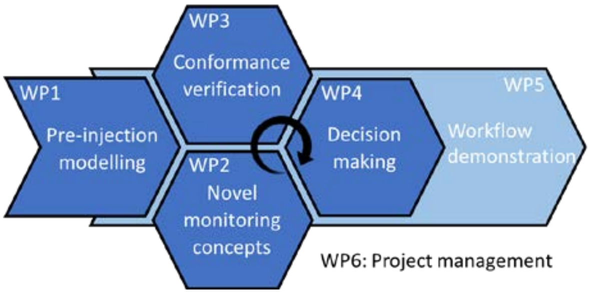
ACT Project Pre-ACT
Final report

1. Identification of the project and report

Project title	Pressure control and conformance management for safe and efficient CO_2 storage - Accelerating CCS Technologies (Acronym: Pre-ACT)
Project ID	271496
Coordinator	SINTEF AS
Project website	www.sintef.no/pre-act
Reporting period	1 September 2017 – 31 August 2020

The objective of Pre-ACT is to equip operators and regulators with **pressure-driven decision support protocols (Pre-ACT Protocols)** that enable them to establish a safe and efficient CO_2 monitoring system and to make quantitative assessments of site conformance.



Participants

Organisation	Main contact
SINTEF	Peder Eliasson
NORSAR	Andreas Wüstefeld
BGS	Jim White
PML	Jerry Blackford
TNO	Simona Bottero
GFZ	Conny Schmidt-Hattenberger
Equinor	Bamshad Nazarian
Shell	Jeroen Snippe
TAQA	Chris Gittins
Total	Guillaume Bergery

Acknowledgement

This work has been produced with support from the SINTEF-coordinated Pre-ACT project (Project No. 271497) funded by RCN (Norway), Gassnova (Norway), BEIS (UK), RVO (Netherlands), and BMWi (Germany) and co-funded by the European Commission under the Horizon 2020 programme, ACT Grant Agreement No 691712. We also acknowledge the industry partners for their contributions: Total, Equinor, Shell, TAQA.

2. Short description of activities and final results

The Pre-ACT project brought together a partnership of 10 research institutes and industrial companies to target three key challenges for CO_2 storage: capacity, confidence, and cost. The focus of the project was on improving strategies for monitoring and management of the pore pressure distribution within a storage complex. Pre-ACT has developed methodologies for monitoring and assessment of conformance (relative to expected performance) for CO_2 storage sites at all scales, from pilot to mega storage projects. This rare overview of monitoring methods ensures that the results of the Pre-ACT project are universally applicable, and not limited by scale or geology. Early input from our industrial partners highlighted the need to produce quantitative assessments of conformance based on cost-effective monitoring strategies. The workflow developed in Pre-ACT tried to answer this need. It has been applied to various case studies, presented at international conferences, and has received positive feedback from industry. The developed approach is unique in CO_2 research, since it integrates elements from reservoir modelling, statistical analysis, and decision making. It compares monitoring data from a suite of plausible models, reflecting our limited knowledge about reservoir properties, to assess the likelihood that given (limited) observations contribute to better evaluation of conformance. Active and passive monitoring techniques have been studied with measurements ranging from direct borehole pressure measurements to indirect surface geophysical measurements aiming at monitoring pressure and saturation changes due to CO_2 injection. Three North Sea case studies, each one being headed by a different research group and linked to an industrial partner, have been conducted. Operational data from a Pre-ACT experimental campaign at the onshore Svelvik CO_2 Field Lab have also been considered. Based on input from our industrial partners, Pre-ACT aimed at supporting site operators when confronted with challenging questions like: Is my site conforming to expectations? How reliable is my conformance assessment? The proposed solution consisted in a mathematically complex, but intuitively accessible, tool providing a means to answer such questions.

The project has investigated subsurface pressure and saturation changes during injection operations in heterogeneous environments. This has ensured that a suitable degree of complexity has been included in our modelling realisations whilst the work has enhanced knowledge of the capacity of water production to control pressure build up during CO_2 storage. These studies have resulted in a significantly improved understanding of the spatial build-up and distribution of pressure and saturation changes during CO_2 injection and water production.

Pre-ACT has also assisted in the re-establishment of the Svelvik CO_2 Field Lab by input on a suitable well layout, by providing additional instrumentation of the wells and specialized equipment for geophysical monitoring of pressure and saturation, by performing the first experimental campaign at the lab, and by co-arranging the lab inauguration and disseminating the experimental results of the campaign. Through a series of pressure and saturation discrimination experiments undertaken in 2019 at Svelvik and the analysis of the recorded data, Pre-ACT has delivered an enhanced understanding of pressure and saturation modelling, monitoring and control. The studies have been backed up by a comprehensive modelling platform, which ensures that the subsurface regime is understood during the monitoring phase. These unique experiments have allowed the testing of innovative geophysical investigations targeting controlled pressure and saturation build-up with techniques that can be used in the monitoring of large-scale CO_2 storage projects. For the first time, Pre-ACT has presented a verifiable pressure-saturation discrimination experiment monitored with a comprehensive suite of tools. This is a world class facility undertaking cutting edge scientific experiments.

The analysis of the Svelvik data has been wide-ranging and enabled the passive-active monitoring ideas, modelled in the initial phase of Pre-ACT to be tested with real data. Most significantly the value of the different data streams could be directly compared, and the capacity of each technique to contribute to the site conformance verification established using methods developed in the Pre-ACT project. Significant effort has gone into the development of the Svelvik CO_2 Field Lab, and Pre-ACT is proud to be the first research programme that has used the newly reopened field laboratory.

Pre-ACT has also investigated strategies for operational decision-making when monitoring data suggests non-conformance. Workshops have been held to bring together industry, stakeholders, and researchers to discuss the actions necessary to return a site to acceptable behaviour. These ideas have also been tested as part of the Pre-ACT case studies. Pre-ACT researchers, with help from the involved industry partners, have set up three offshore case studies, and these were used to demonstrate various aspects of the developed conformance workflow. The case studies are Endurance (led by BGS and linked to Shell), the Smeaheia site (led by SINTEF and linked to Equinor), and the P18-4 case (led by TNO and linked to TAQA). For maximum impact, Pre-ACT has focused on reporting the project findings applied to these major potential European storage sites. In general, Pre-ACT has made a significant effort to disseminate results actively, both through technical workshops, conference participation, publications, but also via three stakeholder meetings (in Trondheim, Brussels, and at Svelvik CO_2 Field Lab), and via a very successful webinar series.

All in all we consider our ten most important achievements to be: 1) Studies of effects of uncertainties and heterogeneities on prior reservoir modelling 2) Studies of the effect of hypersaline discharge 3) Novel methods for pressure/saturation quantification 4) Svelvik CO2 Field Lab instrumentation and first Svelvik campaign 5) Development of quantitative conformance workflow 6) Development of methods for data acquisition optimization 7) Studies of optimal timing for the purchase of monitoring data 8) The three case studies 9) The three stakeholder meetings, and 10) The webinar series. Those achievements are described in more detail below and summarized in the Impacts section.

Work package	**WP1: Optimal injection planning via effective pressure control**							
Participant (lead underlined)	BGS	GFZ	NORSAR	SINTEF	TNO	PML	Industry	SUM
Estimated budget (kEuro)	145	50	60	300	60	95	80	790

WP1 focused on understanding the propagation and potential control of subsurface pressure changes following injection - through a program of modelling and laboratory work. This work was fundamental to the overall quantitative workflow developed in Pre-ACT, as the approach compares monitoring data from a suite of synthetic realisations to assess the likelihood that the limited information in an observed data set represents conformance to expected operations (WP3). Testing of this scheme used the synthetic models and results developed in WP1.

Initially, WP1 studied the role of geological heterogeneity at two major CO_2 storage demonstration sites, Sleipner and Snøhvit, highlighting how heterogeneity plays a significant role in the development of the subsurface anomalies and also, ultimately, in the success of an injection operation. SINTEF used these findings and investigated the role of heterogeneity on the Horda Platform, offshore Norway with a study highlighting the role of fault transmissivity and geological heterogeneity on pressure build-up (M1.1.1, D1.1.1). These large-scale pressure simulations varied the fault parameters along the edge of the reservoir compartment, the potential CO_2 storage site at Smeaheia, to model the pressure response (Figure 1).

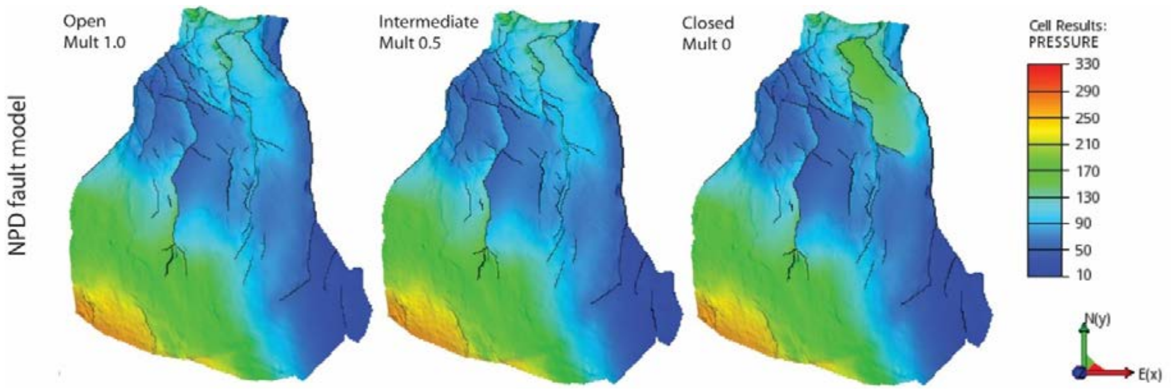


Figure 1: Simulated pore pressure after 27 years production from Troll and 50 years CO_2 injection with continued hydrocarbon production. The maps highlight consequences of varying fault sealing properties from open (left), to intermediate (centre) to sealing (right), from Lothe et al. (2018).

Regional studies matched the pressure depletion in the adjacent Troll field and demonstrated that with sealing relay zones along the western border (Vette Fault zone), the pressure in the Smeaheia area will be higher and less affected by the Troll Field depletion. As such, the gas plume and gas saturation will affect a smaller area, compared to assuming open or semi-sealing faults.

Within WP1, BGS questioned how heterogeneity affects the migration of CO_2 and the propagation of pressure (M1.2.1, D1.2.1). In addition, they investigated how water production could be used to control the pressure and produced guidelines for key stakeholders and regulators on the consequences of injection for the future use of pore space at a regional scale (M1.2.2, D1.2.2). A suite of models (Vosper et al., 2018) were constructed, parameterised with porosity and permeability values from Smeaheia data. The spatial distributions of geological heterogeneity were randomly generated using a newly developed code and assessed for 50 years of injection at 1 MT/year (Figure 2). The models highlighted, and provided visualisation, that: CO_2 will migrate to high porosity/permeability areas; well location is key parameter for injectivity; high permeability areas allow for pressure dissipation over a wider area; pockets of high porosity can be inaccessible; the area of the fluid substitution plume is relatively fixed but the extent of the pressure footprint varies significantly due to heterogeneity.

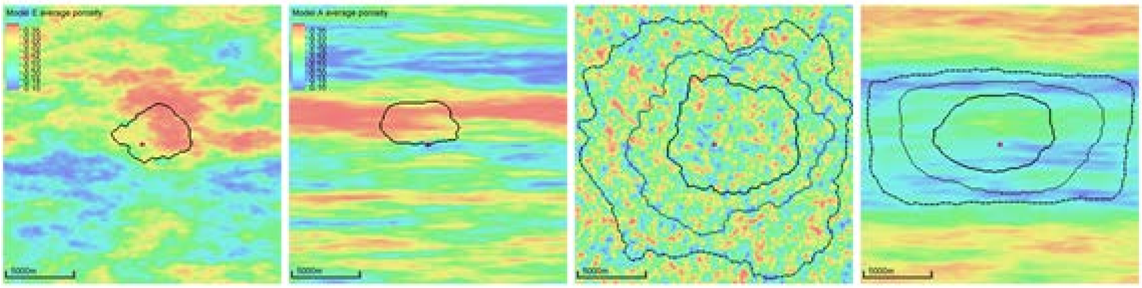


Figure 2: Examples of saturation changes in subsurface following injection (two left images) highlighting migration to higher permeability regions. The two right images show 1, 5 and 10 bar pressure changes and demonstrate preferential propagation of pressure in high quality reservoir areas. The pressure increase on the right very clearly follows the heterogeneity and it is able to dissipate once it reaches the edge of the low-permeability channel.

Brine production strategies were also studied (Figure 3) and concluded that: connectivity between injection and production wells is crucial; placement of any well in poor-quality reservoir hinders effectiveness; high-frequency variations can be averaged to a homogeneous model more justifiably than low-frequency variations; water production has a limited impact on CO_2 migration but is an effective pressure control tool. The combination of the use of water production to enhance storage capacity, and control pressure build-up, alongside an assessment of the significance of geological heterogeneity in the spatial distribution of pressure and saturation changes during CO_2 injection is a unique Pre-ACT development.

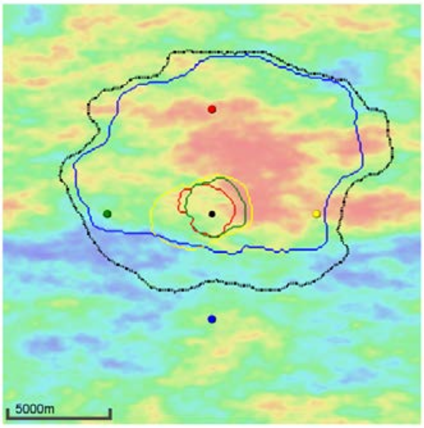


Figure 3: One bar pressure contours, coloured contours corresponding to the cases with a production well and black contour to the case without water production. There is a discontinuous flow barrier across the middle of this model, just south of the injection point. As a result, the blue production well is not as effective as the other locations at reducing the pressure. The flow barrier is incomplete and therefore some impact is visible.

Pre-ACT WP1 also examined the release of highly toxic brines into the water column. PML investigated if natural mixing in marine systems was sufficient to disperse and dilute these brines below impact thresholds. Utilising a very high resolution nested hydrodynamic model (FVCOM) and detailed bathymetry of the seafloor morphology, they were able to simulate realistic tidal, current, thermal and wind driven mixing in the water over the Goldeneye storage complex and a Southern

North Sea site. Each study simulated for 6 months after spin up, falling into a quasi-steady state (M1.5.1).

Figure 4 shows the 24-hour integrated plume footprint for release over a Southern North Sea site, with little evidence of a sea floor morphology effect. PML concluded that direct disposal of brines into seawater will have a limited impact in terms of salinity and highlighted that heavy metal contamination is a greater issue than salinity itself, as the North Sea experiences strong tides that ensure good mixing. However, they noted the results may not extrapolate to sites where mixing is limited. Key recommendations from the studies emphasised that releasing the brine at the sea surface, rather than the sea floor significantly increases dispersion and reduces impact and that monitoring may be effectively achieved by using standard temperature-salinity sensors deployed ~ 50 m laterally from the discharge point, aligned with the dominant tidal axis (D1.5.1). This work had significant impact with external operator providing additional support to extend the range of scenarios covered for the Southern North Sea site, with results used to inform the FEED and permitting of the Southern North Sea site (D1.5.2).

