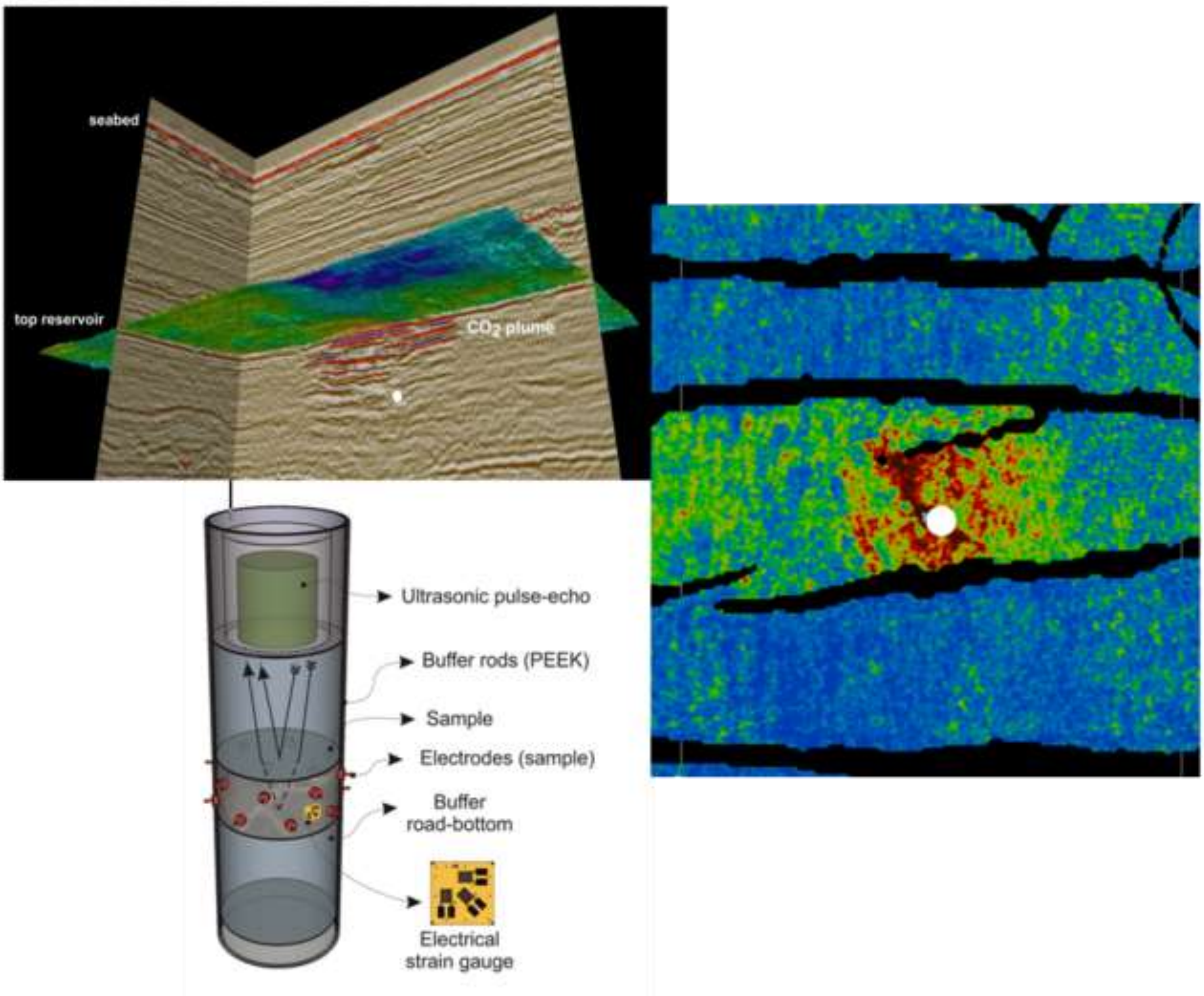
DiSECCS - Diagnostic Seismic Toolbox for Efficient Control of CO_2 Storage

Work Package 5 - Insights and Recommendations

BGS Energy Programme Report OR/17/022



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Diagnostic Seismic Toolbox for Efficient Control of CO_2 Storage:
DiSECCS

BRITISH GEOLOGICAL SURVEY

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Work Package 5 – Insights and Recommendations

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Foreword

This document comprises a set of insights into and recommendations for the monitoring systems and protocols required to maintain the integrity of storage reservoirs suitable for large-scale CO_2 storage and to obtain a social licence to operate a CCS project.

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Executive Summary

This DiSECCS deliverable presents insights into and recommendations for the monitoring systems and protocols required to maintain the integrity of storage reservoirs suitable for large-scale CO_2 storage and for obtaining a social licence to operate a CCS project.

DiSECCS research has focussed on the use of seismic monitoring tools combined with social science research to identify key factors in establishing trust and confidence in the storage system.

Key areas of research cover:

- Demonstrating the capability of modern seismic monitoring to provide high resolution images of CO_2 stored in the reservoir that enable determination of migration and trapping processes with a degree of confidence sufficient to make robust predictions about future, long-term, storage performance.
- Developing new understanding of rock physics and seismic wave propagation that reduce uncertainty in the quantitative analysis of time-lapse seismic monitoring data.
- Providing new laboratory data to constrain new rock physics theory and support quantitative analysis of seismic datasets.
- Identifying significant factors in establishing a social licence in the context of CCS and in particular offshore CO_2 storage in the UK.

The overall aim was to show that storage monitoring systems really do enable operators and regulators to understand what is happening at a storage site and to respond as necessary to any unexpected or irregular behaviour. Insights and recommendations have been developed in the following areas:

- CO_2 plume location and detection.
- CO_2 layer thickness and characterisation.
- New rock physics.
- Pressure mapping.
- Experimental procedures and constraints.
- Developing and maintaining a social licence to operate

N.B. Many of the techniques mentioned here are summarised further in the DISECCS Final Summary Report (BGS 2017a) and in the DiSECCS Toolbox (BGS 2017b). Background information and further results from DiSECCS can be found on the project website https://www.bgs.ac.uk/diseccs/

1 Introduction

The two key regulatory treaties governing CO_2 storage in the UK offshore area are the OSPAR Guidelines (*OSPAR 2007*) and the European Storage Directive (*EC 2009*). A third document, the EU Monitoring and Reporting Guidelines (*EC 2011*), deals with the accounting of leaked emissions from storage sites under the EU Emissions Trading Scheme.

