Obstacles and opportunities for onshore geological carbon storage in the UK

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Contents

List of Abbreviations

BECCS	Bioenergy with Carbon Capture and Storage
BEIS	Department for Business, Energy, and Industrial Strategy
CCC	Climate Change Committee/Committee on Climate Change
CDR	Carbon Dioxide Removal
CCA	Climate Change Act
CCS	Carbon Capture and Storage
CNS	Central North Sea
CCUS	Carbon Capture, Usage, and Storage
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DACCS	Direct-Air Carbon Capture and Storage
DESNZ	Department of Energy Security and Net Zero
EIS	Eastern Irish Sea
EOR	Enhanced Oil Recovery
EPR	Extended Producer Responsibility
ERW	Enhanced Rock Weathering
ETI	Energy Technologies Institute
EU CRCF	EU Carbon Removal Certification Framework
GCS	Geological Carbon Storage
GGR	Greenhouse Gas Removal
GHG	Greenhouse Gas
Gt	Gigatonne, 10^9 tonnes
IAMs	Integrated Assessment Models
IDS	Industrial Decarbonisation Strategy
IPCC	International Panel on Climate Change
ktCO2	Kilotonne of CO_2, 10^3 tonnes
MRV	Monitoring, Reporting and Verification
Mt	Million metric tonnes, 10^6 tonnes
Mtpa	Million metric tonnes per annum
NbS	Nature-based Solutions

NET	Negative Emissions Technology
NNS	Northern North Sea
NSTA	North Sea Transition Authority
N-ZIP	Net-Zero Industry Pathways
OFGEM	Office of Gas and Electricity Markets
OGA	Oil and Gas Authority
OPEX	Operational Expenditure
PPP	Polluter Pay Principle
SAF	Sustainable Aviation Fuel
SI	Statutory Instruments
SNS	Southern North Sea
tCO_2	Tonne of CO_2
TRL	Technology readiness level
T&S	Transport and storage
UNFCCC	United Nations Framework Convention on Climate Change

Executive Summary

This report evaluates the current state of knowledge on onshore geological carbon storage (GCS) and its feasibility in the UK by examining its technological, economic, regulatory and social aspects. Research and regulatory gaps are highlighted, showing where onshore GCS is under-researched.

We find that many industrial point sources are located outside of industrial clusters and will not be able to access CO_2 transport and storage (T&S) infrastructure. This is due to the distance between dispersed industrial sites from carbon capture and storage (CCS) clusters. Even if T&S networks were deployed to unrealistically large distances of 100 km, 136 sites would remain dispersed (i.e., outside of the T&S networks). These sites collectively emit 9 ± 1 $MtCO_2$pa ($\sim 9\%$ of industrial point source emissions). The addition of onshore GCS could improve access to CCS as an abatement option for dispersed point sources by reducing the CO_2 transport distance. The UK aviation sector is highly reliant on engineered carbon dioxide removal (CDR). This sector could utilise engineered CDR with onshore GCS as a supplemental option to durably compensate for its emissions. Offsetting must be combined with demand-side reductions in emissions, to avoid substantial resource usage, which includes CO_2 storage space. The use of onshore GCS could serve as a complement to offshore GCS, if competition from other emissions sources for CO_2 storage space becomes too high.

There is little detailed geological data on onshore CO_2 reservoirs in the UK, and few published studies have analysed their potential for GCS. The onshore CO_2 storage capacity and injectivity thus remain uncertain and under-researched. A preliminary assessment has shown that several onshore geological formations may be suitable for GCS projects, although these storage projects would be at smaller scale when compared to the large offshore GCS projects that are under development on the UK continental shelf. Nonetheless, smaller scale onshore reservoirs could provide the required CO_2 storage space for certain dispersed point sources. Given that the extraction of conventional oil and gas resources is also widespread onshore in the UK, depleted hydrocarbon fields and pre-existing deep well infrastructure could be potentially repurposed for small-scale onshore GCS projects. However, further CO_2 storage prospecting and assessments on the suitability of specific sites are required to accurately determine their potential.

Our analysis of the UK regulatory environment shows that the UK government industrial decarbonisation strategy focuses on highly-emitting industrial clusters and offshore storage. There are few regulations tailored to onshore GCS, as well as significant legal,

regulatory, and policy hurdles that prevent the development of onshore GCS. As opposed to offshore GCS, where the North Sea Transition Authority acts as the governing entity, there is currently no relevant authority overseeing the licensing, permitting, and regulatory aspects of onshore GCS deployment in the UK. The governance surrounding the implementation of onshore GCS will likely be shared across several government departments and jurisdictions, although this has yet to be clearly defined by the UK government due to its current focus on offshore GCS development. Moreover, following the withdrawal of the UK from the EU, the introduction of the Retained EU Law (Revocation and Reform) Act 2023 revoked the legal mechanisms for onshore storage that were originally mandated by the EU in 2009 and implemented into UK regulation. As such, there is no legal mechanism enabling the use of onshore storage in the UK, as opposed to its European, American, and Canadian counterparts.

High-profile cases of public opposition to onshore storage in Europe and analogous technologies in the UK have led to a widely held assumption that gaining a social licence for onshore projects will be difficult. We find that offshore GCS is not necessarily preferred to onshore GCS by the UK public. The likely determinants of public opinion of GCS are: distance to people, media response, ecological impacts, societal and personal risks and opportunities, climate concern, regulatory and legal uncertainty, and trust in governing bodies. There are mixed results from the literature on the true impact of proximity to people on risk perception and public acceptance. Comparative research on onshore and offshore GCS is scant, particularly due to low public awareness of CCS and low acceptability of both onshore and offshore GCS. The place, history, and social contexts are crucial to public perceptions, and as such, large-scale public engagement consultations are needed at specific locales and jurisdictions.

The cost of onshore GCS is estimated to be around 50% lower compared to offshore GCS. However, these estimates do not account for additional costs linked to licenses, permitting and increased public engagement. Furthermore, onshore costs in the UK may be higher than expected because of rigorous monitoring, reporting and verification (MRV), and regulatory requirements. The unique financial challenge for GCS hinges on the longevity of the project, and how these will be funded in the long term. The UK's CCS Investment Roadmap is a financial model supporting CCS investment and offshore GCS based on government subsidies, which will taper off after 15 years. No plans for funding CCS and GCS projects after 2028 have been published. The financial planning and costs of onshore GCS in the UK remain uncertain, as no projects are being planned. Funding for GCS in the offshore context also lack the certainty in the source of capital and in financial direction, and a clear market signal from the UK government in the long-term.

Introduction

The large-scale deployment of carbon dioxide removal (CDR) to remove CO_2 from the atmosphere is essential to limit global warming under 2°C[1,2]. This is a necessity due to insufficient progress in emissions management and demand-side reductions in the last decade, thus increasing the probability of a climate overshoot[3–7]. Climate scenarios analysed by the Intergovernmental Panel on Climate Change (IPCC) have shown that further delays in the peak of global CO_2 emissions would entail a greater dependence on CDR in order to meet climate goals, further highlighting their importance in climate mitigation strategies[6,8]. The Sixth Carbon Budget published by the Climate Change Committee (CCC) – which acts as the country's primary independent advisory public body on climate change response and carbon budget target-setting – presents an increased reliance on "engineered removals"[9], in which the "Balanced Net Zero" pathway describes the use of geological removals (i.e., injection of CO_2 deep underground) of around 63 $MtCO_2$/year or million tonnes per annum (Mtpa) by 2050 (~ 20% of present day emissions). Naturally, these removals need to be developed alongside significant reductions in emissions, as the vast majority of the effort is still required to reduce present emissions by around 80%. CDR should not be a mean of drawing focus away from decarbonisation efforts, although it will be required to mitigate hard-to-abate emissions from industrial processes which are very likely to still exist in 2050.

Carbon capture and storage (CCS) deployment is primarily being used to decarbonise hard-to-abate industries (e.g., cement, iron and steel processing) by capturing and permanently storing emissions from industrial point sources[10,11]. This does not remove previously-emitted CO_2 from the atmosphere, and thus, by itself, is not a form of CDR. However, components of CCS can be applied to CO_2 streams sourced from biomass or directly from the atmosphere to conduct engineered CDR. CCS is instrumental in the scale-up of engineered CDR, as bioenergy with carbon capture and storage (BECCS), or direct-air carbon capture and storage (DACCS) may rely on the same carbon transport (e.g., pipeline) and storage infrastructure as CCS[12].