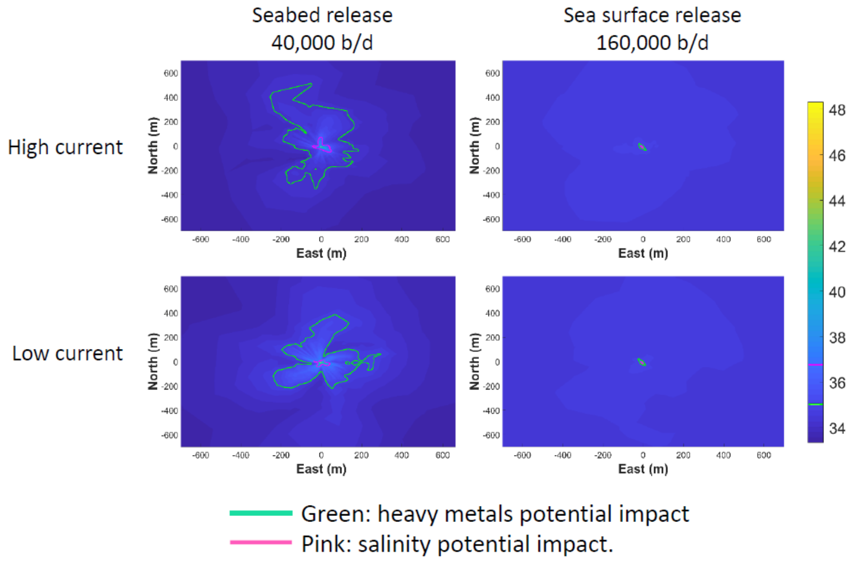


Figure 4: 24-hour integrated hypersaline plume footprint over a Southern North Sea site indicating zones of potential impact

Pre-ACT WP1 has also had a significant laboratory experimental campaign with two distinct areas of investigation (M1.3.1, M1.3.2). Pre-ACT scrutinised the mechanisms involved in acoustic emission (AE) release due to pore pressure changes at grain level. The laboratory campaign created stress induced faults in triaxially compressed plugs then reactivated fault movement with pressure changes to explore the extent to which aseismic fault displacement is linked to gouge presence (Figure 5).

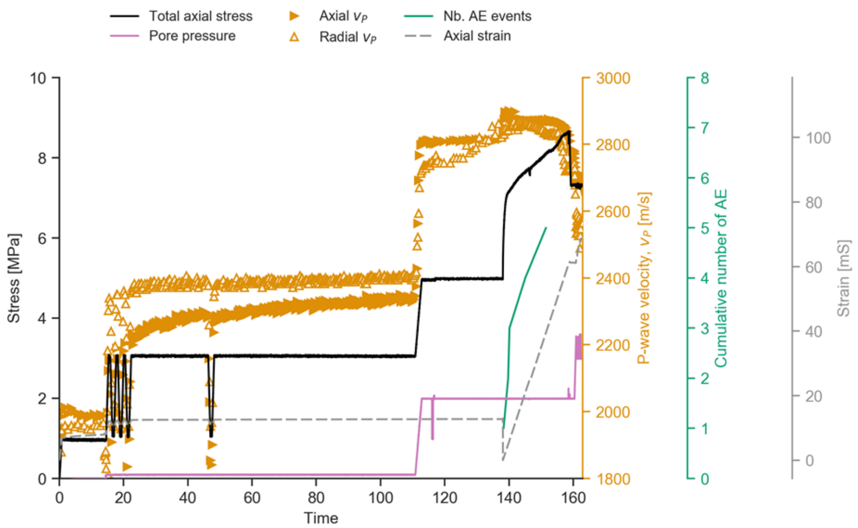


Figure 5: Observed acoustic emission events.

The studies concluded that the pore pressure increase rate had no clear effect on the reactivation pressure, suggesting no weakening at higher injection rates. Experiments also demonstrated that AE magnitudes are generally lower during reactivation than during initial shearing and this could be determinant for detailed passive seismic monitoring. When a gouge was added to the induced fault plane, very little AE was observed. It was shown that the fault becomes stronger with deformation: no stabilisation stress was reached during shearing. These results provide clear route to understanding the mechanisms that trigger observed passive seismic events and provide a high impact area for further work (D1.4.1).

Finite Element modelling was performed by TNO to evaluate the fault reactivation risk upon pressure increase in a storage reservoir bounded by a fault (D1.3.1, D1.3.2). The simulations used the DIANA software with a user-modified geomechanical model. The fault was assumed to have an angle of 75° with respect to the horizontal direction and to traverse both reservoir and overburden (Figure 6). Linear elastic and plasticity models (modified cam clay) were compared, with different stress paths covering injection with or without prior depletion in the reservoir and cooling during injection (to capture the appearance of thermal stresses when CO_2 expands into a depleted reservoir). Results show that the stress path in the reservoir during depletion is nearly linear, hence the elastic model is sufficient. However, the stress path during injection and/or cooling is different because the Poisson's ratio during loading (depletion) is different from unloading (injection) in the non-linear model. Occurrence of elastic hardening leads to a higher bulk and Young's moduli, causing a larger thermal stress change upon cooling. The fault could be reactivated in the reservoir section for a considered case where a 35 MPa depletion was followed by 25 MPa injection and 65 °C cooling, while in the caprock the situation for the same case showed to be stable.

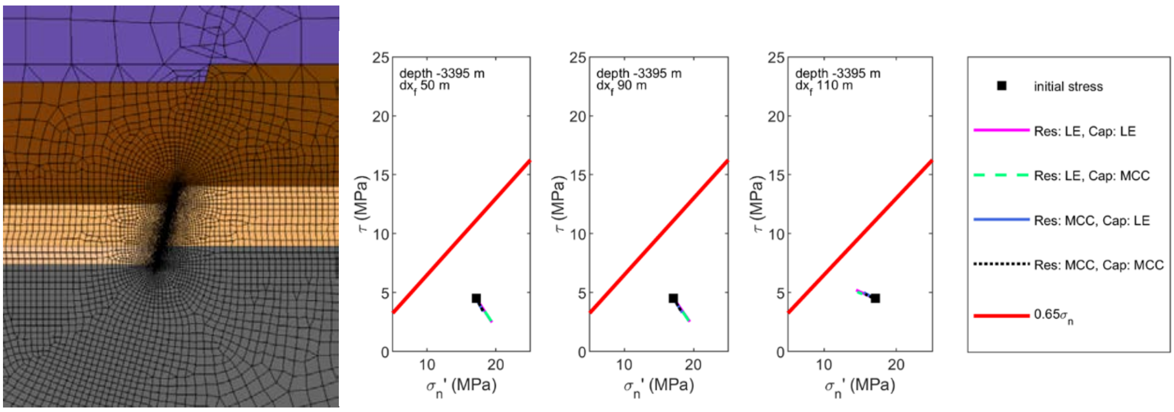


Figure 6: Finite element mesh with a fault spanning reservoir and overburden (left). Stress paths in the caprock at increasing distance from the fault (right). The red line shows the failure criterion and the different stress paths correspond to different models for reservoir and caprock (LE: linear elastic, MCC: modified Cam-clay plasticity).

Work package	**WP2: Novel concepts for quantitative monitoring of pore pressure**							
Participant (lead underlined)	BGS	GFZ	NORSAR	SINTEF	TNO	PML	Industry	SUM
Estimated budget (kEuro)	70	400	79	1320	100	0	40	2009

The objective of WP2 was to establish monitoring concepts combining continuous passive and sparse active methods for an efficient evaluation and management of reservoir pressure. Different approaches for pressure/saturation quantification and discrimination were developed and tested in field experiments. Technical workshops served as a platform for discussions on the quality and suitability of selected data, addressing pressure irregularities and near- and far-field monitoring options for pressure and saturation (D2.1.1, D2.2.1, D2.3.3, and D2.2.2).

A novel capillary-based pressure monitoring system was developed and tested in a CO_2 migration test conducted at the Svelvik CO_2 Field Lab (ECCSEL NO3.12). The sensors were located at ground level and the pressure signal transferred from the reservoir to the ground by means of a capillary. This allowed the use of smaller bottom hole diameters and made sensor retrieval possible. The Svelvik CO_2 Field Lab was equipped with a total number of 16 pressure sensors in the observation wells. Three piezo-electric downhole sensors and the remaining surface sensors were in communication with the subsurface via capillaries. As shown in Figure 7, the active capillaries recorded a very similar pressure signal as the bottom hole sensors acting as reference (Wiese et al., 2020, D2.4.2).

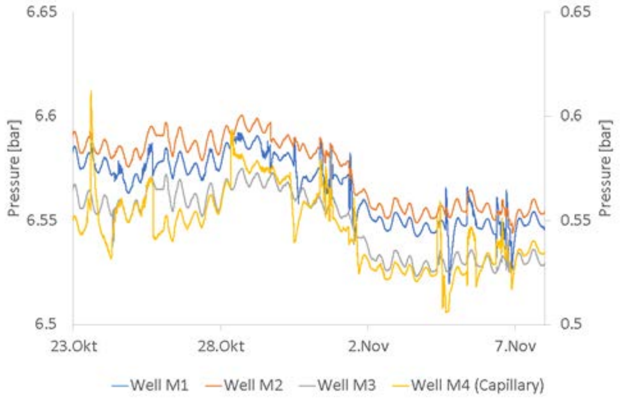


Figure 7: Pressure data from the Svelvik observation wells. The left axis refers to the pressure recorded at the bottom hole sensors, and the right axis refers to the pressure recorded at the capillary connected surface sensor. The capillary connected sensors show very similar pressure signal, but also react to mechanical operations, as e.g. packer setting in the respective observation well.

A geoelectric array with 64 electrodes was installed at the Svelvik field site to help determine the location of the CO_2 plume. Although the amount of injected CO_2 was very small, the geoelectric survey was able to locate the existence of the plume (Figure 8). Unexpectedly, the plume was not located close to the injection well, but several metres above with a lateral shift. Nevertheless, the location was considered reliable, as consistent results were obtained with crosswell-based velocity tomography (D2.3.1, D2.3.2, and D2.3.3).

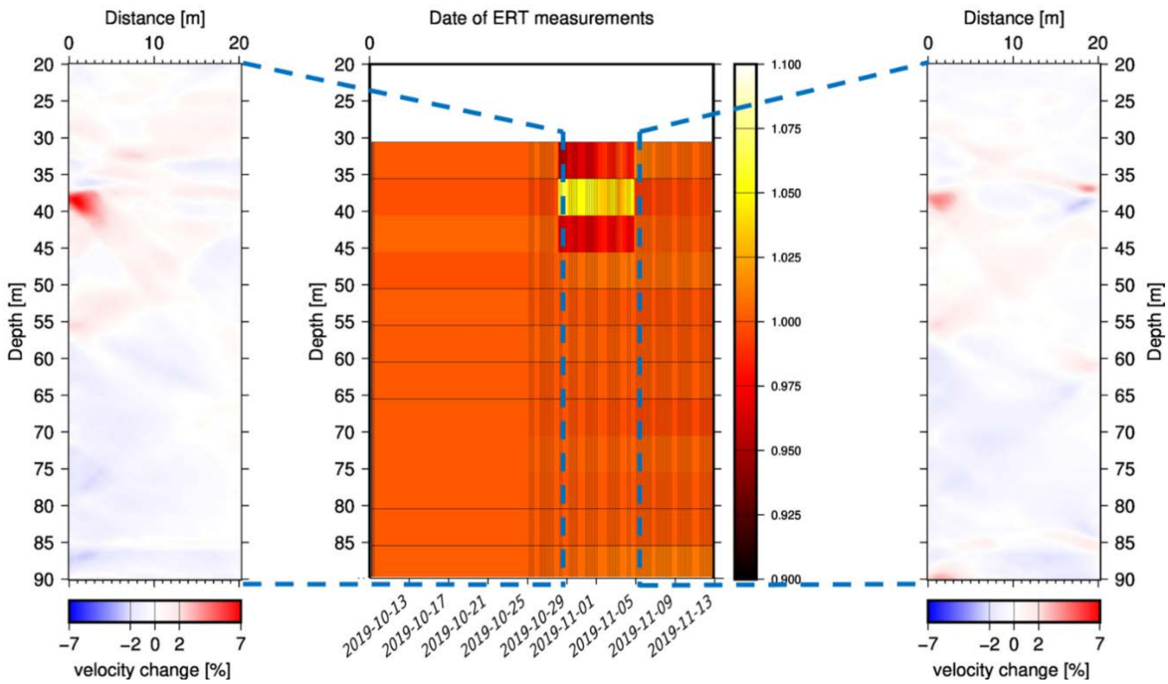


Figure 8: Velocity changes (left and right) derived from the cross-well seismic tomography at two time steps (Jordan et al. 2020, in prep.). Time series of crosswell geoelectric inversion of the Svelvik CO_2 injection experiment. The plot shows the resistivity ratio between baseline and repeat surveys. Brighter colour indicates a lower conductivity related to the CO_2 plume. The plume was detected at 40 m depth close to observation well M3 during the injection of CO_2. After injection stopped, the plume signal disappeared within 1 to 2 days. (Raab et al., Advances in Geosciences, in review).

To quantify (with uncertainty assessment) pore pressure and saturation changes in geophysical data, a two-step Bayesian inversion approach was developed. In the first step, geophysical inversion is used to transform seismic, electrical, electromagnetic or gravimetry data into geophysical properties. In the second step, rock physics inversion combines those geophysical properties (and an appropriate rock physics model) to recover the spatial distribution of selected rock physics properties with uncertainty assessment. To monitor the stored CO_2, a specific workflow to determine rock physics properties (porosity, rock frame moduli before injection; pore pressure, Brie exponent, and CO_2 saturation after injection) was proposed and applied to Sleipner and Snøhvit real data (Figure 9, D2.3.3, and D2.3.5) and Svelvik synthetic data. (Dupuy et al., 2018; Dupuy et al., 2019; Dupuy and Romdhane, 2020; Dupuy and Romdhane, 2020; Dupuy et al., 2020, in review).

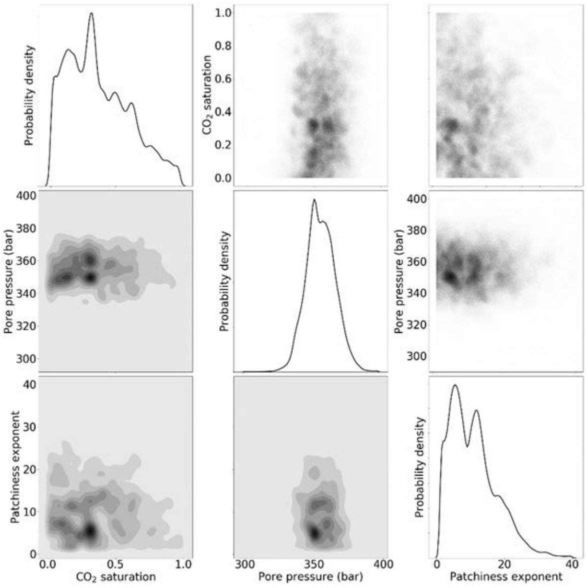


Figure 9: Inversion of pore pressure, CO_2 saturation and patchiness exponent for the Snøvhit data using a pore space stiffness rock physics model. The diagonal gives the 1D marginal posterior distributions, the lower left corner gives the 2D marginal posterior distributions while the upper right corner gives the model space after statistical Bayesian resampling.

