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Risk from CO_2 storage in saline aquifers: a comparison of lay and expert perceptions of risk

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Abstract

Public perceptions of CCS are seen as crucial in terms of the deployment. Recent opposition to CO_2 storage projects, such as Vattenfall's Schwarze Pump project in northern Germany, demonstrates that addressing public concerns is a crucial factor in securing support for a CO_2 scheme. Risk communication will be affected by multiple issues such as the language used, trust in the communicating actors and the opportunities for dialogue. The literature on siting of facilities also cautions that in many cases there in a mismatch between experts and lay perceptions of risk. This paper compares expert and lay perceptions of the risks associated with CCS in two case study areas and is based on the work undertaken in the CASSEM project, which is developing tools for the evaluation of CO_2 storage potential in saline aquifer.

Keywords: Carban capture; public perceptions; risk assessment

1. Introduction

If CCS is to play a significant role in climate change mitigation, it must be deployed on a wide scale and the injected CO_2 has to stay in the reservoir for hundreds if not thousands of years. The UK has a large offshore storage resource within depleted oil and gas fields and saline aquifers, with enough capacity to provide storage for other EU countries as well as the UK (DECC, 2010). Data and understanding of the reservoir characteristics built up over the lifetime of oil and gas extraction in UK waters means that the oil and gas storage sites are well understood, and there is a high level of confidence associated with the models used to simulate the process of geological storage. This contrasts with the high levels of uncertainty associated with the modelling of saline aquifers which are considerably less well understood. Furthermore, given that potential UK storage sites are offshore, data collection to evaluate a reservoir will be expensive. The CASSEM (CO_2 Aquifer Storage Site Evaluation and Monitoring) project has adapted existing tools and techniques such that the suitability of an aquifer for CO_2 storage may be assessed prior to committing financial resource to expensive drilling.

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When a specific project is being considered, many factors will influence the selection of a reservoir, in a technical process in which a risk assessment process plays a key role. In the CASSEM methodology, a process of expert elicitation using Features, Events and Processes (FEP) technique, similar to that used in the nuclear industry, is used to identify the elements of the reservoir assessment which are associated with the greatest uncertainty; it is in these areas where data gathering is focused. This technique was applied to a saline aquifer in each of two case study areas, the Firth of Forth and Lincolnshire. Moving onto commercial deployment of CCS, once the process of developing a full commercial CCS project begins, risk assessment and communication is no longer the concern solely of experts but instead evaluation becomes a more social process, influenced by a range of key local influences. To explore public perceptions of CCS, and its associated risks, a series of citizen panels were conducted in Dunfermline, on the Firth of Forth, and Pontefract, in Yorkshire and Humber. Both these towns are close to coal fired power stations where CCS may be deployed in the future, and in the vicinity of the aquifers evaluated in the CASSEM project.

This paper compares the expert and lay understandings of the risks associated with CCS identified by the CASSEM project. Section 2 discusses how the expert risk assessment was conducted; Section 3 describes the process of lay risk assessment. Section 4 outlines the risks associated with storage of CO_2 from the perspective of experts and Section 5 focuses on the lay assessment of risk. The two elements of the evaluation are brought together in Section 6, the discussion and conclusions.

2. Experts, CCS and risk

From a technical risk assessment perspective, risk is a function of the likelihood and the severity of some adverse event. It is an essential part of the decision process for determining the suitability of a reservoir for storage. Risk assessment can be used to determine which of a number of potential storage sites are worthy of further evaluation, the types of studies it may be necessary to undertake to characterise a storage site, to identify potential risk mitigation activities, and ultimately to decide whether a reservoir should be used for CO_2 storage.

In the CASSEM project, a six step process has been developed for the compilation of a project-specific risk register which is applied to the two storage case studies; this is described in detailed in Polson, Curtis et al. (2009) [1] . The register contains a list of FEPs which define relevant scenarios and behaviour of CO_2 in the storage reservoir; these are assessed by experts for their likelihood (L) of impacting the project, and the severity (S) of this impact. Each is assessed on a 1 to 5 scale where 1 is low and 5 high. The two scores are multiplied to give a combined score where a total score of 1 is considered negligible risk, a score of 2 to 4 is considered low risk, a score of 5 to 9 is considered moderate risk, a score of 10 to 16 is considered high risk and a score from 17 to 25 is considered very high risk. A FEP that scores in the high risk banding or above is regarded as prohibitively high for the project and mitigation activities should be implemented to reduce the risk to the moderate banding or below.

