AN ETI INSIGHTS REPORT

BRINE PRODUCTION AND ITS POTENTIAL IMPACT ON UK CARBON DIOXIDE STORAGE

Delivered by

Catapult Energy Systems

Contents

Carbon capture and storage (CCS) delivers the most competitive and productive transition to a least cost low carbon future.

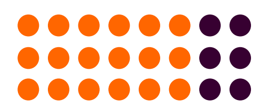
There are 575 potential CO_2 stores, with 76,000 million tonnes of storage capacity.

Just 10% of this capacity would be needed to deliver the lowest-cost decarbonisation pathways containing CCS.

BRINE PRODUCTION AND ITS POTENTIAL IMPACT ON UK CARBON DIOXIDE STORAGE

Brine production alleviates the limiting pressure in a saline aquifer from the injection of CO_2.

Over 75% of potential UK CO_2 storage capacity is found in saline aquifers.



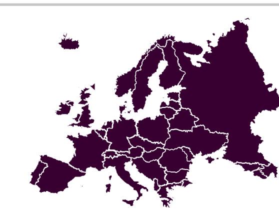
Brine production as part of a CCS rollout implementation strategy could save the UK at least £2 billion.

£2bn

Brine production can increase a store's capacity, extending operational life by as much as 20 years, reducing risk for developers.

Enlarging cheaper stores with brine production changes the optimal order of infrastructure investments reducing the overall costs of CCS.

The UK has the skills, capabilities and expertise for brine production technology, opening up wider export opportunities.



EXECUTIVE SUMMARY

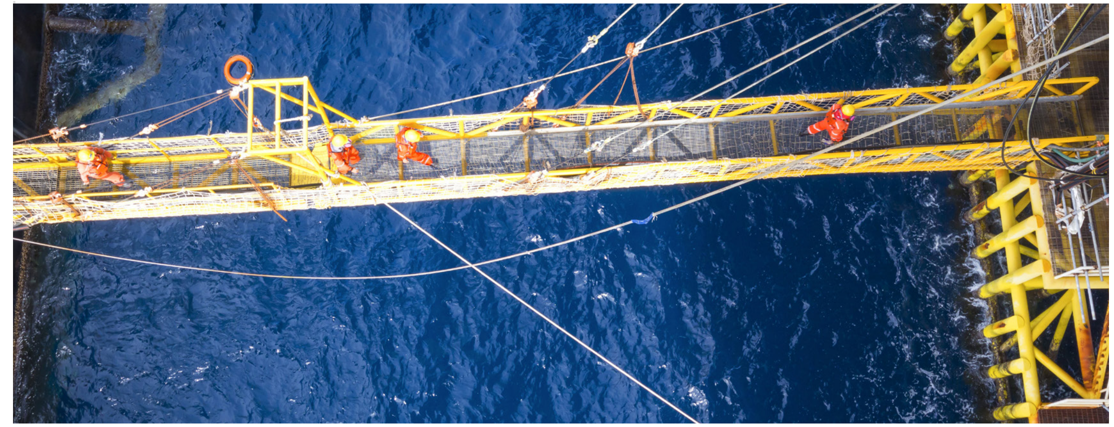
A range of evidence supports the role of carbon capture, usage and storage (CCUS) in delivering the most competitive and productive UK transition to a low carbon future. Numerous whole energy system analyses demonstrate the robustness of the future role of carbon capture, usage and storage (CCUS[1]), even with a conservative view of future cost reduction; for example those produced by the ETI and quoted by the Committee on Climate Change (CCC). This is underpinned by the versatility of CCUS and its unique potential for industrial decarbonisation. Failure to develop the capacity to deploy CCUS at commercial scale by 2030 will significantly increase the costs and risks of delivering the emissions reductions required for the fifth carbon budget and beyond.

Progress with CCUS development in the UK, however, has been slow, and the exposure of project performance due to geological variability, when combined with the higher costs associated with the offshore CO_2 storage elements of carbon capture and storage (CCS) projects, is one factor hindering deployment in the UK[1]. The UK government has funded appraisal work on several of the many offshore saline aquifers potentially suitable for CO_2 storage. As a result, our knowledge base relating to these stores is high, and some stores are 'ready for business'. Injecting CO_2 into saline aquifers pressurises them, and since each store has a limiting pressure for integrity reasons, this can limit the storage capacity and CO_2 injection rate, and so affect costs. This paper describes the efficacy of a simple technique to alleviate this constraint – pressure is relieved by releasing the native water in the aquifer as it is filled with CO_2. This is termed 'brine production'. It has been researched, but it has not yet been tested at scale or used commercially. The project which underpins the findings in this Insight paper was commissioned and funded by the ETI and led by Heriot-Watt University, and used detailed geological models of prospective UK stores to investigate the value of brine production.

The key insights from our analysis are as follows:

Based on the analysis summarised in this report the savings to the UK from deploying brine production as part of a UK CCS rollout implementation strategy in line with that needed to deliver lowest-cost decarbonisation pathways would be at least £2 billion, but would most likely be more. This cost benefit is derived from a combination of:

- In-store cost reduction from economies of scale by enabling significantly increased storage capacity to reduce unit storage costs (in one example studied this was worth £1 billion over the life of the store - a 33% reduction); and
- Enhancing the capacity of cheaper stores, thereby obviating the need to appraise and develop more expensive stores (for the limited examples studied this was valued at another £1 billion).



The value to the public sector from the availability of brine production as a tool to support a CCS rollout strategy is likely to be much greater than this given the value it can also provide in terms of:

- Investment risk mitigation and improved management of strategic investments - particularly in terms of being able to deploy brine production several years after initial store operation to mitigate the impact of unexpected conditions being experienced within the store geology, or in response to changing operational conditions; and
- Technical risk mitigation – enabling a store to be operated (and decommissioned) at lower operating pressures than conventional injection approaches that don't use brine production, thereby improving operational flexibility and reducing the risk of leakage from the stores
- Skills development and wealth creation - although the brine production technology is physically relatively simple to implement, garnering the full benefit from its use will need skills, capabilities and expertise that the UK is well placed to develop from its offshore oil & gas industry, and offer as a service abroad.

If a strategic approach is taken to rolling out CCS at a meaningful scale, and this focusses on cost and flexibility, brine production is likely to be a key enabling technology.

To enable the UK to capitalise on the value of brine production within a CCS rollout, it is recommended that consideration is given to:

- Encouraging developers to consider brine production options in the assessment and processes for new CCS facilities, and in broader UK CCS rollout strategy development
- Further developing brine production modelling techniques in the context of CCS deployment
- Developing a consistent cost database for UK storage options, recognising the differences in confidence in the stores
- Exploring analytical solutions for estimating brine production benefits, which may make semi-quantitative screening more straightforward
- Exploring the environmental case and developing technology for the option to release brine at depth from subsea templates, and preparing for environmental assessments of brine production to be part of storage licence applications
- Developing technical co-operation with existing or planned projects which may use brine production and scoping a physical research and development (R&D) project designed to assist prospective users of the technology.

CO_2 STORAGE CONTEXT

Offshore geological structures deep below the UK Continental Shelf have been extensively explored for oil and gas (O&G) production. This has provided sufficient data to identify large saline aquifers, which are potential CO_2 stores, and an atlas of the UK's CO_2 stores (CO_2Stored[2]) has been developed to assist high-level planning and screening of stores. This identifies an inventory of 575 potential stores for CO_2, totalling 76,000 million tonnes of storage capacity, around 10% of which would be needed to deliver lowest-cost UK decarbonisation pathways containing CCS. Aquifers are layers of porous rock containing salt water (saline or brine aquifers) overlain by a cap rock layer which is impervious to water, hydrocarbons, and CO_2. Over 75% of the potential UK CO_2 storage capacity is found in saline aquifers (CO_2Stored) and these are described in Box 1: Types of Aquifer. As production of natural gas from offshore oil fields and gas fields comes to an end, these are also increasingly becoming available to be used as CO_2 stores.