In addition to the developed Bayesian inversion, a deep neural network (DNN) algorithm trained to recover rock physics properties from seismic attributes was developed and tested, with the objective of reducing processing time and supporting rapid decision making. Training datasets were generated from the Svelvik ridge geomodel. The results showed that once trained, the algorithm was able to derive rock physics parameters such as pressure, clay content, saturation and porosity from seismic attributes (Figure 10), with a reliability ranging from acceptable to very accurate, depending on the accuracy of the applied seismic method. Although pressure is known to be the most difficult parameter to determine, the method was seen to improve considerably the accuracy compared to prior knowledge (Weinzierl and Wiese, Geophysics, in review). The present approach allows fast and potentially real-time field site analysis during seismic campaigns.

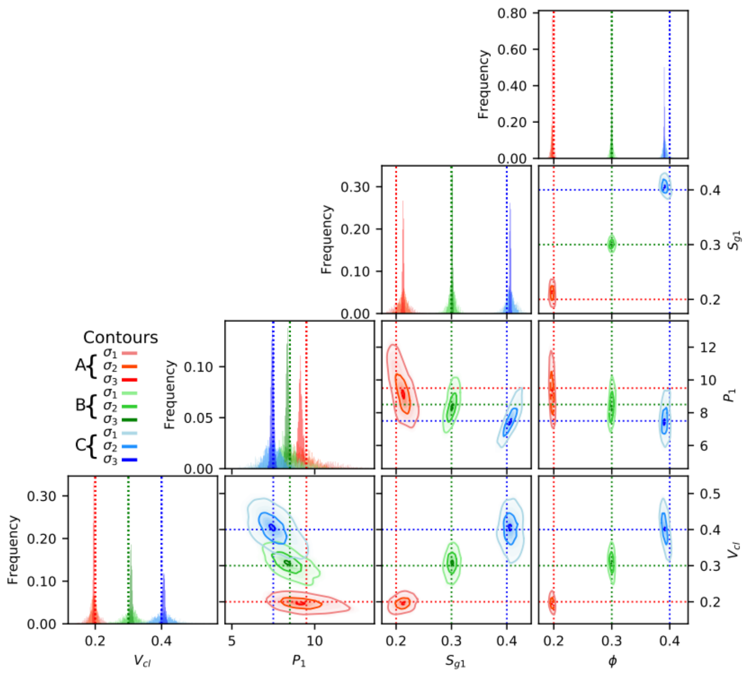


Figure 10: Deep learning derived rock physical properties for clay content, pore pressure, CO2 saturation and porosity (Vcl, P1, Sg1 and φ, respectively). The dashed lines show the true values. The histograms show the distribution, of each parameter, the cross-plots show cross correlation for surface seismic (σ1, large error) to crosshole seismic (σ3, small error).

WP2 also looked at the value of DAS systems for the injection campaign at Svelvik. Downhole monitoring with fibre optic DAS systems offers unprecedented potential for high resolution mapping of the injected CO_2 at reduced costs since repeated wireline surveys can be replaced by permanent installations of comparatively cheap fibre cables. However, as fibres only record one seismic component, novel approaches are required for interpretation. One important challenge at Svelvik was related to the well spacing constraints. A cross-well survey design study using DAS for CO_2 monitoring at Svelvik (Figure 11, Wuestefeld and Weinzierl, 2020) analysed the sensitivity to different well spacings and discussed the challenges, specific to DAS strain measurements, due to characteristic amplitude changes along the fibre. Based on the state of the art, a toolbox evaluating and comparing different monitoring design options for fibre optic downhole installations in a cross-well setting was developed (D2.3.1, D2.3.2, and D2.3.4).

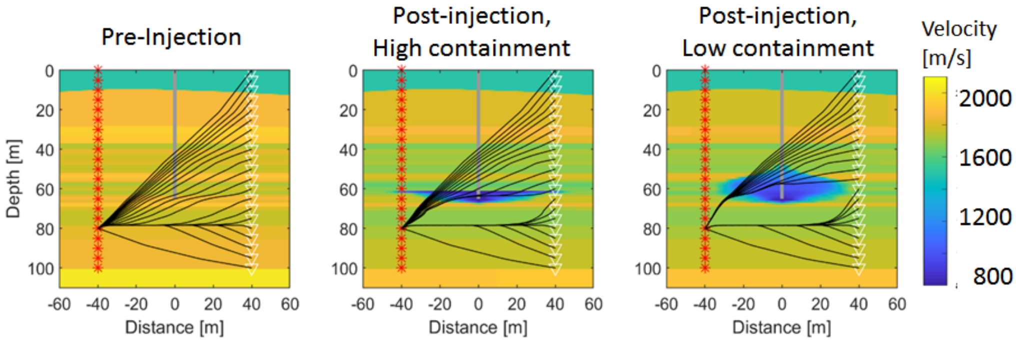


Figure 11: P-Wave velocity models and ray paths for a well based DAS seismic acquisition. A seismic shot is carried out at 80 m depth. The CO_2 plume shape for high containment scenario can be distinguished from the low containment scenario.

A few studies of the potential of using passive surveys to image time-lapse effects from the CO_2 plume at the Svelvik site was also carried out. In one of those studies, passive body waves, as emitted by natural or induced seismic sources, were simulated in a synthetic Svelvik model. A body-wave seismic interferometry approach based on previous work at the Ketzin CCS site was then applied. Acoustic measurements of band-limited noise sources, triggered randomly in a region below the reservoir, were modelled and the autocorrelation of the recordings used to retrieve zero-offset pseudo-physical reflection responses. Three scenarios with different repeatability and source distributions were simulated. The result is good when repeatability of the time-lapse interferometric surveys t0 and t1 is high (Figure 12, Scenario 1 in first row). The result is degraded when the random spatio-temporal distribution of the same noise sources is different at t1 as compared to at t0 (Figure 12, Scenario 2 in second row). Scenario 3 reflects a more realistic situation, where several noise sources exist, but the number of incidences varies for each source. The difference in the source distribution gets compensated as the overall source area is better sampled. This leads to an improved retrieval of the time-lapse reflection signal (last row in Figure 12).

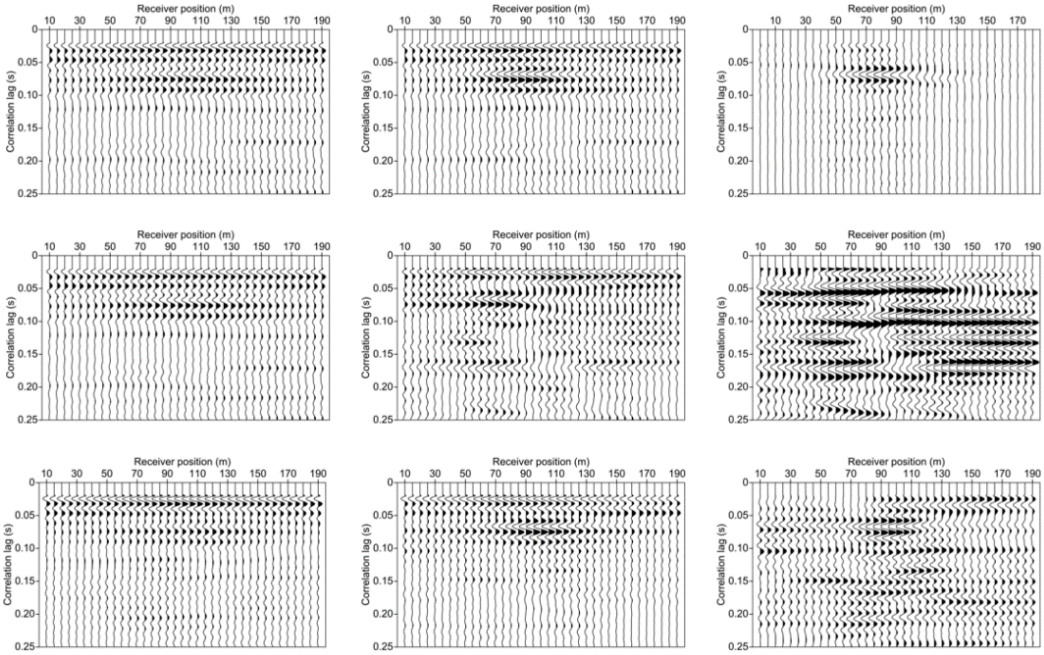


Figure 12: Retrieved zero-offset reflection responses. From left to right, result at t0, result at t1 and the difference scaled by a factor 2. Top row: same source distributions at t0 and t1. Mid row: different distributions. Bottom row: different distributions, approaching conditions in the field by applying a higher number of events.

Work package	WP3: Verification of site performance							
Participant (lead underlined)	BGS	GFZ	NORSAR	SINTEF	TNO	PML	Industry	SUM
Estimated budget (kEuro)	70	213	20	200	411	0	60	974

In WP3 a quantitative workflow combining reservoir modelling, monitoring data, and uncertainty analysis was developed for assessing industrial scale CO_2 storage site conformance. The workflow can be applied prior to injection to evaluate alternative monitoring strategies. It can be part of risk-based frameworks traditionally used in the industry, replacing or supporting the qualitative ranking of monitoring strategies by expert judgement. It builds on Value of Information (VOI) theory and extends a practical workflow for VOI assessment developed recently for application to oil field development.

The WP3 workflow supports relevant definitions of conformance coming from CCS operators and regulators. Conformance has been defined as consistency between modelled and measured data in compliance with storage permit requirements. For individual CCS sites conformance assessments may be based on, for example, reservoir pressure or temperature limits, containment in a confined reservoir volume, or any other indicator. A conformance metric has been proposed that can be derived also in the presence of multiple types of data. Due to uncertainties, conformance assessment should also depend on desired or required confidence levels for identifying conformance and non-conformance situations. Because of its model-based approach, the workflow allows for the verification of future conformance based on current and past data, enabling the prediction of CO_2 behaviour and the early identification of possible development of non-conformance situations. It also supports decision making for implementing risk mitigating measures.

The workflow (Figure 13) was developed and demonstrated with relatively simple conceptual 2D and 3D models in combination with different risks, such as migration of the CO_2 outside of laterally defined boundaries, and leakage of CO_2 through a vertical barrier. Monitoring strategies in these cases include

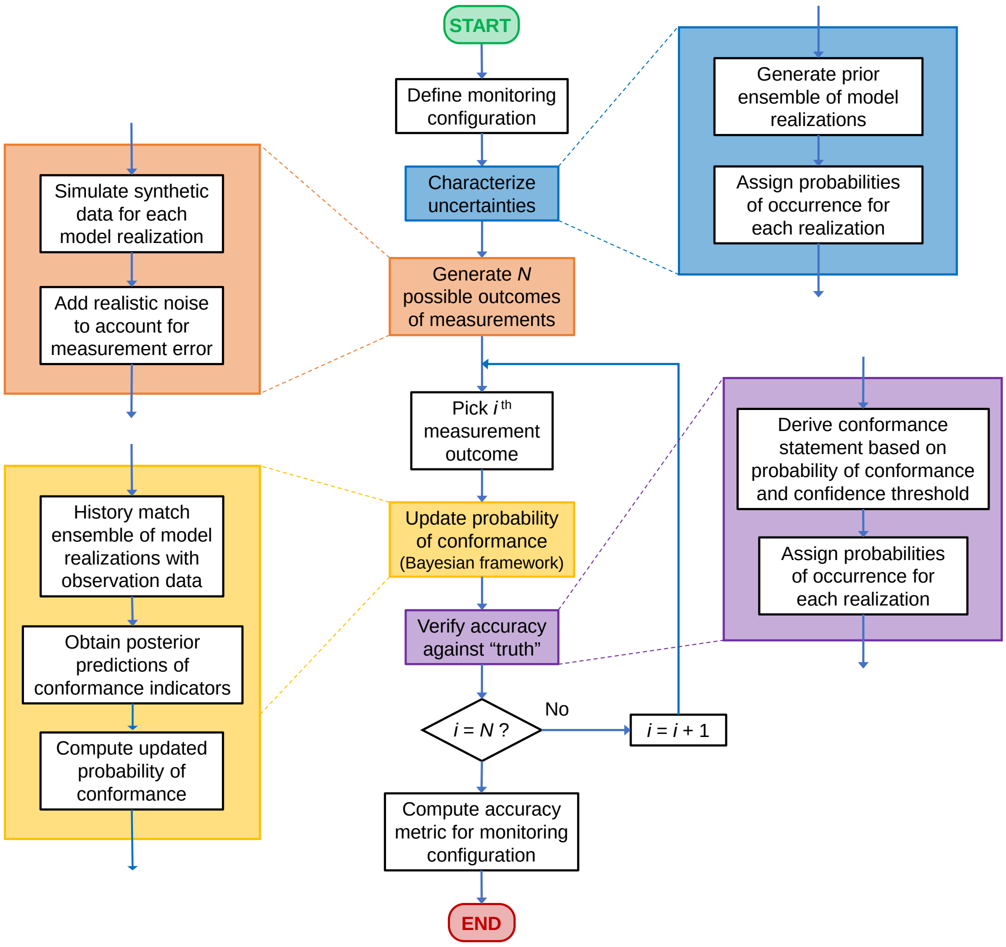


Figure 13 Sketch of the workflow for application of the conformance verification methodology to the evaluation of monitoring strategies.

reflection seismic (tested on a 2D case) and pressure measurements at monitoring wells (3D case). A study using the WP3 conformance workflow was also performed for the Smeaheia candidate CO_2 storage site. Conformance and Value of Information were assessed using Bottom Hole Pressure (BHP) and geophysical 'pinger' measurements with a conformance indicator defined as the pressure near an internal fault. This was all done in the context of CO_2 storage decision making including an underlying economic model further elaborated in WP4. The loop is over multiple random model realizations and measurement outcomes. An application to a simple 3D case is illustrated in Figure 14. The workflow was applied for different BHP measurement accuracies. The outcome of each application is the probability of conformance. A final assessment (in terms of conformance or non-conformance) resulting from applying a confidence threshold α was considered. Here, a threshold of 0.8 means that a state is associated with conformance if 80% of the assessments based on multiple repeats for random model and data realizations suggest conformance.

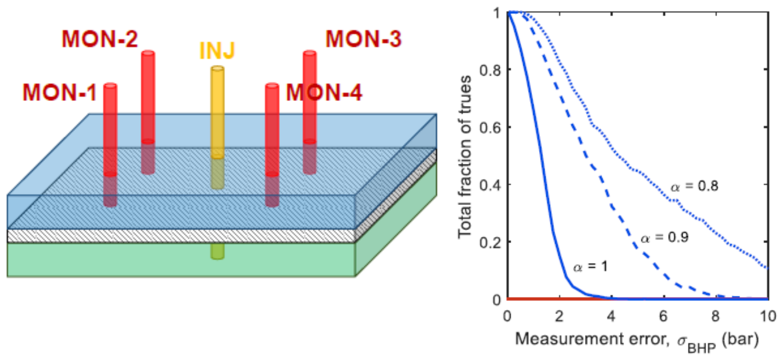


Figure 14 (Left) 3D conceptual CO_2 storage case consisting of a storage reservoir (green), a vertical flow barrier (white) and an overlying fresh water aquifer (white) that is accessed by 4 monitoring wells (red). (Right) Expected quality of conformance assessments for varying BHP measurement accuracies and probability thresholds α.

