ENSURE final report

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1. Identification of the project and report

Project title	Effective monitoring of long-term site stability for transparent carbon capture and storage hazard assessment (ENSURE)
Project ID	327317
Coordinator	NORSAR
Project website	https://ensure.norsar.no/
Reporting date	31.01.2025

Participants

Organisation	Main contact(s) + E-mail	Role in the project
NORSAR	Bettina Goertz-Allmann, bettina@norsar.no	Project coordinator, coordinate work conducted by NORSAR, active WP1,2,3
	Daniela Kuehn, daniela@norsar.no	WP2 lead, active WP1,2,3
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TotalEnergies One Tech	Estelle Rebel, estelle.rebel@totalenergies.com	National coordination, coordinate work conducted by TotalEnergies, task 1.2 lead, active WP1,2
Shell Global Solutions International B.V.	Steve Oates, steve.oates@shell.com	WP1 lead, active WP1,2,3
Shell Canada Energy	Carrie Rowe, carrie.rowe@shell.com	Coordinate work conducted by Shell Canada, active WP1
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INGV	Thomas Braun, thomas.braun@ingv.it	Coordinate work conducted by INGV, task 2.3 lead, active WP2
Battelle Memorial Institute (MRCI partner)	Neeraj Gupta, gupta@battelle.org	National coordination, coordinate work conducted by Battelle and ISGS, active WP1,3
	Mark Kelley, kelleym@battelle.org	Provide micro-seismic data from a CO_2 injection project conducted by Battelle under the U.S.

		Department of Energy Midwest Regional Carbon Initiative.

2. Executive summary

This project focused on advancing microseismic monitoring technology for Carbon Capture and Storage (CCS), with the goal of improving data integration, processing methods, and public engagement strategies. Through collaboration with industry leaders and academic institutions, the project addressed significant challenges in CCS monitoring, validation, and public perception. We developed solutions that contribute to more efficient, cost-effective, and transparent CCS implementation.

Some key achievements of the project include:

- The project demonstrated the **usability of hybrid monitoring networks** that integrate Distributed Acoustic Sensing (DAS) with surface and downhole geophones. These hybrid systems significantly improve detection and location accuracy while offering a more cost-effective solution for large-scale CCS monitoring. These findings were further corroborated by modelling. To this end, our results contribute to reducing the cost of monitoring while ensuring the reliability and accuracy needed to maintain storage integrity.

- The project **advanced data processing techniques** to enhance the detection and location of microseismic events. Methods such as spectral detectors and template matching, combined with machine learning (ML) algorithms, and double-difference event relocation were employed to optimize event detection in real time. These monitoring system advancements lead to more accurately tracking potential risks at CCS sites and provide timely data for safety assurances.

- The application of **array processing techniques** such as beamforming further enhanced the performance of monitoring systems. By improving signal-to-noise ratios, these methods allow for more precise event detection, even in challenging noise environments, ultimately boosting the overall efficiency and reliability of the monitoring networks.

- A crucial aspect of the project was **understanding public perceptions of CCS**, particularly regarding concerns about induced seismicity. A large-scale survey conducted across several countries revealed valuable insights into how public trust in CCS technologies can be improved. Transparent communication and clear risk mitigation strategies emerged as key factors in fostering public acceptance of CCS projects. It demonstrated the importance of engagement with local communities and stakeholders.

Throughout the project, industry partners such as Shell, TotalEnergies, and BP played a central role in ensuring that the research outcomes were practically applicable and aligned with real-world challenges. The collaboration facilitated knowledge-sharing and contributed to the development of monitoring recommendations that can be directly implemented in ongoing and future CCS projects.

In conclusion, this project has made significant contributions to both the **technological** and **social** advancement of CCS. By testing advanced but cost-effective monitoring systems, improving data accuracy, and addressing public concerns, the project has provided valuable tools and strategies that support the widespread deployment of CCS as a critical technology for mitigating climate change.

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3. Role and contributions of each project partners

Each partner contributed to delivering key elements of the project, defined by theme within three Work Packages (WP1 – WP3), which were each sub-divided into tasks (e.g. 1.1, 1.2, etc…) and deliverables (further described in section 4).

NORSAR was the project coordinator, national coordinator for Norway and WP2 lead. NORSAR was actively involved in all three work packages. The research within WP1 was focused on data analysis and technology comparison with a special effort on processing development of DAS for microseismic analysis and array processing. They also provided partner access to the HNET data. In WP2, NORSAR contributed to all three tasks with modelled event detection thresholds and location uncertainties, and input magnitude and location uncertainties for the development of traffic light systems and advanced source parameter analysis with relative event relocation. Furthermore, in WP3 NORSAR supported the development of the public perception survey and contributed to discussions and dissemination, taking the lead in organizing a public perception and communication workshop.

The **University of Alberta (UA)** was the national coordinator for Canada and actively involved in all three work packages. The focus in WP1 was data processing, examining both the data provided by Shell Canada Energy and TotalEnergies. WP2 extended the data analyses, using two independent event detection approaches, to demonstrate that event catalogs can be significantly expanded using more advanced algorithms than commonly used by vendors. The UA also investigated whether correlations exist between injection and event rates at the Quest site. Furthermore, UA led WP3 and was the main contributor responsible for developing the public perception survey and processing its results.

INGV was the main contributor responsible for task 2.3 and focused its efforts on the comparison of existing traffic light protocols.

Shell Global Solutions International B.V. (SGSI) was WP1 lead. They contributed with modelling efforts to WP2. They also served as discussion partners in WP3. Shell hosted one consortium meeting and the public perception and communications workshop.

Shell Canada Energy (SCE) focused their involvement on WP1. They provided partner access to the Quest CCS site data and served as discussion partner throughout the project.

Alcatel Submarine Networks Norway AS (ASN) were involved mainly in WP1. ASN supplied an OptoDAS interrogator and performed the field trial at the Quest CCS site, Canada. They delivered the acquired DAS data and provided insights regarding data processing and interpretation. Furthermore, ASN contributed to dissemination of field trial results.

TotalEnergies OneTech was the national coordinator for France and was actively involved in WP1. TotalEnergies also provided access to monitoring data from the Southern France site. Their research focused on the comparison of noise levels between instrumentations and different sites. They were responsible for task 1.2.

BP International Ltd contributed mainly to WP1 and WP2. BP generated synthetic data of a virtual offshore CCS site and provided this data for further analysis to the consortium.

Midwest Regional Carbon Initiative (MRCI) contributed to all three work packages as discussion partner. MRCI also provided monitoring data access to the Dover 33 and Decatur site.

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4. Short description of activities and final results

The project was structured into three key work packages (WP1 – WP3), each designed to address critical aspects of Carbon Capture and Storage (CCS) technology, focusing on monitoring, data processing, and public engagement.

WP1: Success factors for robust validation of seal integrity with cost-effective monitoring networks

contributors: SGSI (lead), NORSAR, UA, TotalEnergies, BP, MRCI, ASN, SCE

The objectives of WP1 were to demonstrate the suitability of DAS and surface node acquisition for CCS monitoring, further develop processing techniques for handling the resulting integrated datasets and determine the relative value of these various data types for CCS monitoring.