From these treaties, two key monitoring-related themes have emerged: the requirement firstly to demonstrate that a storage site is currently performing effectively and safely and secondly to ensure that it continues to do via the provision of information supporting robust prediction of future performance.

These requirements can be distilled into a number of necessary actions which fall within two main monitoring objectives, containment assurance and conformance assurance. A third category, contingency monitoring might be required in the event that containment and/or conformance expectations are not met.

Monitoring objectives that fall under Containment and Conformance include:

- Plume location and detection limits
- CO_2 layer thickness and properties
- Pressure mapping
- Geomechanical stability

DiSECCS has focussed on some aspects of Containment and Conformance, together with societal aspects that can be influenced by the monitoring information. Insights and recommendations as derived from the DiSECCS work are discussed below, focussing on the specific techniques and approaches addressed in the project (BGS 2017a). As such this document does not aim to provide a fully comprehensive critique of seismic monitoring for CCS or societal aspects.

N.B. References cited in standard font are DiSECCS publications, references in italics font are non-DiSECCS publications.

2 Plume location and detection

Plume location and detection are key aspects of containment assurance - both in terms of tracking CO_2 movement in the storage reservoir and in detecting any out-of-reservoir escape (Jenkins et al 2015). Monitoring experience worldwide at a range of scales demonstrates the efficacy of seismic techniques to image CO_2 in the subsurface, both with surface methods (e.g. Sleipner, Snøhvit, Ketzin) and also downhole (e.g. Frio, Nagaoka).

Sleipner and Snøhvit have demonstrated the ability of surface seismics to image CO_2 plumes in a robust and repeatable manner in different reservoir types and at a range of depths. In 1999 the first repeat survey at Sleipner imaged a plume containing 2.1 million tonnes (Mt) of CO_2 in the Utsira Sand reservoir at depths between ~800 m and ~1000 m. Two small discrete CO_2 accumulations clearly imaged at 800 m depth at the top of the plume were estimated from amplitude analysis (see below) to contain ~7700 tonnes and 6300 tonnes of CO_2 respectively (*Chadwick et al. 2014*). It is notable moreover that recent surveys at Sleipner have much improved resolution and subsurface coverage consistency, and the recent datasets require severe decimation in order to be time-lapse processed with the 1994 baseline data.

Snøhvit is much deeper but again surface seismic has successfully imaged 500 kt of CO_2 at a depth of ~2600 m in the Tubåen reservoir, and 130 kt of CO_2 in the Stø reservoir at a depth of ~2400 m. Until recently, the smallest amount of CO_2 definitively imaged with surface seismics was 22 kt at Ketzin (*Ivanova et al. 2012*) at a depth of ~630 m. A pilot-scale test at Otway is currently demonstrating detection and imaging capability in the range 5 kt to 15 kt.

At the Aquistore injection project in Canada, surface seismics have detected around 36 kt of injected CO_2, but analysis in DiSECCS suggests that the main detectable reflection amplitude anomaly is coming from an estimated 18 kt of CO_2 accumulating in a distinct reservoir unit (Roach et al. 2017). Because of the permanent recording array, repeatability at Aquistore is very good with normalised root-mean square (NRMS) values typically around 10% and it might well be the case that, even given the deep reservoir (~3200 m), a few thousand tonnes of CO_2 would be detectable,

Detection limits for leaking CO_2 can differ significantly from detection limits in storage reservoirs, because the former can involve CO_2 in the gas phase. Work at Sleipner has determined minimum amounts of CO_2 that might be detectable in shallower overburden in a hypothetical leakage scenario. At a few hundred metres depth it is estimated that amounts of gaseous CO_2 as small as 300 tonnes could be detected (*Chadwick et al. 2014*).

It is notable that at reservoir levels downhole seismic methods have lower detection limits than surface seismics. For example imaging of 1600 tonnes of CO_2 at Frio (*Freifeld et al. 2009*) and 3200 tonnes at Nagaoka (*Sato et al. 2011*) has been demonstrated with cross-hole tomography. However downhole seismic methods require instrumented wellbores and don't provide the uniform coverage in terms of fold-of-cover and azimuthal content that surface seismic surveys provide.

2.1 SUMMARY INSIGHTS AND RECOMMENDATIONS

- Surface seismic surveys are recommended for robust plume detection, mapping and tracking, including migrating/leaking CO_2 in the overburden. They provide full 3D volumetric subsurface coverage, and their rather uniform fold of cover and azimuthal content allow reliable spatial mapping of CO_2 layer properties from seismic attributes.

- For dense-phase CO_2, surface seismic methods have proven detection and imaging capability of the order of a few thousand tonnes over a wide range of reservoir depths (800 to ~3000 m). For gaseous CO_2 at shallow overburden depths, detection limits should be significantly lower, in the order of a few hundred tonnes.

- Permanent recording arrays can achieve very high repeatability and potentially very low detection limits.

- Recent developments in acquisition techniques offshore have yielded significantly improved resolution. In the light of this, older baseline surveys are now not fully fit-for-purpose.

3 CO_2 layer thickness

Determining the thickness of a migrating CO_2 layer is a key element in quantifying *in situ* amounts, or for history-matching observations against numerical and analytical fluid flow modelling or simulation. Most straightforward is to determine the temporal thickness of the CO_2 layer; determination of true layer thickness requires, in addition, knowledge of layer velocity.

3.1 TEMPORAL THICKNESS

A key seismic property of a thin (a few metres thick) layer of CO_2, migrating in a storage reservoir, is its temporal thickness. If the layer is sufficiently thick, the temporal separation of its top and base reflections can be measured directly. If however the layer is thinner, and not explicitly resolved, interference of the top and base reflections produces amplitude and frequency modulation effects in the composite wavelet which are diagnostic of temporal thickness (*Arts et al. 2004*).

3.1.1 Temporal separation

The most straightforward approach is to measure directly the temporal separation between the reflections from the top and base of a layer, but this is only possible if the layer is explicitly resolved (above the tuning thickness). The 2010 seismic dataset from Sleipner (Chadwick et al. 2016; White et al. submitted) and the 2012 dataset from Snøhvit (White et al. submitted) both show explicit resolution of the top and base of a CO_2 layer where it is thickest. This allows direct measurement of temporal separation (White et al. submitted), but even with explicit layer resolution, measured temporal spacings require a further significant correction to allow for interference effects above the tuning thickness (*Kallweit & Wood 1982*).