The workflow was also applied to models of the Smeaheia aquifer, a candidate site for CO_2 storage in the Norwegian section of the North Sea. Possible conformance and non-conformance scenarios were created and simulated based on an identified risk of pressure communication with the neighbouring depleting troll gas field. The workflow results (Figure 15) suggested that seismic data would provide additional value over BHP data in terms of conformance assessment accuracy only if the seismic data are recorded after 7500 days of injection. For CDP data the results suggested that the data should be of high accuracy (low noise level) to be valuable.

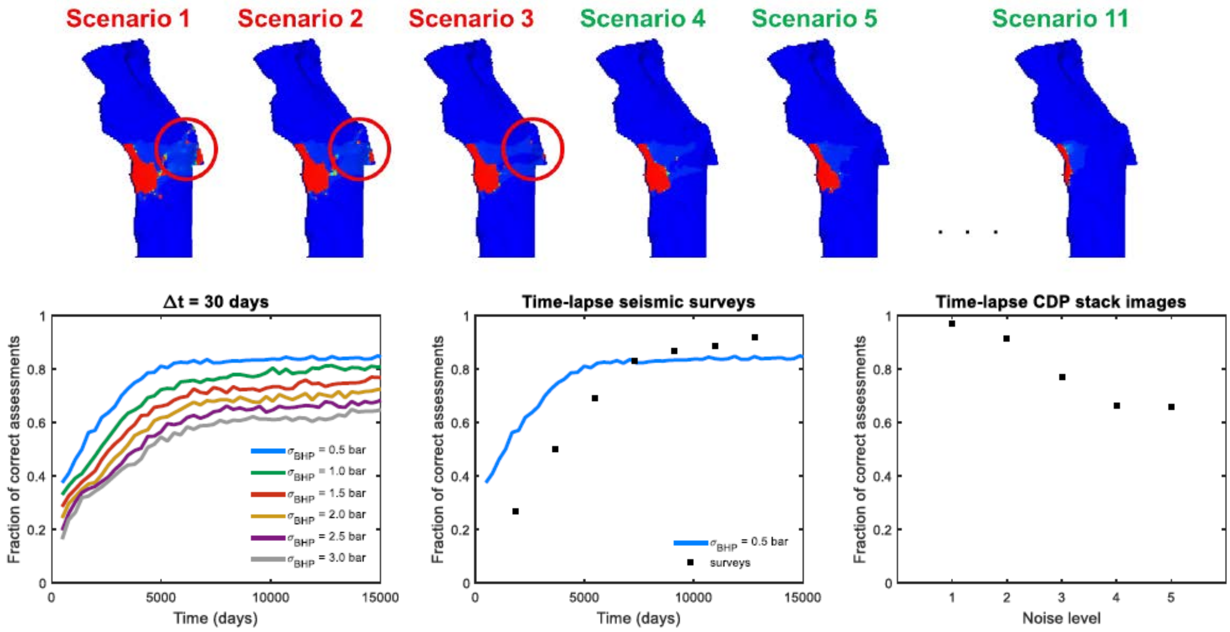
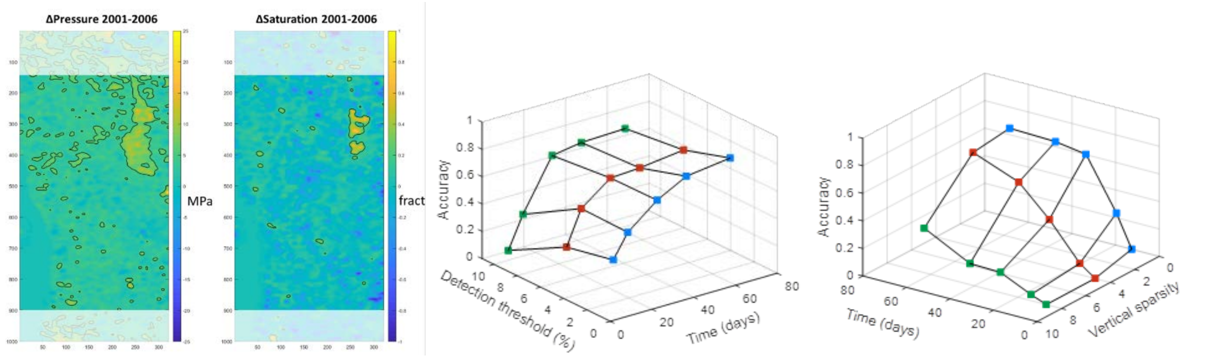


Figure 15 Conformance scenarios showing CO_2 spreading (top) and monitoring performance metrics (bottom) for various strategies.

WP3 has investigated the use of multiple data types that may be used in conformance verification, including geophysical data such as gravity, CSEM, seismic and derived features like inversions or interpretations of these data. Time-lapse AVO and time-shift data were inverted to reservoir pressure and saturation changes, data conditioned and converted to thresholds and fronts. The approach was tested on both synthetic data of the Smeaheia model, data from Norne, and data from the Svelvik test site (Figure 16).

Different approaches for evaluation of survey acquisition optimisation, reprocessing, and conditioning schemes for value-of-information (VOI) assessments were also developed and successfully demonstrated in WP3 (see Romdhane and Eliasson (2018); Carpentier and Boullenger (2019); Carpentier et al. (2018)).



(a) (b)

Figure 16. (a) Inverted pressure and saturation differences for Norne. (b) Expected accuracy of conformance assessment for the Svelvik site achieved with monitoring by changes in acoustic impedance as a function of detection threshold and time of measurement (left) and time of measurement and vertical sparsity (right). The colours indicate the time-series for various detection thresholds (left) and vertical sparsity (right).

Work package	**WP4: Decision making for safe storage (Pressure-driven ACTion)**							
Participant (lead underlined)	BGS	GFZ	NORSAR	SINTEF	TNO	PML	Industry	SUM
Estimated budget (kEuro)	20	50	20	100	80	0	80	350

The objective of WP4 has been to investigate the options that are available to an operator if a conformance test for a CO_2 storage site fails, and to illustrate how the decision-making process could be implemented in the probabilistic framework of the WP3 conformance testing. The work was organised in three tasks: Task 4.1 – Review of demonstration and pilots; Task 4.2 – Actions for pressure non-conformance; and Task 4.3 – Recommendations for decision-making.

An important part of WP4 has been to learn from the experience of current and past operators of CO_2 injection sites and from the results at demonstration and pilot sites. Much can also be learnt by examining operating procedures in use in the oil and gas industry. To facilitate the dialogue between research partners in the project and the industry partners, a workshop was organised in Task 4.1 on the day after the project kick-off meeting in November 2017 (D4.1.1). The objective of this workshop was to engage with the industry in discussions on how their experience with previous non-conformance events in injection operations, both in oil and gas production and in CO_2 operations, can be used to improve decision making for future CO_2-injection operations.

Statoil (now Equinor) presented their in-house procedures for surveillance and anomaly handling of CO_2 injection wells. They focussed on general procedures for CO_2 injection and for handling of irregularities. The presentation covered Statoil's experience with injection wells (including water injection wells) and gave some details on the CO_2 injection into the Tubåen formation at the Snøhvit Field. For an injection operation, a number of key parameters of the injection well have to be monitored, and safety windows for the parameters defined. Trends in the monitored parameters are followed up manually. The effectiveness of this barrier philosophy depends on the knowledge in the organisation. In case of alarms, a cross-disciplinary team will be set up to evaluate the situation.

Total presented experience from the operation of the Lacq-Rousse CO_2 injection pilot, and from their participation in the Decatur project. Important aspects for Total in these projects have been to understand the observed microseismic events in the region around an injection operation, and whether these indicate deviation from expected CO_2 migration.

TNO gave a presentation of the work to define a monitoring plan for the P18-4 storage site in the ROAD project. For the depleted gas field, a monitoring plan based on a traffic light philosophy was adopted. Monitoring frequency is either gradually reduced, maintained, or increased based on whether the monitoring data falls within the expected range or outside of a pre-defined bandwidth. Combined with WP3 results this enables probabilistic-based decision-making.

GFZ presented the modelling and conformance assessment work done for the Ketzin CO_2 injection pilot. An extensive set of monitoring data has been collected for this site during the various phases of the project.

The workshop was concluded with a discussion of what kind of tools the industry will need for their decision support in CO_2 injection operations. A general comment was that the industry has their own procedures for safety of operations that can be adapted for use also for CO_2 injection. The industry would be interested in modelling studies and scenario analyses to examine the consequences of various types of actions in given non-conformance situations. The workshop, and the minutes of meeting constitutes deliverable (D4.1.1) of the project.

GFZ has further contributed to the work in Task 4.1 and Milestone (M4.1.1) by identifying a non-conformance issue from the Ketzin injection history and sorting it into the catalogue of possible non-conformance scenarios.

The overarching objective in the operation of a storage site, and therefore in decisions on possible changes to the operation, is the safe and permanent containment of the injected CO_2. If analysis of monitoring data and the assessment of the degree of conformance to predictions indicate that changes to the operation is necessary, the possible actions will be evaluated based on their efficiency in bringing the storage operation back on track towards safe storage. The actions to be evaluated will depend on the character of the non-conformance event. A list of available remediation actions for the specific storage project is typically set up in the development phase of the storage site as part of the risk analysis and the definition of a corrective actions plan. Discussions in FEED documents of White Rose, Peterhead are excellent examples of this for CO_2 storage operations. The operator should also be prepared to handle unforeseen developments by assembling an expert team to analyse the situation. It is important to note that the timing of the collection of future monitoring data also is something that should be subject to analysis, since the time at which new information is available, and the decision on the further course of action can be made, can impact the efficiency of this action in remediating a potential deviation from the desired development.

A decision-making framework was set up in WP4, building on the probabilistic conformance analysis of WP3 and adding a decision-tree analysis. The decision tree was coupled to an economic model of the total value of the storage operation, to allow quantitative analysis. The decision-making framework was tested on a CO_2 storage scenario developed in several meetings with the WP4 research partners, and with invited advice from industry partners.

In the scenario a storage site operator wants to inject CO_2 into a reservoir that is bisected by a fault with uncertain transmissibility. An identified risk scenario for the storage operation is rapidly increasing reservoir pressure due to limited pressure communication across the fault. This would in effect limit the amount of CO_2 that can safely be injected with a single injection well (the initial operation mode). A threshold value is defined for the pore pressure near the fault to be able to categorise reservoir behaviour as acceptable or not acceptable. It is assumed that the site operator has set up a monitoring plan to be able to estimate the actual value of the pore pressure at the point of interest from measurements. These estimates would, however, be associated with some uncertainty due to measurement errors and uncertainties in model predictions linking the observed parameter to the pressure near the fault.

The decision problem set up will allow the operator to analyse the probability that the site is developing towards an unacceptable state, but also analyse whether the available actions (in our case either stopping injection or extracting formation brine from a second well in the reservoir) will be able to bring the site back to an acceptable state. An important aspect in this analysis is to assess not just what type of information to collect for the conformance assessment, but also the timing of the data collection, since this timing also will determine when any necessary corrective actions can be implemented. This can affect the efficiency of such actions.

The scenario studies and subsequent analysis were performed by Pre-ACT partners SINTEF and TNO, while several of the other research partners contributed to discussions. The studied scenario was based on a reservoir model of the Smeaheia site, released by Equinor for use in the project. Figure 18 (left) shows the initial pressure in the reservoir, and also indicates the fault where we assumed, for the sake of the scenario analysis, that transmissibility properties were uncertain. The fault in the reservoir model is artificially extended to the eastern boundary of the model. The porosity and permeability of the reservoir were assumed to be uncertain, and Figure 18 (right) shows the predicted pore pressure development at a point near the fault, for each of a set of 200 realisations of the model. For some of the models the pore pressure will exceed the defined threshold value if injection is continued throughout the 20-year operating period. Figure 18 shows the decision tree used in the analysis.

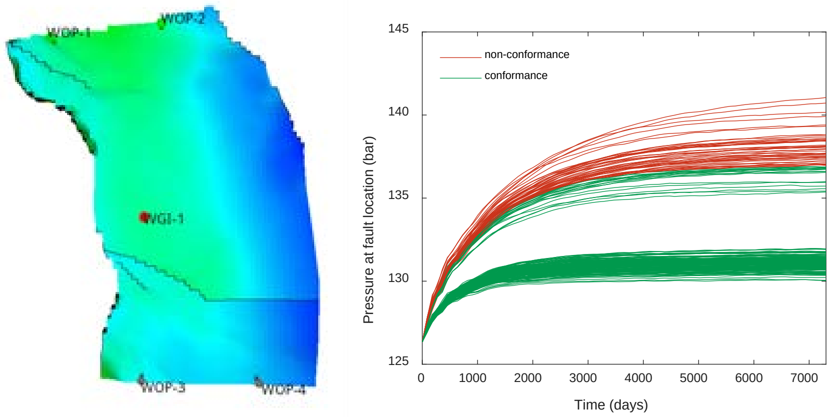


Figure 17: Illustration of reservoir model for scenario analysis (left). Base predictions of pore pressure for 200 realisations of model, half of them with zero-transmissibility fault (right).

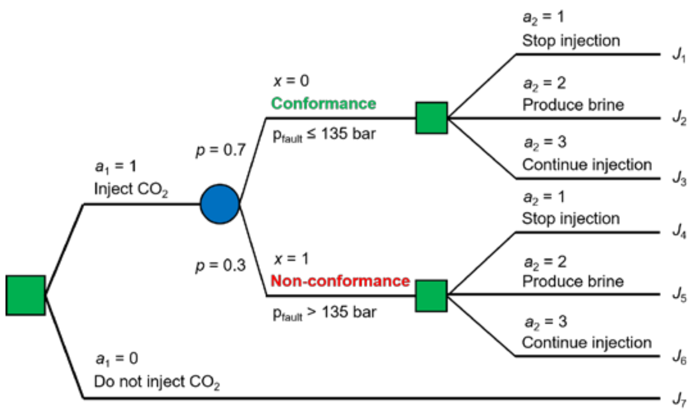


Figure 18 Decision tree for analysis of total system value for different actions.

The analysis assumed that information up to a given time is used to decide on further actions. At this time the real state of the system will be uncertain, but the probability of false positives or false negatives in the conformance statement will be in general be gradually reduced as more data is collected. This is somewhat dependent on the magnitude of the error in the monitoring data, however. The reduced uncertainty will not in all cases lead to a desire to postpone decisions, since implemented corrective actions such as brine production, will be less effective at later times, and may eventually not be sufficient to avoid pressure above the threshold. We showed that this could mean that the expected value of the system as a function of the time of measurement increases initially but reaches a maximum at some point in time and thereafter is gradually reduced.

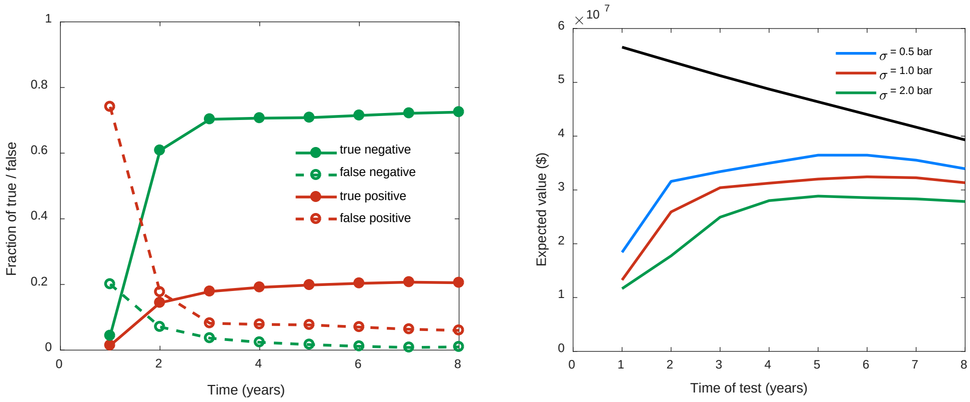


Figure 19. Development of fraction of true/false positives and negatives as more information in collected (left). Expected value of system as function of the time of decision-making (right).

