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Managing CO_2 storage resources in a mature CCS future

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Abstract

This paper summarises the potential for surface and subsurface interactions which might occur during CO_2 storage operations. We discuss possible options for managing these interactions to provide timely storage capacity, illustrated with a regional case study from the Southern North Sea. The case study evaluates storage site options to provide storage capacity for CO_2 supplied to the region until 2050.

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Keywords: Southern North Sea; CO_2 stroage management

1. Introduction

Under current arrangements and regulations, potential storage sites are likely to be selected by their operators on a “most economically advantageous” basis, to match the needs of individual, or clusters of, carbon capture and storage (CCS) projects. Providing these sites do not adversely impact on other existing users and they are deemed by the relevant authorities to be suitable for CO_2 storage, the expectation is that they will be licensed.

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One benefit of this approach is that the operator can decide where to develop CO_2 storage and, as a result, the State will likely have to share less risk than if it took a more active role in managing options for storage development. Sedimentary basins typically have multiple resources and hence there is potential for conflict of use between CO_2 storage projects and other subsurface and surface uses. These resources include, inter alia, pore volumes for CO_2 storage, hydrocarbon exploration and production, natural gas storage and mineral resources. Moreover, in some reservoir formations, CO_2 injection that results in increased pore fluid pressure may reduce storage capacity and increase costs in adjacent sites which are in pressure communication, potentially reducing efficient use of the overall storage resource either permanently or for a period of time. Pressure management may be required to optimise the storage efficiency in some sites. In some circumstances, pressure increases are not expected to result in significant detrimental impacts, but pressure responses in hydraulically connected storage sites would be expected to be the focus of detailed assessment.

Therefore, it is considered that a more strategic approach to the exploitation of resources in sedimentary basins *might* be required to ensure that basins realise their full storage resource potential. This raises important questions:

- How can CO_2 storage capacity be fully utilised in the presence of potentially competing uses of the subsurface and overlying ground surface, seabed or sea?
- How should store boundaries be defined in potentially pressure-interacting CO_2 storage projects?
- How should potentially interacting resources be developed most economically in the light of national or jurisdictional policies?

In reality, these questions reflect a complex problem because the metrics by which the development of a basin's resources would be judged could depend on a perceived optimisation of several interacting criteria, considered within the framework of government energy (and other) policies. It may also be necessary to consider the much less tangible but potentially significant future uses of the basin as well.

A case study in the UK sector of the Southern North Sea (SNS) highlights relevant interactions in a future scenario to 2050, which assumes CO_2 storage development will be needed to contribute to reductions in UK CO_2 emissions. The case study compares First-Come, First-Served and more strategically managed approaches to the basin resource development to determine the benefits and consequences of these broad strategies for both the pore space owner and storage site operator. It is concluded that management of storage on a first-come, first-served basis is likely to be sustainable in the short to medium term. Though relative costs have not been estimated in this study, it is recognised that this approach may not necessarily lead to development at least cost. Nevertheless, it is clear that in the UK at least, the current economics of CCS are driving potential project developers to consider project clustering as a means of cost sharing. This is likely to lead to a more economically efficient development of basin resources. However, in many basins there could be competition for pore space, ground surface or seabed space and use of areas of the sea, which could become more pronounced as CCS and other industries develop. Therefore, a more strategic approach to storage resource management could be required in the future to minimise these interactions and to maximise the efficient use of the storage resource and associated infrastructure.

Possible conceptual routes to storage development have been considered to examine the issues described above. Storage development will be initiated from early catalyst projects that are likely to select the most geologically suitable sites. Clusters of storage sites could be developed where regions have multiple, connected storage options. Management and infrastructure could be integrated in clusters to provide more flexible operation and cost savings through economies of scale. Also, the experience obtained in the catalyst project could benefit follow-on projects in the same formation. Such clustered development might occur without strong intervention except that transport (pipeline) over-sizing might be necessary. Follow-on storage permits might be encouraged from regions centred on these first projects. As expertise and experience in storage operations increase, additional sites will be exploited, which might include smaller sites near early catalyst projects, rather than commissioning larger storage sites in virgin areas at greater distances. That said, we have shown here that in one scenario for the SNS targeting fewer but larger storage sites could meet future storage requirements as an alternative to the development of clusters. These larger sites are more geographically dispersed and would not require development of multiple sites in close proximity to provide the same amount of storage capacity (albeit estimated as largely theoretical capacity). This could reduce the potential need for development of groups of more closely integrated and connected stores.

1.1. Storage options in the Southern North Sea (SNS) and potential interactions

The UK sector of the SNS is one of the areas offshore UK with greatest potential for CO_2 storage. Previous studies have evaluated the storage capacities of the region [1] and [2]. The most recent data is provided by the online CO_2 Stored database (CO_2 Storage Evaluation Database, [3]), a search of the SNS region suggests that it has a theoretical storage capacity at 50% probability (P50) of 8 Gt. Potential storage capacity is proved by saline water filled-domes of the Triassic Bunter Sandstone and depleted gas fields in sandstones of Carboniferous age, within the Permian Rotliegend Leman Sandstone Formation and the Triassic Bunter Sandstone Formation. The shallow water depths found in the SNS (average of approximately 50 m) and its proximity to the UK coast also make this region a favourable target for CO_2 storage sites (Fig. 1.).