There is a decades-long precedent for the sequestration of CO_2; the first patent for CO_2 capture was filed in 1931[13], and the CCS industry was born out of the use of enhanced oil recovery (EOR) in the oil and gas industry in the US[14] in the 1970s. EOR refers to the extraction process of crude oil, which involves the injection of fluids (i.e., CO_2) into geological formations to displace and mobilise oil into production wells[15]. Experience in geological CO_2 injection for EOR and learnings from past full-scale CCS projects (Sleipner, In Salah, Snøhvit, Gorgon, etc) have shown that it is technically feasible to safely inject over

1 $MtCO_2$pa into a geologic storage reservoir[16,17]. Because of this experience, geological carbon storage (GCS) operators are now designing projects with injection rates of over 10 $MtCO_2$pa[14,18]. However, despite large scale GCS deployment being intrinsic to many plans for transitioning to net zero, substantial uncertainties and barriers – primarily regarding financing – still remain, widening the gap between the expected and actual rates of implementation[19–27].

Although GCS is primarily deployed offshore in Europe, several pilot-scale onshore GCS infrastructure projects have been conducted across the region to further explore its feasibility[28–30]. Pycasso is an ongoing project at the French-Spanish border, aiming to capture CO_2 from multiple industrial sources for onshore GCS at the Mt scale[31]. The project builds upon the Lacq-Rousse pilot onshore GCS project by Total Energies, which successfully stored 51 $ktCO_2$ in the Rousse depleted gas fields between 2010 and 2013[30,32]. Other ongoing pilot onshore GCS projects include Hontomin in Spain which sequestered 3.4 $ktCO_2$ between 2015-2018, and the Ketzin project in Germany which injected and stored 67 $ktCO_2$ between 2008-2013[29,33,34]. In the UK, GeoEnergy Test Bed is currently the only onshore CO_2 injection project, although it focuses on carbon leakage research with shallow injection at depths ranging from 10 to 250 m[28,35,36]. Operating at a closer proximity to CO_2 sources through onshore GCS could reduce CO_2 transport distance, infrastructure requirements and costs[37]. Onshore GCS, whether for CCS or engineered CDR, could also enable local authorities to exert greater control over their own emissions through more localised management and provide jobs for local economies[28]. Despite interest in the use of onshore GCS in Europe, no development of an onshore CCS, BECCS, or DACCS project is currently under consideration in the UK.

Purpose and outline

This work reviews the current state of knowledge on onshore GCS in its technological, economic, regulatory, and social aspects to assess its current viability in a UK context. Research gaps are presented to show that the use of onshore GCS is still underdeveloped. Section 3 presents an analysis on dispersed industrial sites in the UK to highlight limitations associated with solely relying on offshore GCS. A case study on the UK aviation sector is also presented as an example of a hard-to-abate sector which could durably offset its emissions using BECCS or DACCS with onshore GCS. Section 4 presents a review on the CO_2 storage processes, storage capacity, and geological suitability for GCS in the UK. Section 5 reviews the UK policy and regulatory landscape of onshore and offshore GCS, while section 6 assesses public perceptions and social acceptance and section 7 reviews the comparative costs and economics of GCS. Section 8 provides a discussion on the viability of onshore GCS, given findings presented in this report. Section 9 concludes our findings and presents opportunities for future research.

Box 2.1: Working terminology

Carbon dioxide removal (CDR): the set of technologies for removing atmospheric CO_2 through biological, geochemical, and engineered capture processes, and its subsequent storage in biological, shallow sediments, or geological sinks for climate mitigation purposes[38]. The terms negative emission technologies (NETs), greenhouse gas removals (GGR), and CDR are often used interchangeably in the academic literature[39,40]. Biological CDR methods are widely termed nature-based solutions (NbS). Examples of NbS include afforestation, reforestation, soil carbon sequestration, and blue carbon management. Each could in theory provide co-benefits beyond just CO_2 removal, such as enhancing biodiversity, improving air quality and human health[8,41]. Engineered CDR methods require higher levels of human intervention. Examples include bioenergy with carbon capture and storage (BECCS) and direct-air carbon capture and storage (DACCS) which geologically sequester CO_2[42].

Carbon capture and storage (CCS): the management of emissions from industrial point sources through the chemical capture of CO_2 from industrial flue gas, followed by CO_2 transport via pipelines or other means (i.e., road vehicles, shipping, rail), and the subsequent injection of supercritical CO_2 into deep (>800m) geological rock formations for permanent storage[43]. As CCS only reduces outgoing CO_2 emissions into the atmosphere from industrial sources, and does not physically remove CO_2 from the atmosphere, CCS is not always a means of CDR. However, in cases where components of the CCS process are applied to CO_2 streams sourced from biomass or directly from the atmosphere, it is considered to be a CDR method (i.e., BECCS or DACCS respectively)[38].

Geological carbon storage (GCS): storage process where CO_2 is injected in its supercritical state into deep geological rock formations for permanent (multi-century timescale) storage. The CO_2 can be sourced from industrial processes, biomass, or directly from the atmosphere. This term refers to one step in the process of CCS or CDR with GCS (i.e., BECCS and DACCS).

Durable storage: varying levels of risk of reversal are associated with each type of carbon storage, with certain storage options being more durable, as they are less vulnerable to the re-emission of CO_2 to the atmosphere, and securely storing CO_2 at longer timescales[38]. Reversal risks within storage types vary under different contexts and governance arrangements, thus influencing risk management[44]. The large-scale implementation of geological storage is crucial in climate mitigation strategies over the long-term. It ensures the highest degree of storage security and longevity, and ease of carbon accounting and monitoring relative to other storage options[45–47].

Geological net zero: the net balance between CO_2-equivalent emissions and removals with GCS over multi-decadal or multi-century timescales. This term stems from the recognition that biological storage is limited in capacity in the long term and stores CO_2 at shorter timescales than geological storage[48,49].

Emissions sources

3.1 Dispersed industrial point sources

CCS implementation in the UK has focused on industrial clusters for offshore GCS. The UK government published the Industrial Decarbonisation Strategy (IDS) on March 2021, which sets out a shared CO_2 transport & storage (T&S) infrastructure for co-located industries in industrial clusters, where emissions are most concentrated[50]. All industrial clusters defined in the IDS, which act as CO_2 transport hubs, are situated near the UK coast. All planned GCS sites are located offshore, primarily in the North Sea. As such, dispersed industrial sites situated at great distances from industrial clusters will experience difficulties utilising CCS as an abatement option, due to more limited access to T&S infrastructure.

According to the IDS, dispersed industrial sites contributed to almost half of the UK's industrial emissions in 2018[50]. Currently, there is no formal definition, but dispersed sites are loosely defined as “industrial sites located outside of industrial clusters” in government reports[50]. Decarbonising dispersed sites using CCS with offshore GCS may require a national CO_2 pipeline network, as modelled in the “National Network” decarbonisation pathway model described in the IDS. Moreover, the implementation of a large-scale national CO_2 transport network whether by pipeline, rail transport, road transport or a combination of these methods to connect to dispersed sites is associated with significant risks and uncertainties[51,52].

Moreover, values for CO_2 emissions from dispersed sites presented in the IDS[50] and aforementioned government publications primarily stem from two key sources: the "CCS deployment at dispersed industrial sites" report by Element Energy commissioned by the UK Department for Business, Energy & Industrial Strategy (BEIS)[52]; and the Net-Zero Industry Pathways (N-ZIP) model developed by Element Energy for BEIS and the CCC[53]. The N-ZIP model provides possible industrial decarbonisation pathways which includes CCS deployment, and has guided both the IDS and the UK's sixth carbon budget[9,50]. Dispersed sites were defined as industrial sites that fall outside a 30 km and 25 km radius from industrial clusters, in the report and model, respectively. A 30 km radius was determined to be the threshold distance where establishing a T&S connection to a site was considered to be prohibitive, and the distance in which CO_2 pipeline capital expenditure would exceed 33% of CCS plant capital expenditure[52].

The report published by Element Energy is the only technical analysis to date that directly identifies dispersed industrial sites and addresses potential geographical constraints to the UK's cluster-based strategy for CCS deployment[52]. No sensitivity analysis has been conducted for this work. Additionally, sensitivity analyses for the N-ZIP model only examines its techno-economic elements[54,55]. As such, these two works neglect to tackle more fundamental aspects, such as the underlying assumptions made in the definition of dispersed sites (i.e., the threshold wherein sites are considered to be dispersed) and the location of industrial clusters.

Furthermore, industrial sites with less than 50 $ktCO_2$ were excluded, based on the assumption that CCS deployment would only be economically feasible if the emissions of a site surpassed this threshold[52]. This suggests that a portion of the UK's point source emissions in 2016 were excluded from their analysis, and industrial emissions were not represented in their entirety. Indeed, emissions from point sources below 50 $ktCO_2$ have been found to be significant, collectively amounting to 11.4% (11.88 $MtCO_2$) of total point source emissions in 2020, or around 3.7% of total UK CO_2 emissions[56,57].