Figure 19 illustrates these aspects; both the increased confidence and accuracy of the conformance assessment, and the eventual reduction in expected system value as the decision is postponed.

Results from WP4 were presented in an open webinar in March 2020 and in a project workshop with industry participation in June 2020 (D4.2.1 and D4.3.1). The scenario analysis with presentation of the probabilistic decision-making framework is further presented in an extended abstract for the GHGT-15 conference (D4.1.2).

Work package	**WP5: Case studies and stakeholder confidence**							
Participant (lead underlined)	BGS	GFZ	NORSAR	SINTEF	TNO	PML	Industry	SUM
Estimated budget (kEuro)	85	25	20	200	80	0	112	522

The results from WP1 through WP4 were applied to three storage sites, to demonstrate the development of injection strategies and monitoring plans that are both cost-effective and efficient given the uncertainty of the geological description of the sites, and that provide a clear path towards demonstration of conformance. The aim of WP5 was to demonstrate the value of the project's results through application of the methodology to storage scenarios at realistic sites and to communicate the results to stakeholders: authorities, regulators, policy and decision makers, politicians, etc.

T5.1.1: Smeaheia case. *(SINTEF, Equinor)*

Injection into saline aquifers was studied using a case built around the Smeaheia site, offshore Norway, which is one of the potential storage locations for the next Norwegian full-chain CCS demonstration project (Lothe et al. 2019). The geological complexity was linked to studies in WP1 on the dissipation of pressure into aquifers during CO_2 storage, and the effect of the depletion due to gas production from the Troll Field and effect of fault properties was simulated (Lothe et al. 2018).

The simulated pore pressure were used as input into reservoir modelling varying the reservoir heterogeneity properties (Lothe et al. 2019; Emmel et al. 2020, to be submitted, see Figure 20). The work relied on the understanding gained in WP1 to assess the role of heterogeneous fault systems during CO_2 injection and fluid extraction, and on the understanding of monitoring systems and data built up in WP3. The activities in WP5 revolved around the application of the WP3 methodology to realistic problems based on current challenges encountered in real CO_2 storage sites. The quantitative conformance assessment approach with multiple types of data (e.g., BHP measurements and time-lapse seismic surveys) to obtain early signals of possible migration of the CO_2 plume to undesired areas of the Smeaheia aquifer was tested (see Barros et al. 2020).

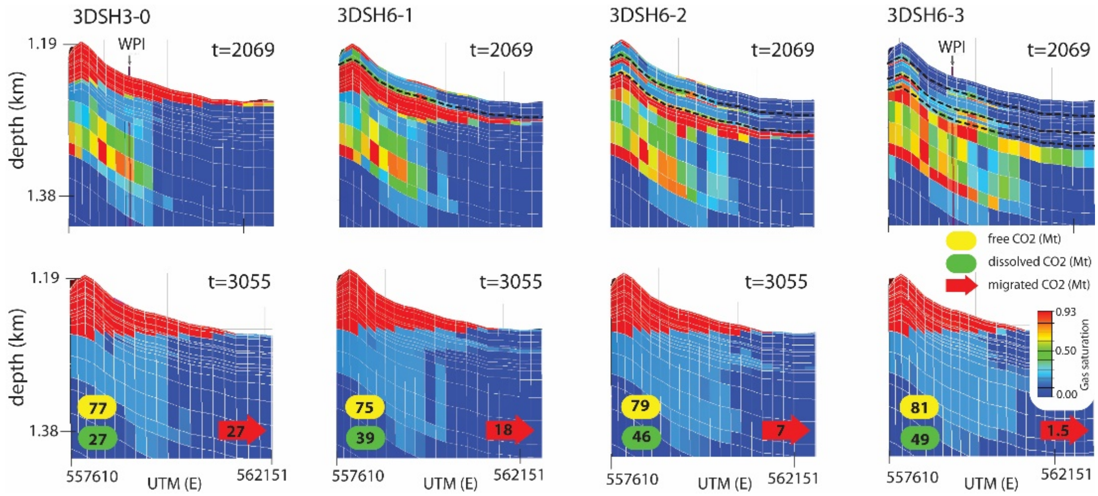


Figure 20: Dynamic modelling results along a cross section through the alpha structure showing gas saturation for two timesteps. The influence of 0 to 3 low permeable shale layers within the Sognefjord Formation (black dashed lines) beneath the major caprock unit is tested. CO_2 injection started in year 2019, with a rate of 3 Mt/year over 44 years. A CO_2 saturation segmentation pattern developed beneath the low permeable layers resulting in longer migration paths and time favouring CO_2 dissolution (Emmel et al. 2020, to be submitted; D5.1.1b).

T5.1.2: Depleted gas fields (TNO, TAQA)

TNO formulated the quantitative conformance verification problem for an injection well system in a depleted gas field as a representative configuration of CO_2 storage operations in the Dutch sector of the North Sea. In this case, they evaluated the usefulness of pressure and temperature measurements at various downhole depths for verifying conformance related to bottom-hole conditions.

Figure 21 depicts a schematic representation of this second case study and the results obtained for the analysis of pressure measurements at different gauge depths. As a general trend, we noted that accuracy starts increasing only for gauges at lower depths (> 3500 m, in this case), confirming expectations that many gauge depths would lead to ambiguous discrimination of conformance and non-conformance cases (i.e. here determined based on pressure and temperature bottom-hole conditions). The impact of noise also confirmed intuitive results which can now be supported quantitatively: higher levels of noise leads to a decrease in accuracy.

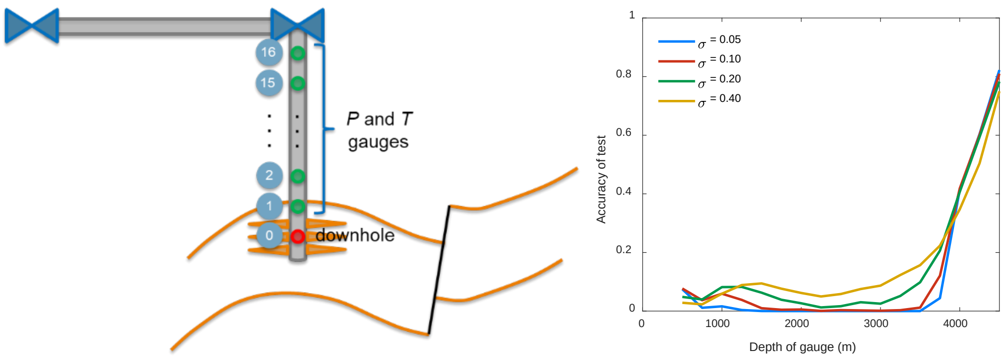


Figure 21: Schematic representation of injection well system with candidate locations for the downhole gauges (left panel). Accuracy of monitoring configurations with different levels of noise in the data as a function of depth of downhole gauges for the case with both pressure gauges for a confidence threshold of 95%.

The results obtained illustrated the sort of insights that can be derived from this kind of quantitative exercises. These results were disseminated among Pre-ACT research and industrial partners throughout the 3-year project, including presentations at various progress meetings, workshops and open webinars (D5.1.2).

T5.1.3: Pressure-linked sites case. *(BGS)*

The Pre-ACT conformance approach was applied to the Endurance Structure in the UK Southern North Sea. CO_2 Storage was modelled in the Triassic Bunter Sandstone Formation where regional seals have a history of hydrocarbon trapping. The structure (Figure 22) is a long-term target for saline aquifer CO_2 storage, ensuring research applicability to interested stakeholders, with several current industrial-led projects targeting the closure. Data interpretation was carried out enabling attribution of a 3D reservoir model, whilst also providing datasets to the wider community on reservoir and caprock properties from core plug analysis and seismic interpretation.

In line with the Pre-ACT conformance approach, an ensemble of models was constructed to test the Pre-ACT protocols (Figure 23). Each of these models was taken through a processing pathway that featured reservoir flow modelling and synthetic data generation. Site-specific conformance criteria were set, enabling the modelled data (downhole pressure and sparse 2D seismic) to be assessed in line with expected site performance. The ensemble was used to capture the quantitative likelihood of an accurate prediction by comparing the monitoring data from a 'true' scenario with the suite of model outputs. As such, in addition to offering an assessment of quantitative conformance the tools can also be used to provide information on the most suitable time to undertake measurement campaigns – improving site cost effectiveness.

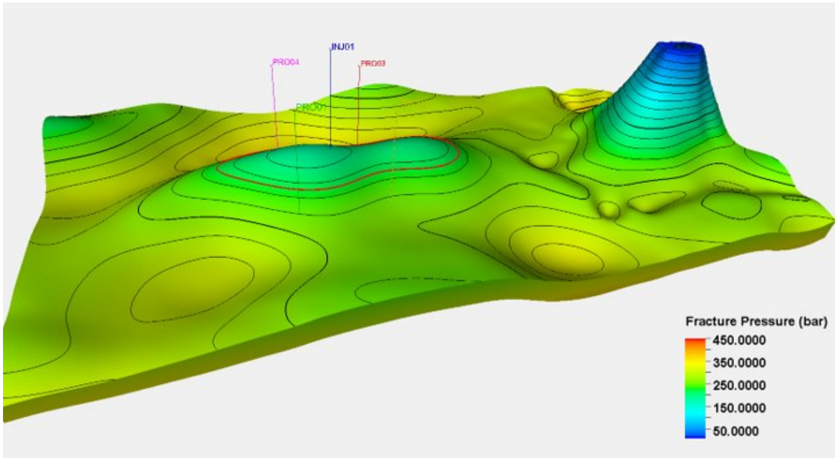


Figure 22: Endurance reservoir model, attributed with fracture pressure limits, a key conformance criteria.

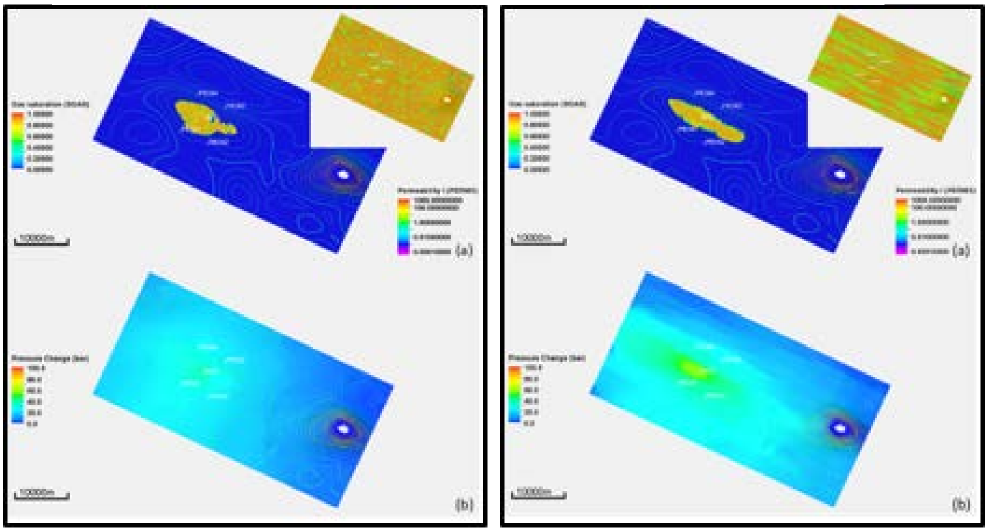


Figure 23: Two examples from the ensemble of reservoir models showing CO_2 saturation (top), pressure (bottom) and structure (inset).

T5.2: Stakeholder workshops

Three stakeholder workshops were arranged to communicate Pre-ACT results and how we can help accelerating CCS to authorities, regulators, policy and decision makers, politicians, etc. (D5.2.1).

The First Pre-ACT Stakeholder Workshop in WP5 took place in Trondheim, 10th of April 2019. The theme was: "The first government exploitation permit for CO_2 storage at the Norwegian Continental Shelf has been awarded to Equinor". How will this influence research in Norway and Europe? And how can the research contribute to safe storage in the next phase? Key stakeholders from the Norwegian Ministry of Petroleum and Energy, Gassnova, Bellona, Equinor, Lundin attended alongside several industry representatives and funding agencies from the UK and Norway. The mix of skills, experience and focus contributed to a fruitful workshop.

The Second Pre-ACT Stakeholder Workshop was arranged at Hilton Grand Place, in Brussels, the 10th of September 2019 with the theme "Mission: Safe and Cost-efficient CO_2 storage for European Industries". For this workshop we also invited other ACT-projects, other European storage sites and Vassilios Kougionas, from the European Commission to present. Attendees from EU system, and key stakeholders in Brussels included NHO, Bellona, Zero, Shell, Total, Equinor and TAQA.

The Third Pre-ACT Stakeholder Meeting was arranged the 13th of November 2019, at Svelvik, Norway in collaboration with the official opening of the ECCSEL Svelvik CO_2 Field Lab. We had 55 participants mainly from the local community (Hurum Kommune, Svelvik Sand), the Norwegian government (Stortinget, NPD), from funding agencies (Gassnova, NFR), research institutes (NORCE, SINTEF, NGI, IFE BGS, TNO, GFZ), and from industry (Lundin).

Figure 24: The discussion panel at the 2nd Stakeholder meeting in Brussels, from left; Nils Røkke (SINTEF, EERA Chair), Eric Cauquil (Total, Leader Gas and CCUS Risk Management), Ane Lothe (SINTEF, WP5 leader Pre-ACT), Jonas Helseth (Bellona, Director of Bellona Europe) and Anne Cavendish (Equinor EU Affairs Office).

Work package	**WP6: Project management**							
Participant (lead underlined)	BGS	GFZ	NORSAR	<u>SINTEF</u>	TNO	PML	Industry	SUM
Estimated budget (kEuro)	0	0	0	358	0	0	0	358

The work in WP6 started with a significant effort to establish a Consortium Agreement and an updated project master plan (Gantt with deliverables, milestones and responsible partners, D6.3.1). The project was launched as planned with a kick-off meeting in November 2017 (M6.3.1) and the first Executive Board meeting was arranged before the end of the year (M6.3.2). Both the Executive Board and a management team were established at the very start of the project (M6.3.3). The management team met, mainly via Skype/Teams, every quarter to discuss status, coordinate work package activities, update plans, and prepare the quarterly traffic light reports (D6.3.2). In addition, the work package leaders have arranged, individually, shorter and more specific update meetings.

A first version of the Pre-ACT website was established only few days after the official start date of the project (D6.4.1) and except for the first 6 months, the website has been regularly updated.