At Sleipner the individual plume layers remained beneath seismic resolution on the 3D datasets until 2010 when 3D data with markedly improved resolution data became available (*Furre & Eiken 2014*). It is notable however that as far back as 2006, high resolution 'site investigation' 2D surface seismic data also succeeded in providing local layer resolution (*Williams & Chadwick 2013*).

It is notable that, even for layers beneath the tuning thickness, with strongly interfering top and base reflections, very detailed measurement of subtle time-shifts on these reflections can yield important insights into the layer temporal thickness *(Furre et al. 2015; Cowton et al. 2016).*

Where layer thicknesses are beneath seismic resolution, which is generally the case early in layer development, or at the pilot-scale where only small amounts of CO_2 are involved, additional ways of obtaining temporal spacing are available. These rely on the amplitude and frequency modulation effects that occur as the reflections from the top and the base of the thin layer interfere.

3.1.2 Amplitude analysis

Amplitude analysis has the great advantage of simplicity and exploits the relationship between amplitude and layer temporal thickness which holds below the tuning thickness ($< \lambda/4$) *(Arts et al. 2004)*. A simple convolutional model can be used to establish the amplitude – thicknesses relationship for a given seismic dataset and used in look-up mode whereby temporal thicknesses can be read directly from reflection amplitudes. This is quite a robust approach and gives temporal thicknesses right down to the detected edge of the layer (typically 1 m thick or less at Sleipner).

Chadwick et al. (2004, 2005) used reflection amplitudes and reflection time-shifts to analyse the Sleipner plume on the first repeat time-lapse survey in 1999. In this particular situation individual layers within the plume were generally beneath the tuning thickness, and attenuation effects were small so layer temporal thickness determinations were likely quite reliable. As the Sleipner plume developed further however, CO_2 layers thickened beyond the tuning thickness, and signal attenuation (see Section 4) became increasingly evident. Simple amplitude analysis became progressively less useful therefore for subsequent repeat surveys.

Caution needs to be exercised in amplitude analysis which assumes that amplitude variation across a layer is a function solely of its temporal thickness. Layer reflection amplitudes can be quite noisy and also vary directly with the strength of the impedance contrast at the top and base layer interface, which depends on CO_2 properties and the geology of the reservoir and the overburden. Ambiguity arises close to the tuning thickness where a layer with a temporal separation just below the tuning thickness gives rise to the same reflection amplitude as a layer just above the tuning thickness *(Kiær 2015)*.

3.1.3 Frequency analysis

Like amplitude, wavelet frequency is also modulated by interference between the reflections from the top and base of a CO_2 layer. Analysing frequency is more complex than amplitude analysis but has some significant benefits, notably in the fact that the frequencies are not so strongly affected by the impedance contrasts at the layer interfaces. The technique of spectral decomposition enables us to interrogate the layer at a range of discrete frequencies throughout the power spectrum of the wavelet. It effectively exploits the resolution of the highest frequency components in the seismic wavelet and is ultimately limited by signal-to-noise ratios at higher frequencies.

DiSECCS utilised a spectral decomposition tool termed the Smoothed Pseudo Wigner-Ville Distribution (SPWVD) which enables frequency spectra to be extracted from narrow time windows focussed on the discrete layer reflection wavelet *(Williams & Chadwick 2013)*. Identifying the tuning frequency is not trivial because over the range of useful frequencies the power spectrum is not flat, with amplitude fall-off at both low and high ends being much greater than the tuning effect. It is necessary therefore to accurately flatten the spectrum so that the tuning peak can be identified, a procedure termed spectral balancing. This important step can be approached in a number of ways. The commonest method is perhaps to determine the power spectrum of an 'untuned' wavelet away from the CO_2 layer, determine the spectral balancing correction, then apply the same correction to the CO_2-layer reflection data. This assumes that the CO_2-free reflectivity sequence is essentially random, or that any geological layer-related frequency enhancements are identical to those around the CO_2 layer. A simpler method is to scale the maximum amplitude measured at each discrete frequency to the maximum amplitude recorded across all the frequencies, and then apply this scaling factor to normalise each discrete frequency across the layer. This approach is valid if tuning is achieved at one of the discrete frequencies at some location across analysed footprint of the layer.

Williams & Chadwick (2013) deployed the SPWVD tool on the topmost layer at Sleipner using time-lapse seismic data up to 2006 and were able to clearly determine tuning frequencies from which temporal thickness could be derived. In DiSECCS this was repeated on the 2010 datasets which had the benefit of thicker layer and data with a much wider bandwidth (White et al. submitted).

A very good approach is to combine the three approaches in an integrated analysis. White et al. (submitted) mapped temporal thickness for the topmost layer at Sleipner. Amplitudes were used to map the thinnest most peripheral parts of the layer, inwards from the layer edge. Further inboard the SPWVD was used to map in the range from the tuning thickness for the highest frequencies inward to the tuning thickness for the lowest frequencies frequency. The central, thickest part of the layer showed explicit temporal separation from which, after application of the interference correction, temporal thicknesses were derived directly.

A similar integrated approach using amplitudes, frequencies and direct measurement was applied to map temporal thickness of the spreading CO_2 layer in the Stø reservoir at Snohvit (White et al submitted).

3.1.4 Convolutional based modelling incorporating the effects of frequency-dependent reflectivity

Most CO_2 layers actually contain partial saturations of CO_2 and so will exhibit wave attenuation and velocity dispersion effects. In this situation, reflection coefficients become complex and frequency-dependent. This leads to subtle, but important, phase effects on the reflected waveforms. These effects may be directly indicative of fluid saturation (*Wu et al., 2014*), but perhaps more importantly, in thin layer situations the phase shifts can change the layer temporal thickness. This effect was studied by *Jin et al. (2017),* who gave a method for calculating full well log synthetic seismograms for dispersive situations, and performed an exercise on inversion of thickness and saturation in an idealized layer. The work was important for demonstrating that the inversion was possible in principle, but the methodology was idealized and might not be suitable for immediate practical application.

An alternative method of dealing with frequency-dependent reflectivity is to use matching pursuit methods as proposed by Papageorgiou et al. (in preparation). The method is an extension of that of *Zhang & Castagna (2011)*, and involves decomposing seismic data as the sum of a number of idealized thin layer responses, known as a dictionary. Papageorgiou et al. (in preparation) created a dictionary which consists of reflections from thin layers which exhibit varying degrees of velocity dispersion, and showed using real and synthetic data that the method could be useful for estimation of dispersive layer properties. The method shows promise for estimation of the temporal thickness of a CO_2-saturated layer.