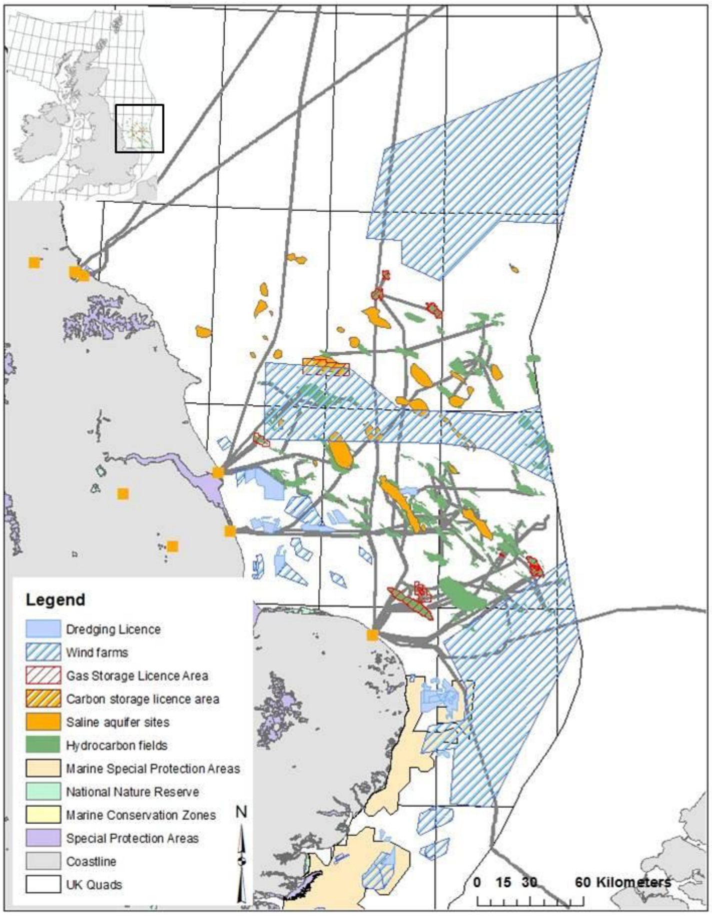

Fig. 1. Activity map of the UK sector of the Southern North Sea.

CCS operations would have to be managed, along with other users of the surface and subsurface, for this potential storage capacity is to be utilised. A number of activities specific to the SNS were identified that would also have to be taken into consideration (Table 1). Other UK offshore areas could have additional uses such as; tidal and wave power generation schemes, sub-seabed mining and geothermal energy production. This study only considered the activities specific to the SNS.

Table 1. Users of the UK sector of the SNS

Surface users	Subsurface users
Wind farm licence areas	Hydrocarbon operations
Dredging licence areas	Gas storage
Pipeline routes	CCS sites within the same geological formation
Hydrocarbon and gas storage operations	
Shipping routes	
Fishing	
Conservation areas	

2. Methodology

A number of scenarios were developed to explore the advantages and disadvantages of different approaches to CCS development. Users of the surface, subsurface and location of potential CO_2 storage sites were identified. The basic methodology for the scenario development was:

- Prior evaluation and ranking of all of the potential storage sites in the SNS based on the methodology described by the IEAGHG [4].
- Selection of scenarios to be evaluated and their time spans.
- Estimation of the amount of CO_2 that might be stored in the SNS at two time points within the scenario timeframe.
- Apply assumption that the storage sites will be used in order of rank unless the scenario applies constraints that preclude their use.
- Observation of potential interactions between sites and other legitimate uses (and in some cases potential future uses) of the surface and subsurface during the lifetime of the CCS site as CO_2 storage proceeds.

The scenarios evaluated used were:

- The ‘First-Come, First-Served’ (FCFS) Scenario in which the project developer is assumed to choose the sites ranked first based on geotechnical criteria on a first-come, first-served basis. It would be the responsibility of later project developers or users of the subsurface accommodate any implications of any pre-existing licensed or legitimate operations, and to demonstrate no negative interactions with existing users.
- The ‘Managed Storage Resource’ (MSR) Scenario. In the MSR scenario, site selection is restricted by adding criteria that must be met before a site can be developed, in a way which minimises the surface and subsurface impact whist maximising the amount of CO_2 that can be ultimately stored.

Both scenarios run from 2020 to 2050. “Snapshots” of CO_2 storage and interactions were taken at 2030 and 2050. The methodology used to estimate the mass of CO_2 to be stored by 2030 and 2050 (Fig. 2) and the methodology used to rank the storage sites is described further in [4]. The projected volume of CO_2 to be stored between 2020 and 2030 was 735 Mt and an additional 3650 Mt of CO_2 that would require storage between 2030 and 2050 Mt. The potential storage sites chosen in each scenario were analysed using a GIS (Geographical Information System) to identify potential overlap and conflicts within an assigned radius of 40 km of each site with the activities of other users of the surface and subsurface in the region.