Key project personnel met with Norwegian and UK funding agencies directly after the first stakeholder meeting (in April 2019, see WP5 description above) to discuss improved communication strategies for Pre-ACT. The main message from ACT was that dissemination activities towards the public and towards European stakeholders had to be strengthened. Pre-ACT responded to this by arranging a second stakeholder meeting in Brussels and by co-arranging the inauguration of the Svelvik CO_2 Field Lab open to both the public and to various stakeholders. The Pre-ACT web page was updated with more popular-science material (e.g. videos with key messages from Pre-ACT, operators, and other stakeholders). The opening of Svelvik was also covered by both Norwegian and Swedish media.

As described in Sections 3 and 5 below, the webinar series (D6.4.2) was delayed until the last 6 months of the project instead of being arranged continuously throughout the project. The timing of the webinars, however, turned out to be ideal. Nearly all final results could be presented, and as the Pre-ACT project had become widely recognized at this point the *open* webinars were extremely well attended. The Covid-19 situation and many scientists starving for conferences/workshops certainly helped as well.

Other outreach activities such as an active website, presentations and posters at many workshops/conferences, and the dialogue with other ACT-projects have also contributed to dissemination of project results.

Risks and mitigation measures are continuously assessed. In particular, risks related to data access and to the Svelvik experimental campaign have been revised regularly (D6.2.1).

3. Project impact

The main outcome of the Pre-ACT project consisted in methodologies and recommendations for cost-efficient monitoring, reliable conformance assessment, and decision making (Pre-ACT Protocols). The main contribution to the emergence of CCS has been to provide the future CO_2 storage operators with protocols that help verify that the storage operations can be performed in a safe manner as part of a competitive business. The methodologies developed for this purpose have been demonstrated through case studies for realistic scenarios based on three relevant North Sea cases; a Smeaheia case (led by SINTEF and linked to Equinor), a P18-4 case (led by TNO and linked to TAQA), and an Endurance case (led by BGS and linked to Shell). The scenarios and simulation models were developed in close dialogue with the industry partners to ensure their relevance to issues important for current and future CO_2 storage operations. This has allowed demonstration of the value of the Pre-ACT results and provided a route to market (commercialization) for the Pre-ACT Protocols. Central in Pre-ACT are the conformance assessment and decision-making support methods. Workshops have been held to bring together industry, stakeholders, and researchers to discuss the actions necessary to return a site to acceptable behaviour in case of non-conformance. Further workshops were organised to ensure maximum impact of the developed methodologies.

The Svelvik CO_2 Field Lab has been reopened with the aid of ECCSEL financing and Pre-ACT has been the first significant project to conduct experiments at the site. Pre-ACT researchers have been central in the design of the well instrumentation and the planning of the first-of-its-kind experimental campaign. The goal of the injection test conducted was to verify recently developed techniques for distinguishing between saturation and pressure changes in the subsurface. Accompanying this surge in activity, measures were already taken to use the unique location and visibility of Svelvik to engage with local residents. This impact on public acceptance and information about CCS has already had a positive effect by Svelvik being added to retained sites for participatory monitoring research in another project, the H2020 LCE 27 SECURe project. The Pre-ACT project itself also partnered up with other projects interested in the data generated by the project: the NTNU-coordinated ICO2P project was given permission to acquire data during the Pre-ACT injection campaigns and a similar offer was given to the ACT Phase 2 project DigiMon, but they were not able to come to the site as their project was still in the start-up phase. A Gassnova-funded project coordinated by SINTEF acquired a large amount of fibre-optics data from Svelvik during the Pre-ACT CO_2 injections.

An open webinar series with six webinars was conducted during the first half of 2020, show-casing important results from Pre-ACT and providing an accessible platform for interested stakeholders to hear about Pre-ACT and interact with its scientists. Announcements of the webinar series were spread throughout the global CCS research community via newsletters, information at other meetings and email, using the extensive contact network of the project participants. The webinars, which started just as the research community drastically reduced travel activities due to the Covid-19 outbreak, saw very good attendance from persons both inside and outside the Pre-ACT consortium, with attendance ranging from 49 to 110 registered participants.

Three stakeholder events have been organised by the Pre-ACT project (see more detailed description in the section on Task 5.2 above). The first stakeholder workshop was held in April 2019 in Trondheim.

The second was held in Brussels in October 2019, and the third in connection with the official opening of the Svelvik CO_2 Field Laboratory in November 2019.

Among other outreach activities that have gained attention, can be mentioned the work on how a hypersaline release of water at the surface in the northern North Sea would behave under tidal conditions. A video released to demonstrate this, won the ARCHER Competition in 2018: https://www.pml.ac.uk/News_and_media/News/Video_victory_for_PML_scientist.

The hypersaline release work has also received additional funding from BP and PML has submitted a report to inform the FEED and permitting of a Southern North Sea site. This resulted in a workshop (M1.5.2) on 'Geophysics for CCUS and the Controlled Release of Produced Brine' with senior staff at BP.

The Pre-ACT project provided a visible evidence that accelerating CCS technology must be done in consortia with complementary experiences, gained by the project partners from their research on still operating or successfully finished storage cases. This has also been underlined by the continuous interest from overseas institutions, as e.g., CO2CRC in Australia and CaMI of Carbon Management Canada. As examples of this can be mentioned that Pre-ACT was invited to take part in the Otway Stage 3 Peer Review panel in 2018. This ensured international exposure to the project and built on the understanding of pressure propagation gained in Pre-ACT WP1.

In January 2019, Equinor was awarded the first exploitation permit for CO_2 storage on the Norwegian Continental Shelf. By involving Equinor, and its partners Total and Shell, closely in Pre-ACT and answering to their immediate needs, we believe that the Pre-ACT project has contributed to the emergence of CCS in the North Sea and to the competitiveness of those industry partners within CCS. A decision for the Norwegian full-scale carbon capture and storage project is expected in 2020/2021. While the Johansen formation is the planned initial storage location, the Pre-ACT project has in the same way as Equinor's research groups investigated Smeaheia as a later and potentially larger storage location for Norwegian full-scale storage. Pre-ACT has followed the progress of the project closely, with continuous updates on the status from Equinor.

Pre-ACT has tried to encourage gender balance, and women led two very important work packages (WP2 and WP5). In addition, the Svelvik CO_2 Field Lab project leader is a woman who has been very visible during the Pre-ACT experimental campaigns and often even helped presenting results from the Pre-ACT work at the site. For Pre-ACT workshops and stakeholder meetings, female participants have been invited as central speakers.

During the final Pre-ACT meeting, Aage Stangeland (on behalf of ACT) challenged the project members to include the ten main findings from the Pre-ACT project in the final report. Table 1 shows a list of what we feel are the main achievements of the project with short descriptions of each.

Table 1:Ten key finding/achievements as requested by ACT (Aage Stangeland) during the final Pre-ACT meeting.

Finding/Achievement	Remarks
Effects of uncertainties and heterogeneities on prior reservoir modelling	Methodologies for prior reservoir modelling in storage complexes with uncertain fault properties and heterogeneous porosity/permeability distribution have been developed. Such modelling approaches are mandatory for predicting pressure response and need for pressure management before starting any injection. Pre-ACT has also shown the importance of multiple scenario modelling and uncertainty assessment as input for the conformance verification workflow.
Effect of hypersaline discharge	Pressure management of reservoirs used for CO_2 storage is a key component of maintaining cap rock and reservoir integrity of the storage complex. Where storage utilizes saline aquifers, pressure management may potentially require production of reservoir brines. Careful Pre-ACT studies of brine dispersion into seawater have been conducted and show that in relatively shallow well-mixed environments, we find that the natural mixing

	processes, dominated by tidal flow, disperse hypersaline plumes rapidly. The developed approach will allow future cost-benefit appraisal of brine disposal methodologies.
Pressure/saturation quantification	A central research question in Pre-ACT has been how to quantify pressure and saturation changes accurately and cost-efficiently in the CO_2 storage complex. Such quantitative monitoring information and associated uncertainties are crucial for comparisons to prior reservoir models, reliable conformance assessment, and decision making. Two novel approaches for quantitative monitoring have been successfully developed in Pre-ACT: one based on combined Bayesian geophysical and rock physics inversion, and one based on deep neural networks. The methods have been demonstrated using real data from Sleipner, Snøhvit, and Svelvik, and with synthetic data from Svelvik. The inversion for rock frame parameters as well as for saturation and pressure is almost instantaneous.
Svelvik CO_2 Field Lab instrumentation and first Svelvik campaign	A significant effort in Pre-ACT has been put into instrumenting and acquiring new data at the Svelvik CO_2 Field Lab during injection. For instance, the design of fibre-optic cross-well monitoring was studied together with its implications on optimal observation well placement. A new low-cost pressure monitoring system, based on hydrostatic transfer of pressure using capillaries, was also developed and tested The Svelvik campaign was delayed by unforeseen problems in the establishment of the field lab, but through a tremendous team effort, injection of saline water and CO_2 under careful monitoring was successfully carried out with a wealth of geophysical data recorded. Initial studies have shown how the CO_2 can be accurately localized by seismic and electrical methods. Several future studies of those valuable data sets are already foreseen.
Conformance workflow	Conformance was early placed at the center of Pre-ACT's attention, being the link between model predictions, monitoring data, and informed decision making. We have shown that it is possible to formulate a quantitative, repeatable, and verifiable model-based process for conformance verification that can be used to support human expert-based assessments. The quantitative process can also be used to evaluate the expected contribution of alternative monitoring strategies to the quality of conformance assessments prior to data purchasing. Useful quantitative conformance criteria imply clear definitions of: (1) conformance indicators (or quantities of interest), (2) acceptable limits for these indicators, and (3) the required (or desired) level of confidence in the conformance statements.
Value-of-information / optimal monitoring data	Pre-ACT has investigated the use of multiple data types (e.g. gravity, CSEM, seismic, and properties derived from those) for conformance verification. The value of different types of data, with respect to their capability to help verifying conformance, vary significantly. Several ways of assessing the value of data and optimizing acquisition of geophysical data have been developed and tested. In combination with the developed conformance workflow such optimization techniques could lead to significantly reduced monitoring costs while still giving all the information needed for informed decisions.
Optimal timing for decisions	The combination of increasing knowledge, through collection of observations of the development of a storage site, and the potentially

	decreasing efficiency of measures to correct the course of development as the operation progresses, leads to the existence of an *optimal timing* for making decisions and implementing actions based on accumulated observations. We have shown how this optimal timing depends on the model and measurement uncertainties, and on the details of the economic evaluation of possible future development scenarios.
Case studies	The three case studies have been instrumental for the dialogue between institutes and industry partners and have resulted in demonstration of key Pre-ACT developments at Smeaheia (led by SINTEF and Equinor), at P18-4 (led by TNO and TAQA), and for Endurance (led by BGS and Shell).
Stakeholder meetings	The three stakeholder meetings arranged in Pre-ACT's months 20-27, gave the project, its results, and CO_2 storage in general a lot of attention among Norwegian and European stakeholders. The meetings were also very valuable to the researchers in Pre-ACT, giving a better understanding of how the research needs are seen at a political level.
Webinar series	With the open webinar series, Pre-ACT managed to reach out to a large number of researchers outside the project and outside the ACT family. The success can be measured in number of participants, but also in the geographical spread and in the different technical backgrounds of the participants.

4. Collaboration and coordination within the Consortium

The collaboration in the Pre-ACT project was coordinated by a trans-national management team, with work package leaders from each of the participating countries. Quarterly management team Skype meetings were organized to share the status of the different work packages and discuss plans for the upcoming quarter(s). For more detailed technical discussions, individual WP's have organised monthly or even weekly Skype meetings to coordinate activities between the different partners. Examples of activities that required more frequent interaction include: feasibility studies, instrumentation planning, and design of the injection campaign for the Svelvik field laboratory as part of WP2; development and demonstration of a value-of-information and conformance workflow as part of WP3; and scenario building and analysis in WP4.

In general, the management structure seemed to be adequate, but in periods some of the monthly WP meetings were not easy to organise due to different availability of personnel at the different research institutes.

The trans-national collaboration has been essential for all work packages. In WP1, BGS coordinated the research with their expertise on pressure propagation and control, with input from Shell. BGS and SINTEF worked together on the analysis of the Smeaheia data, building on an understanding gained in the Norwegian CCS Centre (NCCS). Within WP1, PML's unique competence on hypersaline water discharge was undertaken in conjunction with Shell. Additionally, the work was seized upon by BP as part of their Clean Gas Project in the Southern North Sea. The program of modelling was expanded to assist with increased desire from UK industry to understand the environmental impacts of water disposal. SINTEF helped with large-scale pressure modelling studies, with input from NPD and in close dialogue with Equinor, to provide results of relevance to the Northern Lights project. As SINTEF's geomechanical lab got critically undermanned, their unique competence on how CO_2 injection affects the reservoir from a geomechanical perspective was complemented by available staff and lab equipment at the Norwegian research institute NGI (brought in as a third-party into the project). In WP2, the work at Svelvik benefited from GFZ's experience with the Ketzin project, combined with SINTEF's experience from the CO_2 Field Lab project. The two organisations led the developments of the monitoring platforms required to undertake pressure and saturation discrimination experiments. This collaboration was seen in planning workshops, international visits, joint deliverables and in a

Svelvik planning group containing researchers from both organisations. This was further augmented by NORSAR, with their valuable experience with the design of micro-seismic monitoring systems and the use of fibre-optic DAS sensors. The team worked efficiently, under sometimes difficult conditions as the time schedule had been compressed and the winter season was getting closer, to deliver a world-leading scientific laboratory at Svelvik addressing outstanding monitoring issues for CO_2 storage.

The conformance work in WP3 was coordinated by TNO with significant experience from their work on history matching for the oil and gas industry. This topic was central to Pre-ACT and many of the other partners provided input; BGS with seismic modelling, SINTEF with quantitative inversion and survey optimization, and GFZ with the set up and testing of the workflow. These collaborations resulted in short researcher exchange visits and regular video conferences to ensure that the flow of models, data and outputs were aligned with each organisation's requirements. SINTEF and TNO collaborated closely in WP4, where the quantitative conformance testing methodology from WP3 was integrated into a case study to demonstrate how it can support decision making for a CO_2 storage operation. Industry partners in Norway, UK, Netherlands, and France have also been essential contributors. Without the engagement of our industrial partners, the objectives of WP4 would have been very difficult to achieve, so a close relationship with industrial partners and interested stakeholders have been essential for a full utilisation of results. The case studies in WP5 were meant to demonstrate the value of the Pre-ACT results through the application of the developed methods to different North Sea sites. All partners contributed to conduct the case studies, and the partnerships provided a route to market for Pre-ACT Protocols using projects led by SINTEF (for Smeaheia), TNO (for P18), and BGS (for Endurance).

The collaboration in Pre-ACT has also resulted in many trans-national publications and conference presentations which contributed to accelerate and increase the project outreach. Combining the efforts in this way certainly contributed to the objectives of the individual work packages and allowed for a more seamless transition to the large-scale case studies of WP5.

5. Dissemination activities (including list of publications where applicable)

During the first 18 months of the Pre-ACT project, dissemination activities included mainly organization of technical workshops, participation in international conferences and workshops with oral and poster presentations, publications including extended abstracts and papers, and regular updates of the project website. Following the first stakeholder meeting in Trondheim in April 2019 and feedback from the ACT consortium on the importance of reaching out to a broader audience and to European stakeholders, the dissemination in the second half of the project got a different character. In addition to technical workshops, popular scientific material was prepared, a stakeholder meeting in Brussels was arranged, Pre-ACT contributed to the inauguration of Svelvik CO_2 Field Lab (open to local, national, and international stakeholders and covered by Norwegian and Swedish media), and a very successful open webinar series was arranged. Below follows a summary of those activities. An overview of workshops with access to open documents can be found at https://www.sintef.no/projectweb/pre-act/events/. Similarly, a list of published papers, posters and presentations with links can be found at https://www.sintef.no/projectweb/pre-act/results/ (to be updated also after Pre-ACT has finished as several papers are in review and both EAGE and GHGT-15 have been delayed).