3.2 TRUE THICKNESS

To convert layer temporal thickness to true layer thickness requires knowledge of the layer velocity. This is very challenging. A number of inversion-type procedures have been applied to the Sleipner datasets in the past (summarised in *Chadwick et al. 2010*), but these have had limited success in extracting plausible layer velocities, with limitations on resolution tending to smear or smooth the layer and inter-layer velocity values.

3.2.1 Velocity from rock physics and laboratory experiments

Rock physics estimates of layer velocities at Sleipner have been available for several years (e.g. *Arts et al. 2014*), but these have remained somewhat unconstrained, not least in understanding the variation of seismic velocity with fluid saturation. Uncertainty is greatest in the mixed CO_2/water saturation range where velocity is influenced by kinetic interactions of the two fluids as the seismic wave propagates (see Section 4) – the so-called 'patchiness' parameter (*Bergmann & Chadwick 2015*).

Laboratory measurements on the Utsira Sand have not been available until recently, due to the difficulty in setting up the experiments under reservoir conditions with the core samples of poorly-consolidated sand. The DiSECCS project has succeeded in obtaining acoustic velocity measurements for the first time and these are roughly in line with the rock physics predictions, irrespective of frequency. The experiments, combined with novel rock physics models developed in DiSECCS have also started to cast some light on the variation of velocity with CO_2 saturation (see Section 4).

3.2.2 Spectral inversion

Spectral inversion is a technique that uses both amplitude and frequency modulation to characterise thin layers below the seismic tuning thickness and a tool has been developed in the DiSECCS Toolbox (BGS 2017b). Layer temporal thickness can be determined together with the reflection coefficients of the upper and lower layer interfaces. If the properties of the overlying and underlying rocks are known, which is likely if they contain just brine in the pore-spaces, then the velocity of the CO_2 layer can be estimated. The technique is however very sensitive to noise and to distortions of the wavelet shape by adjacent reflectivity and has not yet been successfully demonstrated.

3.2.3 Geological constraints on velocity

A drawback of core measurements is that they effectively measure only a tiny (0-D) sample of the reservoir, which might not be representative of other locations or of the range of larger spatial scales which control fluid flow.

In order to obtain estimates of layer velocity at plume scales we have focussed in DiSECCS on the topmost CO_2 layer in the Sleipner plume. This might be considered something of a special case in that it has accumulated beneath the reservoir topseal whose topographic relief can be mapped from the baseline dataset, but velocity determinations in principle should be quite robust. Integration of evidence from geological analysis, fluid flow modelling and synthetic seismic modelling is used to constrain CO_2-layer geometry. Combining this with precision measurements of reflectivity time-shifts on the high resolution 2010 datasets allows layer velocity to be extracted. Nevertheless, this type of analysis is complex and not yet fully developed. Preliminary results are outlined in Chadwick et al. (2016) and work is ongoing. More generally application of this method is feasible wherever CO_2 accumulates beneath a known topography.

3.3 SUMMARY INSIGHTS AND RECOMMENDATIONS

- Knowledge of CO_2-layer geometry is crucial to verifying and calibrating predictive fluid flow models via history-matching.
- Determining temporal thickness is a key first step in establishing CO_2 layer geometry
- Temporal thickness can be determined via amplitude and frequency (spectral) analysis. If resolution permits, direct measurement of top and base layer reflection spacing is possible, but residual interference effects require an additional correction.
- Combination of the above methods, across the range of layer thicknesses, offers the best approach to accurately mapping layer temporal thickness.
- Both above and below the tuning thickness, very small time-shifts of layer top and base reflections yield diagnostic information of layer temporal thickness. Analysis of dispersive effects is also promising in this regard.
- Spectral decomposition via the SPWVD seems to provide stable spectral characterisation on real seismic datasets over the narrow time-windows required.
- Determination of CO_2-layer velocities remains challenging. Direct seismic methods have so far not proved very successful.
- Indirect methods integrating geological analysis and fluid flow and seismic modelling with reflection time-shifts offer the possibility of deriving layer velocity in some specific cases.
- Laboratory methods have improved sufficiently to allow reliable measurement of velocity in poorly-consolidated core samples.
- Laboratory measurements combined with innovative rock physics have to some extent overcome the uncertainty associated with the radically different frequencies of lab-scale acoustics and field-scale seismics.

- The seismic processing sequence should be carefully tailored to preserve true reflection amplitudes and frequencies as accurately as possible.

- Detailed assessment of single CO_2 layers seems to pay dividends in understanding fluid migration processes, such as the topmost layer at Sleipner or the layer in the Stø reservoir at Snøhvit.

4 CO_2 layer characterisation

Direct seismic methods of layer characterisation, in terms of fluid distribution, require that layer velocity be determined and also some knowledge of fluid mixing scales. This is traditionally very challenging and requires proper understanding of the physical processes involved when seismic waves propagate through a compliant porous medium containing more than one fluid in the pore-space. This, combined with knowledge of the velocity and the frequency-dependent attenuation characteristics of the layer, enables fluid (CO_2/brine) saturations and distributions to be surmised.

Indirect supporting evidence is available from laboratory petrophysical data. So for example the capillary pressure curve of the reservoir rock, balanced against CO_2 buoyancy, can be used to derive a saturation – height relationship for a thin spreading CO_2 layer (Chadwick et al. 2005).

4.1 ROCK PHYSICS

A central problem for application of rock physics to CO_2 monitoring lies in the determination of an appropriate fluid mixing law. This problem is traditionally approached by assuming either uniform or patchy saturation. In other words, whether the two fluid phases behave as a single 'effective' fluid, or as 3D 'patches' of two separate fluids with distinct physical properties. It is commonly understood that the appropriate choice is determined by the interplay between the frequency of the interrogating seismic wavelet and the patch size.

Work in DiSSECCS has led to a new understanding of the physics relevant to fluid mixing. A key advance has been the recognition of the impact of capillary effects on the seismic response. Amalokwu et al. (2017) showed that capillarity was a plausible mechanism for low-saturation discontinuous changes in measured bulk modulus for air-water systems. Papageorgiou et al. (2016) showed how assumption of an intuitively reasonable capillary pressure law led to a model which very closely resembled the empirical Brie's law, which had been widely understood to capture the degree of patchiness in a given system. A key conclusion of this work is that patchy effects are not necessarily related to measurement frequency or patch size. The extension of this work to incorporate squirt flow has been given by Papageorgiou and Chapman (2017).