A substantial amount of emissions from industrial sites would still be excluded from the T&S infrastructure even if it were to be extensively deployed at distances of 100 km from industrial clusters for offshore GCS (Table 3.1). To determine the amount of emissions associated with industrial sites included in clusters and those that are dispersed, three industrial cluster sizes (30, 50, 100 km) were spatially modelled as circular shapes of fixed radius alongside the locations of point sources. In this reanalysis, dispersed sites are defined as point sources that are excluded from T&S infrastructure for a given cluster radius. The cluster radius represents the maximum distance within which industrial clusters are able to connect to point sources to transport CO_2 to offshore GCS sites. Data on point sources from the National Atmospheric Emissions Inventory[56]) were analysed in two parts:

- With all point sources included (AS).
- With point sources in selected industries that could potentially deploy CCS (SI). The list of sectors categorised in SI are included in Fig. 3.2.

The distribution of CO_2 emissions in 2020 from all point sources and industrial sites with CCS deployment potential are shown in Fig. 3.1. All 1400 point sources in the NAEI dataset (AS) amount to 104.17 $MtCO_2$, whilst 782 industrial sites with CCS deployment potential (SI) contributed to 94.99 $MtCO_2$ (91.19% of total point source emissions) in 2020 as it includes energy-intensive industries. Both histograms present a log-normal distribution pattern, with numerous small emitters concentrating around a median value ($\sim$9 $ktCO_2$ when considering all point sources; $\sim$10 $ktCO_2$ for SI sites).

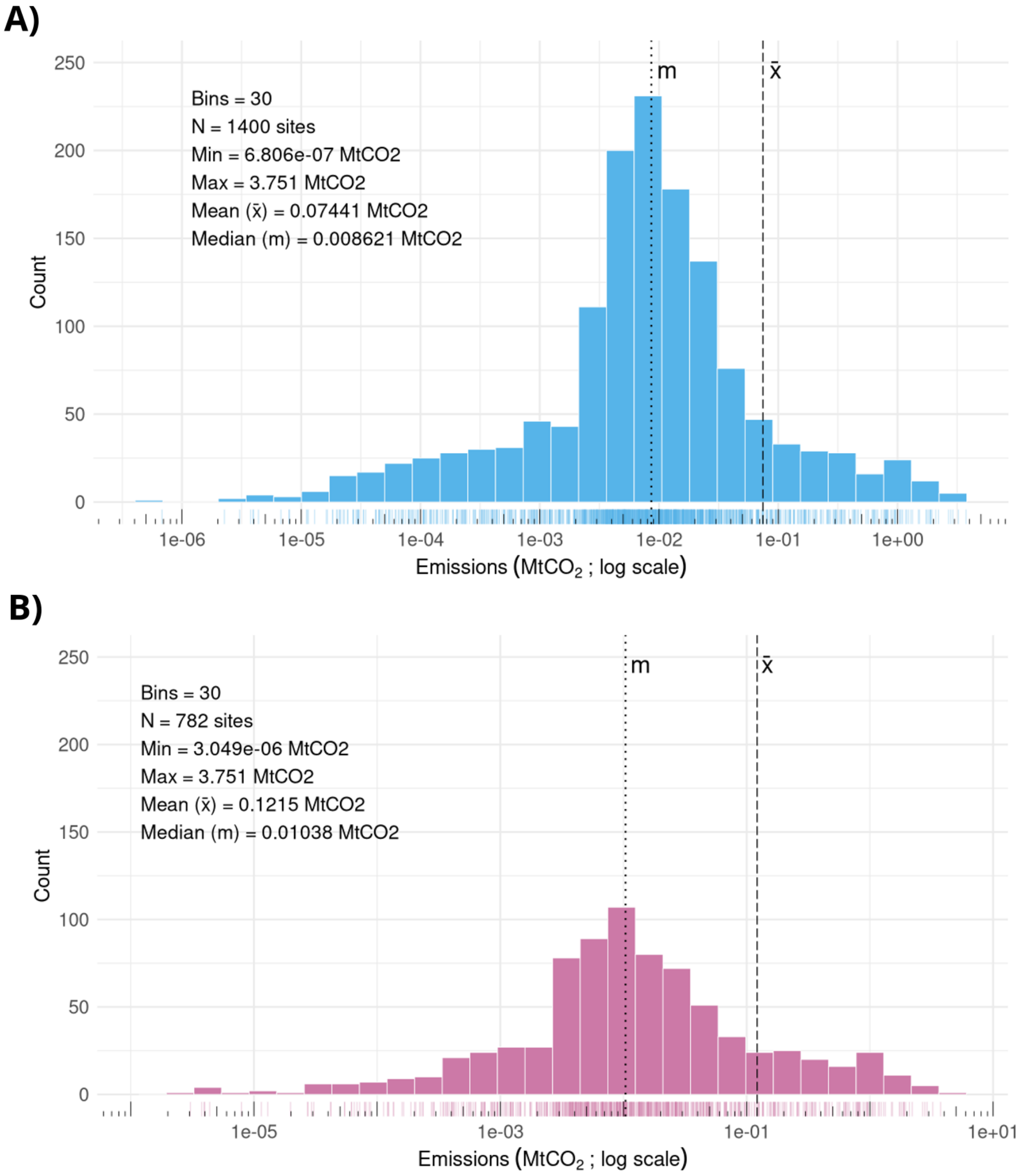

Figure 3.1: Histograms of CO_2 emissions in 2020 from point sources in A) all sectors (AS) combined and B) point sectors in selected industries (SI) suitable for CCS. Offshore emissions were excluded. Dataset on emissions from point sources in 2020 sourced from NAEI[56].

Table 3.1 presents the sums of emissions from dispersed (outside the cluster radius) and clustered (within the cluster radius) sites under each cluster size scenarios, with uncertainties. To obtain the uncertainties, the Monte Carlo method was implemented by randomly sampling the position of the origin of each cluster centre, then calculating the sum of dispersed and clustered emissions across 1500 iterations to obtain the mean absolute deviation values. If the T&S infrastructure were to expand only 30 km from industrial clusters, 509 industrial sites, emitting 35.8 ± 0.2 $MtCO_2$ (34.37% of total point source emissions), would remain dispersed and unable to access T&S infrastructure. With the expansion of the T&S infrastructure to distant sites at an unrealistic distance of 100 km from industrial clusters, 9 ± 1 $MtCO_2$ (8.64% of total point source emissions) from 136 sites belonging in sectors that could deploy CCS would still remain dispersed.

Table 3.1: Representative sums of clustered and dispersed emissions in 2020 ($MtCO_2$) for AS and SI sites under three cluster scenarios with number of associated sites (N). Using the Monte Carlo iterations, uncertainties were obtained with the median absolute deviation (MAD) of the distribution of sums of dispersed and clustered emissions.

Dispersed	30 km	50 km	100 km
All Sectors	42.7 ± 0.2 N = 1038	36.2 ± 0.3 N = 839	11 ± 0.9 N = 256
Selected Industries	35.8 ± 0.2 N = 509	30.7 ± 0.2 N = 414	9 ± 1 N = 136
Clustered	30 km	50 km	100 km
All Sectors	61.5 ± 0.2 N = 362	68.0 ± 0.3 N = 561	92.9 ± 0.9 N = 1144
Selected Industries	59.2 ± 0.2 N = 273	64.3 ± 0.2 N = 368	86 ± 1 N = 646

Fig. 3.2 presents a map of UK point sources belonging to the AS and SI categories, plotted with hypothetical industrial clusters of varying sizes. Three iron and steel sites collectively emitting ∼0.02199 $MtCO_2$ (0.065% of total point source emissions; PlantID 992, 13641, 13645) and two cement plants contributing ∼1.599 $MtCO_2$ (1.53% of total point source emissions; PlantID 8059, 8037) are located in the UK Midlands. These sites will be the most challenging to decarbonise due to the sectors' reliance on CCS and distance from clusters. Moreover, major power producers represent the largest point source emitters in the UK by a wide margin relative to other sectors, emitting 42.31 $MtCO_2$ (40.62% of total point source emissions). In comparison, the second-highest emitting sector is the iron and steel industry in 2020, emitting 11.57 $MtCO_2$ (11.1% of point source emissions). A full sectoral breakdown of emissions from dispersed point sources according to each

cluster radius scenario is provided in Fig. 3.3. Among dispersed sites, major power producers and cement plants represent the most significant sources of point source emissions. Iron and steel sites represent a smaller share of dispersed emissions as they are located at proximity from industrial clusters.