Experts were assigned to assess FEP's based on their expertise and were required to complete assessments at regular intervals throughout the project so that changes in their perception of risk, arising for example from new information concerning reservoir properties, could be tracked. The experts were asked to give 'best-guess' values for the likelihood and severity scores and also lower and upper bounds which could be used to assess the uncertainty in these scores. The process is designed to highlight the areas where risk is highest, with the intention that this information feeds into project decisions. The risk assessment results from the start of the project fed directly into project decisions, with a range of additional data acquisition activities identified which were in large part aimed at addressing areas perceived as high risk by the experts.

3. Lay people, CCS and risk

The risk assessment approach described in Section 2 typifies how decision makers seek information to predict and evaluate the consequences of various activities [2]. CCS deployment will ultimately take place within the social setting of towns, workplaces and wider society and there is a growing recognition that risk assessments can be improved by incorporating a wider knowledge base into these 'technocratic' approaches in relation to complex projects, with a high level of uncertainty [3]. The lay public, particularly those living in the vicinity of power station or new pipeline route will understandably have concerns over the deployment of a new and unfamiliar technology, and local knowledge of material importance to the development of a scheme, therefore a central function of contemporary risk assessment is to engage with the concerns held by members of the public. Contemporary 'risk discourses' have become dominated by the anticipation or perception of risk, consequently, the perceived risks of a new technologies are often a far greater threat, financially, politically and socially than the original physical threat [4].

The research to explore public perceptions of the risks associated with CCS within the CASSEM case study areas was one element of a wider set of research questions focused on public perceptions of CCS and the factors which influence those perceptions explored in a series of citizen panels. Citizen panel participants met for a total of 10 hours, over the course of which experts from the CASSEM consortium presented information on CCS; they also received written briefing notes. The presentations focused on climate change and energy generation, CCS technology, CO_2 storage and risks associated with CCS. The CCS focused presentations were designed in response to specific requests for information gathered during the introductory session. Plentiful opportunities were provided for participants to discuss CCS with the experts, and small facilitated discussion groups ensured that everyone had the opportunity to be heard. In addition the participants were asked to give feed back on the information they had been provided and comment on the citizen panel process. The citizen panel methodology is outlined in greater detail in the project report [5].

Although the risks associated with CCS were frequently mentioned by participants throughout the whole process, the specific risk assessment element of the citizen panels took place in the later stages, once the panel participants had received an overview of all aspects of CCS from the expert presentations, and had had the opportunity to discuss the technology with the experts. A risk mapping exercise was performed in small facilitated groups where participants were asked to describe the risks they associated with CCS, and locate these within the CCS chain. The mapping exercise was followed by an expert presentation focusing initially on the expert risk assessment undertaken within the CASSEM project and then responding to the lay perceptions of risk as revealed by the mapping exercise. Following the risk presentation, participants were asked for their reactions to the risk presentation, and to highlight remaining areas of concern.

4. Expert assessment of risk

Figure 1 shows the best-guess scores for those FEP's that were perceived as high risk (i.e. $LxS \geq 10$) at the start of the project for either site. The scores for each site for both the start and the end of the project are shown. The risk assessment results at the start of the project showed that overall the highest perception of risk for both sites related to the financial viability of the project. Financial viability is not necessarily related directly to the properties of the storage sites but instead to the huge costs associated with any CCS project. The FEP's 'Construction of pipelines', 'Construction and site logistics' and 'Public perception and security' are also perceived as high risk and tend not to relate directly to the physical properties of the storage sites but instead are likely to reflect experts' general concerns for any CCS project.

However a number of the FEP's do relate directly to the physical properties of the storage site and for these FEP's it was possible to see a clear difference between the perceived risk for each site. In particular we see that for a range of FEP's relating to the geological properties of the sites ('Fractures and faults', 'Undetected features', 'Formation pressure', 'Lithology' and 'Heterogeneities') are perceived as higher risk for the Firth of Forth site than the Yorkshire/Lincolnshire site [1]. This is related to the greater uncertainty in the geological properties of the Firth of Forth site which is far more complex structurally and has poorer quality and fewer data with which to constrain the geological model of the subsurface than the Yorkshire/Lincolnshire site.