The approach taken was to gather and analyze a suite of datasets from new/ongoing field trials in the South of France, Norway (HNAR) and Alberta (Quest), existing data from the Decatur and Dover-33 projects, and synthetic data from a model study for the UK offshore. Event catalogues for these datasets were compiled and shared with the ENSURE partners for analysis.

The key deliverables in WP1 were the shared raw datasets and the report documenting the data analysis and comparison of the datasets (Table 1).

Table 1: WP1 deliverables

Task ID	Task	Deliverable	Type	Contributing partners
1	*Compilation of available data from all sites for advanced analysis*	D1.1 Recommendations for cost-effective, validation-optimized microseismic monitoring networks	Data deliverable (confidential)	NORSAR, SCE, SGSI, TotalEnergies, BP, MRCI
2	*Data analysis and comparison of the datasets*	D1.2 Comparison of different sensor technologies and network setups and noise levels, quantifying the acquisition footprints at different sites	Report: Baird et al., 2023 (confidential)	NORSAR, TotalEnergies

WP1 involved a comprehensive study of various data types for monitoring and detection, with a focus on evaluating the effectiveness of different methods for Carbon Capture and Storage (CCS) monitoring. A variety of data sources were integrated, including surface and in-well Distributed Acoustic Sensing (DAS), geophone, and seismometer data from CCS sites in Europe, Canada, and the United States. These data were processed, combined and compared in terms of how well to detect and locate microseismic events (Goertz-Allmann et al. 2024). This provided a unique opportunity to compare different processing methods and assess their suitability for cost-effective CCS monitoring (see Figure 1). To ensure accurate integration, a standardized analysis of the noise content (Power Spectral Density) of each data type was performed, enabling like-for-like comparisons.

One of the key achievements was the demonstration of hybrid monitoring networks. These networks, which combine complementary microseismic monitoring systems such as surface and downhole geophones with DAS, proved to provide more cost-effective coverage. They also enhanced detection and location performance, offering a more efficient monitoring solution for CCS applications.

Additionally, advanced data processing methods were developed and tested, significantly improving event detection and location accuracy. Techniques like template matching, machine learning (ML), and frequency domain detectors were employed to optimize performance, while double-differencing was used to refine event location methods (Goertz-Allmann et al. 2024).

The application of array acquisition and processing techniques further enhanced monitoring capabilities. Data were acquired using surface subarrays at the Quest site in Canada and the test site in Southern France. By applying array data processing methods, including beamforming, the signal-to-noise ratio (S/N) was improved, which in turn improved both detection and location performance.

Results from the Quest and southern France test sites showed significant advancements in DAS data acquisition for event detection capabilities. DAS is now capable of complementing or, with certain considerations, even being an alternative to conventional seismometers. The Quest dataset offered nearly co-located recordings from both downhole geophones and downhole DAS. A processing workflow was developed to rescale DAS data to match the response of geophones, allowing for a quantitative comparison of these two data types.

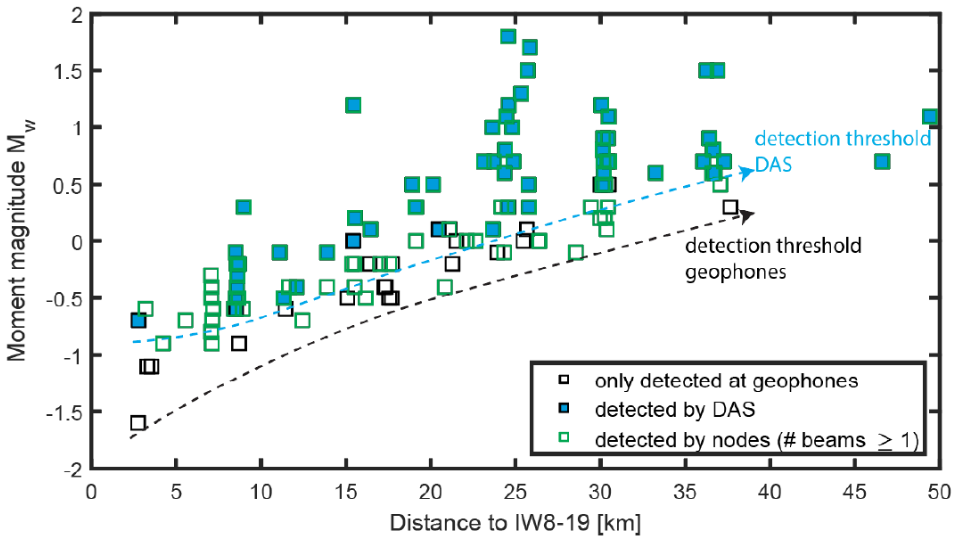

Figure 1 Comparison of event detections for downhole geophones, surface nodes and downhole DAS at Quest. The dashed lines indicate an approximate detection threshold.

WP2 – Advanced microseismic interpretation and comparison between sites

contributors: NORSAR (lead), U. of Alberta, TotalEnergies, SGSI, INGV, MRCI, BP

The main objective of WP2 was using the seismicity catalogues created in WP1 to evaluate differences in seismicity levels and statistics between the sites. The focus was on the detection and characterisation of differences due to tectonic settings, target depths, and variation in injection parameters. The overall goal was an accelerated and improved interpretation of microseismic data, suitable for real-time application, and for use in a traffic light system. This goal was partly reached through a set of three deliverables listed in WP2.

A main hinderance in the comparison between datasets of different sites was that seismicity at the French testbed occurs only at larger distances. The Quest dataset, however, was very rich and proved to be very valuable for a comparison of different network components. However, also at Quest, there is no relationship recognisable between injection parameters and seismicity properties, such that it could not be used as testbed for investigating the feasibility of traffic light protocols. Instead, we reviewed existing traffic light systems regarding their applicability to CO_2 storage sites.

Table 2: WP2 deliverables

Task ID	Task	Deliverable	Type	Contributing partners
1	*Model the influence of data acquisition geometry on event detectability, and uncertainties in location, magnitude and focal mechanism computation for the specific sites*	D2.1a Design recommendations for cost-effective, validation-optimized networks with minimal uncertainties for specific storage sites: modelling	Report (Kühn et al., 2024), confidential	NORSAR, SGSI
		D2.1b Recommendations for cost-effective, validation-optimized microseismic monitoring networks	Report (Kühn et al., 2024), public	NORSAR, SGSI, SCE
2	*Calculation of high-resolution relative event locations, source-, and statistical event parameters and separation of natural (background) from induced seismicity. Comparison to injection parameters.*	D2.2 Report on importance of source parameters for reservoir characterization	Report (Fadil et al., 2024), confidential	UA, NORSAR
3	*Correlation of the high-resolution seismicity with injection activity to investigate feasibility of traffic light protocols in the CCS context. Augment reservoir characterization with information from high-resolution seismicity catalogue*	D2.3 Review of existing Traffic Light Systems and their potential for application to CO_2 storages	Report (Braun et al., 2024), public	INGV, NORSAR

In this work package, we computed the acquisition footprints of individual and combined monitoring networks installed at Quest for event detection, location and source mechanism inversion and compared the results to the observations (D2.1a). We note that different types of monitoring systems can complement each other. On the one hand, we need monitoring systems which lower the detection threshold, increase spatial coverage and improve location precision. On the other hand, it is beneficial if at the same time the acquisition footprint is homogenised, since this will allow for a less biased spatial interpretation of observed seismicity. This aim can be reached by combining a network of surface stations with in-well geophones or DAS to extend the region of good detection and stabilize the event location performance away from the monitoring well. Surface networks should be installed with 3C sensors and the ability to apply array processing techniques to reduce effective noise levels

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and increase the robustness of the event location by using the back azimuth in addition to phase onsets. The presence of in-well geophones or surface arrays allows for the detection of significantly lower magnitude events, such that false negatives - vital for the monitoring of the caprock integrity - can be avoided. Especially automatic event triggering, which is one obligation of a robust, cost-efficient monitoring network, requires in many cases the installation of borehole geophones.