Box 1: Types of Aquifer

There are four types of saline aquifer store classified in CO_2Stored:

- Open, with structure
- Open, without some structure
- Structural trap
- Fully confined

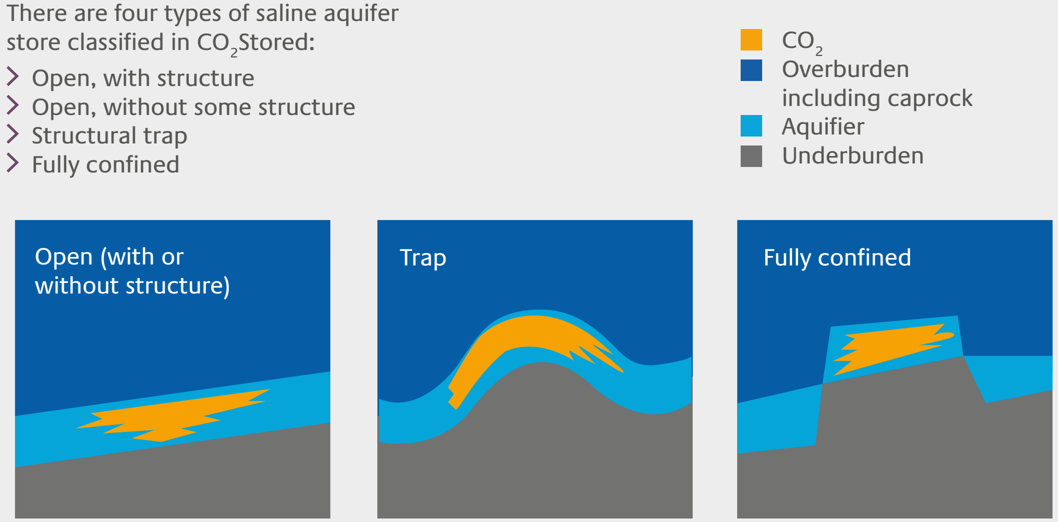


Figure 1
Different types of store

In fully confined stores, as CO_2 is pumped in, aquifer brine is unable to move out of the store as it is completely surrounded by impervious rock. Injection increases the pressure in the store, and the ability of the caprock to remain impervious as the pressure increases sets the limit on the capacity of the store. This type of store is the largest in terms of the contribution to total storage capacity, number of stores and by individual size, and is the most likely to benefit from brine production. However, such stores tend to be in deeper, remote, more complex rock formations, requiring a lot of data for analysis and so may not be included in the initial phases of CCS development.

In open stores, the aquifer is large, and injection of CO_2 would not normally be restricted by the caprock pressure constraint as the brine can be pushed away into the surrounding aquifer. The store capacity in this case is more likely to be constrained by the need to ensure that CO_2 stays within the licensed area of the store, as the CO_2 will tend to float to the roof of the store and migrate up any slope. That said, even in an open store, the injection rate has a local limit - if you inject faster than you can push water out of the way, then the pressure will rise.

Traps in open stores are an ideal combination, in that the CO_2's buoyancy in the saline aquifer concentrates the CO_2 in one small area (the top), yet brine can be displaced to make room for CO_2 and alleviate the local pressure rise. It is estimated that some traps can utilise as much as 20% of the 'pore space' (the space in the rock available for CO_2), whereas pore space utilisation in fully confined stores and open, unstructured stores could be less than 2%, with many less than 1%. High utilisation of pore space keeps the store small, which saves appraisal, infrastructure and monitoring costs, and can reduce the likelihood of problems with legacy wells or interference with oil and gas operators.

STORAGE APPRAISAL

Storage appraisal to support three full chain CCS projects has been funded by the UK Government, covering a range of store types and locations. These, plus five other stores which could be in use by 2030, were benchmarked in an appraisal project[3] managed by the ETI in 2016. The total storage resource[1] of these eight stores, based on conventional injection methods is c.1,650 million tonnes, which is more than enough to start several large CCS projects lasting through to 2050. The ETI project also identified a 'top 20' of UK stores, selected to provide a secure, geographical and geological diverse portfolio, which could hold c. 6,800 million tonnes of CO_2. These stores are mapped in Figure 2.

This is more than enough storage to hold all the emissions for the lifetime of all CCS plant that the UK would need to deploy between now and 2050, if it chooses to follow lowest-cost decarbonisation scenarios. The UK is therefore not short of storage opportunities, but there is a need to deliver practical storage facilities at lowest cost with manageable performance risk. For example, in the eight stores benchmarked by the ETI, the lowest cost store was one third of the unit cost of the most expensive; hence increasing the capacity of the lowest cost stores could reduce overall costs and obviate the need to appraise and develop more expensive or higher risk storage projects.

Although store depth, water depth, and injectivity affect cost, larger stores, and those which can support higher injection rates will generally have better economics, assuming there is sufficient CO_2 being captured to make use of the available capacity.

Capacity increases could also unlock value in some smaller stores that have favourable attributes (e.g. good location, existing infrastructure) but lack economy of scale without brine production.

Although the cost structure of individual full chain CCS projects varies, depending on the store selected, we can expect about 15-50% of the total capital costs of capture, transportation and storage of CO_2 to be spent on the offshore pipeline transportation and storage (T&S) assets of a major new build project. When operational costs are added, about 65%-85% (NPV @10% discount rate) of the levelised offshore costs are attributable to storage alone. Hence any interventions that can reduce the costs of storage can have a significant impact on the overall cost effectiveness of a CCS project.

Additionally, since the stores are natural features deep below the surface, and not man-made, there will be uncertainties in how they perform once in operation. Therefore, any intervention or technique that can help an operator manage the performance risks associated with geological uncertainty is also likely to add significant value.