Other FEP's relating to the properties of the storage site that are ranked as high risk relate to the hydrology of the region. For both sites at the start of the project the FEP's 'Hydrogeology' which relates to the hydrogeological regime within the reservoir and the FEP's 'Near-surface aquifers and surface water bodies' and 'Near-surface Hydrogeological regime and water balance' which relate to the hydrological properties of the near-surface environment are perceived as high risk [1]. Again this can be related to uncertainty with the experts unsure of the response to CO_2 injection. In particular for the Yorkshire/Lincolnshire site there are concerns about the structure of the storage formation as is also shown in the FEP 'Storage Concept' which is also considered high risk. The Yorkshire/Lincolnshire formation is made up of a series of shallowly dipping layers which comes to outcrop far up-dip from the injection site. Consequently there is not complete geometrical closure of the reservoir by the caprock and in the shallow near-surface, the aquifer contains fresh water. The perceived risks relating to the hydrogeology for this site relates primarily to the potential for contamination of this fresh water.

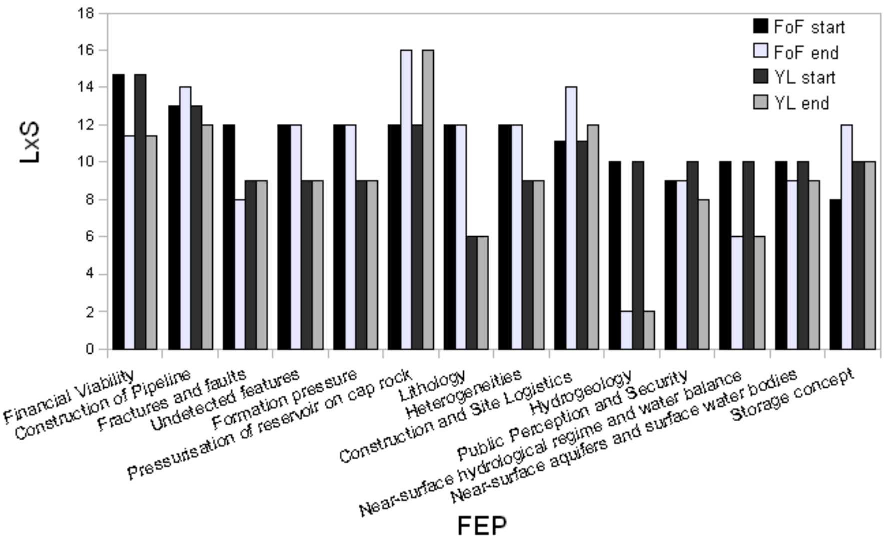

Figure 1. The best-guess likelihood (L) x severity (S) scores for the star and end of the project for each site for those FEP's that rank in the high risk or greater (≥10) at the start of the project for either site.

These results were used to help select a range of data acquisition activities. These included reprocessing of seismic data for the Firth of Forth site with modern processing techniques to improve the quality of the data and a hydrogeological study of the region around the Yorkshire/Lincolnshire site. Comparing the experts' risk scores at the end of the project we can assess whether these activities have changed the experts' perception of risk. However as experts scores may change due to factors other than new information (for example cognitive biases) we need also to consult the experts to understand why they have changed their scores. By the end of the project the improved seismic data for the Firth of Forth had a noticeable impact on the 'Fractures and faults' FEP which decreased in response to fewer faults being interpreted in the re-processed data. The hydrology related FEP's also saw their scores decrease for both sites. The results of the hydrological study showed that the interface between the fresh and salt water was unlikely to move as a result of injecting CO_2. Therefore the experts' perception of risk decreased for the Yorkshire/Lincolnshire site. This increased understanding also seems to have been transferred to the Firth of Forth site.

Other noticeable changes include a decrease in the scores for the 'Financial viability' FEP. This change is a result of the alterations to the risk register with this FEP being divided into individual FEP's which are assessed independently. The average of these is shown on Figure 1. The 'Storage Concept' FEP for the Firth of Forth site is seen as higher risk at the end of the project. This relates to a number of factors with the results of various work done within the project showing this site to be less suitable for CO_2 storage than originally thought. The FEP

'Pressurisation of reservoir on caprock' also shows an increase in score however it remains in the same high risk band from the start to the end of the project.

Overall the main factor affecting experts' perception of risk is uncertainty with greater uncertainty tending to increase their perception of risk. The range (upper – lower bound) tends to be strongly correlated with the best-guess risk score (typical R value ~ 0.6, p-value < 0.001) showing that as the experts' uncertainty increases, so does their perception of risk. Only through addressing this uncertainty will the experts' perception of risk decrease, though it does not necessarily follow that less uncertainty will lead to a reduced perception of risk.