Webinars:

The Pre-ACT webinar series was arranged in the period March to May 2020, with an ambition to spread the main results of the project to a mix of researchers and stakeholders. The six webinars had between 49 – 110 registered participants, with an excellent geographical mix (many European countries, but also from US, Japan, Australia, and even Africa). With a total of 229 unique participants representing industry, research institutes, academia, and funding agencies, it can be considered a huge success for this type of webinars. The complete agenda is shown in Figure 25 and screen shot from the final webinar in Figure 26. All webinar presentations and webinar recordings are collected in D6.4.2.

Pre-ACT webinar #1 — **24 March, 10:00 AM CET**

- Part 1: Pressure propagation and saturation changes in reservoirs displaying geological heterogeneity (*Hayley Vosper, BGS*)
- Part 2: Acoustic emission testing - Investigation of the footprint of a pressure plume (*Pierre Cerasi, SINTEF*)

Pre-ACT webinar #2 — **31 March, 10:00 AM CET**

- Assessing monitoring effectiveness in CO_2 storage operations using a novel conformance verification workflow and decision analysis (*Eduardo Barros, TNO; Alv-Arne Grimstad, SINTEF*)

Pre-ACT webinar #3 — **17 April, 11:00 AM CET**

- Impact potential of hypersaline brines released into the marine environment as part of reservoir pressure management (*Jerry Blackford and Marius Dewar, Plymouth Marine Laboratory*)

Pre-ACT webinar #4 — **13 May, 10:00 AM CET**

- Part 1: Deep Learning a poro-elastic rock physics model for pressure and saturation discrimination (*Wolfgang Weinzierl, GFZ*)
- Part 2: Bayesian rock physics inversion for pore pressure estimation (*Bastien Dupuy, SINTEF*)

Pre-ACT webinar #5 — **20 May, 13:00 PM CET**

- Part 1: Case study: Smeaheia – effect of faults and heterogeneities on CO_2 storage capacity (*Ane Lothe, SINTEF*)
- Part 2: Case study: Endurance, UK (*Jim White, BGS*)
- Part 3: Case study: P18 – CO_2 storage in depleted gas field (*Stefan Carpentier, TNO*)

Pre-ACT webinar #6 — **27 May, 10:00 AM CET**

- Svelvik CO_2 Field Lab: Review of the 2019 injection campaign and interpretation of acquired data (*Michael Jordan, SINTEF; Wolfgang Weinzierl, GFZ*)

Figure 25: Schedule for the Pre-ACT webinar series.

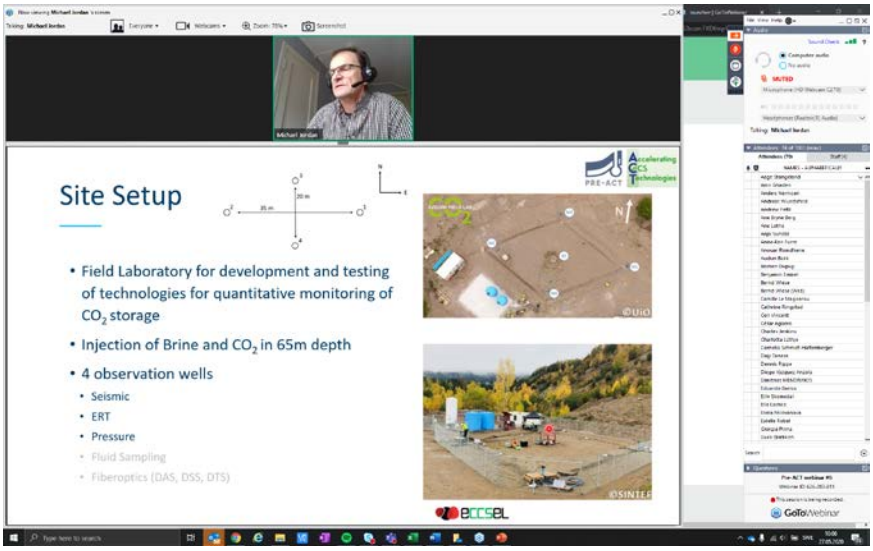


Figure 26: Screenshot from the final webinar on the Svelvik CO_2 Field Lab campaign carried out in Pre-ACT.

Organized workshops:

- Pre-ACT kick-off days at Sem Gjestegård, Norway, 7-9 November 2017.
  - Open workshop about and a field trip to the ECCSEL Svelvik CO_2 Field Lab. Apart from Pre-ACT members, representatives from e.g. NFR, Gassnova, NPD, UiO, Uppsala University, Aker Solutions, smaller vendors and several different research institutes participated in the site visit (see Figure 27).
  - Pre-ACT kick-off meeting (see Figure 28)
  - Pre-ACT WP4 workshop on decision-making

Figure 27: Visit at the Svelvik CO_2 Field Lab in November 2017.

Figure 28: Pre-ACT partners at the Pre-ACT kick-off meeting (November 2017).

- Combined WP2 and WP3 meeting with public workshop on "Quantitative measures of site conformance" (20-21 February 2018, Utrecht, Netherlands). External participation from EBN (Netherlands) and NPD (Norway).
- Pre-ACT Annual Meeting (19-20 November 2018, Utrecht, Netherlands)
  - Annual meeting
  - CO_2 monitoring/conformance workshop (semi-public). This meeting included a common lunch with the ACT ECOBASE project, participants from other ACT projects (Elegancy and DETECT) and projects such as ENOS, the Field Research Station (FRS), and ICO2P.
- 1st Pre-ACT stakeholder workshop in Trondheim 10 April 2019 (Figure 29). See also WP5 status in Section 2.

Figure 29: Group meeting from the 1st Stakeholder meeting in Trondheim, 10th of April 2019.

- 2nd Pre-ACT stakeholder workshop in Brussels 10 September 2019
- 3rd Pre-ACT stakeholder workshop at Svelvik CO_2 Field Lab 13 November 2019
- Pre-ACT annual meeting 2019, Sem Gjestegård, Norway 13-14 November 2019
- Combined WP2 and WP4 workshop 3 June 2020. The workshop was organised as an online meeting, with nearly 20 participants. Topics covered included how to adapt monitoring plans to an ongoing injection operation (WP2), and how to describe a quantitative probabilistic methodology for decision analysis for an injection operation (WP4).
- Pre-ACT final meeting 24-25 June 2020. Online (Teams) meeting due to Covid-19 (Figure 30).

Figure 31: End of the Pre-ACT final meeting.

Invited talks / other Pre-ACT contributions:

- Project leader Peder Eliasson participated in three ACT Knowledge Sharing Workshops; one in Bucharest, Romania (23-24 October 2017), one in Cologne, Germany (13 November 2018), and one in Athens, Greece (6-7 November 2019).
- Pre-ACT's Pierre Cerasi presented a poster at the CO2GeoNet meeting, Venice 23-26 April 2019.
- Jim White took part in the Otway Stage 3 Peer Review panel (2018) as a representative of Pre-ACT. This ensured international exposure to the project and built on the understanding of pressure propagation gained in Pre-ACT WP1.

- Pre-ACT was invited to meet with a combined US federal-and state-government delegation led by Alexander Stapleton, a Climate and Energy Advisor at the UK's US Embassy in Washington who works around CCUS. We discussed monitoring and modelling concepts during their UK visit.
- Pre-ACT provided input and project posters at the Accelerating CCUS International Conference in Edinburgh (November 2018). Additionally, the BGS delegation distributed project information about the three ACT projects with BGS involvement (Pre-ACT, ALIGN, Elegancy).
- Pre-ACT was invited to the "NCCS workshop on fault derisking" at NGI in Oslo, to present the paper from GHGT-14 (Lothe et al. 2018) the 12-13 February 2019.
- Pre-ACT' Peder Eliasson was invited to present "Pre-ACT – for safe and cost-efficient CO_2 storage" at the Carbon Sequestration Leadership Forum in Chatou, France, 5 November 2019.
- Jim White was invited to present Pre-ACT at the EU CCS Storage Research Projects Science-Policy Showcase in Brussels, September 2019.
- Pre-ACT's Bastien Dupuy was invited to give a keynote speak at the SEG Postconvention Workshop on "Long term monitoring of CO_2 geosequestration: continuous surveillance and quantitative interpretation" in San Antonio, September 2019. The title of his talk was "*Quantitative monitoring and uncertainties during multiphysics inversion*".

Publications (papers, abstracts, presentations, posters)

Barros E., Leeuwenburgh O., Carpentier S., Wilschut F., and Neele F. (2018). *Quantifying Efficiency Of Field-Wide Geophysical Surveys For Verifying CO2 Plume Conformance During Storage Operations*. In Fifth CO2 Geological Storage Workshop. (proceedings)

Barros E. and Boullenger B. (2020). Quantitative Conformance Assessment in CO2 Storage Reservoirs under Geological Uncertainties Using Convolutional Neural Network Classifiers. EAGE GET 2020. (extended abstract)

Barros, E., Leeuwenburgh, O. and Boullenger B. (2020). Practical quantitative monitoring strategy assessment for conformance verification of CO_2 storage projects. Paper to be presented at the 82nd EAGE Conference and Exhibition 2020, Amsterdam, The Netherlands, December 8-11. (extended abstract)

Blackford J., Dewar M., Espie T., Wilford S., and Bouffin N. (2020). *Impact potential of hypersaline brines released into the marine environment as part of reservoir pressure management.* 4th International Workshop on Offshore Geologic CO2 Storage. (abstract)

Blackford J., Dewar M., Espie T., Wilford S., and Bouffin N. (2020). *Impact potential of hypersaline brines released into the marine environment as part of reservoir pressure management*. GHGT-15. (extended abstract)

Carpentier S., Abidin H., Steeghs P., and Veldkamp H. (2018). *Identifying Hidden Risk Elements For CO2 Storage From Reprocessed Seismic Data*. In Fifth CO2 Geological Storage Workshop. (proceedings) (presentation)

Carpentier S. and Boullenger B. (2019). *Optimization of sparse 4D seismic surveys using seismic full waveform inversion*. EAGE Workshop Practical Reservoir Monitoring (Amsterdam). (proceedings)

Carpentier S., Boullenger B., and Barros E. (2020). *CCS monitoring by inversion of reservoir pressure and saturation changes from time-lapse AVO differences and time-shifts*. In: Paper # 1837, 82nd EAGE Conference & Exhibition 2020, Amsterdam 2020. (extend abstract)

Dupuy B., Torres V., Romdhane A., and Ghaderi A. (2018). *Norwegian large-scale CO2 storage project (Smeaheia): baseline geophysical models.* 14th Greenhouse Gas Control Technologies Conference (GHGT-14). (abstract) (presentation) (paper)

Dupuy, B., Romdhane, A., and Eliasson, P. (2018). *Bayesian Inference In CO2 Storage Monitoring: A Way To Assess Uncertainties In Geophysical Inversions*. In Fifth CO2 Geological Storage Workshop. (proceedings) (poster)

Dupuy B., Nordmann P.-L., Romdhane A., and Eliasson P. (2019). *Bayesian rock physics inversion for CO2 storage monitoring*. Fourth EAGE Conference on Petroleum Geostatistics. (proceedings) (presentation)

Dupuy B, Romdhane A., Eliasson P., and Park J. (2019). *Quantitative monitoring and uncertainties during multiphysics inversion*. SEG Postconvention Workshop 11, San Antonio, 2019. (presentation)

Dupuy B. and Romdhane A. (2020), *Pore pressure and saturation effects on geophysical observables*. EAGE 82nd conference and exhibition. (extended abstract)

Dupuy B. and Romdhane A. (2020), *Toward quantitative CO_2 storage monitoring: estimation of pore pressure and saturation from geophysical inputs*. Submitted to EAGE 1st Geoscience in Energy Transition Conference (extended abstract).

Dupuy B., Romdhane A., Nordmann P.-L., and Eliasson P. (2020). *Bayesian rock physics inversion: application to CO_2 storage monitoring*, Geophysics, under review. (draft paper)

Eliasson P., Cerasi P., Romdhane A, White J.C., Schmidt-Hattenberger C., Carpentier S., Grimstad A.-A., and Lothe A.E. (2018). *Pressure control and conformance management for safe and efficient CO2 storage – an overview of the Pre-ACT project*. 14th Greenhouse Gas Control Technologies Conference (GHGT-14). (abstract) (poster) (paper)

Eliasson P., Ringstad C., Grimstad A.-A., Jordan M., and Romdhane A. (2018). *Svelvik CO2 Field Lab: Upgrade And Experimental Campaign*. In Fifth CO2 Geological Storage Workshop. (proceedings) (presentation)

Eliasson P., Jordan M., Ringstad C., Raphaug M. and Hagby K. (2020). *A CO2 monitoring experiment for pressure-saturation discrimination at the new Svelvik CO2 Field Lab*. Nordic Geological Winter Meeting. (abstract) (presentation)

Eliasson P., Cerasi P, Romdhane A., White J.C., Schmidt-Hattenberger C., Carpentier S., Grimstad A.-A., Lothe A.E. (2020). *Pressure control and conformance management for safe and efficient CO2 storage – lessons learned in the Pre-ACT project*. Accepted for oral presentation at 15th International Conference on Greenhouse Gas Control Technologies GHGT-15. (extended abstract)

Emmel B., Bergmo P., Lothe A.E., and Eliasson P. (2020, to be submitted). CO2 sequestration potential of the Jurassic formations at Smeaheia fault block, Norwegian North Sea, evaluated by dynamic reservoir models. International Journal of Greenhouse Gas Control. (draft paper)

Lothe A.E., Eliasson P., Bergmo P.E., and Emmel B. (2018). *Effects of uncertainties in fault and seismic interpretations on CO2 storage pressure distribution and pressure control*. 14th Greenhouse Gas Control Technologies Conference (GHGT-14). (abstract) (paper)

Lothe A.E., Emmel B.U., and Bergmo P. (2019). *Heterogeneities in the reservoir models; effect on CO2 storage capacity and plume modelling in areas with pressure depletion*. 10th Trondheim CCS Conference (TCCS-10). (poster) (paper)

Lothe A.E., Bergmo P.E.S, Emmel B.U., Grimstad A.-A., and Eliasson P. (2020). *How to evaluate and quantify safe CO2 storage? Workflow demonstration on the Smeaheia area, offshore Norway*. Accepted for oral presentation at 15th International Conference on Greenhouse Gas Control Technologies GHGT-15. (abstract)

Lothe, A.E., Emmel., B., Lavrov, A., Cerasi, P.R. 2019: A review of fault modelling approaches. Fifth International Conference on Fault and Top Seals. Palermo, Italy, (proceedings)

Raab T., Weinzierl W., Wiese B., Rippe D., and Schmidt-Hattenberger C. (in review 2020). *Development of an Electrical Resistivity Tomography Monitoring Concept for the Svelvik CO2 Field Lab*. Advances in Geosciences, Manuscript number: adgeo-2020-42 (draft paper)