Strategic UK CO_2 storage appraisal project selected sites

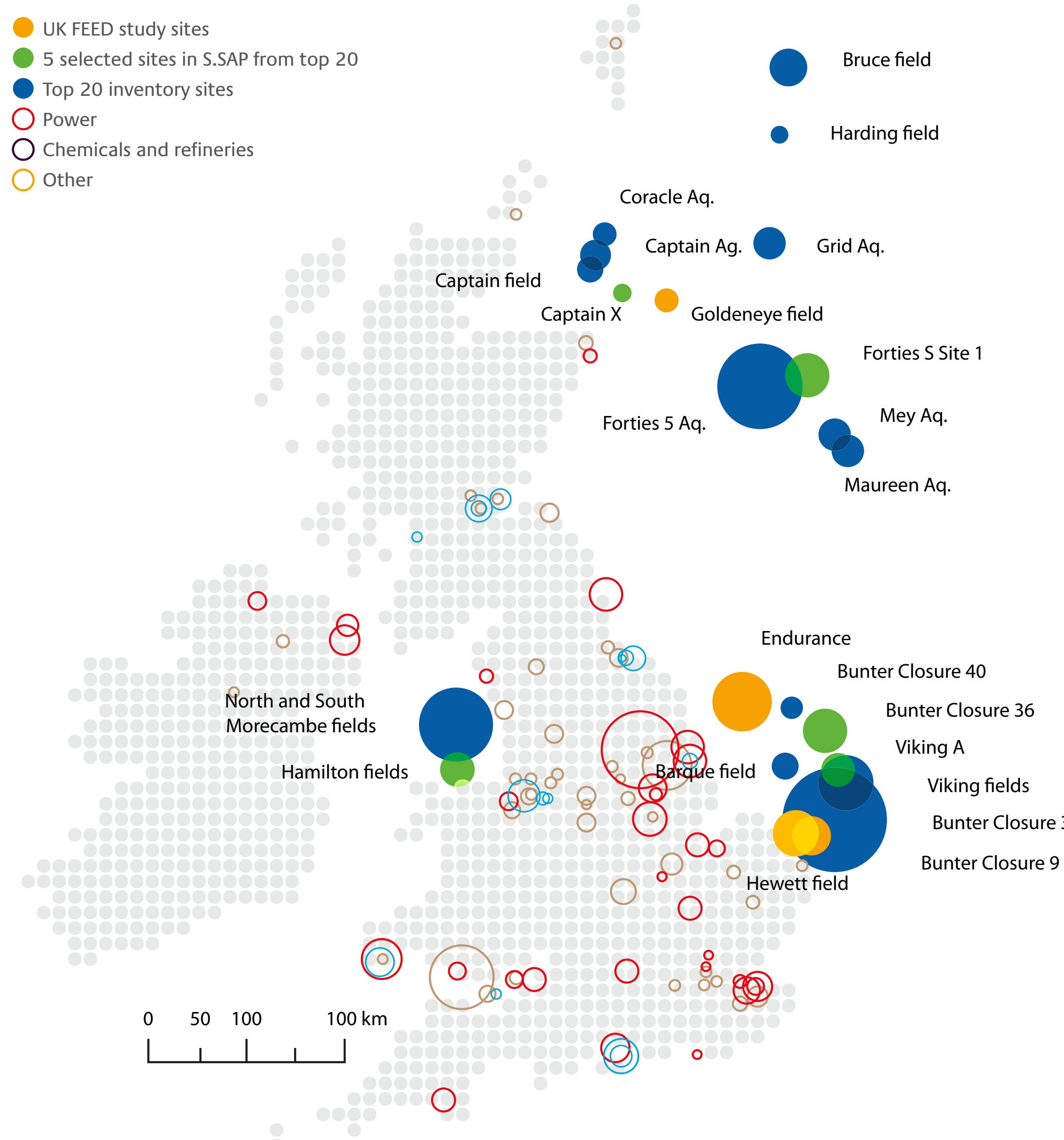


Figure 2
Key near term stores in the UK, including depleted oil and gas fields.

1. When talking about the size of specific stores, the term 'capacity' is reserved for a fully appraised, financed store. The term 'resource' is used for stores still in various stages of appraisal.

BRINE PRODUCTION

In saline aquifers the pore space between grains in the reservoir rock is flooded with brine hence the term ‘saline aquifer’ (it is normally only very shallow rock formations that hold fresh water and are termed fresh water aquifers). When injecting CO_2 into underground storage, the achievable capacity and injection rates are often restricted by the fracture pressure of the caprock which seals the CO_2 in the reservoir below. High pressure injection is needed to push the CO_2 into the reservoir. If the pressure increases too much it is possible for this to exceed the containment strength of the rock and might even lead to fractures in the seal.

The pressure increase caused by the injection of CO_2 can be alleviated by removing some of the brine, in a process called ‘brine production’. As shown in Figure 3, constantly injecting CO_2 pressurises the liquids at the injection point, and the CO_2 is pushed through the pores in the reservoir rock, pushing away brine as it does so. It doesn’t mix fully with the brine, but it is partially soluble in it. A ‘plume’ of CO_2 rich fluid spreads from the injection point. Once the CO_2 moves away from the immediate vicinity of the well, the main driving force becomes buoyancy, and the CO_2 flows up the slope directly underneath the cap rock. Once brine production starts, the area around the brine well loses pressure, and brine pressurised by the CO_2 injection naturally heads for this ‘outlet’. The movement of the CO_2 is influenced by the balance of the buoyancy force and the draw from the depressurisation. At some point, the brine entering the production well may get contaminated with dissolved CO_2 and the well may have to be closed, or possibly converted to an injection well, and a new production well opened in a deeper part of the formation.

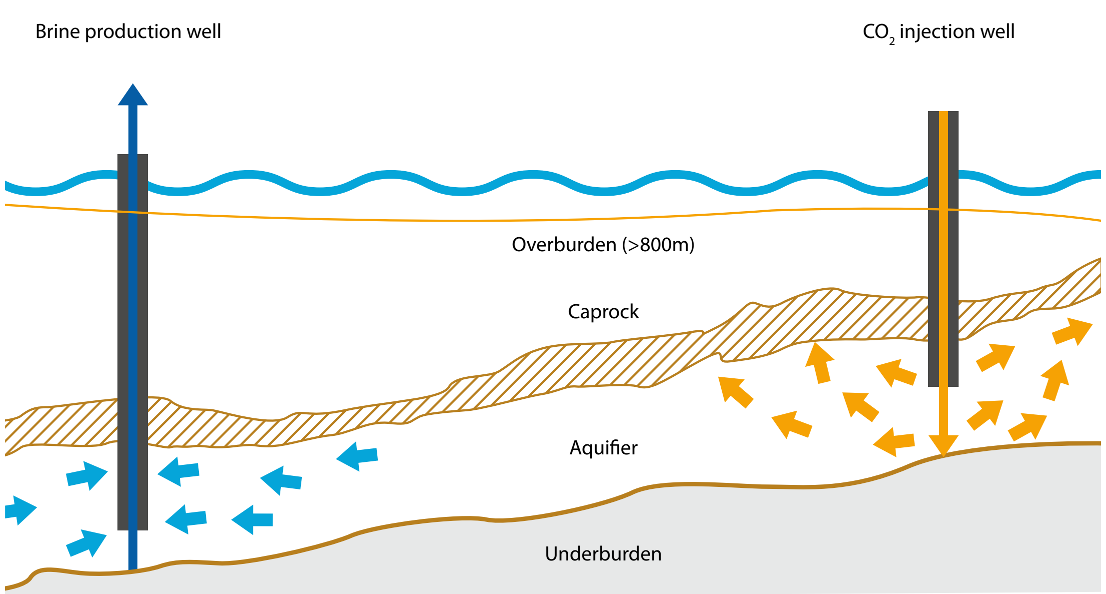


Figure 3
Brine production in section.

This method increases the quantity of CO_2 that can be stored, and avoids the pressure constraint on the cap rock. Depending on the interplay of cost vs increase in storage this has the potential to reduce the unit cost of CO_2 storage.

BRINE DISPOSAL

Huge quantities of brine are co-produced as part of oil and gas production. It accompanies oil and gas production, particularly late in a field’s life because as oil and gas is removed, brine moves into the space around the producing well to replace it and the wells then produce a mixture of water and oil/gas – they ‘water out’. Brine disposal is regulated, and it is treated and analysed for key contaminants such as hydrocarbons, oxygenates and toxic metals prior to disposal from the oil platform into the sea. Over the period since from 1975 until 2017, the Oil & Gas Authority (OGA) database[4] recorded a monthly brine production which averages over 0.4 million m^3/day. Brine production to assist CO_2 storage, even for high storage rate scenarios in the UK, is likely to be less than 20% of this.