5. Lay assessment of risk

Whilst the citizen panel sessions focused in risk took place once participants had learnt about CCS, questions of risk unsurprisingly were raised throughout the whole panel. When participants were initial introduced to the concept of CCS their early concerns focused on safety and particularly leakage, areas where they requested information to be provided during the experts presentations. The participants were keen to know whether the CO_2 could leak and the consequences of a leak; would it be a danger to human health? Could CO_2 explode? What happens if there is an earth quake? Will the CO_2 remain stable for thousands of years? A number of people considered CO_2 storage to pass the responsibility for climate change mitigation onto future generations and wanted to know whether CO_2 was safer to store than nuclear waste. CO_2 storage sites were perceived, by some, to be potential targets for a terrorist attack. A number of questions were raised about who decides the location of CO_2 stores and how this is decided. Participants in the Dunfermline panel were concerned that there was a danger that rich countries could end up dumping CO_2 in unsafe and poorly regulated storage sites in the developing world.

Maps of the CCS chain which detail the risks associated with CCS from a lay perspective are contained within the project report [5]. Table 1 summarises the lay risks for each of the case study areas and indicates where on the CCS chain the risk is judged to occur

Table 1 Lay assessment of the risks associated with CCS

	Dunfermline	**Pontefract**
Human health and safety	▪ Risks from the chemicals used in CCS process (C) ▪ Explosions (C) ▪ Potential target for terrorism ▪ Health and safety of staff (C)	▪ Accident in the chemical process (C) ▪ Explosions in compression (C) ▪ Potential target for terrorism (C) ▪ Safety of workforce (C, T, S) ▪ What happens to the CO_2 if the technology fails? (C)
Environmental impact/damage	▪ What is the effect of CO_2 storage on the marine ecology? (S) ▪ Pipeline leak (T) ▪ Impact on food chain from leaks (T and S) ▪ Leak effects on sea acidity (T and S) ▪ What is the effect of CO_2 storage on the marine ecology? (T and S) ▪ Concern about the effect on rocks, life, bacteria in the long term (S) ▪ Water displacement (S) ▪ How secure will it be in the long term? Plates moving (S) ▪ Will there be sea level rise from CO_2 pushing the cap or filling the space? (S)	▪ Environmental impacts of building pipelines – land/sea (T) ▪ Impact on marine life (T) ▪ Leakage from pipeline (T) ▪ Large-scale environmental damage (S) ▪ Impact of leakage on the surrounding area (C) ▪ Leakage from cap-rock (S) ▪ Seismic activity (S)

	Dunfermline	Pontefract
Financial, regulation/governance	▪ How prepared is the Government for leaks? Is there a contingency plan? ▪ Cost of monitoring ▪ Who takes responsibility for cross-border issues? ▪ What are the financial risks? ▪ Will Scotland benefit financially or will the money go to the UK Government in London?	▪ Companies trying to save money by implementing the technology on the cheap (C) ▪ Risk from private companies – money – regulatory failure (C, T, S) ▪ Taking away investment from renewables ▪ Political risk - territory
CCS concept	▪ Impact of the capture process on the efficiency of the power station (C) ▪ Drilling (S)	▪ Contamination of oil fields (S) ▪ Long term behaviour of CO_2 (S) ▪ Uncertainty of new system – no proof it will actually work (C, T, S)

(C) risk associated with the capture of CO_2; (T) risk associated with the transport of CO_2; (S) risk associated with the storage of CO_2

Members of the CASSEM consortium with expertise in risk, CO_2 storage and capture and transport engineering attended the citizen panels to provide information on CCS to the participants and to discuss their concerns with them. Following the risk presentation, participants were able to respond to the information they had received; Table 2 outlines the remaining concerns.

Table 2 Lay assessment of risk associated with CCS at the end of the citizen panel process

	Combined results from both panels
Human health and safety	
Environmental impact/damage	▪ There will always be a potential for leakage ▪ Damage to the marine ecology from leaks
Financial, regulation/governance	▪ The final costs are not known and could be very high; these will impact on the price of electricity ▪ Investment will be taken away from renewable energy ▪ How can monitoring be assured over 1000's of years? ▪ Are international governance structures adequate to ensure cross-border regulation?
CCS concept	▪ Risk to climate change mitigation from relying on an uncommercialised technology ▪ Risks arising from the continued use of coal ▪ CO_2 storage network, what risk to the UK from storing other country's CO_2?