Subsequently, we presented monitoring recommendations which we derived mainly from technological advancements achieved within the project (D2.1b). These recommendations were developed from analysing and comparing microseismic data from different monitoring technologies but also from summarizing conclusions of expert discussion groups. Every monitoring network needs to provide robust observations in a cost-effective manner. As the purpose of monitoring differs between projects and subsurface geology is inherently site specific, the network design will likewise be site-specific. Hence, it is impossible to construct one general robust and fit-for purpose monitoring network. While we focus our conclusions on our results obtained from the Quest CCS site, Alberta, Canada, many of our recommendations are also more generally applicable.

Due to the mostly large distances between network and event locations at Quest as well as their small moment magnitudes, both the computation of focal mechanisms as well as the estimation of stress drops was unfeasible (D2.2). Instead, the focus was increased on event detection, extending the existing vendor catalogue by 70% to 200% using a spectral detector and template matching combined with machine learning, respectively. High-resolution relative event locations were achieved employing a modified double-difference method, which also incorporates back azimuth observations from borehole geophones, to yield tighter lineations of microseismic clusters. However, results depend on the availability of a large number of microseismic events, which highlights the need of lowering the event detection threshold by more advanced processing methods. Further, we investigated whether a direct correlation exists between injection rates and event rates, but no correlation was found within the area of review. A Davis-Frohlich test was employed to determine whether observed seismicity is most likely natural or induced. On balance, it indicates induced is more likely than natural, which is supported by the observation (which includes approximately 8 months of pre-injection baseline monitoring) that seismicity within the 10 km Area of Review (AOR) around Quest started approximately nine months after injection began, and has been occurring at a relatively consistent rate since.

Traffic light systems (TLS) are widely used for monitoring seismicity induced by human operations. In case of a seismic event inside a defined monitoring domain, the monitoring agency assigns a color (green/ yellow/amber/red) according to the threshold exceedance of seismic monitoring parameters. If a seismicity response scheme exists, the competent authority may reduce or suspend the operations based on a specific alert level. The choice of the monitoring parameters and thresholds depends on the type of anthropogenic activity, the operation site (remote/urban, on-/offshore) and on the country specific legislation/regulation. The most frequent applications are connected to the injection of incompressible fluids, such as geothermal systems or reinjection of wastewater resulting from the production of oil and gas, practiced for decades. In newer applications, such as carbon capture and storage (CCS), which consists of the one-way injection of compressible fluid into a (potentially) depleted reservoir, the experience level is lower, such that specific guidelines still must be developed. D2.3 summarizes common practices of existing traffic light systems, which may be useful for the future definition of a monitor scheme applied to CCS. Uncertainties in computation of the local magnitude (M_L) should be critically assessed as the use of various attenuation functions, input data and methodologies may lead to significant differences. In addition, if only few local records are available, radiation pattern and directivity effects will not average out in the estimation of M_L. Finally, errors in event location are propagated to the magnitude value. Computing a physics-based moment magnitude (M_w) offers an alternative that negates many of the issues associated with using M_L.

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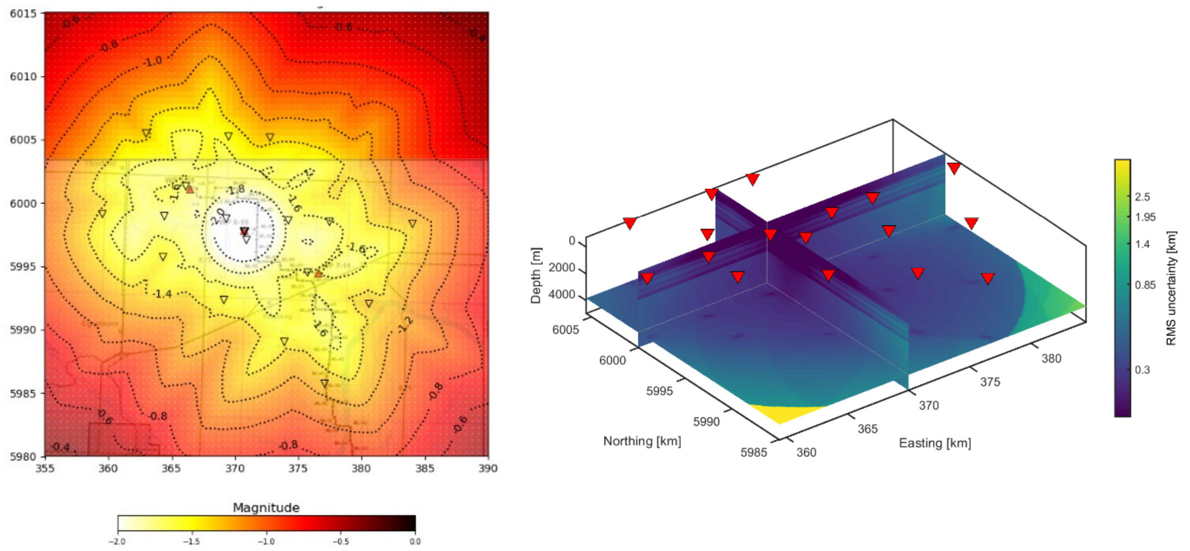

Figure 2: Modelling examples for network consisting of combination of 8 downhole geophones and surface nodes processed as 17 arrays. Left: smallest detectable moment magnitude for a sheet of sources at a depth of 3875 m below datum; right: location in terms of RMS uncertainty (bottom) for a moment magnitude M_w=-0.5 event.

WP3: Effective communication strategies

contributors: U. of Alberta (lead), MRCI, TotalEnergies, SGSI, BP, NORSAR

The objective of the WP3 was to generate reliable quantitative information regarding public perceptions and preferences about underground storage of CO_2. A specific focus was the perception of potentially induced seismicity and associated risk mitigation via different monitoring regimes. The goal of WP3 was to gather public response data in four European countries and in Canada as input to the development of stakeholder communication strategies for CCS.