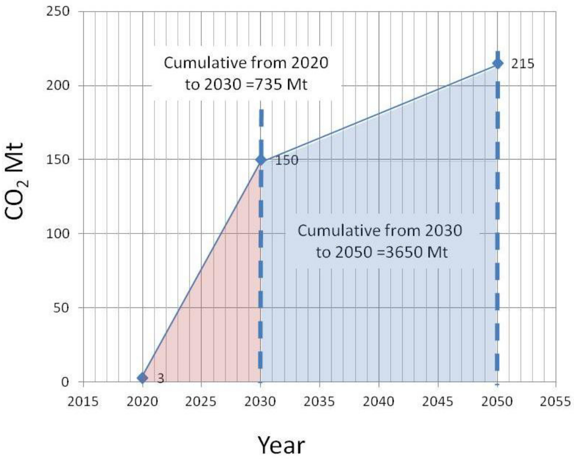

Fig. 2. Projected volumes of CO_2 captured and to be stored in the UK from 2020 to 2050 (data from [5]). Area of pink shading shows the area of cumulative emissions from 2020 until 2030, area of blue shading shows the cumulative emissions from 2030 until 2050.

3. Scenario 1 First Come First Served (FCFS)

In the FCFS scenario (Fig. 3) the storage sites are permitted in order of rank, starting with the highest rank and working down the list, using the storage capacity in each site until the storage needs are met. This simulates a market-driven approach where the market selects the geologically optimum storage units (in this case based on the selection criteria) that are available at the time required.

It was assumed that the maximum storage capacity of each site could be used, and wells to manage pressure would not be used. The cumulative total storage capacity was summed for the snapshot years 2030 and 2050 until all the CO_2 emissions could be accommodated. Only one aquifer site is required to meet the storage requirements up to 2030. By 2050 an additional twelve separate storage sites (two saline aquifer sites and ten gas fields) are in operation.

The FCFS sites were ranked, based on a set of criteria and then deployed in ranked order until the storage targets for 2030 and 2050 were met. In the snapshot at 2030 only one site (Site 1) is required to meet the storage targets. All potential interactions within a radius of 40 km of Site 1 were examined for spatial and subsurface interactions which may require planning decisions. Site 1 already has a CCS exploration licence, despite overlap with a wind farm licence area. Site 1 lies within a connected aquifer unit and this could lead to potential pressure and brine interactions in the subsurface with a number of other potential storage sites and active gas fields, if this is not assessed and managed.

In the 2050 snapshot, Site 1 would still be in operation. To meet the target storage needs by 2050 a further 12 sites would be operating (2 aquifers and 10 gas fields). Many of these sites have potential conflicts of use with other surface and subsurface users, some of which may be difficult to mitigate, with only 2 gas fields (Sites 6 and 13) showing minimal potential for interaction.

Site 2 lies above a producing gas field. It may be more difficult to use this site for CO_2 storage if this field is still operating. It is possible that CO_2 storage in the Bunter Sandstone could take place at the same time as gas production from the underlying Leman Sandstone gas reservoir, but it would involve negotiation and agreement with the operator of the field. This could increase the lead time and cost of storage development.

Site 9 and site 4 sit within a gas storage licence area. The market value of natural gas and the need for seasonal delivery and security of supply means that is more likely that site 9 and site 4 will have more value as natural gas storage than as CO_2 storage sites. As a result they are unlikely to be available for storage during the timeframe of the FCFS scenario. Site 4 will not be considered in further scenarios as a CO_2 storage site due to this potential conflict.

Sites 5, 7 and 10 are all located within wind farm licence areas. A wind farm licence does not mean that there are necessarily any wind turbines present, only that the area is a prospect for wind-generated energy. Should there be a wind farm or planned wind farm developed in these locations, monitoring of stored CO_2 could be problematic.

Therefore, these sites are considered to be unavailable for CO_2 storage, for the FCFS scenario.

Current UK policy does not appear to prioritise between wind farms or CO_2 storage should the choice be between one or the other. Current high-level UK Government policy encourages wind energy, nuclear energy and CCS.

Sites 3 and 4 are in very close proximity and in the FCFS Scenario are likely to be in operation at the same time with site 4 possibly being used for gas storage. As a result the pressure rise from injection of CO_2 into site 3 could reduce the storage capacity or increase the need for pressure management wells. In this scenario this interaction could be avoided, either by using sites which are further apart, by changing the order of utilisation or by accepting the use of pressure management wells.

The 13 storage sites chosen in the FCFS Scenario are geographically spread throughout the SNS (Fig. 3) and it is unlikely that this configuration of storage sites would enable an optimised pipeline network.