6. Discussion and conclusions

In this paper, we describe two assessments of the risks associated with CCS, one from an expert perspective, and the other from a lay perspective. The results of the expert assessment were presented to the participants at a series of citizen panels focusing on CCS, at which experts who had contributed to the expert assessment were able to discuss risk with the panel participants.

Taking the expert assessment as a starting point, there was a strong relationship between the risk associated with an aspect of CO_2 storage, and uncertainty. Thus, a higher level of risk was associated with those elements of the risk register which were the most uncertain. In project terms, this was a useful means of guiding data acquisition; reprocessing of seismic data took place for the Firth of Forth site and hydrogeological assessments were performed for the Lincolnshire aquifer. A decrease in the risk associated with these elements is clear by the end of the project which the experts attribute to the new knowledge. Interestingly the impact of public perceptions on a project also emerges as a significant risk from the expert assessment, with little change in the associated risk between the beginning and end of the project.

There were some risks associated with CCS that were perceived as important by both experts and the lay public. In both the lay and expert assessment, financial risks were ranked most highly, though unsurprisingly focused on different aspects: the expert assessment was over the viability of the industry, whereas for the lay public it was a concern over who would pay and the impact of CCS upon their energy bills. The potential for leakage also emerged as a high risk from both assessments, though with differing levels of detail. The technical assessment of the experts was multi-dimensional, considering the risk of leakage from a variety of different pathways e.g. fractures, faults and pressurisation of the cap rock. In contrast, the lay assessment of leakage did not unpack leakage in the same manner, for reasons of lack of technical knowledge. The influence of uncertainty was also evident on the lay assessment of risk, with participants pushing the experts to be explicit about the uncertainty associated with their assessments. Ultimately uncertainty was accepted and risks judged to be acceptable as a consequence of the trust built between experts and participants, a point which is returned to later. Given that CCS is a new technology, and few people as yet have direct experience of living with a CCS neighbour, our participants did not have their own experiences of risks with which to counter the expert assessment. This may explain, in part, the similarity between the lay and expert assessments, as well as the good relationships that developed between experts and participants.

Moving on to consider the lay risk perceptions in more detail, these clearly evolved and became more sophisticated over the course of the citizen panels. Giddens (1999) [6] describes how 'society is becoming more pre-occupied with the future (and safety)' which provides an insight into the initial focus of panel participants on the risks associated with CCS. As people learnt more about the technology, and were able to enter into discussions both with each other and with experts, their understanding of the risks associated with CCS evolved and became more subtle. Whilst there were clearly risks which were of concern to local people which did not appear on the risk register e.g. sea level rise because of bubbles of stored CO_2 pushing up the rock beneath the sea bed, others such as security, site logistics and pipeline construction were of concern to experts and the lay public alike. Although the number of areas of concern increased during the panel process, by the end of the process, fewer outstanding concerns remained. Thus whilst the potential for environmental damage and leakage remained of concern, the areas of greatest risk were associated with regulation, governance, finance and the basic CCS concept.

The citizen panels were designed as a highly deliberative process, with ample opportunity for discussions between experts and participants who, at the beginning of the process knew nothing about CCS, and little about climate change. CCS is a highly technical and complex process of which people, as yet, have little experience. The panel participants did not make technical judgments themselves, but instead made decisions about the risks associated with the technology based on their interactions with the experts and the information they provided. These decisions are guided by social trust, where social trust refers to the processes people use to reduce the complexities surrounding the formation of a perspective on new technology or other potentially risky innovation [7]. When people do not have the technical knowledge to evaluate a risk themselves, they base their judgment on their evaluation of those managing the risk or hazard. As the participants built a relationship with the experts, who were happy to discuss all aspects of CCS and answer questions, they decided they trusted them and were willing to accept the information provided. This resulted partly in less uncertainty in the minds of participants, but also in the acceptance of uncertainty. Thus, many of the concerns over CO_2 storage, capture and transport were addressed through discussions with the experts. For those areas, particularly regulation and governance for which no experts were present, concern remained. It is however useful to note that a distrust of government was highlighted in questionnaire responses.

In some ways the process of expert elucidation of risk was comforting to the citizen panel participants, as it demonstrated a logical and structured way of thinking about CCS and the risks of storage, and for the siting of reservoirs. On the other hand it raised concerns over who makes the final decision about whether a particular reservoir should be used and the need for trust in the organisation making the final decision. Deliberative processes as demonstrated in the CASSEM citizen panels are a useful approach to facilitate discussions between those deploying CCS and affected communities.

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