In contrast to brine associated with oil production, there would be no expectation of oil contamination, and it may be possible to simplify disposal by mounting equipment on the seafloor or on a monopile, rather than bringing the brine back up to a platform for oil separation as is required for hydrocarbon applications. Naturally every release into the environment is subject to an environmental impact study and assessment. As an alternative to disposal in the sea, brine can be reinjected subsurface into an oilfield to assist oil production, or even into a different aquifer formation. If CO_2 injection cannot be carried out by subsea facilities (cheaper for deep water), then brine must be processed and disposed of on the surface at a platform, otherwise the cost benefit of brine production can be lost.

Some brines are rich in minerals (e.g. lithium), and there are proposals to extract these, but the technologies have not yet reached commercial status. On the other hand, solids can precipitate from the brine onto the inner walls of the production wells, pipes and equipment – termed scale. This is comparable to lime scale in a hard water area, though the minerals deposited might be different. Fortunately, comparable de-scaling products are available, based on extensive oil and gas experience.

BRINE PRODUCTION PROJECT AND ITS IMPLICATIONS

This Insight report sets out the strategic implications of deploying brine production as part of UK CCS strategy. It is based on a project commissioned and funded by the ETI and undertaken by a consortium led by Heriot-Watt University and comprising of Element Energy, Durham University and T2 Production Technology which was reported in the ETI publication 'The Impact of Brine Production on Aquifer Storage of Captured CO_2 - Final Report'[5] and its supporting package of sub-studies. These studies are based on detailed modelling of the geological structure of the store and how fluids flow within it, to inform estimates of store capacity, injection rates, fluid migration and pressure profiles in the store, in much the same way that oil and gas operators have successfully modelled hydrocarbon reservoirs. The modelling tools were developed during the project and the sensitivity of results to key assumptions were explored. A good estimation of the optimal distance between the CO_2 injection wells and brine production wells is important to ensure success, and requires a good geological dataset.

Five stores were studied in detail, each representative of key types of store, and three of which were studied in a previous appraisal project[2] (Forties 5, Bunter Zone 4 and Hamilton). The Forth is a relatively small store of low permeability, conveniently near the large emitters in central Scotland. The store is deep and the geology relatively uncertain, and its storage resource is estimated at 100 million tonnes. The Tay is a large highly permeable aquifer also rated in CO_2Stored at 100 million tonnes. The stores and an indication of the size of the 'family' of stores they represent are provided in Table 1 below:

STORE in STUDY	RESOURCE (cost) million tonnes (injection without brine)	RESOURCE (cost) million tonnes (injection with brine)	% COST REDUCTION (approx)	TYPE / REGION	TOP 20 RESOURCE million tonnes in TYPE, rounded (no. of stores)
Forth	100 (£9.5/tonne)	300 (£6.6/tonne)	33	Open Aquifier (inc oil) - Central Scotland	2300(7)
Tay	150 (£8/tonne)	450 (£9.7/tonne)	0		
Forties (part)	400 (£27/tonne)	450 (£26/tonne)	4		
Bunter Zone 4	200 (£11.3/tonne)	200 (£11.6/tonne)	0	Bunter Domes / trap - East of England	2400(5)
Hamilton	124	157	NA	Depressurised Gasfield - East Irish Sea	
Others					300(1)

Table 1
Resource and cost characteristics of the stores studied. Costs in this table are undiscounted, levalised and relate only to the injection scenario which fills the store completely.

KEY FINDINGS

1. Capacity and injection rate increases

Including brine production options in the appraisal stage of the UK's CO_2 storage sites can add significant value to store selection and strategic planning. In deployment terms this value primarily comes from its ability to increase a store's capacity, thereby extending the operational life of a store and minimising the need to develop less commercially-attractive stores.

As can be seen from Table 1, for the five aquifer stores analysed, brine production:

- Tripled the storage capacity of two stores (two of the three open aquifer stores serving Central Scotland), and roughly doubled the optimal injection rates of these two stores. This would deliver a reduction in the through-life unit costs of these stores in the range of 4% to 33%[(2)])
- Delivered a modest capacity increase of 10-25% in two of the stores, and
- Did not deliver any storage capacity benefit in the fifth store.

These benefits generally apply at high injection rates (e.g. over 15 million tonnes/year, the output from a typical industrial cluster) and can extend the life of the store by as much as twenty years. This could deliver cost savings of up to 33% (undiscounted £/tonne) due to efficiency improvement within the stores themselves. Further it can be seen that there are considerable differences in cost between different stores. This is not unique to this selective list – similar variations in unit cost can be observed in other reports which have worked up full costs of the more secure and economical stores, and are influenced by variations in economy of scale, location and reservoir characteristics[2]. Therefore, savings in infrastructure can be made by expanding the cheaper stores and deferring deployment of more expensive ones.

Even late in a store's life, when the reservoir pressure has risen, the permissible injection rates with brine production would be expected to be around double those of simple injection schemes. Although this analysis is restricted to only a few stores, it is important to note that about 2,300 million tonnes of the total capacity of the 'top 20' stores (6,800 million tonnes) consists of Central North Sea aquifers and their associated fields, and some of these may also be amenable to improvement by brine production. As an example, the Tay expansion is summarised in Box 2: Increasing Capacity.

By contrast, when injecting CO_2 at low rates (i.e. 2 million tonnes/year from a single large emitter), in highly permeable, open large aquifers, where the injection pressures can dissipate freely into a huge volume of aquifer, brine production is likely to be of limited or no value in terms of its ability to increase a store's capacity or lower its costs. Even in such cases where the geology offers good pressure dissipation, the presence of a neighbouring store in the same formation, which has been pressurised, could restrict flow and so create a need for brine production. This situation is to be anticipated in the Southern North Sea, where several stores (again c.2,400 million tonnes out of the 'top 20') sit in the same formation (Bunter sandstone).

None of the stores currently identified as near-term prospects are fully confined aquifers which make up much of the UK stock. In fact, these fully confined aquifers would benefit the most from brine production, even at low injection rates. The benefits to this type of store was quantified by the project, and is described in Box 5: Closed Aquifers, which can be found after Appendix 1.

2. The typical through-life cost of operating a CO_2 store would be expected to be ~ £750 million

Box 2: Increasing Capacity - Tay Aquifer (open)

The Tay aquifer structure is large (3,000 km²), and has good permeability. It is narrow, and slopes gently upwards from south east to north west (Figure 4), changing depth by c.2.5 km over a length of over c.100 km. It also slopes upwards from north east to south west.

Injection plans were modelled as a series of five developments each with its own platform. Each platform had five injectors which were complemented by two brine producers which, due to the slope, were located in the north east of each group in Figure 4. At high rates, the ratio of producers to injectors had to be increased, and more brine had to be removed per tonne of CO_2 stored. Local pressurisation occurs at higher injection rates.