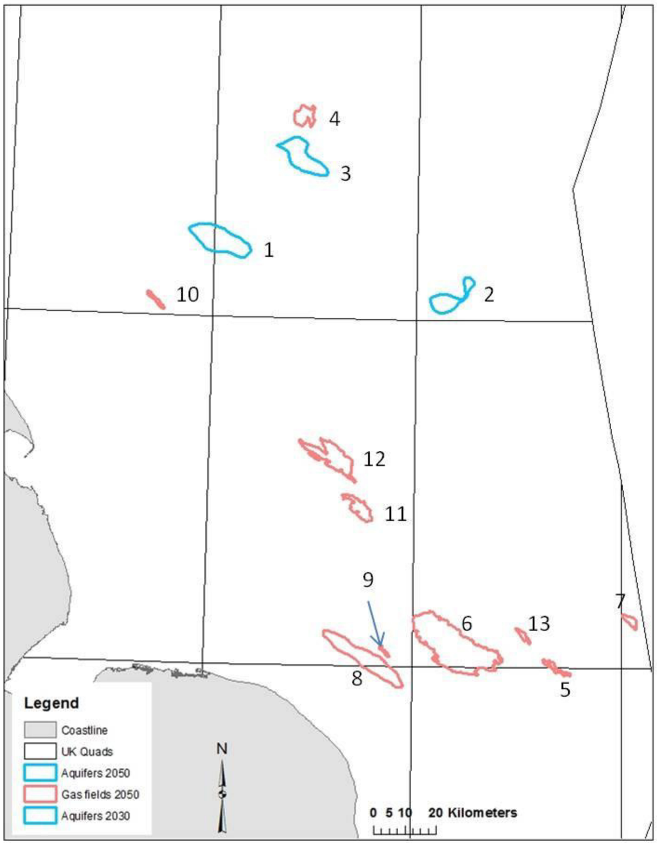

Fig. 3 Location of storage sites in the First Come Forst Served scenario. The sites are numbered by rank.

4. Scenario 2 Managed Storage Resource (MSR)

This section describes the development of a Managed Storage Resource (MSR) scenario, for the 13 prospective storage sites considered in the FCFS scenario (Fig. 3), scenario within which three options were developed in order to explore how storage in the Southern North Sea could be managed to fulfil different needs.

One challenge that the FCFS approach creates is that the storage sites are geographically spread across the SNS and therefore pipeline sizes and lengths would be designed to connect only these specific storage sites to shore terminals or capture plants, unless the project developers were sufficiently confident that an economic benefit would accrue to them from oversizing their pipelines.

In order to examine if the detrimental interactions and potential impacts identified above in the FCFS Scenario can be successfully mitigated, a (MSR) scenario has been developed, within which three broad options are discussed. The aims of the MSR Scenario are the following:

- Reduce conflict with other uses of the subsurface, seabed and sea;
- Reduce the length of pipelines needed to transport CO_2;
- Maximise storage capacity

This has been achieved by considering the interactions identified in the FCFS Scenario and determining if the interactions require the removal of a specific site and its replacement by another site, or if the interactions can be mitigated by other means. Each site in the FCFS Scenario has been considered in turn, starting with the highest ranked site. It is assumed that where possible, sites will still be developed broadly in rank order. However, in contrast to the FCFS Scenario, which applied this rank in strict order, in the MSR Scenario substitution of sites is allowed if it leads to an increasingly optimised development of the necessary storage capacity.

The MSR scenario assumes that hydrocarbon, groundwater or mineral resources will always be protected as is currently the case in globally most regions and that protection and exploitation of these resources will be given priority over storage rights. It is also assumed that storage will only take place where evidence is provided that indicates it is likely to be safe to store CO_2. The extent of strategic planning may depend on the relative weights placed on storage capacity, resource protection and exploitation, and cost minimisation.

No assessment has been made of the relative costs of implementing each option. Since site characterisation and commissioning costs may vary for each site in isolation, differences will arise due to costs of the construction of the connecting and integrating infrastructure and the discounted future value of site development costs. Development of each option could occur as demand for storage capacity increases. In the cluster option it may be assumed that initial transport connections to the catalyst project should be oversized, to the extent possible, to reduce future costs of resizing as storage capacity is commissioned. However, no evaluation of the relative benefit of this approach has been made for this study and a number of options for this would need to be evaluated, including adding further capacity as needed compared to oversizing all components (compression and pipelines) initially.

This case study shows that even in an area with plentiful storage options there is the possibility for interactions in the surface and in the subsurface. Early projects will benefit from being able to choose the ‘best’ sites with minimum likelihood for interactions. The likelihood of potential interactions within the region will increase as the number of storage projects increases. This scenario shows that CCS could face competition from nearby CCS projects, wind energy generation, gas storage and ongoing hydrocarbon production. It is possible that only the ‘Competent Authority’ will have a sufficient overview of the whole storage region to monitor, manage and arbitrate.

In order to minimise interactions between potential CO_2 storage sites and other users of the region several ‘management’ options were proposed: Option 1, avoiding conflicts by developing different sites; Option 2, target sites with larger storage capacities; Option 3, developing clusters. The options and the impacts of such interventions were examined.

The options and the impacts of such interventions are discussed below.

4.1 Option 1: Avoiding conflicts by developing different sites

Choosing sites which avoid potential conflicts of use could be one approach to manage the development of storage sites. To replace the capacity lost by removal of the discounted storage sites, the next highest ranked units were considered in turn. Each site was examined for conflicts, resulting in some sites being discounted.

The portfolios of thirteen potential storage sites that could be developed, which are ranked highest but avoid the identified conflicts, are listed in Table 2. It is assumed that Sites 3 and 4 are managed using pressure relief wells. By coincidence five new sites replace the five discounted sites from the FCFS scenario; however, it should be noted that both Site 14 and Site 20 are made up of more than one accumulation of natural gas.

This option could be implemented by allowing leases in specified areas at certain times. The advantage of this approach is that potential detrimental surface and subsurface interactions are avoided by discounting those sites where such interactions occur and replacing them with new sites. The disadvantage is that the replacement sites may not be as geologically suitable as the original sites, which is reflected here by their lower ranking when assessed against the basic criteria in this study. This may result in higher site characterisation costs and possible higher construction and operational costs. However it must be stressed that the costs associated with characterisation, design, construction and operation of storage sites have not been evaluated in this study. A further disadvantage is that sites are widely distributed over the SNS and are still assumed to be developed separately in this option, reflecting an element of independent operators within a storage market. This development may not optimise the potential for sharing pipeline infrastructure.