While research on various aspects of CCS including monitoring technologies and seismic data processing is much advanced, knowledge of the perception by members of the public, or laypersons, is still scarce. To address this gap, the work package developed a social science survey instrument to assess a wide range of factors known to affect individuals' perceptions of energy-related technologies. Building on evidence in the energy economics literature, these factors included familiarity with energy technologies including carbon storage, perceptions of potential risks (environmental, seismic), and the economic benefit of CCS. The survey also elicited preferences in terms of required levels of stringency of monitoring regimes, as well as trust in different actors in the CCS industry and policy spaces. In addition, the study included a number of survey experiments that were designed to quantify trade-offs inherent to the national implementation of CCS hard-to-abate industries.

First, a vignette experiment (known as multifactorial survey experiment) was conducted to measure acceptance levels of different (hypothetical) national CCS implementation scenarios. The experiment was composed of seven attributes known to influence the public acceptance of energy infrastructure: (i) proximity to place of residence, (ii) project lead organization, (iii) proposed storage capacity, (iv) availability of local economic benefits, (v) pre-approval consultation, (vi) availability of risk assessment information, and (vii) the source of carbon to be stored (domestic/imported). Our findings indicate that cross-border import of CO_2 for storage has a strong effect on the acceptance of CCS projects (Mohammed et al. 2024). Consultation, compensation, proximity, knowledge, risks, and trust are critical drivers of CCS acceptance. The study concluded that communication efforts to improve public understanding and acceptance of CCS should focus on demystifying the risks of CCS instead of its technicalities and climate change mitigation capacity.

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A second experiment, known in the economic literature as best-worst scaling (BWS), was conducted to elicit public preferences for existing alternative policies (policy proposals) aimed at reducing carbon emissions. These included putting a price on carbon emissions, ending fossil fuel subsidies, increasing share of renewable energy, nurture forest landscapes, deploy CCS technology, force households to adapt energy efficiency measures for home heating and electricity consumption, enforce reductions in personal vehicle transport to encourage public transportation, or do nothing.

Finally, a third economic choice experiment was conducted to specifically measure individuals' willingness to accept the inherent (hypothetical) benefit-risk and cost trade-offs involved in large-scale implementations of carbon storage. Attributes used to construct a wide range of alternative scenarios included levels of contribution of carbon storage to emission reduction, the extent of seismic monitoring of CCS facilities, the availability of risk monitoring data/information, the seismic risk potential of CCS based on a 6-step Mercalli scale, and the hypothesized impact of national scale implementation of CCS on per household annual energy cost.

National public experimental surveys were implemented in December of 2022 and data collection was completed in February of 2023. Using the services of a reputable survey and market research provider approximately 5,140 members of the general public that were selected to represent their respective adult (census conforming) populations by age, gender, household income, and educational attainment, participated in the study in Canada, Germany, the Netherlands, Norway and the UK.

The survey provided several unique insights into how members of the public view CCS technology and how they evaluate important aspects of its large-scale deployment across parts of Europe, and in Canada. For example, a detailed analysis of the Canadian responses revealed that Canadians have strong preferences for CCS monitoring and data transparency (Lokuge et al. 2024). However, Canadians do not choose CCS scenarios that suggest any possibility of more severe seismic risks. Results also indicate significant heterogeneity in individuals' preferences, especially regarding the contribution of CCS to emissions reduction and data transparency, influenced by political orientation, perceived trust in domestic energy companies, and education levels.

Regarding the need for cross-national CO_2 transport infrastructure in Europe that is considered essential to connect carbon emitters with CCS operators Anders et al. 2024 revealed widespread public skepticism regarding any form of cross border transport of carbon emissions for CCS. A result that contrasts current EU strategic policy around the construction of a multinational CCS transport network.

Table 3: WP3 deliverables

Task ID	Task	Deliverable	Type	Contributing partners
1	*Develop site-specific survey questionnaires, vignette survey scenarios and behavioural nudges in consultation with WP partners and based on existing research*	D3.1 Detailed empirical data and experimental evidence on ENSURE country-specific public perceptions and related preferences for CCS technologies in GHG management	Data deliverable (internal)	UA, NORSAR
2	*Model the influence of site-specific survey-experimental response data regarding*	D3.2 Report on public preferences for behaviours around CCS technology in	Report (Anders et	UA, NORSAR

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	influence of CCS scenarios and respondent characteristics on project acceptance and communication mechanisms using probabilistic econometric models	different social and geographical contexts	al., 2024), public	
3	*Develop recommendation to ENSURE partners regarding presentation of CCS information and targeted public communication options*	D3.3 Report on comprehensive sets of recommendations that advance industry partners' communication and public engagement around CCS technology benefits, acceptance, and trust in energy technology applications	Report (Kühn et al., 2024), public	UA, NORSAR

The ENSURE deliverable report D3.2 entitled *"Public Preferences for Behaviours around CCS technology in different Social and Geographical Contexts"* highlights the variation in public awareness and knowledge of carbon dioxide storage across all countries surveyed. With close to 50 % of members of the public stating to not know (much at all) about CCS. This project report speaks to the various socio-economic, demographic, and country-specific factors that explain existing low levels of acceptance of a large-scale implementation of CCS as a major carbon dioxide reduction strategy in the jurisdictions studied (see Figure 3). An important outcome of the survey is that (independent) microseismic monitoring can play a pivotal role in enhancing public acceptance of CCS. The findings also identified the importance the public places on the transparent sharing of information about CO_2 storage projects, benefit and risk factors, and especially regarding the potential for induced seismicity as part of building trust in proponents of CCS facility development towards gaining greater overall public support of this critical technology. Results from this work led to an article published in the prestigious journal Nature Climate Change entitled "Cross-border CO_2 Transport Decreases Public Acceptance of Carbon Capture and Storage". The article is the first to address the issue of the potential for cross-border transport of carbon emissions for CCS, a topic especially relevant to the emerging collaborative CCS infrastructure in Europe.

To help advance the development of effective stakeholder communication with the public around CO_2 storage, a dedicated workshop was held in the Netherlands in November 2023. Workshop results were compiled in the WP3 report *"Comprehensive sets of recommendations that advance industry partners' communication and public engagement around CCS technology benefits, acceptance, and trust in energy technology applications"* (D3.3, see table 3). The workshop concluded that improved effective CCS communication rests first and foremost on a solid understanding of public attitudes, perceptions, and preferences and the availability of dedicated and secure funding to support any communication strategy that attempts to provide transparent information and data sharing that align with often complex regulatory and industry environments.