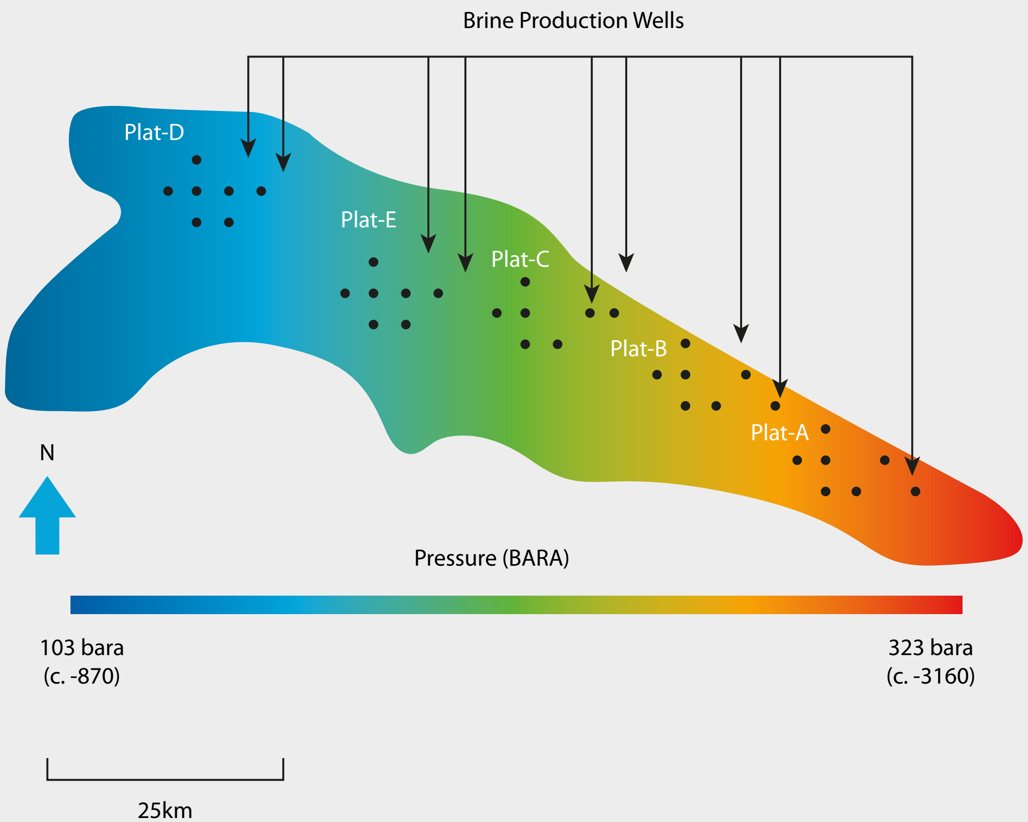


Figure 4
The Tay, from above, showing several platforms for up to 40 million tonnes/year storage

Figure 5 shows an injection plan for the Tay which starts at 10 million tonnes/year. Without brine production (shown in orange) the pressure rises rapidly in the first few years of operation, and the injection rate must be slowed down after only eight years. Even slowing the injection rate to 2 million tonnes/year after 30 years does not stop the reservoir pressure from continuing to rise. However, with just two brine production wells, and the same total number of wells, the full production rate can be sustained for decades longer (shown in blue). This has the effect of increasing the maximum practical storage capacity from c.150 to 450 million tonnes with brine production.

Additionally, average field pressures are kept lower, reducing the drive for any brine to seep through any legacy well paths.

Tay - CO_2 Flow and Reservoir Pressure over time years with brine and without brine production

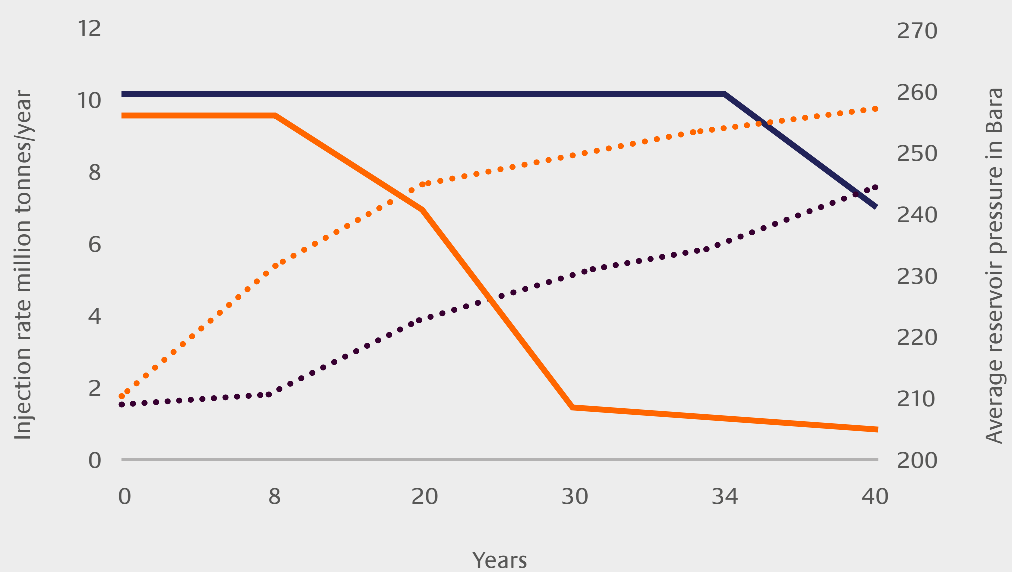


Figure 5
Injecting 10 million tonnes/year into the Tay Aquifer, by year over 40 years

2. Effective Risk Mitigation

Offshore geological structures are subject to naturally-occurring geological faults (normally vertical or slanted), and they can also contain thin deposits of relatively impermeable material (normally horizontal or tilted) within the reservoir. Both of these can introduce unexpected barriers to CO_2 flow that can limit the permissible injection rate and significantly reduce storage capacity. In cases where these unexpected barriers to flow occur, brine production has been shown to restore the performance of the store to that which would have been anticipated if the barrier did not exist. This implies that the brine production technique can help store owners in circumstances where the initial appraisal of the store did not identify unfavourable geological features, and had thereby overestimated the true level of pressure dissipation that the geology could provide. Having the brine production process available for deployment in this way can therefore provide significant commercial risk mitigation for store developers. All stores could benefit from risk mitigation in this manner. See Box 3: Performance Remediation for an example.

Box 3: Performance Remediation - Bunter Closure 36 (structural trap)

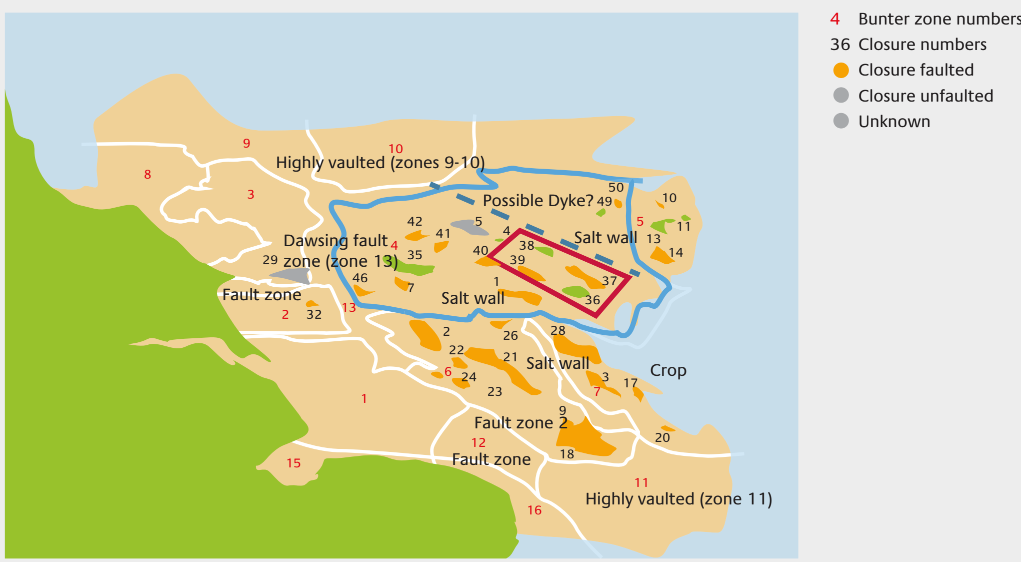


Figure 6
Bunter Zone 4. The green shape labelled '35' is the White Rose 'Endurance' store.