In DiSECCS we have measured elastic properties of synthetic sandstones during flooding by supercritical CO_2 (Falcon-Suarez et al. 2016; Falcon-Suarez et al., 2018). The theory of Papageorgiou and Chapman (2016) has allowed the results to be interpreted in terms of squirt-flow and patch-style effects (Papageorgiou et al., 2016). When squirt effects are removed, it appears that the behaviour of the samples follows a simple empirical law, based on the Papageorgiou et al. (2017) model. The law relates the patchiness parameter in Papageorgiou et al. (2017) to volume fractions of water and CO_2 and the fluid pressure. This is consistent with an intuitive notion of effective patch size reducing with fluid pressure, and the relationship is not necessarily expected to depend on frequency.

The DiSECCS research therefore has provided an improved version of the patchy saturation model, and has shown how to calibrate this on laboratory core measurements. This provides relationships which are ready to apply, and which should provide more accurate results and supersede the current generation of patch models. The models have been applied in the context of thin-layer characterization, with credible and important results.

4.2 ATTENUATION /DISPERSION

When a seismic wave passes through a porous medium it suffers a frequency-dependent attenuation due to the energy loss associated with kinetic interactions of the different fluids (usually water and CO_2) in the pore space. Measurement of the quality factor Q (inverse of the attenuation factor) can provide insights into fluid saturations within the pore-space.

Comparison of Q values obtained from the seismic data with Q from the DiSECCS laboratory measurements of attenuation versus fluid saturation are showing some promise. Qualitative agreement has been achieved between developed rock physics models and measured Q values, but there is also evidence of an additional mechanism, which we believe to be related to elastic scattering. Both fluid and scattering effects are frequency-dependent, so direct comparison of Q measured in-situ with laboratory values remains a very challenging problem.

Two approaches to assessing Q on real seismic datasets have been tested in DiSECCS: the log spectral ratio method and the peak frequency shift method (BGS 2017b). Both methods worked well on (noise-free) synthetic data, but both are highly sensitive to random noise, so application to a real dataset will require careful selection of appropriate time windows to isolate high signal-to-noise ratios. Trials on the Sleipner 1999 repeat dataset assessed attenuation between reflection wavelets from the top of the Utsira reservoir and deeper wavelets some distance beneath the base of the reservoir. Both methods gave reasonably consistent results, with Q factors ranging from 19 to 28 for the reservoir section containing the CO_2 plume and from 51 to 66 for the reservoir section containing just water. However translation of Q measurements to fluid saturations is challenging, especially for plumes with multiple stacked CO_2 layers, such as at Sleipner.

4.3 SUMMARY INSIGHTS AND RECOMMENDATIONS

- Patchy-like velocity-saturation behaviour can be related to capillary pressure effects, and is not limited to high frequency conditions or specific patch sizes.
- Brie's empirical law can be matched by models based on capillary effects.
- A combined model including squirt and patch mechanisms has been developed.
- Measurements of supercritical CO_2 flood in synthetic sandstones are well modelled by the combined squirt and patch model.
- We have derived an empirical fluid mixing law for water-CO_2 mixtures which exhibits dependence on fluid pressure.
- Uncertainties remain about the frequency-dependence of patchy mixing effects, and we recommend repeating measurements on synthetic sandstones at lower frequencies to determine if saturation dependence is consistent.
- Interpretation of laboratory Q measurements remains a challenging problem.

- Determination of Q from field data remains challenging because of signal-to-noise limitations.

5 Pressure mapping

Downhole pressure measurement on injector wells will be mandatory under European CCS regulation and pressure monitoring might be additionally implemented in one or more surveillance wells in a storage project. But in some cases there will be a need to map pressure propagation across the reservoir, especially where (shallower) parts of the reservoir are more geomechanically vulnerable than the area around the injectors themselves, such as when injecting on the flank of a closure (*Noy et al. 2012).* 3D time-lapse seismic surveys are potentially well-suited to mapping spatial changes and at Snøhvit, time-lapse seismic data have allowed pressure propagation in the Tubåen reservoir to be mapped and related to the presence of flow boundaries at faults (*Grude et al. 2013; White et al. 2015).*

5.1 TIME-SHIFT MAPPING.

In principle, time-shifts at or beneath the base of a reservoir, relative to the reservoir top, can be used to detect and map fluid pressure changes within the reservoir. The efficacy of this approach depends on two key issues: the accuracy with which the reservoir temporal thickness can be mapped, and the sensitivity of reservoir velocity to changes in effective stress as pore pressure changes. Clearly the method will work best in thick, mechanically compliant reservoirs where time-shifts are likely to be greatest.

Chadwick et al. (2012) measured temporal changes in the Utsira Sand at Sleipner between 1994 (prior to injection) and 2006 (with 8.4 Mt of injected CO_2) to estimate an upper limit on pressure increase in the storage reservoir. They did not attempt to map pressure change spatially, but rather used a statistical analysis of time-shifts on several thousand seismic traces within ~3 km of the injection point but outside of the CO_2 plume, to constrain average pressure increase in the area. This was found to be around 0.1 MPa or less, right at the resolution limit of the technique.

The rock physics relationship of velocity to effective stress is crucial. In the absence of data from the Utsira Sand, *Chadwick et al. (2012)* used published experimental datasets for sandstones over a wide range of effective stresses. DiSECCS has now provided key new measurements on a sample of Utsira Sand and these could be incorporated into a new analysis.

A similar approach has been adopted at Snøhvit where mapped time-shifts in the Tubåen reservoir seem to correspond to the interpreted pressure footprint (*Hansen et al., 2011)*. The reservoir at Snøhvit is much thinner and less compliant than at Sleipner, but this is counteracted by a much greater pressure change (of the order of 8 MPa) at Snøhvit.

5.2 SPECTRAL DISCRIMINATION

In certain circumstances spectral techniques can be used to distinguish between fluid and pressure changes in a storage reservoir. Thus reflectivity from the thin layers typical of CO_2 migrating in a reservoir will tune at significantly higher frequencies than reflectivity changes due to pressure change in the reservoir which are likely to span a much greater thickness of affected strata – perhaps the whole reservoir thickness in some cases. *White et al. (2015)* mapped a high frequency tuning zone around the injection point with a more laterally extensive lower frequency tuning zone away from the injection point. These were interpreted as arising from the CO_2 plume and the pressure-increased reservoir respectively. Mapped changes in pressure are similar to those determined by *Grude et al. (2013)* from Amplitude-versus-offset (AVO) analysis.