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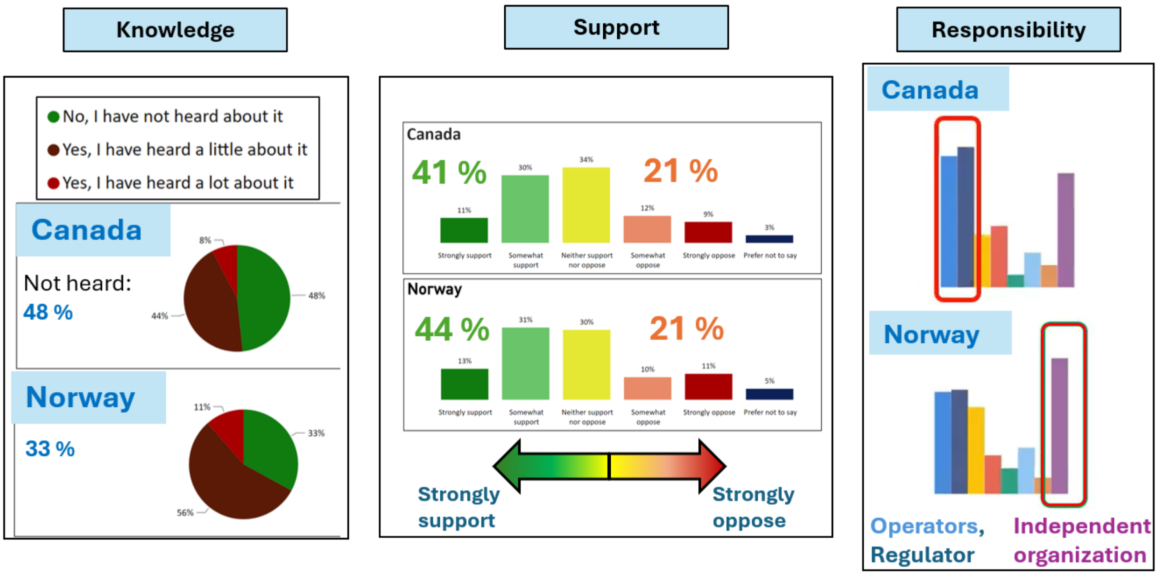

Figure 3: Example statistics comparing Canada and Norway from the public perception survey results.

Financial project overview

Table 4 provides a total expenses overview per partner and work package.

Table 4: Financial overview per work package and partner. Expenses are shown in k Euro.

Partner	WP1	WP2	WP3	Total at month 39	% of total grant
NORSAR	325.5	362.9	127.8	816.2	109%
TotalEnergies	210.105	10.135	14.564	234.804	65%
UA	102.3	102.3	136.4	341	100%
Shell Int.	60	6.799	9.878	76.677	110%
Shell Canada	418.677	0	0	418.677	123%
BP	130	49.372	20	199.372	105%
ASN	127.218	12.277	1.179	140.674	158%
INGV	0	112.88	63.12	176	100%
MRCI	33.091	58.867	66.91	158.868	124%
TOTAL	1406.891	715.53	439.851	2562.272	105%

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5. Project impact

Advancing CCS Technology Readiness

The project contributed significantly to the facilitation of the emergence of CCS by advancing the technology readiness level (TRL) of microseismic monitoring, which is one of the most important vehicles for fostering public acceptance of CCS projects if handled in a transparent way. To this end, the project's international public acceptance survey and economic scenario modeling provided significant insights to both operators and regulators. This will be of substantial value in future projects for the development of effective communication strategies and will therefore further facilitate the success of CCUS projects.

Strengthening Industrial Competitiveness

The project contributed to strengthening the competitiveness of its industry partners and thus to the growth of European companies. Our industrial partners included operators as well as service companies. Specifically, Shell, an industry partner in the project and one of the major European operators of subsurface energy projects, stated the impact of the project on them as follows:

> *"Participation in external collaborative R&D projects plays an important part in the development of the technologies required to support CCS. In the area of induced seismicity monitoring, ENSURE has provided the opportunity to participate in and learn from trials of a number of key MMV technologies. Working with a diverse group of partners makes the best use of available resources, bringing in fresh insights and complementary expertise."*

Additional feedback from TotalEnergies, also industry partner in the project and major European operators of subsurface energy projects has been given as follow:

> *"Thanks to the 'at-scale' field data shared within the JIP, ENSURE has been a real opportunity to benchmark several monitoring technologies, some of them being well established (surface seismometers & borehole geophones) and some other being still in its infancy (DAS at surface & borehole). Lots of learnings have been obtained from the research conducted in this project, especially on the sensitivities and earthquake location uncertainties of the different MMV technologies. The technical discussion between the different partners has also been very valuable and allowed to collaboratively progress for the future of CCS monitoring."*

These statements underscore the value that the project brought to the industrial partners. Similar impact is also stated from BP, industry partner in this project and major player in European energy operations. Seeding such ideas into project partners will give them a competitive advantage, which will eventually also percolate to other actors in the CCUS landscape.

Key Technological Achievements

ENSURE has demonstrated and documented the application of the following data acquisition and analysis techniques:

- The use of hybrid monitoring networks, built from combinations of complementary subsystems (surface and downhole; seismometers and DAS), to provide more cost-effective coverage and improved detection and location performance was demonstrated.
- Advanced data processing methods were shown to significantly improve the performance of event detection and location by respectively 200% and 70% compared to a vendor-provided catalog. Enlarged event catalogs provide opportunities to gain more pertinent insights into the

reservoir and surrounding rock behavior, thereby increasing conformance and containment detection capabilities.
- We demonstrated how S/N ratio and location performance can be improved through employing array processing techniques.
- An in-well DAS system was used at Quest to acquire microseismic data – these results from Quest and data from the TotalEnergies test site in southern France showed that DAS data acquisition and event detection capabilities have now improved to the point at which DAS can be considered as a complement or alternative (with certain caveats) to conventional seismometer recordings.
- The findings from the survey of the public perception and acceptance of CCS inform the development of strategies for external communication and stakeholder engagement.
- Traffic light systems (TLS) for seismicity control from a range of sites were compared and the causes and impact of event magnitude uncertainty on TLS operation were highlighted.

As indicated, the above techniques provide means of increasing the information content and business value of acquired data: data processing techniques which reduce event detection thresholds result in a greater volume of usable data from a given acquisition system; reduced event location uncertainties result in more confident interpretations of data; hybrid networks integrate multiple data types to extend coverage and reduce ambiguities. Summarizing, the value delivered by ENSURE lies in the testing and further development of a suite of techniques which specifically address the needs of CCS projects for cost-effective monitoring. ENSURE has shown which methods are effective and how these can be implemented. Key high-level findings are the value of hybrid networks and a much-improved understanding of the usability and usefulness of DAS for seismicity monitoring.

Industry Perspective and Market Impact

From a service company perspective, participation in the ENSURE project provided valuable insights into the specific characteristics and demands of using different remote sensing systems for CO_2 storage monitoring. In the words of ASN, a provider of geophysical instrumentation and services acting as industry partner in the project,

> *"The project allowed ASN to conduct a field trial at an active CO_2 storage facility, demonstrating the capability of OptoDAS technology at TRL7 (real-world conditions without interference with daily operations). In general, this collaboration strengthened ASN's competitiveness by showcasing its expertise, raising market awareness, expanding into new applications, and positioning ASN Norway as a key player in the growing sector of CO_2 storage monitoring."*

The knowledge and insight gained in the project will accelerate development and improve efficiency in future CCUS projects. From an operator's perspective, the experience gained during the project can be readily employed for speeding up the definition of a more effective monitoring strategy in future projects. Equipment providers gained valuable insight to meet market demand with fit-for-purpose solutions, reduce lead times, and improve cost models.