The deployment of CCS at co-located industries or industrial clusters allows for economies of scale by allowing multiple operators to use CCS and access a shared T&S infrastructure, consequently avoiding the construction of an oversized large-scale CO_2 capture facility or transport infrastructure for use by a single emitter[58,59]. In the UK context, however, dispersed isolated sites cannot use this CCS implementation strategy due to their distance from transport hubs and offshore GCS sites, and may have to rely on the construction of standalone T&S infrastructure, thus increasing the costs and risks of abating emissions[58,60]. This is most significant for dispersed industrial sites in sectors that heavily rely on CCS to decarbonise, such as the iron and steel, and cement production sectors[43].

In addition to the physical constraints associated with a cluster-centric CCS deployment, dispersed sites receive less decarbonisation support and institutional representation than their clustered counterparts. Findings from Rattle et al.[61] suggest that decarbonisation strategies for both clustered and dispersed sites are required to avoid potential regional market distortions, carbon leakage, and uneven transition risks. As the use of onshore GCS could potentially reduce CO_2 transport distance from point sources, dispersed sites could gain better access to CCS as an abatement option. A more localized approach to emissions management could enhance local economic activities and provide local job opportunities[28].

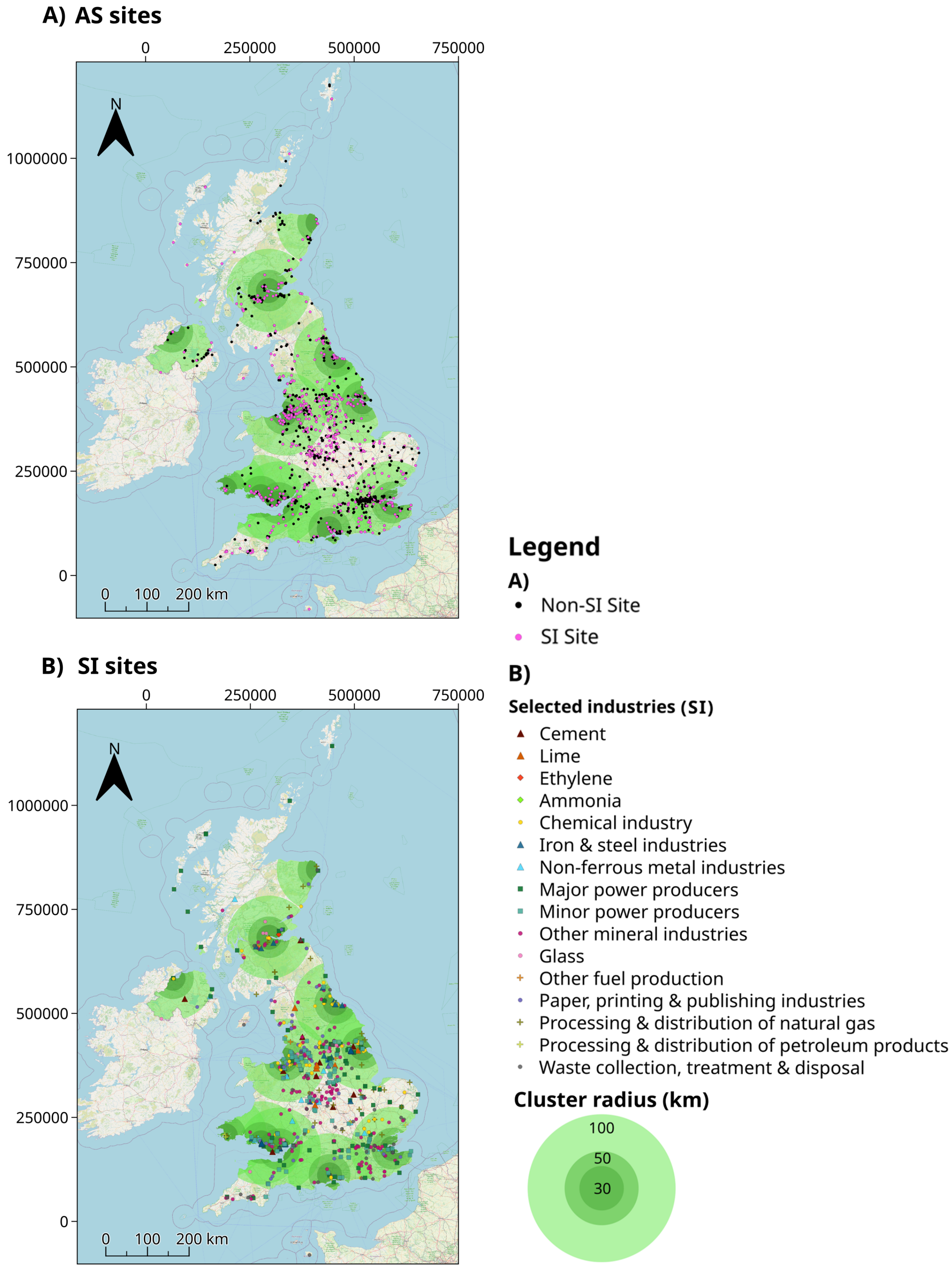

Figure 3.2: UK map with hypothetical cluster radii (30, 50, 100 km) and A) sites in all sectors (AS) consisting of sites from selected industries (SI) suitable for CCS deployment and non-SI sites, and B) SI sites categorised by sector. Non-SI sites refers to the subset of AS sites with low CCS deployment potential. 2020 Point source emissions dataset sourced from NAEI[56]. Cluster centre locations sourced from the Net Zero Industry Pathway (N-ZIP) model published by the CCC and Element Energy[54].

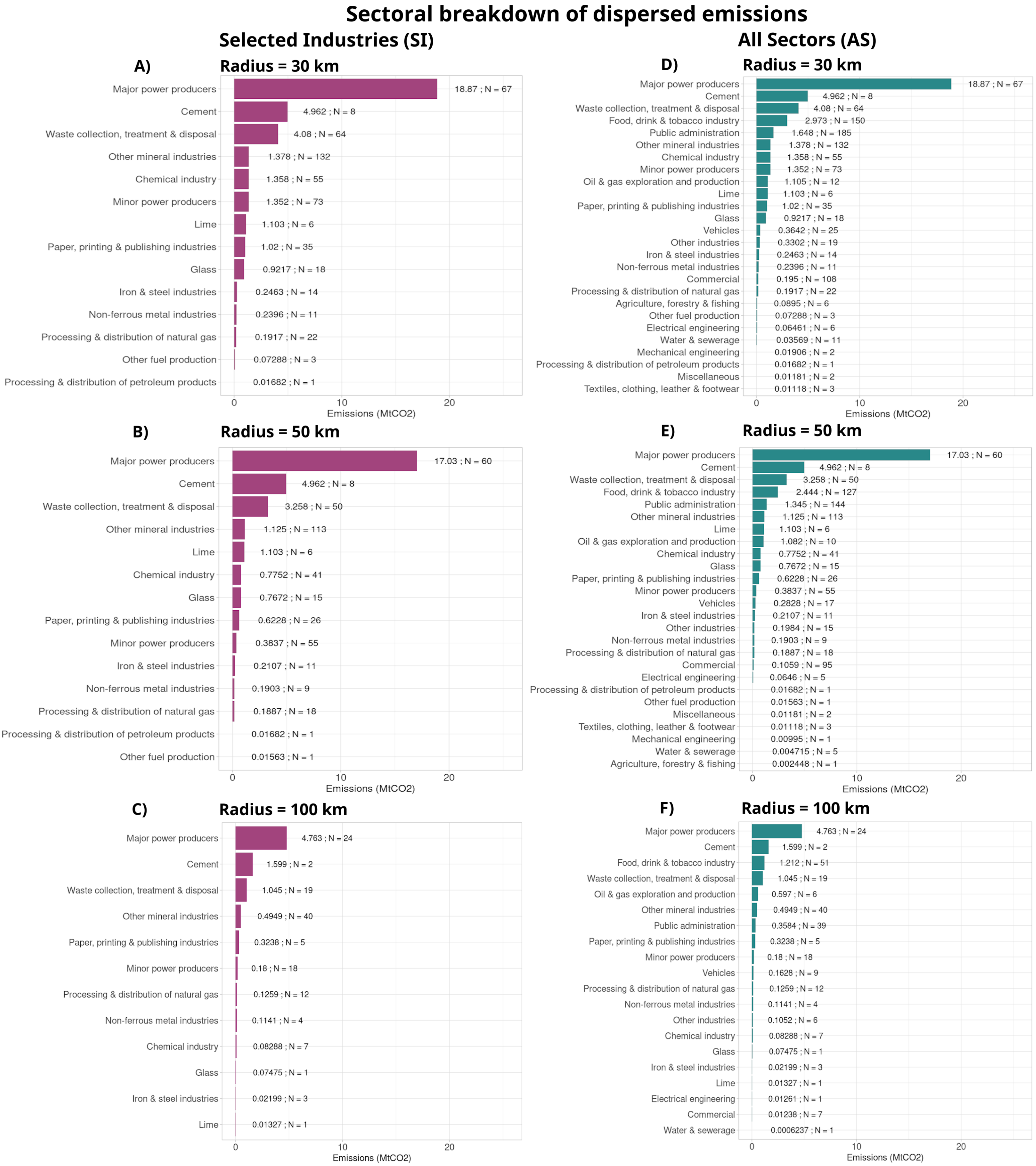

Figure 3.3: Barplot of the sectoral breakdown of dispersed emissions for SI sites (A, B, C) and AS sites (D, E, F) under the three defined cluster radius scenarios.

