third manuscripts are intended for submission to Cement and Concrete Research, and the second, International Journal of Greenhouse Gas Control. In addition, we presented results at the TOUGH Symposium 2023 at Berkeley, California.

Two manuscripts are in preparation for the work performed on corrosion behaviour of different materials under varying CCS conditions at DTU. Both are intended to for submission in high quality corrosion journals. Two master students worked on the project as well for their MSc thesis and the thesis (Understanding corrosion behavior of low alloyed and high alloyed steel materials for CO2 storage application) was submitted at DTU. Further, the results were presented in international journals like EUROCORR, AMPP and the work was appreciated by peers of the field.

Furthermore, DTU have participated in three conferences:

- “Determining CO2 corrosion behavior as well as the mode of corrosion in various steel for CCS applications” – Eurocorr 2023 (Oral Presentation)
- “Spectro-electrochemical analysis of droplet corrosion for Carbon Capture and Storage (CCS) Applications” – AMPP 2024 (Oral Presentation)
- “Corrosion challenges in CO2 capture and storage applications under the influence of impurities” – IIM, India 2023 (Oral Presentation)

6. Utilisation of project results

6.1 Technological Results Utilization

The obtained technological results, including the advanced 3D printed holders and innovative reactors developed by IKM OT, will be utilized in the future by stakeholders across the Carbon Capture and Storage (CCS) value chain. Suppliers to wells for CO2 storage, such as drilling companies and material providers, will incorporate the findings to optimize material choices for enhanced durability and safety in CO2 storage. Utility companies and industries involved in CO2 capture will leverage the technological results to inform their decisions on material selection, contributing to more efficient and effective CCS initiatives. Major operators and industry developers in the CCUS sector will integrate the technological insights into their operations as they shift focus towards sustainable practices. Additionally, research and development (R&D) institutes working on CCUSrelated projects will utilize the obtained technological results, ensuring a collective progression in the field.

6.2 Commercial Results Utilization and Commercialization

The obtained commercial results, coupled with IKM OT's initiative to commercialize the test facility, will be utilized in the future by various entities involved in the CCUS industry. Suppliers providing materials and services for CO2 storage wells will commercialize the results by offering optimized solutions based on the commercial findings. Major operators and industry developers in CCUS will integrate the commercial results into their business strategies, potentially leading to the development of new products or services. Sub-suppliers and related service providers in the evolving CCUS market will find opportunities to commercialize complementary offerings aligned with the obtained results.

6.3 Project Impact: Anticipated Growth

As of now, the project has positively impacted IKM OT, resulting in increased attention from both existing and potential customers due to the new test facilities. IKM OT has received invitations to participate in new development projects, indicating a heightened interest in their capabilities and services.

IKM OT anticipates an increase in turnover as a direct outcome of the project's success, signaling a positive trajectory for the company. In response to this anticipated growth, IKM OT foresees the need for additional employment. Recognizing the value and potential of the material testing business, the company has strategically incorporated it into its overall corporate structure. This integration suggests a proactive approach by IKM OT to leverage the success of the project and align its business operations to accommodate and capitalize on the expanded opportunities in the material testing sector.

6.4 Market

The CCUS industry is currently in its early stages, and its future evolution will largely depend on strategic political decisions aimed at advancing both the method and technology. As the CCUS market and technology mature, ancillary markets are anticipated to emerge, particularly in the form of a sub-supplier market. This growth in the new market is expected to be driven by the overall expansion of the CCUS industry.

Presently, the CCUS industry is at the second stage of its evolutionary development, relying heavily on public funding for feasibility studies and infrastructure development. As the market progresses beyond the feasibility stage, a sub-supplier market is expected to follow suit, mirroring the trend observed in numerous emerging markets across various industries over the years.

Considering the estimated market size, with the potential to exceed +1000 billion DKK in yearly turnover in the EU/UK region alone, the sub-supplier category holds significant potential. The emergence of a robust subsupplier market is poised to complement the maturation of the CCUS industry, providing ample opportunities for growth and investment.

6.5 One off

In the targeted market segment, several competitors are currently operating large and rigid test facilities, emphasizing their capacity for comprehensive testing. In contrast, IKM OT has strategically directed its efforts toward the development of small-scale flow loops, introducing a distinctive approach to material testing.