The spectral discrimination approach has a practical advantage in that standard post-stack datasets can be used for the analysis, whereas AVO requires the use of pre-stack data or specially processed data cubes with variable offset ranges.

5.3 ANISOTROPY

Structural anisotropy in a rock volume becomes more pronounced as pore pressure increases and fracture or joint systems become more dilated. A wide literature already exists in this, particularly related to shear wave propagation and splitting. DiSECCS developed a coda analysis tool to identify azimuthal anisotropy from conventional (p-wave) seismic data (BGS 2017b). However this was difficult to test on our available datasets.

6 Experimental

6.1 EXPERIMENTAL APPROACH

In this study, we sought to address the question of how to distinguish between pore fluid and geomechanical effects from seismic measurements by performing controlled laboratory experiments on rock samples with broadly representative properties of key CO_2 storage reservoir formations (Falcon-Suarez et al. 2016; Falcon-Suarez et al., 2017).

Our experimental rig was originally designed for combined geophysical-hydromechanical studies on rock samples (Falcon-Suarez et al. 2016). Rather than addressing different reservoir conditions, we decided to focus our attention on the understanding and assessment of Sleipner-like reservoirs. At Sleipner the main reservoir is the Utsira Sand, an uncemented high-porosity (~37%) high-permeability (~3 Darcy) rock, from which only a single core has been recovered. We utilised available Utsira Sand samples and also three self-manufactured synthetic sandstones with different porosities (26, 38 and 45%) and permeabilities (1, 50 and 500 mD respectively), to perform CO_2-brine co-injection flooding experiments replicating the confining pressure (~16.4 MPa) at the Sleipner site and with a range of pore pressures (7 to 12 MPa).

6.1.1 Synthetic rocks

In general, the availability of reservoir core samples can be rare, and sample preservation issues are always a problem, especially regarding geomechanical properties that can be altered by the drilling, coring and recovery processes. Most notably, natural core samples typically suffer from stress release micro-cracks, where mineral cementation of sand grains, formed during diagenetic processes under elevated ambient stresses, is damaged; once brought to atmospheric pressures, the bonds break and the grains spring apart, giving rise to micro-cracks both between sand grains and within grains (stress release), and even total disaggregation for weakly cemented sandstones as at Sleipner. While it is possible to substantially close-up artificially induced micro-cracks in core samples during laboratory experiments at elevated pressures, there remains some doubt over how these damaged rock samples can replicate true in situ reservoir behaviour in the laboratory. It can be beneficial therefore to work with synthetic sandstone samples that circumvent some of these problems.

We developed a technique where quartz sand grains are mixed with kaolin and aqueous sodium silicate gel, packed into moulds, then heated under elevated pressures to produce artificially cemented sandstones (the kaolin and silica gel transform into solid silica cement). This technique has the advantage that the sample is cemented under elevated pressure and can, to an extent, replicate natural processes, but with negligible stress release-induced damage during de-pressurisation, as they are quite strongly bonded. This might be because there is generally more cement present in these sandstones than would occur in natural rocks of equivalent porosity.

While it is possible to broadly control the porosity and strength of the synthetic sandstones by varying the amount of cement, it is not an exact process. One issue, evident by the relatively low permeability of the samples, is that there is more cement blocking pore throats than would be expected in natural samples. This is because the cement was emplaced during "deposition" of the mixture into moulds, rather than during flushing by natural pore fluids and mineral cement precipitation on the grain surfaces. That aside, the main advantage is that we can minimise the effect of artificially induced micro-cracks or core damage by using this "intact rock".

Synthetic sandstones that more closely replicate natural cementation processes would be an improvement. The advantage of the aqueous sodium silica gel method is that it is relatively quick and straightforward. We did improve our original method by applying elevated pressure to the mould during the rock-forming process, but this did not address the fundamental issues mentioned above. The laboratory results must be viewed in this context.

6.1.2 Very weakly cemented natural rocks

The limited core sample collection available at the BGS of the Utsira Sand provided the challenge of adapting the triaxial cell to accept the very weakly cemented sandstone samples. We developed a special sample preparation protocol in order to (i) minimize mechanical damages during the assembly of the experiment, (ii) ensure an appropriated repartition of the axial loading and (iii) account for potential grain disaggregation and displacement and pipe clogging effects.

Our experimental methodology was successful only once however. The first experiment resulted in significant damage to the triaxial cell, necessitating re-building of the inner sleeve and the electrical resistivity monitoring system. Nonetheless, the results obtained from the experiments on the real Utsira samples allowed, for the first time, the measurement of lab-based geophysical-geomechanical relationships for the Utsira Sand, with the methodology clearly extendible to similar weakly cemented sandstone reservoirs.

6.2 EXPERIMENTAL RESULTS AND DATA INTERPRETATION

6.2.1 Integrated geophysical measurements

The high resolution and accuracy of the ultrasonic and resistivity measurements have permitted the acquisition of reliable data which cover a wide range of CO_2-brine partial saturations. The combination of acoustic and resistivity data from our experiments will allow improved qualitative and quantitative determination of the CO_2 distribution on shallow, weakly-cemented aquifers from combined seismic-electromagnetic modelling.

In all cases, the experimental procedure used the two phase CO_2 - brine steady state flow technique (*Müller, 2011; Perrin et al. 2009*), where the initial brine-bearing sandstone was flushed with progressively increasing CO_2-to-brine solutions. This method commonly limits the maximum CO_2 saturation achieved in the experiment to rather low contents (Perrin et al., 2009), but we reached CO_2 saturation values in the range 40-55% in our tests. Nonetheless, the methodology allows us to replicate different saturation stages, that might be related either to spatial (distance to the injection point) or temporal (progressive CO_2 saturation increase) fluid flow scenarios, or a combination of both.

Considering the time-scale of the experiments (7 to 10 days each), the collected data are particularly relevant to the early stages of CO_2 injection, when physical trapping is the main storing mechanism. After preliminary processing and interpretation, our experimental data, constrained by the rock physics model of Papageorgiou and Chapman (2017), have been used to establish seismic velocity-saturation relationships for shallow Sleipner-like reservoirs (Falcon-Suarez et al. 2017).