3.2 Case study: UK Aviation sector

The term "residual emissions" generally refers to emissions that are considered hard to abate that will need to be compensated with the use of CDR, as these emissions would persist even after implementing emissions reduction measures. However, this lack of a strict definition has led to confusion regarding which sectors would generate residual emissions, and how they will be compensated by CDR in decarbonisation strategies between countries[62,63]. Quantitative projections of residual emissions in 2050 from UNFCCC Annex I countries that provide sectoral breakdown of residual emissions were collated by Buck et al.[64]. Their results underscore that the UK is the only country that includes aviation in its residual emissions accounting, contributing nearly half of projected residual emissions in 2050.

The aviation sector is typically considered to be a hard-to-abate sector, owing to its reliance on fossil fuels and limited alternatives. Aviation currently contributes around 2.5% of global CO_2 emissions[65]. In addition, the aviation sector contributes significantly to climate impacts through non-CO_2 emissions in the form of short-lived climate forcers[66].

Past attempts at self-regulation by the aviation sector and climate target setting have been unsuccessful in reducing emissions. Beevor et al.[67] highlights that all climate targets related to CO_2 efficiency and the development of alternative fuel set by the aviation industry between 2000-2021 have never been met. Although aircraft fuel efficiency standards are aimed for a 2% annual improvement[68], advancements in aircraft technology have not compensated for the increase in CO_2 emissions caused by increasing demand for air travel over the past two decades[69]. Aviation demand is also expected to grow in the long-term, as the International Air Transport Association estimates that aviation demand will double by 2040, with an annual growth rate of 3.4%[70].

Emissions offsetting standards implemented in the aviation sector are currently insufficient. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) scheme is a non-binding market-based mechanism that requires aircraft operators in participating countries such as the UK to offset 85% of the increase in CO_2 emissions from 2019 baseline levels[71]. CORSIA is currently deemed to be incompatible with the Paris Agreement and the UK's recommended decarbonisation pathway by the CCC[9]. The effectiveness of the CORSIA scheme is limited by allowing the use of alternative aviation fuels, which does not address non-CO_2 impacts from aviation, in addition to the use of emissions avoidance and non-durable removal offsets to meet emissions targets[71–73].

The Jet Zero Strategy published by the Department for Transport outlines the UK government's strategy to achieve net zero emissions from the aviation sector by 2050[74].

According to the strategy, the government is committed to remain in the CORSIA scheme for full integration by 2024, and the use of CDR represents a crucial component of the strategy. The strategy also presents ambitions to mandate the use of sustainable aviation fuels (SAF) by 2025 with at least 10% SAF use by 2030. According to findings from the FlyZero project, which assessed the technological readiness levels (TRLs) of aircraft technologies in the UK, it is anticipated that most zero-carbon aircraft technologies including SAF will be implemented in the 2030s as they are currently in the early stages of development[75].

The "High-ambition" decarbonisation pathway presented in the Jet Zero report estimates that 19.3 $MtCO_2$ equivalent in residual emissions from the aviation sector would remain in 2050[74]. Given that the Jet Zero strategy makes no commitments to reduce emissions through demand-side management, the report illustrates a pathway highly reliant on CDR with GCS. However, results from Sacchi et al.[76] have shown that maintaining the continued growth of the European aviation sector whilst decarbonising aviation would require substantial amounts of resources for DACCS, GCS, and the production of synthetic jet fuels.

The production of synthetic jet fuels would exert excessive strain on economic and natural resources to compensate for emissions from increasing demand. In the case where only DACCS is deployed to offset fossil jet fuels, a CO_2 storage capacity larger than the proven storage capacity in the Norwegian continental shelf would be required, in addition to prolonged fossil fuel dependency[76]. Therefore, a combination of demand reduction, climate neutral jet fuels, and CDR with GCS would all be needed to achieve a durable decarbonisation in the aviation sector[27,76].

Geological carbon storage

4.1 Trapping mechanisms and storage formations

The process of geological sequestration most commonly involves the injection of CO_2 in its supercritical state (around 74 bar and 31.1°C) at depths of >800 m in a porous geological medium confined by an overlying impermeable "cap rock" (i.e., shale, salt) or sealing faults[43]. Supercritical CO_2 is injected due to its higher density, decreasing buoyancy effects, and aiding in the migration of CO_2 into the reservoir. A combination of physical and chemical trapping mechanisms are present following CO_2 injection. The contribution each of these mechanisms evolve overtime, culminating in CO_2 being trapped in the subsurface over geological timescales (Fig. 4.1).

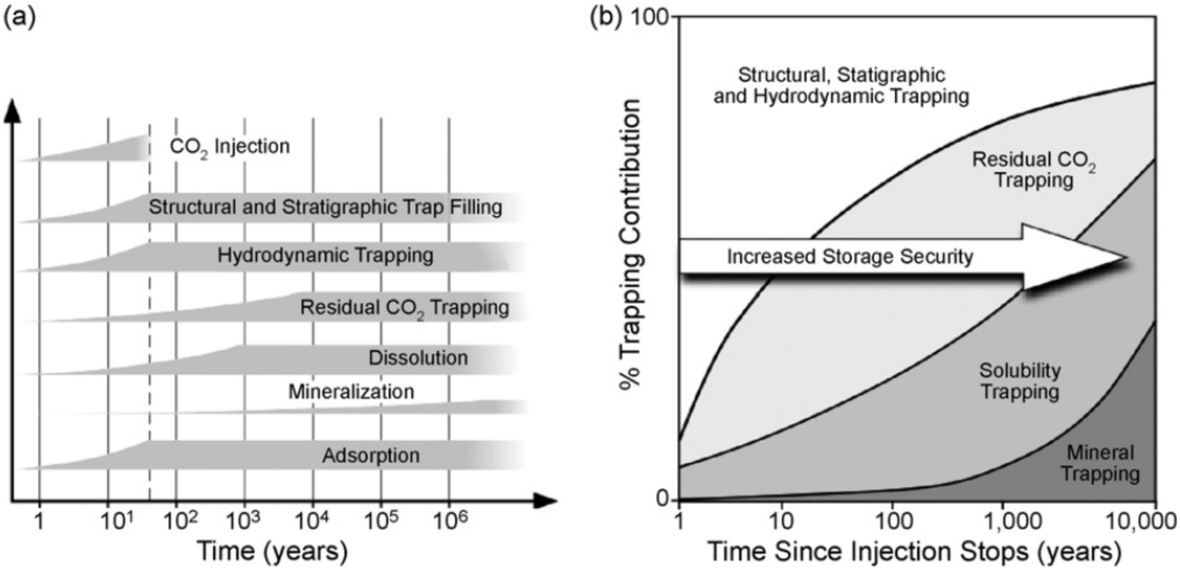

Figure 4.1: Time dependence of a) various CO_2 storage mechanisms and b) storage security overtime resulting from a combination of physical and geochemical trapping mechanisms. Reproduced from Bachu et al.[77], citing Metz et al.[78].

These storage processes can occur in the following geological features found in sedimentary basins:

- **Saline aquifers:** geological formations of permeable rocks (i.e., sandstone, carbonates) bearing saline, non-potable water that enables the dissolution of CO_2 and its subsequent storage[79]. Saline aquifers are generally considered to have the largest storage potential and represents the most significant storage medium in the UK, given their abundances and sizes in the North Sea[80].

- **Depleted oil and gas (O&G) reservoirs:** the same subsurface characteristics that have allowed the formation and trapping of hydrocarbons over geological timescales are also true for CO_2. These reservoirs are generally well characterised due to pre-existing data[81]. Initial CO_2 storage capacity estimates are typically calculated based on historical hydrocarbon production values[82]. The use of depleted reservoirs and legacy wells for geological sequestration provides higher certainty for carbon storage. However, leakage risks may be enhanced due to the presence of abandoned wells, and other physical impacts from past hydrocarbon extraction on the reservoir[83,84]. A recent study on Liverpool Bay highlights the technical and geological risks of using depleted gas fields for GCS[83].

- **Non-mineable coal beds:** carbon storage in this storage medium solely depends on sorption processes as a storage mechanism, and is influenced by coal permeability. Extensive characterisation before storage is thus required[78]. As such, this storage method is generally considered to be less suitable for large scale deployment than the alternatives.