This strategic focus on smaller-scale testing solutions provides IKM OT with a competitive advantage, primarily centered around cost-effectiveness and agility. While some competitors in the industry maintain extensive and sizable facilities, IKM OT's emphasis on smaller-scale flow loops offers a more flexible and affordable alternative for clients seeking efficient testing methodologies.

The prevailing trend in the market leans towards traditional, larger-scale facilities, which are perceived as comprehensive but can be associated with higher costs and potentially longer lead times. In recognizing this, IKM OT positions itself uniquely by catering to the growing demand for more streamlined and adaptable testing solutions.

The significance of this strategic choice becomes evident when considering the market's evolving needs and preferences. The ability to conduct testing in smaller-scale environments allows for quicker adaptations to emerging industry trends and customer requirements. Additionally, it offers a more accessible entry point for clients looking for testing solutions that are both cost-effective and responsive to their specific needs.

6.6 realising energy policy objectives

The project results contribute to realizing energy policy objectives by enhancing the understanding and capabilities within the Carbon Capture, Utilization, and Storage (CCUS) sector. The development of advanced testing facilities, small-scale flow loops, and innovative reactors facilitates more efficient and reliable material testing. This, in turn, supports the overall goal of advancing CCUS technologies, aligning with energy policy objectives in several ways:

1) Environmental Sustainability:

By enabling more accurate and agile testing, the project results contribute to the development of environmentally sustainable practices within the CCUS industry. This aligns with energy policies focused on reducing carbon emissions and promoting cleaner energy solutions.

2) Technological Advancement:

The project's technological results signify advancements in material testing methodologies. This technological progress supports energy policies aimed at fostering innovation and the adoption of cutting-edge technologies to address climate challenges.

3) Market Development:

The development of small-scale flow loops and innovative reactors addresses market needs for more costeffective and adaptable testing solutions. This aligns with energy policies seeking to stimulate the growth of emerging markets and industries, such as CCUS.

4) Economic Growth:

As the project results contribute to the maturation of the CCUS market, there is potential for economic growth. This aligns with broader energy policy objectives related to economic development and job creation within the sustainable energy sector.

5) Global Competitiveness:

The project's focus on differentiation through small-scale and agile testing positions stakeholders for enhanced global competitiveness. This aligns with energy policies emphasizing the importance of maintaining a competitive edge in the international market for clean energy technologies.

6) Carbon Capture and Storage Adoption:

The project's outcomes directly impact the feasibility and infrastructure development stages of CCUS, contributing to the broader adoption of carbon capture and storage technologies. This aligns with energy policy objectives centered on transitioning to low-carbon energy systems.

In summary, the project results play a crucial role in realizing energy policy objectives by promoting environmental sustainability, technological advancement, market development, economic growth, global competitiveness, and the adoption of carbon capture and storage technologies within the CCUS sector.

7. Project conclusion and perspective

7.1 Keeping momentum

The next steps for the developed technology involve a strategic progression towards practical implementation and broader industry integration. Key actions include:

1) Collaboration and Partnerships:

Explore collaboration opportunities and establish partnerships with industry stakeholders, research institutions, and potential end-users. Engaging in collaborative efforts enhances the technology's visibility, facilitates knowledge exchange, and broadens the scope of application.

2) Regulatory Compliance and Standards:

Address regulatory compliance requirements and adhere to industry standards. Ensuring that the developed technology aligns with regulatory frameworks and recognized standards is essential for its acceptance and widespread adoption within the industry.

3) Scale-Up and Commercialization:

Develop a plan for scaling up the technology to meet commercial demands. This involves refining manufacturing processes, optimizing cost-efficiency, and preparing for large-scale deployment. Explore opportunities for commercialization, potentially through licensing or partnerships with industry players.

4) Market Penetration Strategy:

Develop a comprehensive market penetration strategy to introduce the technology to a broader audience. This may include targeted marketing, participation in industry events, and engagement with potential clients to showcase the technology's unique features and benefits.

5) Continuous Improvement and Innovation:

Establish a framework for continuous improvement and innovation. Monitor the technology's performance in the field, gather feedback from users, and incorporate enhancements to address evolving industry needs. Stay abreast of technological advancements to ensure the technology remains competitive and relevant.

By strategically navigating these next steps, the developed technology can transition from a conceptual phase to practical application, contributing to the advancement of the industry it serves.