Bunter Zone 4, shown by the dark blue outline in Figure 6, is a part of the huge Bunter sandstone formation, which holds several prospects for CO_2 storage, including the appraised Endurance site (labelled 35). Stores in this region are termed 'domes' because of their shape, and they trap buoyant CO_2. The aquifer has good permeability, and with the assumption of good connectivity in Zone 4, the store capacity will be not be limited by pressure build-up at practical fill rates. The area shown in red in Figure 6, contains a 'dome' called Bunter Closure 36 (BC36) which was studied in detail, and spills into BC37 when full. Although it is thought that all the brine in the aquifer is connected and able to move within Zone 4, it is possible that baffles, dykes or cemented zones might restrict flow.

An assessment was made to establish whether underperformance of BC36, due to unexpected constraints in brine movement, could be remedied by brine production. Different levels of connectivity of BC 36 to its surroundings were investigated, ranging from an absence of any restriction within Zone 4, to placing a partially restrictive barrier (fault) to the north of BC36, and finally by modelling a rectangular restriction of adjustable transmissibility that surrounded BC36 in its entirety.

Even the insertion of a single straight barrier between BC36 and BC37 changed the store performance considerably - injection rates of 10 million tonnes/year, which cause no pressurisation concerns in the absence of a barrier, could not be sustained with the barrier, irrespective of how many additional injection wells were drilled.

For the case where a partially transmissible rectangular barrier surrounded BC36, store performance collapsed. Only 60 million tonnes could be injected (5 million tonnes/year) without brine production, whereas with brine production over 200 million tonnes could be injected over 40 years (Figure 7). Three brine producing wells were all that was needed to restore the capacity of the store to that achieved when no barriers were in place. Further, with brine production the average pressure increase of the field was less than half that without brine production.

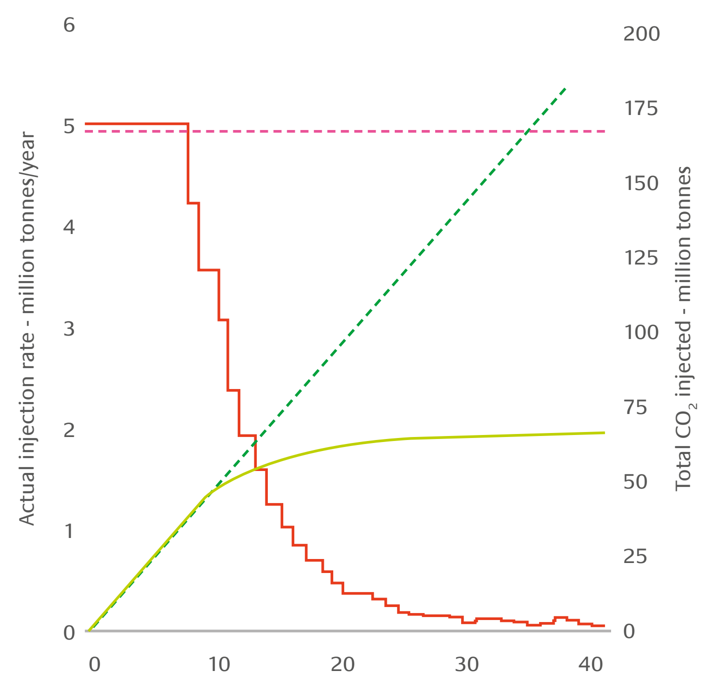


Figure 7 - Performance of BC36 (when confined)
The injection rate profile for the model without water production is shown as a **solid red line** and for the model with brine production as a **dotted pink line.** Also shown in **solid light green** is the total mass of injected CO_2 for the model without brine production and in **dotted dark green line** the injected mass for the model with brine production.

In addition to the above, for a given injection plan, brine production lowers the average reservoir pressure and so reduces the driving force for potential leakage to the surface through any redundant oil and gas wells, and reduces the pressure footprint in neighbouring structures which could be oil and gas assets or future CO_2 stores. Further it can be continued when injection is complete, to reduce residual risk, easing handover of the store and potentially reducing long term monitoring requirements.

When deployed either to increase storage capacity or to restore the performance of a store which had experienced unexpected pressurisation (as above), it was shown that brine production can be deployed successfully at least five to ten years after the store has been originally commissioned, giving the operator time to assess how best to develop his asset in the long term. See Box 4: Delaying brine production until required.

Box 4: Delaying brine production until required (Bunter Closure 36)

Since brine is pushed out of the field slowly at the beginning of the CO_2 injection (because the pressure is still low), an assessment was made to establish whether the installation of brine production equipment could be delayed, giving the store owner time to diagnose the location and nature of an unexpected barrier, or delay investment until injection rate increases were required.

As shown in Figure 8 below, when brine production is delayed by five years or even ten years, the benefits of brine production are still realised, making the technique just as effective overall as if it were used from day one.

This ability to successfully intervene after the initial injection is another illustration of how useful the brine production technique can be in helping the storage operator meet their commercial obligations. When the store was full after 40 years, the brine production wells can be used to de-pressurise the store, reducing the risk of migration and the impact that high pressure might have on other potential stores in the area.

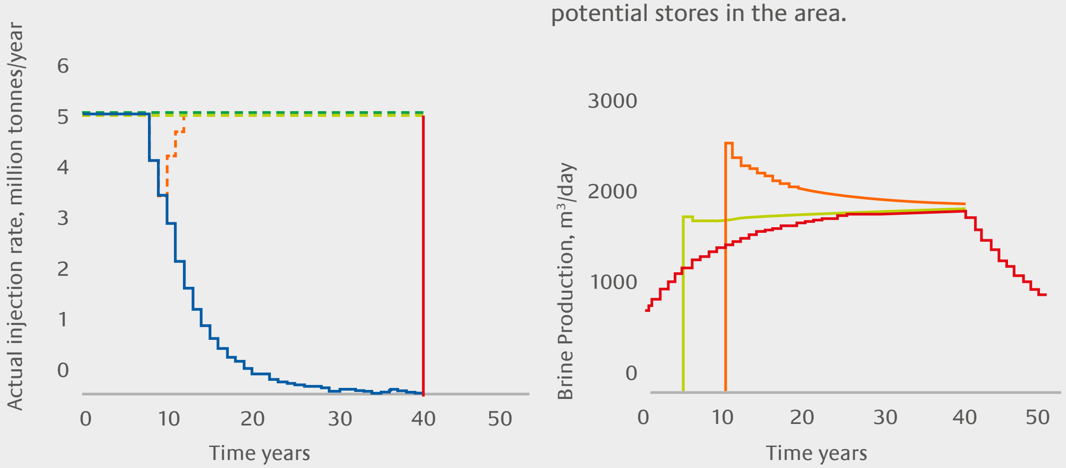


Figure 8 - Bunter 37 (confined)
The left-hand graph shows injection rate profile where there is no brine production in blue, and in models where brine production commences at the same time as CO_2 injection starts in red. The case where brine production starts five years after CO_2 injection is shown in green, and ten years after CO_2 injection starts is shown in dashed orange. The right-hand graph shows the corresponding brine production.