- **Basalts:** igneous formations with geochemical and flow properties that allow the rapid ($\sim$1 year) conversion of injected CO_2 into stable carbonate minerals[85]. Basalt mineralisation is conducted alongside geothermal heat extraction, with CO_2 dissolved to around 10% concentration into water that is circulated at depths of $\sim$1000 m. Water usage and the need for specific chemical and flow properties in rocks make this storage method difficult to deploy universally. The CarbFix storage site in Iceland is currently the only functioning example of this method of GCS[86,87].

4.2 Storage capacity, injectivity and containment

The geographical location where GCS may suitably take place and the economic viability of a storage project depends on a variety of physical and techno-economic factors. Three criteria must be met when selecting a site for GCS, which can be determined at increasing scale and data resolution throughout the selection process: adequate storage capacity, injectivity (the rate at which CO_2 can be injected), and containment security[88]. UK storage site scoping follows guidance on site selection provided by the CCS Directive, the legal framework for geological carbon storage in the EU[89].

The storage capacity designates the volume of pore space that can store CO_2 (rock porosity and unit thickness) for a given site. Methods and standards for assessing the storage capacity have been developed, as reviewed by Bachu et al.[77] and Bradshaw et al.[90]. The injectivity depends on the rock permeability, the ability for a fluid to flow through a rock, which can naturally affect the pressure required to inject CO_2 into the reservoir unit[91]. The storage capacity and efficiency are affected by the injectivity. Pressure build-up from pre-existing sub-surface conditions or during injection could lead to insufficient storage capacity in a given storage site, due to low permeability or unexpected pressure build-up. Therefore, sufficient injectivity is a condition that must be met before conducting further site selection assessments[77,78], since the cost of abatement is highly sensitive to the accuracy of initial injection rate estimates[92,93]. The stability of the geological environment and the presence of other geological features (i.e., faults, hydrocarbon, potable groundwater) that could affect CO_2 migration or leakage should also be assessed to ensure CO_2 containment[88].

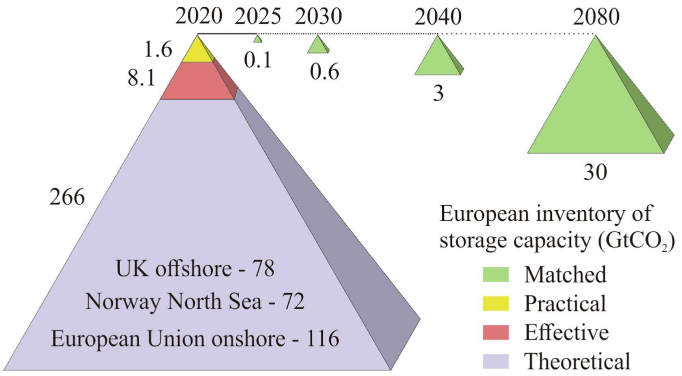

Figure 4.2: Resource pyramid of CO_2 storage capacity ($GtCO_2$) in Europe, showing four levels of techno-economic viability with forecasted matched capacity, as per terminology used by the Carbon Sequestration Leadership Forum: 1) Theoretical: unrealistic regional approximation, 2) Effective: estimates from prospective and exploration sites, 3) Practical: estimates from mature prospective and candidate sites, 4) Matched: storage sites with economically viable capacity for CO_2 injection. Reproduced from Sun et al.[94], citing Cavanagh et al.[95].

Given that the UK continental shelf is well characterised as a result of historical oil and gas extraction, GCS development and storage capacity assessments have been primarily focused offshore[96]. CO_2 storage capacity can be viewed like any other geological resource. The techno-economic resource pyramid provides a categorisation of the storage capacity as four parts associated with higher levels of geological and economic certainty (Fig. 4.2)[90].

4.3 Offshore GCS

Offshore storage capacities are provided by CO2Stored, the UK's primary data repository on offshore storage[97]. The database identifies 579 units, comprised of 361 deep saline aquifer prospects and 218 depleted hydrocarbon field prospects[95]. Research from the Strategic Appraisal Project by the Energy Technologies Institute (ETI) and Front-End Engineering and Design studies further developed the portfolio of prospective sites provided by CO2Stored[95,96]. The total theoretical storage capacity for the UK was estimated to be 78 $GtCO_2$, with most being from deep saline aquifers[97]. Although the theoretical storage capacity greatly exceeds the UK's current emissions (331.5 $MtCO_2$pa[98]), it is an unrealistically optimistic estimate that assumes that all pore volume is available for storage[99]. Furthermore, the theoretical storage capacity would still be insufficient in sequestering the UK's historical emissions (78.51 $GtCO_2$ since 1750 as of 2021) if the country's total contribution to global warming were to be reversed with geological CDR[100].

The effective and practical storage capacity represent more realistic quantities constrained by geological and engineering limitations[95]. The UK's total effective capacity amounts to 8 $GtCO_2$ from 37 prospective sites. The UK practical capacity was estimated to amount to 1.6 $GtCO_2$ by 2070, with injection rates of 50 $MtCO_2$/yr[96]. The practical capacity is associated with 5 mature candidate storage sites (Viking, Captain X, Forties, Bunter, and Hamilton) identified by ETI and 3 pre-existing sites (Goldeneye, Hewett, Endurance)[96]. Although theoretical CO_2 storage capacity estimates greatly exceed the UK's annual emissions, the practical CO_2 storage capacity is much lower. As underlined by Lane et al.[27], the availability of usable storage space may be constrained by challenges in scaling up and competition for storage space between individual CO_2 emitters. In addition to higher uncertainties and risks, this issue would be further exacerbated for dispersed sites, as they will have to compete with sites within clusters for GCS access. A map of offshore hydrocarbon fields, current sites licensed for CCS, and the location of ports and terminals which act or could act as CO_2 transport hubs are shown in Fig. 4.3.

4.4 Onshore GCS

The potential of onshore GCS remains an underexplored subject, as no formal site prospecting or assessments on the onshore storage capacity have been conducted. Holloway et al.[101] is one of the few publicly-available works that identifies onshore areas with theoretical CO_2 storage potential, from which the authors determined that the onshore storage capacity was too small and was not quantified. This work designated the Wytch Farm oil fields in Dorset and the Saltfleetby gas fields in Lincolnshire as hydrocarbon fields with storage potential due to their large hydrocarbon production size, as other hydrocarbon fields were deemed too small (originally containing <100 million barrels) to have significant CO_2 storage capacity. It should be noted that emissions from many individual point-sources that could deploy CCS shown in Section 3 emit much smaller equivalent volumes of CO_2.

Holloway et al.[101] further states that UK onshore gas fields would store 5 $MtCO_2$ at most, and would realistically only be used as demonstration sites for GCS, as gas infrastructure has already been built for production, meaning that most onshore gas fields would not be available for CO_2 storage.

The CO_2 storage potential in onshore deep saline aquifers was based solely on broad-scale lithological assessments[101]. Geological formations such as the Lower Greensand, Portland Sand, Sherwood Sandstone and Permian sandstones were determined to be the onshore formations with sufficient porosity and permeability for GCS (Fig. 4.4). The study does not consider the structural geology that is necessary for secure storage, due to the lack of onshore seismic data required to identify structural and stratigraphic traps. As such, onshore wells and offshore wells are shown in Fig. 4.5 as a proxy to the approximate locations of prospective areas for onshore GCS. The location of onshore and offshore wells broadly aligns with the location of hydrocarbon fields and saline aquifers.