Table 2. Portfolio of 'best' sites selected to avoid potential conflicts with other surface or subsurface uses, MSR Scenario, which provide required storage capacity to 2050.

	Site number and ranked order	Sites removed from FCFS Scenario ranking due to conflicts of use	Additional sites rejected due to conflicts of use	Sites chosen to meet 2030 and 2050 storage targets
Storage sites assessed by FCFS Scenario	1			x
	2	x		
	3			x
	5	x		
	6			x
	7	x		
	8	x		
	9	x		
	10	x		
	11			x
	12			x
	13			x
	14			x
Additional sites reviewed for the MSR Scenario	15		x	
	16			x
	17			x
	18		x	
	19			x
	20			x

4.2 Option 2: Target sites with larger capacities

A second option for reducing the number of storage sites and, therefore, the potential for conflicts of use is to develop a smaller number of potential storage sites which have larger capacities. Here, sites were ranked according to their estimated storage capacity and were selected sequentially from the site with the highest estimated capacity first, until the storage capacity predicted to be required at 2050 was met. Sites with relatively high storage capacities were discounted if conflicts were identified.

Five sites were identified that would provide sufficient storage capacity to meet the capture rates estimated to be required in 2050 (Table 3). The portfolio comprises two saline aquifers and three gas fields.

Table 3: Portfolio of sites with largest capacity to meet predicted requirements for storage capacity MSR Scenario, targeting the minimum number of sites with largest capacity.

ID	Comments	Result
6	No conflict identified	Accepted
1	Underlying gas field. Already a CCS licence area	Accepted
20	No conflict identified	Accepted
26	Overlying potential saline aquifer unit	Accepted
2	In the same unit as other gas fields and potential saline aquifer storage sites	Accepted

The advantage of this option is that a smaller number of sites would be in operation, thereby reducing the amount of infrastructure required. Potential detrimental interactions with other users of the surface and subsurface are reduced. The close proximity of the Viking and Indefatigable fields forms a natural cluster of storage sites which could be developed via an integrated infrastructure (Fig 4).

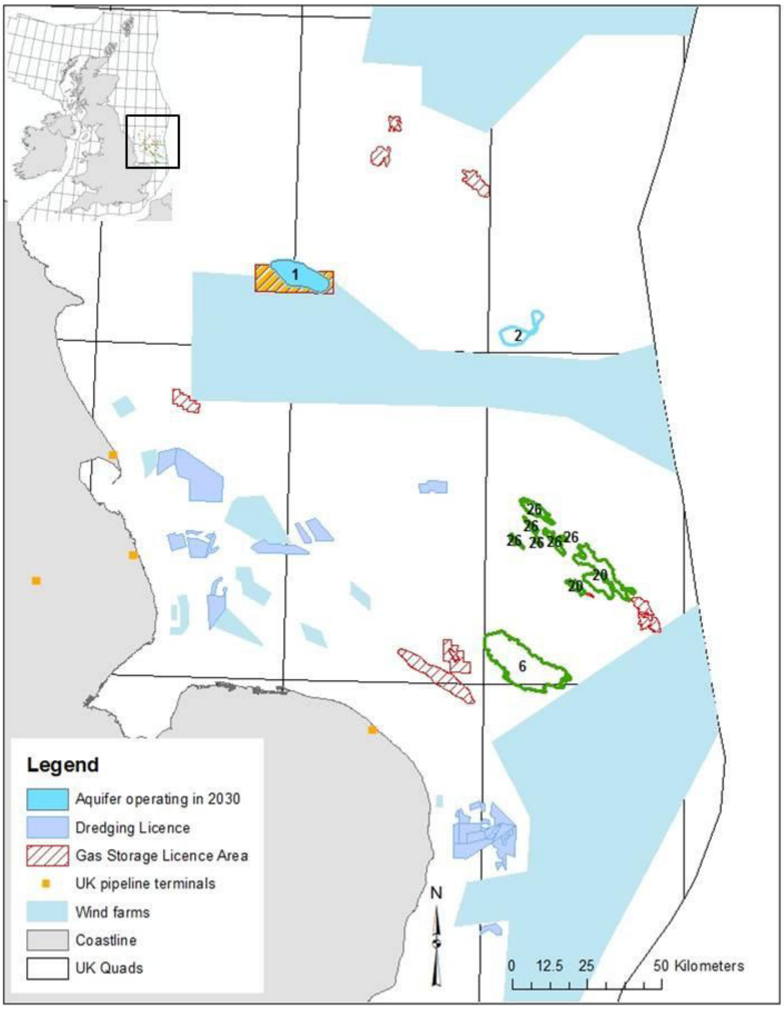

Fig 4. Map of portfolio of the minimum number of sites, regardless of their relative rank in terms of geological suitability or proximity to coast, MSR Scenario, that provide the estimated storage capacity that might be required in 2050.

A disadvantage of this method of selecting sites is that by choosing those sites with the largest estimated capacity, sites with a lower ranking will be used first. Therefore, sites that may be more suitable for early development (based on the criteria used in this study) are not selected. The sites with the largest capacity may not always be the most geologically suitable. For example, Site 20 is ranked 20th using the data available for this project [4]. This may increase the geological risk as defined by the criteria used in this study.