3. Strategic implications

Developing and deploying brine production techniques could provide significant value to a CCS rollout strategy in the UK. The ability to enlarge the cheaper stores changes the optimal order in which infrastructure investments are made and can hence reduce the overall costs of a CCS rollout. Table 2 provides an analysis of the impact of using brine production as part of a CCS implementation plan using the three stores studied in Scotland and alluded to in Table 1. For the different CO_2 injection scenarios shown in the first column, the number of stores required to deliver the scenario with and without brine production are shown, along with a quantification of the potential saving in lifetime storage costs resulting from the use of brine production.

CO_2 injection scenario		Amount of CO_2 injected (total) (million tonnes)	Brine production?	Number of stores needed	Approx. saving in lifetime cost with brine production (£million)
CO_2 injection rate (million tonnes/year)	Injection duration (years)				
2	40	80	No	1	-
5	40	200	No	2	-
5	40	200	Yes	1	700
10	30	300	No	3	-
10	30	300	Yes	1	1,000
10	40	400	No	3	-
10	40	400	Yes	2	1,800
15	40	600	No	4+	-
15	40	600	Yes	2	2,300

Table 2
Cost savings from brine production using just the Scottish stores studied. Costs of storage at moderate injection rates without brine production are capped at £16/tonne, due to the presence of other stores (e.g. Captain) in the area.

The expansion of the notional Forth storage project alone (Table 1), representing only 2% of the storage in the 'top 20', would deliver through life savings of c.£1 billion, and avoid the need to develop two similar stores (which would still need to be identified).

In addition to the example above, there are also additional potential capacity increases due to brine production from Bunter Domes (in the Southern North Sea) and gas fields (all around the UK continental shelf) that should not be overlooked. For example, BC35 (Endurance) is c.£2.5/tonne cheaper than BC36[1], and over twice the size, so any technique which preserves or improves on its performance will be significant. If such improvements can be replicated in even a handful of other key stores, the UK:

- Will avoid expense by appraising and building appreciably fewer stores and less pipeline infrastructure than would be needed without brine production (at c.£750 million each). As clusters develop, the rated capacity of individual stores can be increased without renewing pipelines and other infrastructure.
- Can optionally develop stores that appear less financially attractive without brine production to the point where they could be cheaper to develop than other planned stores.
- Will gain considerable flexibility in how it can cope with situations of rapidly increasing demand for storage.

In addition to the benefits described above, for aquifers where brine production did not show a material uplift in performance because the geology enables pressure to be dissipated easily, it can provide benefits if unexpected resistance to dissipation is found once the store is developed. In these cases, brine production can mitigate the negative impacts of unexpected geological faults and/or deposits of impermeable material within the stores that can reduce injection rate and store capacity.

As described above, in the early phases of a CCS rollout in the UK, the analysis of prospective stores with brine production is likely to focus on risk mitigation or upside expansion options during appraisal. An exception might occur if a developer selects a store with a relatively small capacity or injection rate perhaps due to availability of existing infrastructure, where they may factor in the capacity or injection rate increases brine offers into their assessment.

4. Recommendations

To enable the UK to capitalise on the value of brine production within a CCS rollout, the UK should consider:

- Encouraging developers to consider brine production options in the assessment and processes for new CCS facilities, and in broader UK CCS rollout strategy development
- Further development of modelling techniques including examining the effects of uncertainty in assumptions, and seeking test data sources which may in part validate the improvements suggested by modelling
- Developing a consistent cost database for UK storage options, recognising the differences in confidence in the stores. This should include examining the opportunity brine production might have for several more stores than was possible in this analysis
- Exploring any analytical solutions for estimating brine production benefits, which may make semi-quantitative screening more straightforward and less onerous
- Exploring the environmental case and developing technology for the option to release brine at depth from subsea templates and preparing for environmental assessments of brine production to be part of storage licence applications
- Developing technical co-operation with projects which may use brine production, like Gorgon, Australia, and scoping a physical R&D project designed to assist prospective users of the technology.

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2. CO_2Stored can be found at http://www.co2stored.co.uk/home/index, and is operated by the British Geological Survey (BGS).

3. The Strategic UK Storage Appraisal Project outputs can be found by searching for 'DECC Storage Appraisal' at http://www.eti.co.uk/programmes/carbon-capture-storage?_type=eti-document&query=&programmeName%5B0%5D=Carbon+Capture+and+Storage

4. Data can be accessed at https://www.ogauthority.co.uk/data-centre/data-downloads-and-publications/field-data/

5. The Heriot-Watt Brine Project outputs can be found by searching for 'Brine' at http://www.eti.co.uk/programmes/carbon-capture-storage?_type=eti-document&query=&programmeName%5B0%5D=Carbon+Capture+and+Storage

APPENDIX 1: THE STUDY PROGRAMME AND ANALYSIS

The objective of the brine production project led by the Heriot-Watt consortium was to identify and quantify the additional value the technique might offer in the development of UK CO_2 storage projects. This was approached by carrying out detailed modelling of fluid flow within selected stores, both with and without brine production, and since the intent was to establish the implications for UK storage, a selection of relevant stores for which geological models were available was made. Sources of value included the ability to: expand a store, reduce its unit costs, increase its flexibility, improve the ability to deal with unexpected geological constraints and reduce storage risk profiles. The modelling work specifically estimated:

- The increase in storage capacity if brine production was available from the day the store opened
- The increase in achievable CO_2 injection rates
- The increase in storage capacity and achievable CO_2 injection rates per the above, but in the case where brine production is started ten years after the store begins operation (e.g. when a store takes on a new customer)
- How store performance can be restored if, unexpectedly, a barrier to brine flow is discovered within an aquifer
- The degree of store depressurisation, during and after the store has been filled.

STORE NAME	FORMATION	TYPE (per Figure 1)	NOTE
Synthetic tilted	A synthetic model (with real geology)	Fully confined	Adjustable slope and parameters. Used to explore effect of different injector and producer spacing etc
Tay	Tay	Open aquifier, no structure	Large area - multiple platforms
Forties 5	Forties	Open aquifier, with some structure	Large structure near oilfields
Bunter 36, and neighbours	Bunter	A structural trap	Pressure dissipation is expected to be easy. This study focussed on 'what if it isn't?'
Hamilton	Ormskirk	A depleted gas field (trap)	There is an aquifier below the gas field
Firth of Forth	Kinnesswood / Knox Pulpit	A structural trap (steep)	Low permeability, steep, complex site
North Sea Oilfield	Confidential	An oilfield (trap)	CO_2 injection pressurised the oilfield via an intermediate aquifer section

Table 3
List of potential stores modelled in this study.

For each field the models were run at different CO_2 injection rates over extended time periods (up to 50 years), with and without brine production. Simulations tracked and capped the pressure at the top of the reservoirs as CO_2 injection progressed, and the injection rate was reduced as the reservoir pressure rose, and was stopped when necessary to ensure the pressure did not threaten the store's integrity. The number of wells was chosen to match different total initial injection rates (from 2 million tonnes/year, up to 40 million tonnes/year). Simulations with brine production also monitored the concentration of CO_2 in the produced brine, and if this rose above a critical value (a mole fraction of CO_2 of c.10^{-4}) production from that well was stopped.

Since most reservoirs consist of layers of rock of differing properties (e.g. permeability), each identifiable layer was modelled, which is important because CO_2 could preferentially flow in a highly permeable sublayer (termed a 'thief' zone) and break through into the brine well, necessitating its closure.