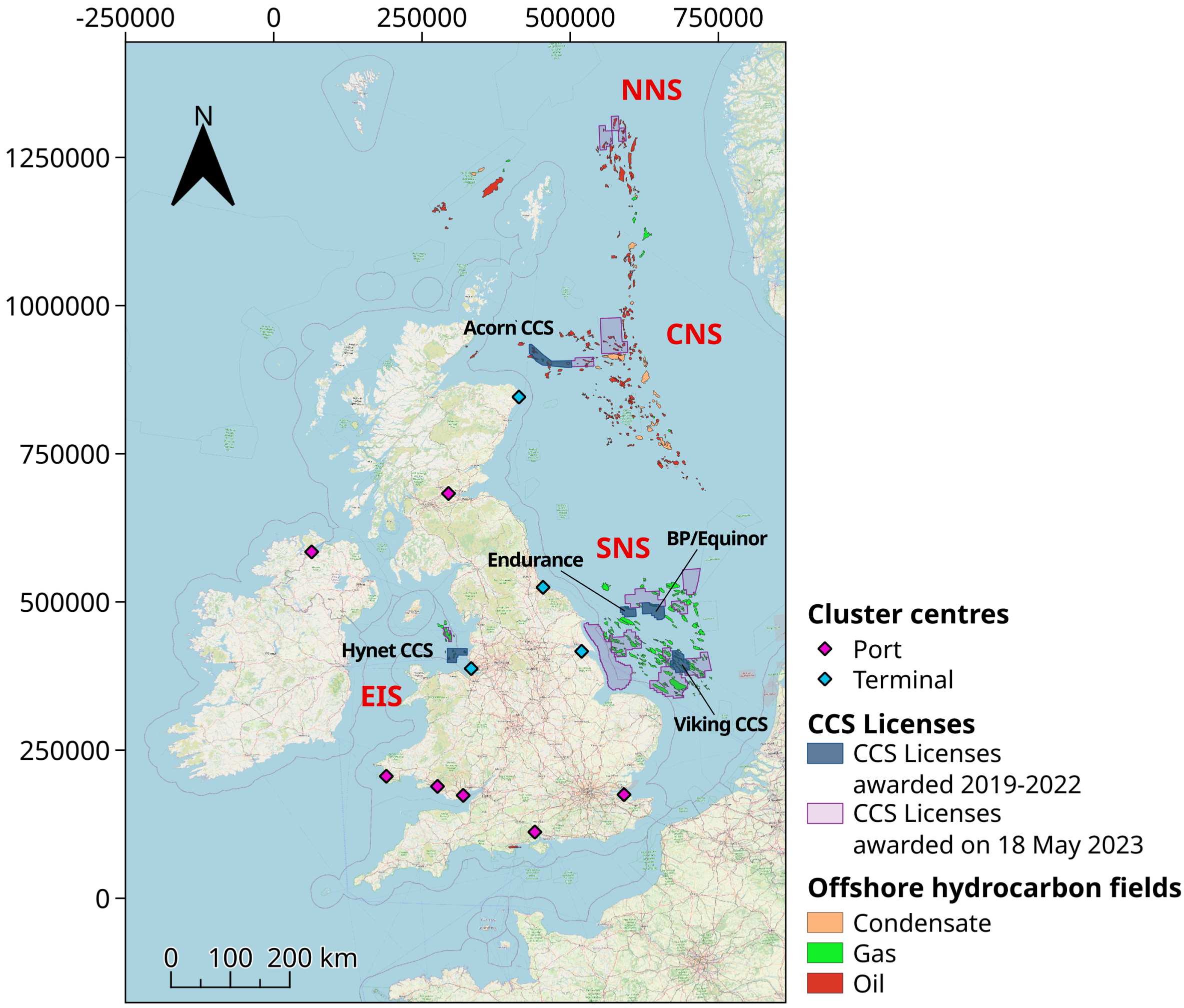

Figure 4.3: UK areas licensed for offshore GCS with cluster centres and hydrocarbon fields. Cluster centres were sourced from the Net Zero Industry Pathway (N-ZIP) model published by the CCC[54]. NNS: Northern North Sea, CNS: Central North Sea, SNS: Southern North Sea, EIS: Eastern Irish Sea. CCS licensing areas and hydrocarbon fields reproduced from NSTA[102–105]. Contains data licensed under OGA Open User License.

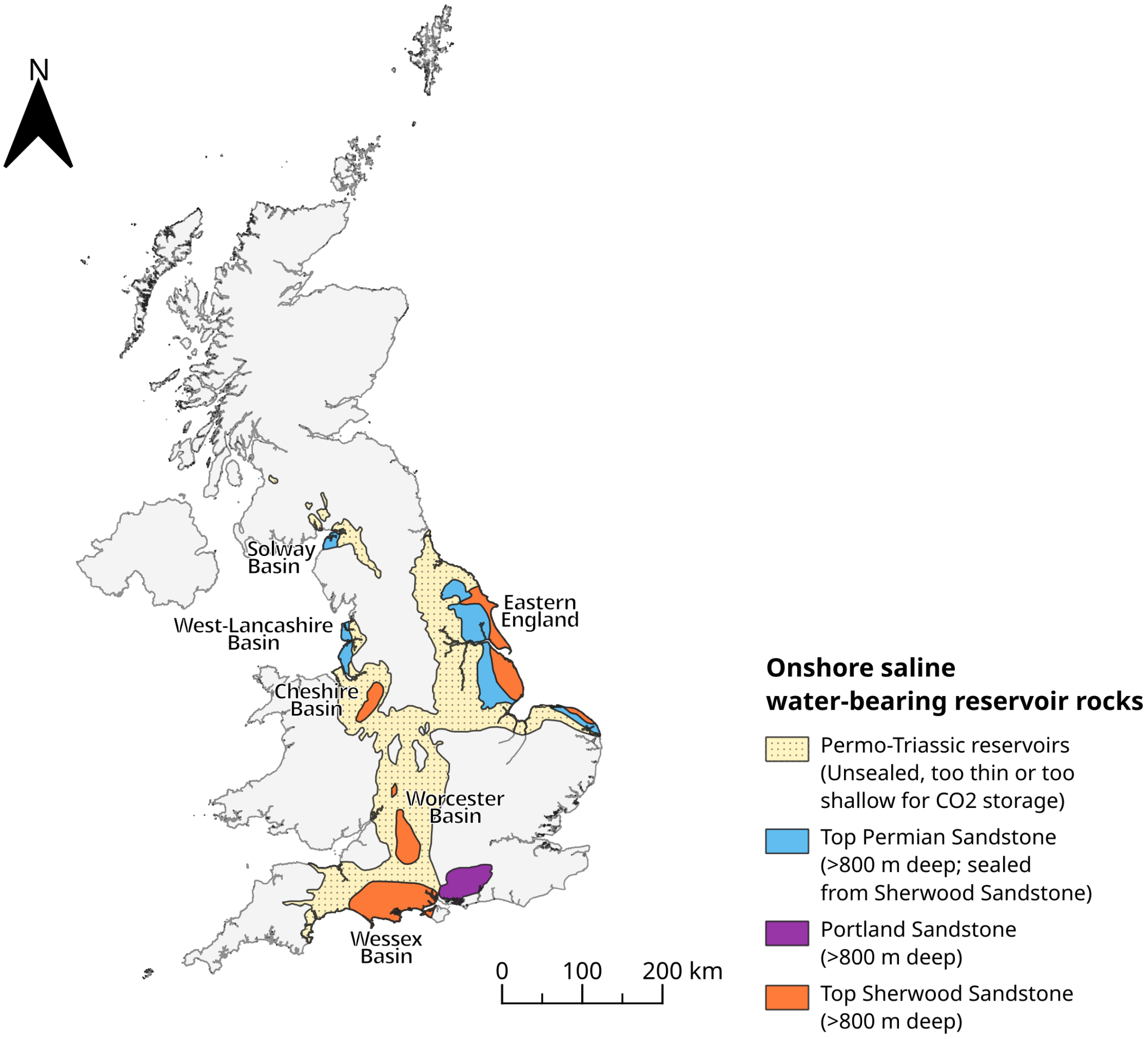

Figure 4.4: UK onshore areas with saline water-bearing reservoir rocks with theoretical CO_2 storage potential. Theoretical CO_2 storage potential is based on a lithological outlook only (i.e., porosity and permeability). The structural geology required for secure storage is not taken into consideration due to the absence of adequate data. Georeferenced from Holloway et al.[101].