It is worth remarking on the importance of the data obtained during the first stages of the experiments, where we simulate steady state brine flow in the brine-saturated sample, replicating original reservoir hydrodynamics. These pre-CO_2 injection stages provide a very accurate geophysical baseline, crucial to separate the individual contributions of pore fluid changes and pore pressure effects from seismic data, in the absence of pre-injection surveys – as the case for the electromagnetic monitoring data obtained at Sleipner (*Park et al., 2013*).

6.2.2 Rock physics

The integrated geophysical, geomechanical and hydrodynamic measurements collected during our experiments are valuable (i) to interpret the hydromechanical behaviour of reservoirs and (ii) to develop and calibrate new rock physics theories for CO_2 storage.

The results from continuous mechanical monitoring during the experiments have informed realistic quantified inflation/depletion mechanisms that can be directly related to the acquired geophysical signatures. This is of direct application to field monitoring tools. We have found that by combining P- and S-wave velocity (Vp, Vs) data and electrical resistivity data, we can determine both the CO_2 distribution and the geomechanical conditions in the reservoir: Vp gives both mechanical and pore fluid distribution information, with very good quantification of both phenomena when combined with electrical resistivity; Vs is an excellent geomechanical indicator itself (Falcon-Suarez et al., 2017).

The experimental results have also drawn our attention to the strain recovery effect observed during imbibition, as clearly indicated by the geophysical parameters. Our analyses suggest that the natural aquifer recharge after the cessation of CO_2 injection could induce important changes in the elastic geomechanical properties of the reservoir (Falcon-Suarez et al., 2017). This highlights the importance of developing further studies towards assessing the geomechanical integrity of the reservoir during and also after cessation of CO_2 injection.

We have also shown that by combining drainage with imbibition in our experiments, the maximum CO_2 saturation during injection (structural trapping) and the CO_2 remaining post-injection during natural aquifer recharge (residual trapping) can be estimated. This information can be used to better constrain the effective CO_2 storage capacity of the simulated reservoir.

6.3 SUMMARY INSIGHTS AND RECOMMENDATIONS

- Synthetic rocks can provide useful material where suitable core material is not available.
- Synthetic rocks can provide material with controlled properties, ideal for calibrating rock physics models.
- Synthetic rocks might overcome the core depressurisation damage issue.
- It is difficult to manufacture synthetic rocks with fully realistic porosity/permeability characteristics.
- Running experiments at reservoir conditions on poorly-consolidated samples is technically challenging but possible.
- Experiments can provide key datasets for constraining rock physics models that seek to overcome the scale-dependency of seismic properties.

7 Towards a social licence for CCS

Here we present insights from the empirical work undertaken in DiSECCS towards building a Social Licence to Operate for CCS in the UK (Gough et al. submitted). In this study, the Social Licence to Operate (SLO) is described as an informal and ongoing process which depends on a wide network of actors with a stake in the development of a particular project or technology. While it requires the assent of those affected, it goes beyond simple acceptance or rejection, and is contingent on a variety of voices including lay publics (the different "publics" comprising different communities which may be host communities, local to a project, or other communities of interest which might go beyond project localities) as well as lay and professional stakeholders. Understanding the potential for establishing a social licence depends on understanding the social context in which a project operates, recognising that the context might change over time and that it might be relevant at different scales. Establishing trust between, and confidence in the responsibilities of, relevant stakeholders is crucial.

DiSECCS research has focussed on the use of seismic monitoring tools to establish trust and confidence in the storage system in three main areas:

- Demonstrating the capability of modern seismic monitoring to provide high-resolution images of CO_2 stored in the reservoir that enable determination of migration and trapping processes with a degree of confidence sufficient to make robust predictions about future, long-term, storage performance.
- Developing new understanding of rock physics and seismic wave propagation that reduce uncertainty in the quantitative analysis of time-lapse seismic monitoring data.
- Providing new laboratory data to constrain new rock physics theory and support quantitative analysis of seismic datasets.

The social research component of DiSECCS was conducted in parallel with development of the seismic monitoring tools, enabling a continuous dialogue between the different research teams. This fostered a mutual understanding of the challenges and insights across the different elements throughout the project, culminating in the participation of the DiSECCS Principal Investigator (PI) in the final empirical element of the social research. Based on the evidence generated by the social research, and informed by the wider project, we signpost key issues which lead to a set of recommendations for establishing and maintaining an SLO for CCS.

7.1 SOCIAL CONTEXT

The social context within which a project is to operate will have a strong influence on how it will be perceived; it describes what makes up the overall 'nature' of a place, area or locality.
Many factors come together to form the context including, but not limited to, features such as demographic profile, local heritage (which may be industrial or agricultural), employment prospects and types of employment in the area, dominant economic sectors (e.g. industry, tourism), long-standing presence of individual companies; history of previous siting controversies or successes (for example for other infrastructure or energy projects); history of successful regulation of other projects; the local physical landscape and how it has evolved in recent history; any governance issues (such as conflict between national, local or regional government; previous consultations and their outcome; the reputation of key organisations or stakeholders. Less tangible factors such as sense of place and identity within the region are also significant. Mapping

elements of the social context, and understanding the relevant spatial, governance and temporal scales is important for each element of the social context.

7.2 STAKEHOLDER NETWORKS

As networks and communities of interest build, the relationships between the various stakeholders to a project are critical; key organisations can be fundamental to this process. For example, the establishment of the Teesside Collective is an important factor in establishing trust between the cluster of industries it represents and the local population, and in enabling the Teesside region to develop and pursue opportunities for establishing CCS; it plays a central role in developing the cluster, provides a point of contact for regional, national and international stakeholders and is active in providing press communications about it. Therefore, the presence of a key stakeholder, or stakeholders, to champion a region, whether an organisation or an individual, can be an important factor. Furthermore, establishing a SLO for a new initiative driven by an existing industry with an established network and reputation (such as CCS, for example) is likely to be quite different to establishing one for a new type of industry or bringing an industry to a new area where the social and stakeholder networks are not established, where trust has to be built from scratch and the industry is seen as an 'outsider' (e.g. fracking in the UK).
Proposals from local known and trusted organisations may be better received than those introduced by 'outsider' organisations, such as national or international corporations with no established local presence.

7.3 COMMUNICATION

CCS is not yet a technology familiar to the wider population - an SLO cannot be achieved unless a project is recognised. People can become aware of a new technology via a number of communication pathways including, including offline networks, online networks and via the press. Existing guidelines for communicating CCS mostly relate to how to conduct public consultation/ engagement activities. These include: Community engagement guidelines for CCS projects – WRI (2010); Guidelines for public consultation and participation in CCS projects – Bellona (2009); Best practices - NETL (2017); Toolkit for community engagement - Ashworth et al. (2011).