4.3 Option 3: Developing clusters

It has been widely recognised[5] that there could be many advantages in developing storage sites in a series of integrated clusters that can share pipeline infrastructure, balance injection with capture rates, provide flexible and increasingly optimised storage and possibly coordinate monitoring, and thereby reduce costs [6],[7], [8].

To develop clusters in this option, three of the higher ranked projects, saline aquifer Sites 1, 3 and gas field Site 6 are used as catalyst projects, from which clusters are assumed to develop. This starting position assumes that these ‘most suitable’ storage sites will be initially selected, characterised and developed separately. It is further assumed that initial development of these catalyst projects would involve construction of suitably oversized infrastructure to support future expansion of the storage portfolio as capture rates increase. To identify those sites that might be included in each cluster, sites were selected and evaluated sequentially with increasing distance from each catalyst site up to 40 km distance, until the estimated storage capacity required in 2050 was reached. This maximum distance was selected as a cut-off above which it is assumed the advantages of clustering are reduced. Again, the relative ranking of individual sites were not considered, though potential detrimental interactions were evaluated. However, here it is assumed that CCS infrastructure would take precedence over wind farm development. This is because, when developing a storage cluster, it is not possible to discount nearby suitable sites due to spatial planning conflicts because replacement by more distant sites would not form a co-located cluster.

Using this approach, two distinct and natural clusters can be defined, which have been called the Easington and Bacton clusters, with reference to the closest onshore connection points for the pipeline networks.

4.4 The Easington Cluster

In this option, the first project to be developed is Site 1, which will be active in the 2030 snapshot. The nearest sites within a 40 km radius of Site 1 on the ranked list are the gas fields sites 32, 35, 10 and 33. All of these are in a wind farm licence area (Table 4). In this case optimisation of CCS infrastructure would need to take precedence over wind development here or CCS would need to be accommodated within the wind farm development (e.g. by developing access corridors). If compromises between CCS and other users of the surface and subsurface are not reached it will make cluster development extremely difficult.

The estimated capacity of this cluster could store approximately 34 % of the required captured CO_2 to 2050. The gas fields in this cluster are already connected by pipeline routes between themselves and the Easington terminal (Fig 5), though the extent to which these might be reused for CO_2 transport has not been evaluated. Development of this cluster would require additional infrastructure to be installed to exploit the storage capacity of the saline aquifers.

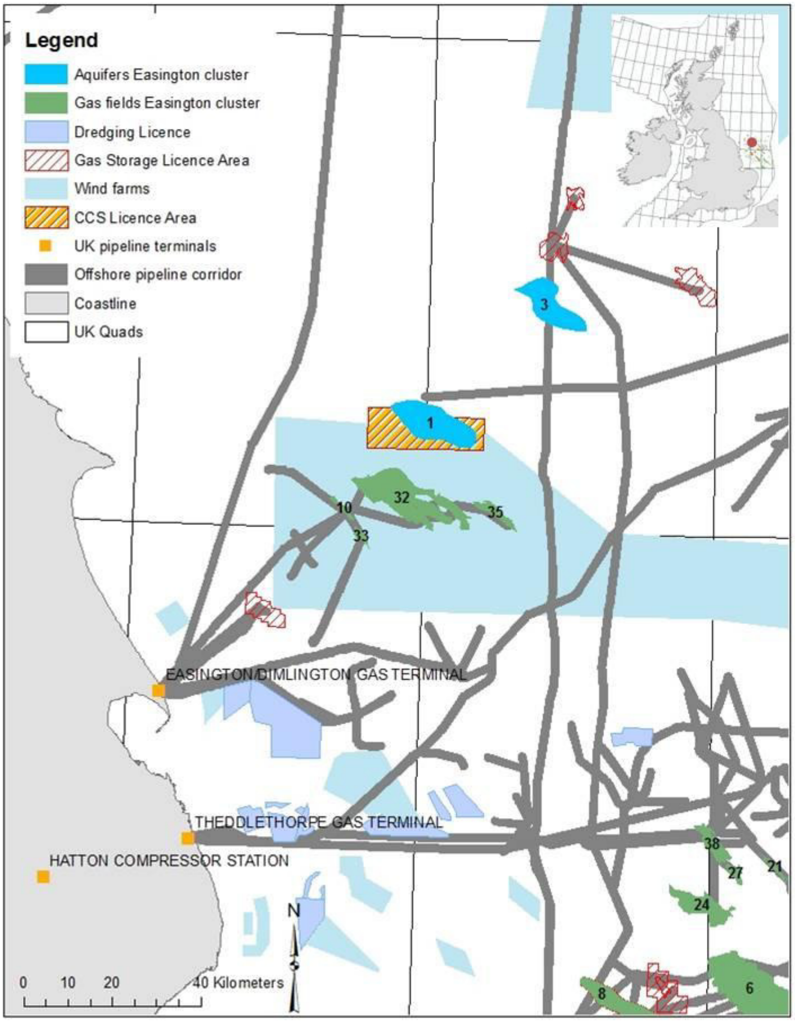

Fig 5. Portfolio of sites identified to form the 'Easington' storage cluster, MSR Scenario, assumed to form from a catalyst Site 1 (AQ01).

Table 4: Portfolio of possible storage sites identified to form the 'Easington' cluster.