Ringstad C., Eliasson P., and Grimstad, A.-A. (2018). *Re-Vitalization and Upgrade of the Svelvik CO2 Field Laboratory in Norway*. In 14th Greenhouse Gas Control Technologies Conference Melbourne 21-26 October 2018. (poster) (proceedings)

Ringstad C., Jordan M., Eliasson P., Grimstad A.-A., Hagby K., Schmidt-Hattenberger C., Weinzierl W., Wiese B., and Wuestefeld A. (2019). *Svelvik CO2 Field Lab: A small-scale laboratory for development of equipment and CO2 monitoring techniques*. Proceedings, 10th International Trondheim CCS Conference -TCCS-10. (abstract)

Ringstad C., Røed M.H., Jestin C., Calbris G., Eliasson P., Jordan M., and Wüstefeld A.A. (2020). *Multi-fibre optic sensing system for cross-well monitoring at the Svelvik CO2 Field Lab*. EAGE Fibre-optic workshop 2020. (abstract) (poster)

Romdhane A., Querendez E., and Eliasson P. (2018). *Surface Seismic Monitoring of Near Surface CO2 Injection at Svelvik-Synthetic Study*. In 24th European Meeting of Environmental and Engineering Geophysics. (abstract) (poster)

Romdhane A. and Eliasson P. (2018). *Optimised geophysical survey design for CO2 monitoring – A synthetic study*. In 14th Greenhouse Gas Control Technologies Conference Melbourne 21-26 October 2018 (GHGT-14). (paper)

Romdhane A., Barros E., Bergmo P.E.S., Leeuwenburgh O., and Grimstad A.-A. (2020). *Quantitative decision analysis for CO_2 storage conformance management: A synthetic case study at Smeaheia, North Sea*. 15th International Conference on Greenhouse Gas Control Technologies GHGT-15, Abu-Dhabi, UAE. (extended abstract)

Schmidt-Hattenberger C., Weinzierl W., Wiese B., Zimmer M., Jordan M., Eliasson P., Ringstad C., Falk Hagby K., and Wuestefeld A. (2019). *Monitoring concept for a CO2 migration experiment at the Svelvik CO2 Field Lab*. In 10th Trondheim Conference on CO2 Capture, Transport and Storage Trondheim 17-19 June 2019. (proceedings)

Vosper H., White J.C., and Gent C. (2018). *Control Of Pressure Propagation In A Heterogeneous CO2 Storage Reservoir Using Water Production*. In Fifth CO2 Geological Storage Workshop. (proceedings)

Weinzierl W., Wiese B., Jordan M., Schmidt-Hattenberger C., Eliasson P., Ringstad C., Lüth S., and Grimstad, A.-A. (2018). *Pre-Operational Considerations In A Poro-Elastic Site Assessment For The Svelvik Field Lab*. In *Fifth CO2 Geological Storage Workshop*. (proceedings)

Weinzierl W., Lüth S., Rippe D., Schmidt-Hattenberger C., and Wiese B. 2018. *Rock Physics Driven Workflow for Pressure and Saturation Control in Quantitative CO2 Monitoring*. In 80th EAGE Conference and Exhibition 2018. (proceedings) (presentation)

Weinzierl W., Wiese B., Lüth S., Rippe D., and Schmidt-Hattenberger C. 2018. *Pre-injection AVO conceptual modeling for the Svelvik CO2 field laboratory*. In SEG Technical Program Expanded Abstracts 2018 (pp. 2800-2804). Society of Exploration Geophysics. (proceedings)

Weinzierl W. and Wiese B., (in review 2020). *Deep Learning a Poro-Elastic Rock Physics Model for Pressure and Saturation Discrimination*. Geophysics (paper)

Weinzierl W. and Wiese B., (2020, November). *Deep Learning a Poro-Elastic Rock Physics Model for Pressure and Saturation Discrimination*. In First EAGE Digitalization Conference and Exhibition(Vol. 2020, No. 1, pp. 1-5) (extended abstract)

Weinzierl W., Barros E., Grimstad A., Wiese B., Leeuwenburgh O., and Schmidt-Hattenberger C. (2020). *Pre-injection Site Investigations in a Poro-elastic Description of the Svelvik Ridge*. 15th International Conference on Greenhouse Gas Control Technologies GHGT-15, Abu-Dhabi, UAE. (draft paper)

White J. (2019) UKCCSRC Biannual meeting, Cardiff April 2019. Assessing conformance in geological storage of CO2: the Pre-ACT project (presentation)

White J. (2019). *How to determine if a CO2 storage site is performing as expected - quantitative conformance assessment tools developed by the Pre-ACT project.* EU CCS Storage Research Projects Science-Policy Showcase, 10 September 2019, Brussels. (presentation)

White J.C. and Williams G. (2020) The convergence of monitoring and modelling to demonstrate conformance and understanding at European CO2 storage sites. 36th International Geological Congress, Delhi, India. 2 - 8 March 2020. (abstract)

Wiese B., Weinzierl W., and Schmidt-Hattenberger C. (2018). *Towards a multiphysical model and inversion of the Ketzin CO2 storage site full operational period.* 14th Greenhouse Gas Control Technologies Conference Melbourne 21-26 October 2018 (GHGT-14). (paper)

Wiese B., Weinzierl W., Pilz P., Raab T., and Schmidt-Hattenberger C. (2020): *Tiny diameter downhole pressure monitoring*, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-5584. (abstract)

Wuestefeld A. and Wilks M., 2019, *How to twist and turn a fiber: Performance modeling for optimal DAS acquisitions*. The Leading Edge, 38(3), 226-231, (paper)

Wuestefeld A. and Wilks M., 2019, *Modelling Microseismic Event Detection and Location Capabilities with DAS Cables*. 81st EAGE Conference and Exhibition 2019 (extended abstract)

Wuestefeld A. and Weinzierl W., 2020, *Design considerations for using Distributed Accoustic Sensing for cross-well seismics: A case study for CO2 storage*. Geophysical Prospecting, 68(6), 1890-1905 (paper)

Wuestefeld A., 2020 Corkscrew well paths for improved microseismic event locations with DAS recordings, Eights EAGE Passive Seismic Workshop, Prague (abstract)

Sign: Eliasson Jon Peder — Digitally signed by Eliasson Jon Peder DN: cn=Eliasson Jon Peder Date: 2021.02.09 15:41:18 +01'00'

Date: 1 September 2020 (contact list update 9 February 2021)

Appendix A: Deliverable list (with links to Pre-ACT partner eRoom)

NB! Not all milestones are associated to something deliverable

WP1: Optimal injection planning via effective pressure control	
Deliverables	**Month**
D1.1.1: Industry uptake deliverable*: Sensitivity modelling study; effect of heterogeneities (sedimentology/faults) on capacity estimates. *(SINTEF)*	24
D1.2.1: Industry uptake deliverable on pressure propagation in reservoirs displaying different structural and stratigraphical complexity. *(BGS, SINTEF)*	21
D1.2.2: Industry uptake deliverable water production as a means to control pressure in heterogeneous reservoirs during CO_2 production. *(BGS)*	30
D1.3.1: Industry uptake deliverable on comparison of analytical models to full scale, geomechanical-fluid flow coupled, field scale simulations for stress concentration during CO_2 injection. *(SINTEF)*	24
D1.3.2: Industry uptake deliverable on Laboratory calibrated simulations of thermal stress development during CO_2 injection. *(SINTEF, TNO)*	30
D1.4.1: Industry uptake deliverable on the triggering mechanisms for acoustic emissions following CO_2 injection. *(SINTEF, NORSAR)*	18
D1.4.2: Industry uptake deliverable on the analysis of microseismic data from Decatur/Ketzin/Rousse in light of laboratory measurements into triggering of acoustic emissions. Boundary effects on acoustic emission strength – the consequences for real data. *(SINTEF, GFZ, NORSAR)*	30
D1.5.1: Industry uptake deliverable describing the impact, best practice and monitoring requirements of hypersaline discharge. *(PML)*	30
D1.5.2: Workshop/partner meeting on hypersaline discharge and water production, presenting Pre-ACT research results. *(PML, BGS, TNO)*	30
Milestones	**Month**
M1.1.1: First model test case varying heterogeneities in storage complex. *(SINTEF)*	12
M1.2.1: Short memo on flow modelling with pressure propagation monitored in heterogeneous reservoirs to demonstrate progress. *(BGS, SINTEF)*	12
M1.2.2: Water production scenario testing underway within flow modelling study. *(BGS)*	24
M1.3.1: First results of thermal stress experiments during CO_2 production. *(SINTEF)*	9
M1.3.2: First acoustic emission experiments underway with memo. *(SINTEF)*	12
M1.4.1: Confirmation of delivery and usability of microseismic data from Decatur/Ketzin/Rousse. *(NORSAR)*	4
M1.5.1: Tested fully functional hypersaline fluid dispersion model and test simulations. *(PML)*	12
M1.5.2: Invitations for workshop/partner meeting on hypersaline discharge and water production. *(PML, BGS)*	28

WP2: Novel concepts for quantitative monitoring of pore pressure and saturation	
Deliverables	**Month**
D2.1.1: Industry uptake deliverable* on selected data (direct and indirect pressure measurements), their quality and suitability for reliable pressure and saturation quantification, and conformity study. *(GFZ, TNO, NORSAR, SINTEF)*	6
D2.2.1: Workshop with operators on scenarios of pressure irregularities, and necessary active surveys as counter-acting measures. *(SINTEF, GFZ, TNO, BGS, NORSAR)*	12
D2.2.2: Workshop with operators on establishing concepts for near- and far-field pressure and saturation monitoring, setting of detection limits and early warning levels. *(SINTEF, GFZ, TNO, BGS)*	30
D2.3.1: Field experiment at the Svelvik site: Design, operation and baseline data acquisition/evaluation of a sparse monitoring concept at small-scale application. Database with collected data. *(SINTEF, GFZ, BGS)*	24

D2.3.2: Field experiment at the Svelvik site: Design, operation and repeat data acquisition/evaluation of a sparse monitoring concept at small-scale application. Database with collected data. *(SINTEF, GFZ, BGS)*	30
D2.3.3: Industry uptake deliverable on cost-efficient target-oriented geophysical pressure monitoring. *(SINTEF, GFZ, BGS)*	34
D2.3.4: Industry uptake deliverable on comparative modelling of observed pressure response for Svelvik, Ketzin and Otway from existing and new data, and analysis of their suitability as input in a conformance study. *(GFZ, SINTEF, BGS)*	27
D2.3.5: Industry uptake deliverable about pressure deviations and corresponding impact on conformance levels, based on the Snøhvit data set. *(SINTEF, GFZ, BGS)*	33
D2.4.1: Industry uptake deliverable about benchmark of inverse parameter estimation (multi-physics simulation): Synthetic data. *(GFZ)*	24
D2.4.2: Industry uptake deliverable about time-lapse pressure tomography based on Svelvik field data (conformance case) and Snøhvit field data (non-conformance case). *(GFZ, SINTEF)*	30
D2.5.1: Industry uptake deliverable on the decision of an optimal microseismic network concept. *(NORSAR, BGS, GFZ, Shell)*	33
Milestones	**Month**
M2.1.1: Access to all relevant direct and indirect pressure data from other sites is feasible and guaranteed. *(GFZ)*	3
M2.1.2: Correlation and quality assessment of the selected data sets is finished. *(GFZ, BGS, SINTEF)*	6
M2.2.1: Established models and selected data are capable to provide conformity criteria. *(GFZ, TNO, SINTEF)*	21
M2.3.1: Baseline acquisition completed. *(SINTEF)*	21
M2.4.1: Compact proxy-model can be derived from the inverse parameter estimation. *(GFZ)*	21
M2.5.1: Geometrical setup for passive microseismic background network performed. *(NORSAR)*	33

WP3: Verification of site conformance	
Deliverables	**Month**
D3.1.1: Workshop on quantitative measures of conformance. *(TNO)*	6
D3.1.2: Industry uptake deliverable* on monitoring-modelling convergence and conformance assessment for industrial-scale operations. *(BGS)*	12
D3.2.1: Workshop on monitoring technologies and their relative merits for conformance verification in different settings. *(TNO, GFZ)*	12
D3.2.2: Industry uptake deliverable on quantitative conformance estimation in relation to detection limits, resolution, and model uncertainty. *(TNO, GFZ)*	24
D3.3.1: Industry uptake deliverable on the development and demonstration of a methodology for conformance assessment with multiple data types. *(TNO, SINTEF)*	30
D3.4.1: Industry uptake deliverable on the measures of conformance and criteria for irregularity or non-conformance. *(GFZ, TNO, BGS, SINTEF, NORSAR)*	36
Milestones	**Month**
M3.1.1: Inventory of potential quantitative measures of conformance (outcomes of Workshop D3.1.1 and input for Task 3.2.	6
M3.2.1: Assessment of monitoring technologies and their application to conformance verification	12
M3.3.1: Final assessment of quantitative site conformance analyses from multiple monitoring data types (Integration of outcomes Task 3.1-3.3 as input for Task 3.4.)	27

WP4: Decision making for safe storage (Pressure-driven ACTion)	
Deliverables:	**Month**
D4.1.1: Workshop with operator and industry experts, discussing the methodology used for decision making in ongoing CO_2 injection operations (in Europe or worldwide).	4
D4.1.2: Industry uptake deliverable* on methods for managing non-conformity situations of a test site.	28
D4.2.1: Course material and/or workshop minutes	34
D4.3.1: Workshop presenting recommendations achieved from the close interaction with operators and their direct requirements from practice.	35
Milestones:	**Month**
M4.1.1: Identification and classification of historical non-conformance issues in closed operations, making input material for alternative action proposal	6
M4.2.1: Ranking of suggested remediation actions in terms of risk, cost and modelled performance	29
M4.3.1: Publication of guidelines to stakeholders, based on final workshop results	36

WP5: Case studies and stakeholder confidence	
Deliverables	**Month**
D5.1.1a: Industry uptake deliverable* on Smeaheia-based case study	26
D5.1.1b: Industry uptake deliverable* on Smeaheia-based case study	35
D5.1.2: Industry uptake deliverable on P18-4 and Q16-Maas-based case study	35
D5.1.3: Industry uptake deliverable on water production as a means to control pressure in heterogeneous reservoirs during CO_2 production. (BGS)	35
D5.2.1: Workshop minutes and information material	30
Milestones	**Month**
M5.1.1: Up-and-running Smeaheia-based simulation model	17
M5.1.2: P18-4 and Q16-Maas-based simulation models	17
M5.1.3: Simulation model for pressure-linked sites	21
M5.1.4: Non-conformity events defined for all case studies	27
M5.2.1: First workshop with policy makers completed	15

WP6: Project management	
Deliverables	**Month**
D6.2.1: Risk assessment with revision	6, 18
D6.3.1: Project master plan including full transparency of resources, schedule and cost/performance, with yearly updates	3, 10, 22, 30
D6.3.2: Periodic project report to ACT (tentative dates, depending on ACT requirements)	12, 24, 36
D6.4.1: Pre-ACT landing website (monthly updated)	3
D6.4.2: Pre-ACT webinar with latest project results	6, 12, 18, 24, 32, 36
Milestones	**Month**
M6.3.1: Project launched	3
M6.3.2: First EB meeting (only EB access)	3
M6.3.3: Necessary committee and panels established	9