Offline CCS networks are formal and informal networks of people that engage and communicate with each other about CCS. They are currently bound primarily within industry, academia and local government but, as awareness grows, these networks will expand and new networks emerge bringing in a greater variety of participants. The flow of scientific or technical information across these networks may be mediated by different parties – e.g. experts, journalists, individuals within lay communities etc. Local CCS stakeholders currently get their information primarily from national sources and share through local sources. Academic and local council umbrella groups are the key sources of information for these stakeholders. For a new technology such as CCS, where policy support and incentives are required from national government to support the work of local and regional government, a social network that is concentrated at the local and regional scale may not reach the seat of power. Furthermore, there is little representation of CCS in social or traditional media, and this is unlikely to change until the prospects for actual deployment become clearer. Social media is increasingly important in establishing and shaping awareness and understanding of new technologies and plans. However, online information flows across social media have not yet emerged as a vehicle for raising awareness of CCS. National media outlets dominate Twitter activity which remains limited among the wider lay public.

7.4 TRUST, RISK AND CONFIDENCE

Risk perceptions, trust and confidence in government and industry to operate, regulate and communicate a project are inherently related. History and past experience plays a role in building trust and confidence, but also can generate scepticism and distrust if experiences are negative. Once trust is breached and SLO shifts, it can be difficult to recover and potentially influence responses in the context of different projects. Past frustrations and lack of agency can erode trust between communities and local government, and between local and national government; for example if national strategies are used to overturn local decisions, or as the role of local government bodies is redefined. Perceptions of competence and integrity are key factors in establishing trust in technology operators and regulators; these are established by factors such as past track records, existence of adequate regulatory bodies and standards for similar processes or contexts, by developing a long standing presence within a community or population (at whatever scale that may be defined). In the case of CO_2 storage, establishing trust in the organisations and processes involved in monitoring and regulation is critical. DiSECCS has focussed on showing that storage monitoring systems really do enable operators and regulators to understand what is happening at a storage site and to respond as necessary to any unexpected or irregular behaviour. The development of trust may also be moderated by interdependence between parties – local communities may be conscious that they are engaged in a social exchange with industry, accepting certain physical risks in a trade-off with benefits from the presence of the industry.

7.5 SCALE

Scale applies across time, organisations, and place and is relevant in defining communities of interest, levels of governance and policy priorities. Dissonance between different scales of governance may create problems for a social licence and can expose tensions in governance processes, for example when local government obligations to the local communities which they represent are in conflict with the political priorities of higher levels of government. The implementation of CCS is also relevant across different scales: for example in the case of offshore storage specifically, there exists a broader community of interest, including diverse stakeholder groups; an SLO for a CCS project encompassing capture, transport and storage requires consideration at different scales for different elements of the chain. In the case of CCS, there may be different temporal scales at play across different elements of the CCS chain, from short term CO_2 capture to much longer term processes associated with storage, and governance processes must take account of these different time scales.

Furthermore, as the technology matures, the physical and geographical scale at which the SLO is relevant may change – for example as part of a wider national strategy for climate change mitigation, in the demonstration phases as first projects are established or in the case where it may be commercially deployed at a larger scale across the country.

7.6 SLO IS A DYNAMIC CONCEPT

SLO is not a static concept which once achieved can be guaranteed over the lifetime of a project; maintaining an SLO depends on the evolving social, industrial and political landscape. If an SLO shifts, whether because trust is breached or other factors come into play, it can be difficult to rebuild. The various characteristics of an SLO described above, including the social context, are all dynamic contexts which may change and evolve over time. Many factors can impact the stability of, or conditions for, an SLO which may be contingent on external effects unrelated to the project itself, for example: industrial closures; industrial accidents or natural disasters which might be geographically remote or in other sectors (e.g. Fukushima) or political events (e.g. Brexit, change of government etc).

Although it will never be possible to guarantee that a Social Licence will be achieved for any given technology or approach, the recommendations documented below provide a basic foundation on which social confidence might be built. The focus of the DiSECCS project is on CO_2 storage; critical to the SLO is establishing confidence in the monitoring and associated regulatory processes that will ensure the safety and security of geological storage of CO_2. It is clear that as monitoring data is progressively collected and understanding of the storage site evolves, the foundations of the SLO might also change, in a positive or negative sense.

7.7 SUMMARY INSIGHTS AND RECOMMENDATIONS

Although it will never be possible to guarantee that a Social Licence will be achieved for any given technology or approach, the recommendations documented below provide a basic foundation on which social confidence might be built.

- *Understanding the social context*. What the area is like: what is there now, what was there before, who lives there, what they do, what has happened there, and how and why did it happen. Noting that the "area" could be a place, a corridor, a region, a country and different areas may be relevant within a single project.

- *Developing key arguments in context*. Successful key arguments for CCS will depend on the social context, for example these may focus on potential economic arguments framed in terms of investment, employment and leadership opportunities and the possible benefits that CCS might bring alongside reductions in greenhouse gas emissions necessary to maintain key industrial activities.

- *Fostering stakeholder networks.* Establishing a relationship between stakeholders that is based on trust is a long term process, dependent on the interactions of a variety of factors, including: current and past associations which build confidence, a reputation for reliability and predictability, and expectations of how the institutions will operate.

- *Growing offline communication networks*. The interaction between key stakeholders, active within offline networks, and the press is central to how press coverage influences opinions on the technology within civil society. Local and regional networks may be insufficient to influence national policies, whether for support moderation of technologies.

- *Establishing online communication networks*. CCS does not yet have an identity on social media outside its own limited niche network; for this presence to extend into wider online communities, it must build a unique identity associated with the "CCS" acronym.

- *Building trust and confidence*. Perceptions of risk are influenced by trust and confidence in institutions and procedures; it takes years to demonstrate competence and integrity, once trust is lost it can damage prospects for an SLO for future proposals in other technologies.

- *Different social licences at different scales*. Multiple SLOs may come in to play across different scales: successful deployment of a technology will require an SLO at an appropriate scale, bearing in mind there may be conflict between the policy priorities at different scales.

- *Maintaining an SLO.* The SLO should be treated as an ongoing process – it might be contingent on a variety of related or unrelated events or factors which might impact the stability of an SLO once established.

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