Societal Impact and Public Acceptance

The extensive survey on the public perception and acceptance of CCS that was run in five countries contributed significantly to understanding the interaction and dynamics between operators, regulators and the public. This will be invaluable when planning the next project to ensure public engagement and communication is handled in the most effective way for fostering acceptance. Lessons learned from the social study and socioeconomic analysis allow better and more targeted public engagement, particularly in the light of recently increased polarization of the public.

Commercialization Pathway and Future Steps

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The commercialization pathway and next steps for the "ENSURE" project can be outlined as follows:

- The project has added significantly to the technology development and could for example showcase DAS as a well-suited microseismic monitoring tool for CCS. However, further research for DAS technology is needed to better understand the instrument response for computing amplitudes and magnitudes correctly, and to be able to apply this technology more independently of others.
- In the longer term the technology developed for microseismic monitoring should be further refined to support the aspired upscaling of CCS to much greater volumes.The close collaboration with industry partners provided an ideal testbed for technology development and data processing advancements and helped to develop new market ideas for our partners. We envision that this will lead to new partnerships and commercial agreements for future projects and larger-scale installations at CCS sites.
- Additional research will be beneficial for an actual implementation of traffic light systems (TLS) for CCS.
- Results from the project have the potential to influence policy and standards for CCS. We expect that microseismic monitoring will become a standard tool for CO_2 storage verification in many future projects. Regulatory bodies are aware of the ENSURE project, which can play a role in defining best practices going forward.
- In particular, the work package on communication research showed that (independent) microseismic monitoring can play a pivotal role in enhancing public acceptance of CCS through its unique capability towards both seal integrity verification and seismic early warning for risk mitigation. This will in particular foster commercialization as it gives operators some hands-on guidelines for embedding microseismic monitoring into their long-term Measurement, Monitoring and Verification (MMV) strategies.

In summary, microseismic monitoring of CCS sites must be implemented over the entire project lifecycle, spanning several decades for most storage sites.

6. Implementation

In our project, we are committed to promoting gender equality and addressing the various challenges that arise from gender disparities. We have equal participation for genders in our project and the project lead is female.
Our project aligns with the **SET Plan Implementation Actions** (Action 9 on CCUS) and the **Mission Innovation research priorities** by addressing critical aspects of Carbon Capture, Utilization, and Storage (CCUS) technologies, particularly in the areas of monitoring, validation, and public engagement. The project's results, spanning multiple work packages (WP1, WP2, WP3), contribute to enhancing CCS monitoring and its acceptance, as well as supporting cost-effective and reliable deployment of CCS solutions.

Alignments of project results with SET Plan

- **Advancements in Monitoring:** WP1 demonstrated the potential of hybrid monitoring networks, combining Distributed Acoustic Sensing (DAS) with geophones and seismometers, to provide cost-effective and improved detection for CCS sites. This supports SET Plan's goal of advancing cost-effective monitoring systems.
- **Cost-Effective and Reliable Solutions:** By integrating surface and downhole sensors, we enhanced detection and location accuracy while reducing costs—critical for scaling CCS technologies.
- **Improved Data Processing:** We developed advanced techniques to enhance microseismic event detection and location accuracy, supporting SET Plan's aim for better data processing for CCS monitoring.

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Alignments of project results with Mission Innovation

- **Advancing Monitoring Technologies:** Our work in WP1 shows that DAS, coupled with other monitoring technologies, can complement conventional seismometers, improving scalability and reducing costs, aligning with Mission Innovation's focus on advancing CCS monitoring systems.
- **Data Integration for Improved Performance:** The integration and analysis of diverse datasets (DAS, geophones, seismometers) improved the overall performance and safety of CCS monitoring, supporting Mission Innovation's focus on data integration.
  Public Engagement and Trust: WP3 explored public perceptions of CCS, especially around induced seismicity. The findings help inform industry communication strategies to build public trust and acceptance, aligning with Mission Innovation's priority of fostering public support for CCS technologies.

Our collaboration involved industry leaders (Shell, TotalEnergies, BP) and academic partners, ensuring that findings were industry-relevant and practically applicable. The project provided industry partners with actionable insights, such as dataset comparisons and monitoring recommendations, for improving CCS site monitoring and network design. Furthermore, our results on public perceptions guide industry partners on effective communication strategies to enhance public acceptance of CCS projects.

In conclusion, the project's results contribute to the SET Plan Implementation Actions (Action 9 on CCUS) by advancing monitoring technologies, improving cost-effectiveness, and integrating data processing methods. These innovations align with Mission Innovation's research priorities by enhancing the reliability and safety of CCS monitoring systems and addressing public perception and acceptance challenges. The active engagement of industry partners throughout the project ensured that the results were practical, industry-relevant, and directly applicable to the real-world deployment of CCS technologies.

7. Collaboration and coordination within the Consortium

Overall, the collaboration within consortium partners worked well. Our project management structure was designed to ensure clear roles and responsibilities, with designated work package managers, task leads, and team members who collaborated closely to achieve the project's objectives. Regular progress meetings, both internally per partner (weekly) and with the larger consortium (monthly), were held to monitor the project's advancements and address any challenges or deviations from the original plan. These meetings helped maintain focus on the project's goals while ensuring that all partners are aligned and informed throughout the project lifecycle. Two consortium meetings were organized per year (usually one online and one in person).

The collaboration among multiple partners within the ENSURE project was a crucial factor in the success of these efforts. The diverse group of partners worked together to address a range of challenging technical questions, leading to successful field trials at the Quest site and the Southern France test site. This cooperative approach generated demonstrable business value and provided valuable insights into the future of CCS monitoring. The transnational project collaboration offered significant added value by bringing together diverse perspectives, expertise, and resources from different countries. Project partners had access to microseismic data from various CCS sites around the globe. In the end this also enabled for an expansion of the social survey being conducted in additional countries, which allowed us to directly compare differences and common views on public acceptance of CCS. In addition, the international scope of the project facilitated a broader reach and impact, allowing us to address global challenges and share our findings with a wider audience. The project helped to create stronger international networks for future partnerships.

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However, the country specific requirements with different defined milestones and reporting deadlines, which sometimes even required additional translations, created significant added workload.

8. Dissemination activities (including list of publications)

Overall, the project has already now led to an above-average publication record which is listed in detail below. Apart from several peer-reviewed publications (including Nature Climate Change, Anders et al., 2024), the collaboration with industry partners and interest of regulating bodies also led to numerous dissemination activities aside from typical academic channels. Also, numerous outreach activities in public and social media can be listed in this context.

The ENSURE project webpage can be accessed here: https://ensure.norsar.no/

A successful workshop *on "Effective Communication Strategies for CCS"* was organized together with the SHARP research consortium in Amsterdam on November 15th 2023. The workshop provided a platform for industry experts, researchers, regulators and policymakers to discuss pathways for the development of transparent and effective communication strategies to foster dialogues able to instill public trust and a better acceptance of CO_2 storage technologies.