Layout and injection plans for exploiting the stores listed in Table 3 were developed, including the number of wells, well layout and well type for the 'with brine' and 'without brine' cases. This provided useful insight, including establishing an appropriate well- spacing between the injectors and producers – if it was too close, CO_2 broke through too early; if too distant, the pressure relief was not effective. The exploration of this dilemma is described in Box 5: Fully Confined Stores. Additionally, different strategies were developed for each store in terms of well layouts and the ratio of producer wells to injection wells.

To test if the models and approach were appropriate for the analysis, separate studies were carried out to determine:

- How the choice of simulation package (software) affected the results
- The optimal choice of cell size used in the model: smaller cells capture more detail of the flow behaviour and the geological heterogeneity, but this increases simulation model run times
- The preferred well type for deployment, and their locations in the reservoir
- The extent to which very high permeability 'thief' zones, which would cause 'fingers' of CO_2 to break through to the production well, could negatively impact the process.

Once the well layouts and injection plans had been completed, a series of economic benefit calculations were performed (see Appendix 2.)

Box 5: Fully Confined Stores (synthetic model with real geological data)

The situation most likely to be amenable to improvement by brine production is when:

a) The store performance is constrained by pressure rise, and not by migration of the CO_2 out of the licensed storage area.

b) Breakthrough of CO_2 to the production well can be delayed for several years, as dictated by permeability distribution, distance and slope.

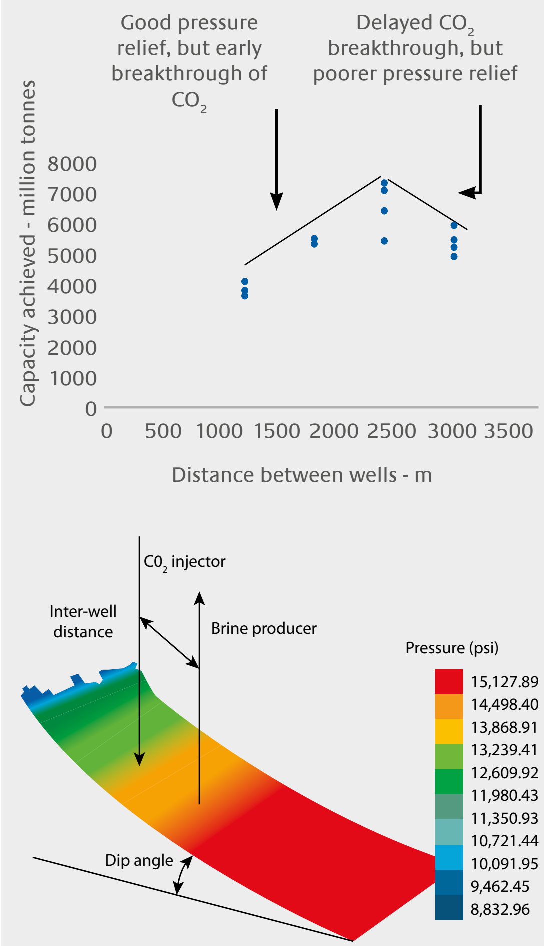

Figure 9 - A smaller synthetic model was used to explore parameters

The synthetic model, which has real geological data (to include heterogeneity of reservoir properties), was configured to demonstrate concepts and explore sensitivities relevant to the brine production technique. These included gaining a working knowledge of the effects of different variables on store capacity.
Within the ranges studied, the key sensitivities driving storage capacity were:

- Sensitivity to layers of high permeability, 'thief zones'. These speed the flow of dissolved CO_2 from the injection well area to the brine production well and so are detrimental to operation. A moderate effect on capacity within the range studied was observed.
- Sensitivity to dip angle. A high dip angle encourages CO_2 to rise through buoyancy away from the brine production well, lengthening its life. A moderate effect on capacity within the range studied was observed.
- The injector-producer inter-well distance. For the reasons noted above this proved to be a highly sensitive parameter.

The choice of inter-well distance is key to optimising the storage capacity. The sensitivity of this variable is shown inserted in Figure 9. In 'Best Case' layouts, the capacity increased by a factor of forty because of brine production. This is a much more considerable increase than in 'real' open stores, where increases were an order of magnitude smaller. Careful consideration of some small fully confined stores is needed before these are judged to be too small for economic development because brine production can increase capacity considerably.

APPENDIX 2: COST BENEFIT ANALYSIS

A Cost Benefit Analysis (CBA) tool was developed by Element Energy to determine the through-life costs associated with the with brine/without brine cases, per the scope shown schematically in Figure 10 below. Storage site descriptors, injection well and production well numbers were provided by Heriot-Watt. From these, an Excel model carried out an outline design to size pipelines and platforms for each case. All these transport and storage capital costs from the shoreline hub booster compressor to the wells were accumulated, together with factored operational costs for each cost element, for the duration of each injection plan. The results were expressed in £/tonne stored. The model optionally permits discounting, well remediation, allowances for spare wells and can force construction of surface platforms in preference to subsea facilities as a sensitivity.

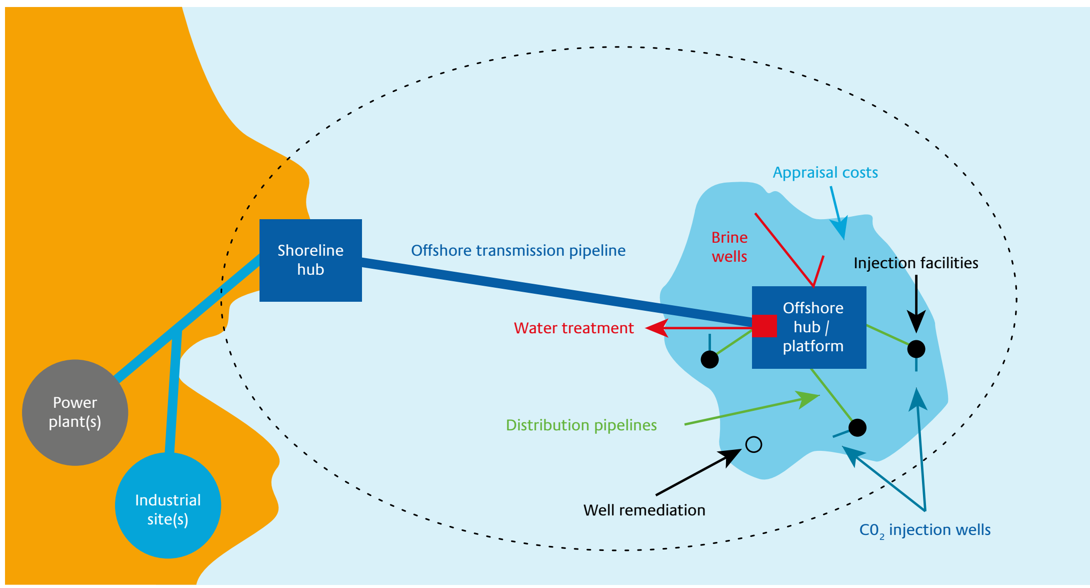

Figure 10
Scope of the Cost Benefit Analysis tool developed to determine the through-life costs of the brine/no-brine store cases.

The cost structure at different injection rates for the Tay is shown in Figure 11 below, from which it can be visualised just how much the technique opens up the store's potential. For projects of short duration and modest injection rates (5 or 10 tonnes/year for 10 years), the extra equipment needed for brine production does not add value, but for projects of a more realistic duration (over 10 tonnes/year for 30 years) brine production is essential. Brine production permitted injection rates all the way up to 40 million tonnes/year for the Tay store.

Figure 11
The costs of Tay pipeline Transportation and Storage (T&S) in £/tonne for different injection scenarios

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