ID	Name	Interaction	Comments
1	AQ01	No conflict	-
32	Ravenspurn	Wind farm licence area	Assumed appropriate arrangement could be made between the CCS operator and the wind farm licence holder or decision reached by the Competent Authority.
35	Johnston	Wind farm licence area	
10	Cleeton	Wind farm licence area	
33	Neptune	Wind farm licence area	
3	AQ03	No conflict	-

The next highest ranked site is Site 2, which is isolated from other nearby sites with no other ranked sites within a 40 km radius. As a result, Site 2 is not a good candidate to act as a catalyst for the development of a local cluster. In addition, the site is approximately 140 km from the nearest gas terminal onshore, which also reduces the likelihood of this site acting as a first site/catalyst for a cluster. Therefore, for the development of this option, Site 2 has not been included in further 'cluster development'. However, it should be noted that there *are* gas fields and saline aquifer potential storage within a 40 km radius of Site 2, but these sites did not make the ranked shortlist [4]. This does not mean however that these sites are not suitable for CO_2 storage.

Site 3 was considered next as a potential candidate to act as a catalyst for a second cluster. However, this site is located close to Site 1 and it is therefore assumed that this site would not form an independent cluster, but would be developed as part of the Easington cluster.

4.5 Bacton cluster

In order to fully provide the required storage capacity predicted to be required, a second cluster must be defined. Sites 1 to 3 are included in the Easington cluster and Site 4 has been discounted due to its location and relatively small storage capacity. Gas field Site 5 is also a small storage site with a storage theoretical capacity of just over 20 Mt, which is located within a wind farm licence area. It was not considered further; though it is located close to the next possible site, Site 6, which is a large gas field that is located close to the coast with many potential storage options close by. Its location does not pose any relevant conflicts of use that have been identified in this scenario. This cluster utilises high ranked gas field Sites 8 and 5 (Table 5).

Table 5: Portfolio of possible sites identified to form the 'Bacton' Cluster.

ID	Interaction	Comments
6	No conflicts	
8	Gas licence in overlying accumulation	Assumed appropriate arrangement could be made between the CCS operator and the gas producer or decision reached by the Competent Authority.
24	No conflicts	
13	No conflicts	
5	Wind farm licence area	Assumed appropriate arrangement could be made between the CCS operator and the wind farm licence holder or decision reached by the Competent Authority.
27	No conflicts	
38	No conflicts	
21	No conflicts	
37	No conflicts	
20	No conflicts	

The sites listed in Table 5 have been selected as a second cluster to the Easington cluster to meet the required storage capacity. This cluster is in approximate distance order from Site 6 (Leman) and contains many units with relatively small capacity. There are already pipelines that could be utilised to connect many of the sites for the Bacton cluster (Fig 6). Another option would be to develop the large gas fields Sites 6 and 20 in preference to these smaller sites. This binary cluster would still provide sufficient storage capacity to meet estimated requirements in 2050 when developed in combination with the Easington cluster.

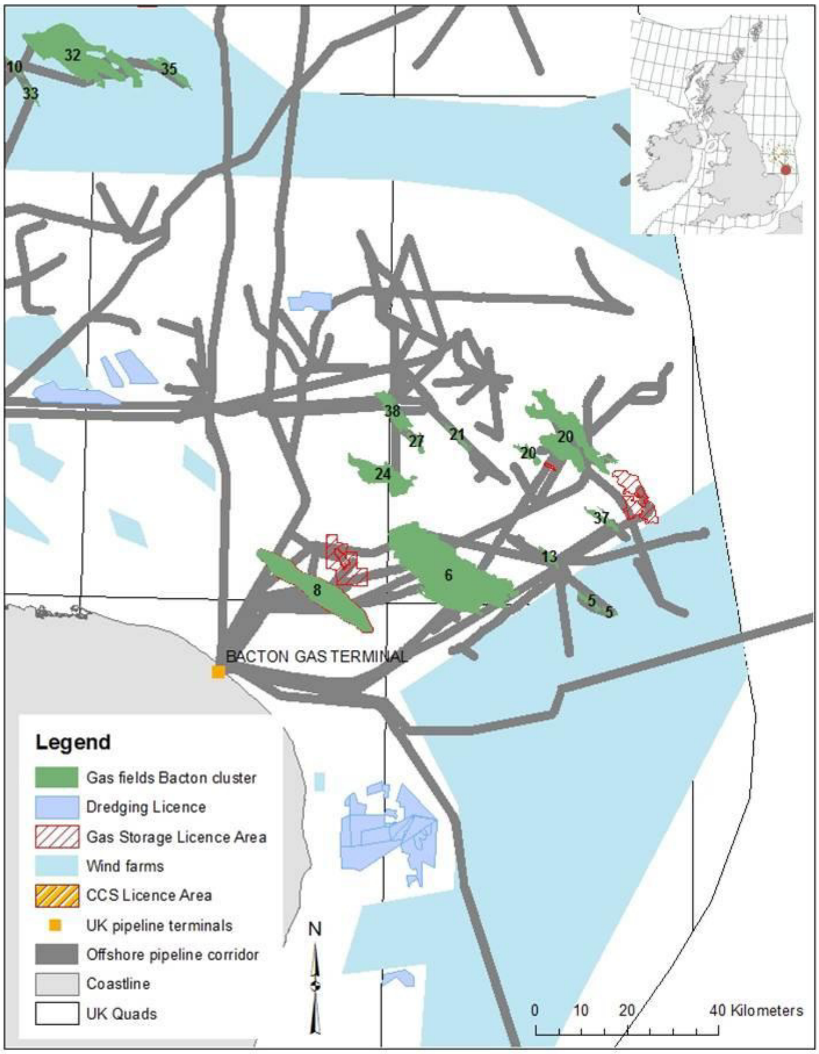

Fig 6. Map of sites that could form the proposed ‘Bacton’ Cluster, MSR Scenario.