Two scientific project publications received prestigious awards:

- Best Oral Presentation, Honorable Mention, Geoconvention 2024, Calgary, to Wardah Fadil for "Improved microseismic event detection with CATS: A case study of the QUEST CO_2 storage facility", Alberta by Fadil, Grubas and Van der Baan.
- Annual paper award 2024 of the International Journal of Greenhouse Gas Control: Effective microseismic monitoring of the Quest CCS site, Alberta, Canada, Goertz-Allmann, B. P., Langet, N., Iranpour, K., Kühn, D., Baird, A., Oates, S., ... & Nakstad, H. All measurable dissemination activities are listed in the following table.

Type of publication: SPa = Peer reviewed Paper, PPa = Popular science presentation, Po = Poster, OPa = Oral presentation and paper, PoPa = Poster and Paper, O = Oral Presentation, Web = Webinar, WS = WorkShop, V = Video, A = Abstract, PR = Press Release

Type of publication	Authors/ Speakers	Title	Reference	Date / year	Project partners involved
WS	Volker Oye	Roundtable conference on safe storage of CO_2	Workshop with invited key actors and decision-makers from the Norwegian CCS community participated at Polyteknisk Forening in Oslo	Nov-21	NORSAR, UA

PR	Adrianna MacPherson	Researchers and industry team up to assess long-term effectiveness and public perceptions of carbon storage technology	Social media release	Mar-22	UA, SCE
https://www.ualberta.ca/folio/2022/03/researchers-and-industry-team-up-to-assess-long-term-effectiveness-and-public-perceptions-of-carbon-storage-technology.html					
PR	ERA	Technological advances and social license to operate both play pertinent roles in advancing and achieving society's net-zero goals.	Government news release	Mar-22	UA, SCE
https://eralberta.ca/media-releases/alberta-partners-in-global-ccus-initiative-to-leverage-investment-from-8-countries/					
Oth	Hilde Nakstad	ASN project highlights	EAGE booth presentation, Madrid	Jun-22	ASN, Shell, NORSAR
O	Bettina Goertz-Allmann et al.	Effective monitoring of long-term site stability for transparent carbon capture and storage hazard assessment (ENSURE)	ACT knowledge sharing workshop, Rotterdam	May-22	All partners
O	Bettina Goertz-Allmann	ENSURE project overview	US-Norway bilateral meeting, Bergen	Jun-22	NORSAR
OPa	V. Oye, B. Goertz-Allmann, N. Langet, A.M. Dichiarante, D. Kuehn	New concepts for independent and transparent monitoring of CO_2 storage verification	EAGE Geotech	Apr-22	NORSAR
OPa	Goertz-Allmann et al.	Effective microseismic monitoring of the Quest CCS site	GHGT-16, Lyon	Aug-22	ASN, SGSI, SCE, NORSAR
V	Sven Anders	Measuring public acceptance of CCS technology	News feed on LinkedIn & webpage	Sep-22	UA
A+O	Susann Wienecke, Bettina P. Goertz-Allmann, Alan Baird, Jan	DAS interrogation in injection well for microseismic event detection – technology demonstration while ongoing operation	Society of Petroleum Engineers *workshop on In-well fiber optic sensing*	Feb-23	ASN, NORSAR, SGSI, SCE

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	Kristoffer Brenne, Steve Oates, Carrie Rowe				
Po	Nimanthika Lokuge, Abdul-Hamid Mohammed, Sven Anders	Public Perceptions of Storing Greenhouse Gas Emissions Underground	Denmark-UAlberta Workshop on Energy Transition	Apr-28	UA
SPa	Nimanthika Lokuge, Jordan Phillips, Sven Anders, Mirko van der Baan	[Human-induced Seismicity and the Public Acceptance of Hydraulic Fracturing – A Vignette Experiment]()	The Extractive Industries and Society (under review)	Under revision	UA
O	Goertz-Allmann et al.	Effective monitoring of long-term site stability for transparent carbon capture and storage hazard assessment (ENSURE)	Climit Summit, Larvik	23-Feb	All partners
A+O	Goertz-Allmann et al.	[Comparing sensitivity of different monitoring configurations at the Quest CCS site, Alberta, Canada]()	TCCS-12, Trondheim	Jun-23	NORSAR, ASN, SGSI, SCE, TotalEnergies
O	Oye et al.	Informal presentation of ENSURE at the HNET project meeting (including Northern Lights and Gassnova)	HNET project meeting	Jun-23	NORSAR, SGSI, Total
O	Sven Anders, Nimanthika Lokuge, Abdul-Hamid Mohammed	Public perceptions and preferences for Carbon Capture and Storage - Europe vs Canada	12th ABBY-Net Research Workshop, Calgary, 2023	Aug-23	UA
O	Volker Oye				

		Presentation on public perception	Arendalsuka	Aug-23	NORSAR, UA
O	Bettina Goertz-Allmann	Microseismic monitoring at the Quest CCS site	CCS networking workshop at NORSAR	Sep-23	NORSAR
O	Bettina Goertz-Allmann	Results from public perception study conducted within ENSURE	CCS networking workshop at NORSAR	Sep-23	NORSAR
O+P	Volker Oye	Microseismic monitoring of storage sites	ACT knowledge sharing workshop, Paris	Oct-23	NORSAR, UA, Total, SGSI, SCE
O	Steve Oates	Developing induced seismicity monitoring options - field trials at Quest CCS	Shell internal geophysics conference	Oct-23	SGSI
O	Volker Oye	Microseismic monitoring of storage sites	US-Norway bilateral meeting	Oct-23	NORSAR, UA, Total, SGSI
O	Bettina Goertz-Allmann	Effective microseismic monitoring at the Quest CCS site	SHARP consortium meeting, Delft, Netherlands	Nov-23	NORSAR, UA, Total, SGSI, SCE
O	Bettina Goertz-Allmann	Effective microseismic monitoring at the Quest CCS site	AGIS workshop, Munich, Germany	Nov-23	NORSAR, UA, Total, SGSI, SCE
WS	Bettina Goertz-Allmann and Elin Skurtveit	Public acceptance and communication of CCS	Public workshop, Amsterdam, Netherland	Nov-23	All ENSURE partners
O	Volker Oye	Monitoring of CO_2 storage sites - examples from the ACT project ENSURE	CO2-H2 seminar, MEET Ullevål, Oslo	Nov-23	NORSAR, UA, Total, SGSI
O	Volker Oye	Findings and ongoing studies on public perception	Evolving Perceptions: CCS and the Road to a Just Transition,	Nov-23	NORSAR, UA

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			Bellona Europa		
O	Steve Oates	Developing induced seismicity monitoring options - field trials at Quest CCS	CCS MMV practitioner s' group	Nov-23	SGSI
O	Thomas Braun and Stefania Danesi	Comparison and calibration of Traffic Light Protocols applied in different countries, in the framework of the ENSURE-project	42 conf. G.N.G.T.S. Bologna	Feb - 24	INGV, NORSAR
PPa	S. Anders, N. Lokuge, A.-H. Mohammed, M. van der Baan	Public Acceptance of CCS - Dutch Citizen Perspectives	EBN Carbon Dialogue, The Hague, Netherlands.	Apr-24	UA, EBN Netherlands
Po	A.-H. Mohammed, S. Anders, N. Lokuge, M. van der Baan, J. Meyerhoff, U. Liebe	Public Perceptions and Preferences for CCS Development in Canada	14th Canadian Agri-Food Policy Conference, Ottawa, Canada.	Feb-24	UA
SPa	N. Lokuge, S. Anders, J. Meyerhoff, U. Liebe, M. van der Baan	How the Canadian public is willing to trade off the deployment costs of carbon capture and storage with its climate benefits? Heterogeneous preferences and lessons for policy	Working paper, Dept of REES, UofAlberta	Mar-24	UA
A	N. Lokuge, S. Anders, J. Meyerhoff, U. Liebe, M. van der Baan	Are Canadians willing to pay for carbon capture and storage projects in Canada	2024 Canadian Resource Economics Society, July 7-9, Winnipeg, Canada.	Feb-24	UA
AO	Goertz-Allmann et al.	Microseismic event analysis using multi-technology sensors at the Quest CCS site	EGU 2024, Vienna	Jan-24	NORSAR, Total, SGSI, SCE
AO	Langet et al.	Multi-Sensor Microseismic Monitoring of the Quest CCS site, Alberta, Canada	SSA 2024, Anchorage	Jan-24	NORSAR, SGSI, SCE

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O	Bettina Goertz-Allmann	Efficient microseismic monitoring of induced seismicity – examples from CCS and geothermal	Seminar presentation at FU Berlin	Feb-24	NORSAR
SPa	Goertz-Allmann et al.	Effective microseismic monitoring of the Quest CCS site, Alberta, Canada	International Journal of Greenhouse Gas Control	Mar-24	NORSAR, SGSI, SCE, ASN
O	Bettina Goertz-Allmann	The value of microseismic in practical applications of CCS monitoring	GeoREST workshop, Palma	Mar-24	NORSAR
PPa	S. Anders, N. Lokuge, A.-H. Mohammed, M. van der Baan	Public Acceptance of CCS - Dutch Citizen Perspectives	EBN Carbon Dialogue, The Hague, Netherlands.	Apr-24	UA, EBN Netherlands
O+A	Goertz-Allmann et al.	Microseismic event analysis using multi-technology sensors at the Quest CCS site	EGU 2024, Vienna	Apr-24	NORSAR, Total, SGSI, SCE
O	Goertz-Allmann	CCS public perception study	Polish CCS delegation to Norway workshop at Equinor	Apr-24	NORSAR, UA
O+A	Langet et al.	Multi-Sensor Microseismic Monitoring of the Quest CCS site, Alberta, Canada	SSA 2024, Anchorage	Apr-24	NORSAR, SGSI, SCE
SPa	S. Anders, U. Liebe, J. Meyerhoff	Cross-border CO_2 Transport Decreases Public Support for Carbon Capture and Storage	Nature Climate Change	Jun-24	UA
O+A	Bettina Goertz-Allmann	Robust and cost-effective monitoring of induced seismic	EAGE workshop: CCS Monitoring "Lessons Learned, Challenges, Opportuni	Jun-24	NORSAR, SGSI, SCE, Total, ASN

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			ties and Strategies"		
OPa	Baird et al.	Improving the detection threshold of borehole DAS for seismic monitoring of CCS fields	EAGE 2024	Jun-24	NORSAR, Total, SGSI, SCE, ASN
OPa	Wardah Fadil, Serafim Grubas, Mirko van der Baan	Improved microseismic event detection with CATS: A case study of the QUEST CO_2 storage facility, Alberta	GeoConvention 2024	Jun-24	UA
O	Anders et al.	Measuring Public Acceptance of CO_2 Sequestration Using Economic Experiments	SEG workshop on Geophysical Research for Gigatonnes CO_2 Storage	Jul-24	UA
O	Sven Anders	Social License to Operate	SEG workshop on Geophysical Research for Gigatonnes CO_2 Storage	Jul-24	UA
PPa	Sven Anders	Radio Interview about CCS study	QR77	Jul-24	UA
O	Goertz-Allmann et al.	Monitoring of long termCO_2storage site stability	ACT knowledge sharing workshop	Sep-24	all partners
O	Bettina Goertz-Allmann	ENSURE: Effective monitoring of long-term site stability for transparent CCS hazard assessment	GEOSTOR Monitoring Symposium	Sep-24	All partners
O	Goertz-Allmann and Skurtveit	Public perception of CCUS – Findings from the ENSURE and SHARP projects	ACT knowledge sharing workshop	Sep-24	NORSAR, UA

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O	Steve Oates	Induced seismicity monitoring for offshore CCS	NSTA (North Sea Transition Authority) CCS MMV Technology Showcase, at the Net Zero Technology Centre, Aberdeen.	Oct-24	SGSI (with acknowledgement to ENSURE partners)
OPa	Goertz-Allmann et al.	Optimized microseismic event detection and source analysis at the Quest CCS site, Alberta, Canada	GHGT-17, Calgary, Canada	Oct-24	NORSAR, Total, SGSI, SCE, UA, ASN
OPa	Mohammed et al.	Public perceptions and the acceptance of CCS development in Canada – A vignette experiment	GHGT-17, Calgary, Canada.	Oct-24	UA
PoPa	N. Lokuge, S. Anders, J. Meyerhoff, U. Liebe, M. van der Baan	What CCS should look like in Canada? Trade-offs between climate benefits, seismic risks and deployment costs	GHGT-17, Calgary, Canada	Oct-24	UA
O	Thomas Braun	Decision Support tools in geothermics and CCS	EPOS TCS-AH Workshop	Nov-24	INGV, NORSAR
O	Goertz-Allmann et al.	Lessons learned from microseismic monitoring of induced seismicity at megaton-scale CCS sites	to be presented at DGG, Bochum	Feb-25	NORSAR, Total, SGSI, SCE, UA, ASN
O	Goertz-Allmann et al.	How do we best monitor induced seismicity of CCS sites?	to be presented at Schatzalp induced seismicity workshop	Mar-25	NORSAR, Total, SGSI, SCE, UA, ASN

Acknowledgement

Quest is an AOSP owned facility operated by Shell Canada on behalf of Canadian Natural Upgrading Limited, and 1745844 Alberta Ltd.

Final financial report

ACT Final Financial Report:

Project name: ENSURE

Project number 327317

Actual costs per country/ per organization

Country	ACT funding	Other public funds	Private funding, R&D instituations	Private funding, industry	In-kind, R&D institutions	In-kind, industry	Other funds	Total after 3 years per org	Total after 3 years per country
Norway									956.874
NORSAR	660				156.2			816.2	
ASN						140.674		140.674	
Canada									759.677
University of Alberta	341							341	
Shell Canada						418.677		418.677	
France									234.803
TotalEnergies	78.268					156.535		234.803	
The Netherlands									76.677
Shell Global International						76.677		76.677	
UK									199.372
bp						199.372		199.372	
Italy									176
INGV					176			176	
US									158.868
MRCI					158.868			158.868	
Total per funding	1079.268	0	0	0	491.068	991.935	0	2562.271	2562.271