5. Conclusion

The benefit of the FCFS approach is that the operator has the final decision on where to develop CO_2 storage, based on the knowledge that their site is fit for storage and, therefore, that they are willing to take on the risks associated with its operation. There are no reasons why this approach should change in areas of multiple, potentially interacting, storage sites. The drawbacks of this approach include the potential for reduced storage capacities in adjacent future storage sites, possible difficulties for monitoring, and lack of regional storage optimisation. It is recognised that this approach may not necessarily lead to a pathway of overall least-cost development for storage.

However, in order to avoid or reduce potential detrimental interactions of the types outlined in this study, some form of strategic planned management may be necessary. The degree to which strategic management might influence site selection will reflect the geological conditions, the current and anticipated future uses, including the expected required storage capacity needed to meet targets in emissions reductions, and the policies and regulations of the region. Nevertheless, we conclude that some form of strategic management is likely to be necessary in most regions to reduce storage risks. Strategic management of storage resources might require prioritisation of development of sites which could, theoretically, lead to increased costs for individual projects (through longer pipelines, deeper wells etc.). However, we have not examined this sufficiently in this study to draw definitive conclusions.

The FCFS scenario approximates to an open, market-driven approach in which storage sites are selected on the basis of their geological merits and proximity to the coastline. In the FCFS scenario, later operations must demonstrate either no or minimal impact on incumbent uses and/or reach compensation agreements with operators with pre-existing rights. Hence, early developers have the benefit of not being restricted by pressure increases. This might encourage earlier storage development. However, the Southern North Sea case study has shown that this approach may not necessarily result in optimised storage performance, since subsequent operations may not be optimally situated. Where an impact might lead to a conflict of use it is assumed it would infringe on pre-existing rights, then that storage site may not be used. This may not necessarily be the case however, as accommodation and agreements may be able to be reached. Furthermore, we have not taken into account the economics of commissioning many independent storage sites which may make this scenario unnecessarily expensive and therefore less likely. More likely is the sequential development of sites by extending infrastructure and by targeting similar structures in the same formations as early developers benefit from increasing knowledge and confidence. This sequential development may also use CO_2 for enhanced oil recovery (EOR) as a step to wider storage development.

The MSR scenario assumes that hydrocarbon, groundwater or mineral resources will always be protected as is currently the case globally and that protection and exploitation of these resources will be given priority over storage rights. It is also assumed that storage will only take place where evidence is provided that indicates it is likely to be safe to store CO_2.

Initial projects are likely to select the most geologically suitable sites. Storage development will be initiated from these early catalyst projects, from which a cluster of storage sites could be developed where regions have multiple storage options. Clustered storage with integrated infrastructure offers several potential advantages, including more flexible operation and cost savings through economies of scale, plus the experience obtained in the catalyst project could benefit follow-on projects in the same cluster. Such clustered development may occur without strong 'regulatory' intervention except where over-sizing of transport pipelines might be necessary. Initial storage permits might be encouraged from regions centred on these first projects. As expertise and experience in storage operations increase, other sites could be exploited, which might include smaller sites near early catalyst projects, rather than commissioning larger storage sites in virgin areas at greater distances. Nevertheless we have shown here that under one scenario of strategic management of the storage resource for the Southern North Sea, targeting fewer but larger storage sites could potentially meet possible future requirements as an alternative to developments of clusters. However, the differences in costs and benefits of these approaches have not been evaluated.

Furthermore, clusters of sources may be focused on one very large storage site or a cluster of smaller ones. Economies of scale and cost-sharing may also encourage the development of clusters.

The managed approaches proposed here will require the relevant Competent Authority to understand the implications of multiple, synchronous storage. This is needed to enable informed decisions to be made concerning choosing storage regions within which operators can undertake detailed site characterisation. To allow the Competent Authority to select the regions to exploit for CCS they will need to know or do the following;

- Have an inventory of current and future users in the region
- Know future storage capacity requirements
- Understand the implications of CO_2 injection in the region
- Identify and map all potential storage sites
- Assess potential interactions between storage sites
- Develop scenarios of potential storage development
- Know the jurisdiction's current permission on primacy (e.g. CO_2 storage vs. Hydrocarbon production).

Combining this information will allow relevant authorities to develop a strategic storage plan to optimise storage and reduce costs and risks. An advantage of the Competent Authority's undertaking regional characterisation would be that industry confidence in storage would increase and lead to more bankable storage sites. A consequence of a more managed approach, where the Competent Authority decides which storage regions should be in operation, could cause a shift in the balance of risk sharing with increased risk for the Competent Authority. To be clear: we are not proposing any change to existing regulations as it will still be for the operator to undertake detailed site characterisation to determine if a site is suitable for CO_2 storage.

In order to regulate and manage interactions between subsurface users, key performance metrics would need to be clearly defined and agreed between operator and regulator.

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