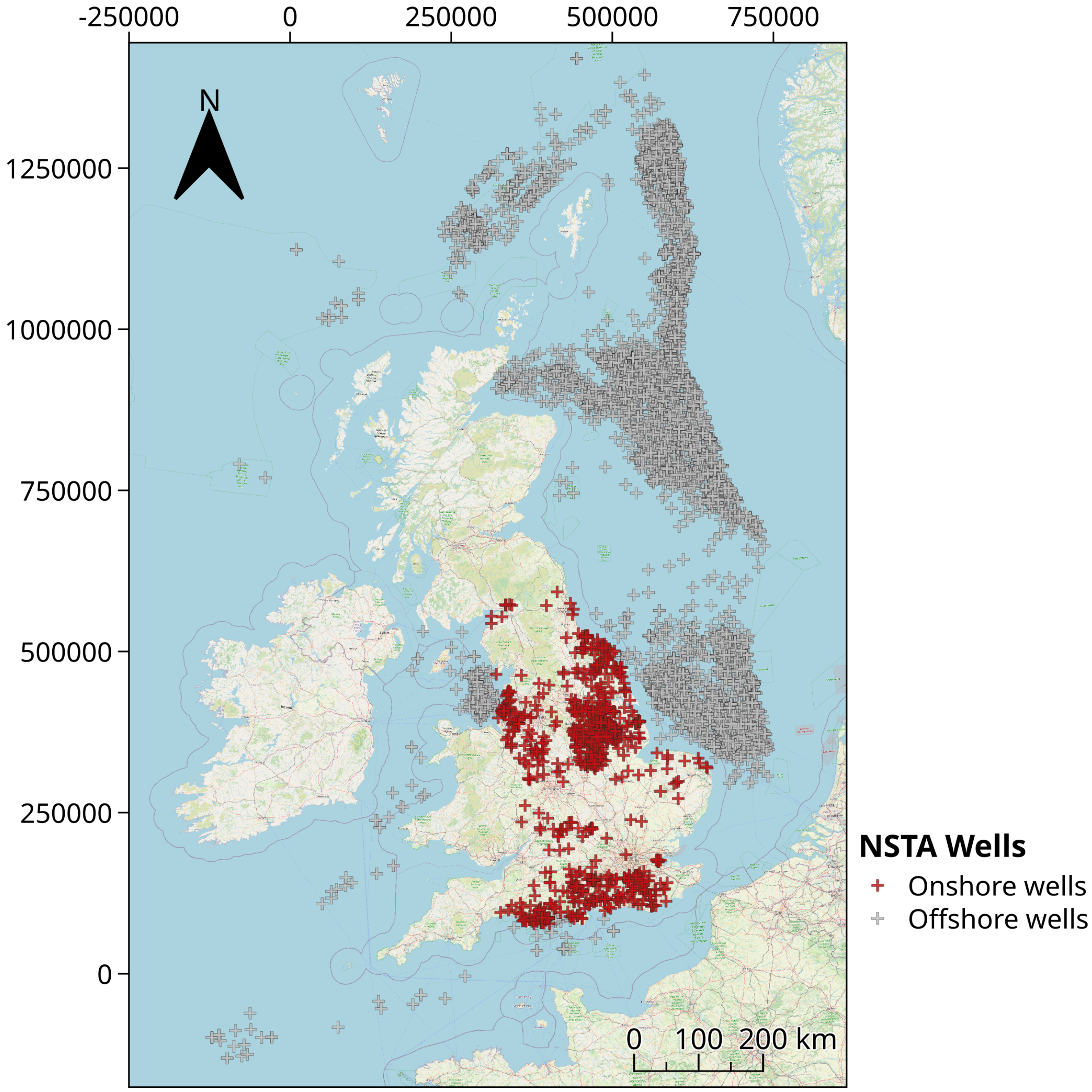

Figure 4.5: Onshore and offshore wells acting as analogues of prospective areas for potential CO_2 storage. Well data reproduced from NSTA[106,107]. Contains data licensed under OGA Open User License.

Policy and regulations

5.1 UK governance

The UK is composed of 4 separate jurisdictions, each with their own climate targets and industry decarbonisation targets.[108]. Devolved administrations are likely to control the final stages of planning approval, environmental impact assessment, environmental policy, and halt a project if the UK government is deemed to overstep its power following the Scotland Act 1998, the Northern Ireland Act 1998, and the Government of Wales Act 1998. Pursuant to the Wales Act 2017, and the Scotland Act 2016, onshore GCS is a ’reserved matter’[109]. This means the U.K. government cannot intervene without reneging commitments under the Sewel Convention and the original devolution Acts. This may have considerable political ramifications. The priority of devolved versus central legislation is an active area of jurisprudence debate. This makes the legislative environment more complex because jurisdictions can choose whether to accept central UK legislation[110]. Coordination by central UK government may be required to ensure proper oversight of planning regimes, and land management trade-offs with storage, pipelines, and CO_2 transport hubs; again, this may have considerable political ramifications. These organisational complexities potentially hinder the ability of the responsible government department – Energy Security and Net Zero (DESNZ) - to co-ordinate planning, licensing, and permitting for onshore GCS. There has been a rapid development of CCS incentives, in an attempt to kickstart the industry. However, the regulatory complexities could be jeopardising the ability of companies to build and operate GCS facilities swiftly and effectively.

In the UK, the North Sea Transition Authority (NSTA) governs offshore GCS storage, granting licences and permits for CO_2 injection. There is no licensing body, regulator, or relevant authority for onshore CO_2 storage in the UK. This policy gap naturally acts to limit the UK-specific development of onshore GCS, for which the different parts of the GCS licensing, permitting, and monitoring, reporting and verification (MRV) processes are housed in different government departments. The NSTA’s responsibility for onshore CO_2 storage are less certain and more diffuse. For onshore GCS, this may extend to over 20 different governmental agencies and public bodies. For example, executive non-departmental public bodies like the NSTA, Environment Agency, Natural England, and National Park authorities all have mandates for climate change and environmental protection, and so in theory could retain some oversight over the permitting of onshore GCS.

The UK deployment of GCS is compartmentalised, operating in regional monopolies around government-designated "clusters" that currently only regulate offshore storage[111].

Therefore, much of the policy work has solely focused on the challenges of implementing this cluster-driven approach to CCS infrastructure development. As such, onshore GCS is not an attractive option in the UK from a policy perspective for the following reasons: there is no comprehensive regulatory framework in place; the government does not currently view onshore GCS as having a use-case for regulation; the legacy of public opposition to hydraulic fracturing; the potential public opposition to onshore as opposed to offshore GCS; and the cost of planning permissions and land is potentially high. Key legislations governing the UK CCS industry – not just GCS – are shown in Box 5.1[112]:

Box 5.1: Key legislation for GCS in the UK

Key primary legislation:
Energy Act 2008; Energy Act 2010; Energy Act 2011; Energy Act 2013; Energy Act 2023

Subordinate legislation:
Energy Act 2008 (Consequential Modifications) (Offshore Environmental Protection) Order 2010/1513
Storage of Carbon Dioxide (Licensing, etc.) Regulations 2010/2221
Storage of Carbon Dioxide (Inspections, etc.) Regulations 2012/461
Storage of Carbon Dioxide (Termination of Licences) Regulations 2011/1483
Storage of Carbon Dioxide (Access to Infrastructure) Regulations 2011/2305
Carbon Capture Readiness (Electricity Generating Stations) Regulations 2013/2696

5.2 UK legislation

There are two types of legislation governing GCS: primary (i.e., acts of parliament) and secondary. Secondary legislation arises from powers conferred by primary legislation (or the parent act) and are referred to as statutory instruments (SIs). SIs incorporate regulations, rules, and orders. Ministers of state and government departments introduce secondary legislation provided it is within their power to do so and consistent with primary legislation. Together, the legislation shown in Box 5.1 govern licensing and planning responsibilities of the relevant authorities. However, all present legislation is orientated towards offshore rather than onshore GCS. This legislation make considerations of timescales, enforcement mechanisms, and other key details governing the CCS industry. As this is a nascent yet vital industry, this is a dynamic policy environment where legislation is still being augmented, interpreted, and enforced in different ways. Therefore, regulators and operators are defining operating practises under a needs-case basis as they licence and permit CO_2 storage projects.

The Climate Change Act (CCA) 2008 also needs to be considered, as it provides a "long-term framework for climate change policy in the UK"[113]. This means that future Energy Acts and GCS legislation need to comply with the emissions reductions targets stipulated in the CCA. The CCA makes UK emissions reductions targets legally binding, with an "80% reduction in GHG levels (below 1990) by 2050" (Climate Change Act 2008). The June 2019 amendment, the Climate Change Act 2008 (2050 Target Amendment) Order 2019 (SI 2019/1056) updated the target to a 100% reduction in GHG emissions by 2050. This Act is essential because it binds the GCS industry commitments in order to achieve net-zero by 2050. Given the climate concern of the UK population[114], and the context of the Glasgow Climate Pact, where signatory countries agreed to accelerate the phase out coal production and use[115], UK GCS legislation could be more explicitly orientated towards GHG mitigation. Legislation enshrining the polluter pays principle (PPP) on heavily-polluting industries could improve both the government's environmental credibility and reduce government environmental spending[116]. However, it is not clear what will be the focus of policy development in the coming years. This gap in policy and the uncertainty of the direction of policy is a key obstacle in the deployment of onshore GCS.

5.3 EU legislation and UK impacts

Although EU law must be enacted into UK law by an Act of Parliament, EU regulations form a considerable portion of the UK GCS legislative regime. Principally, the EU Directive on the Geological Storage of Carbon Dioxide 2009/31/EC applies to member states' onshore territory, offshore European Economic Area, and continental shelf[117]. This directive amended several EU laws for onshore and offshore GCS[118]. Consequently, the UK has fewer onshore GCS laws than the EU[119]. Moreover, the Retained EU Law (Revocation and Reform) Act 2023 "sunset[s]... EU-derived subordinate legislation and retained direct EU legislation"[120] and in essence revokes and amends the above EU regulations for GCS in the UK.

There are ongoing developments to the EU landscape. The EU CCS Directive is the legal framework guiding the CCS value chain, and the EU commission are re-considering the CCS Directive in relation to updated commitments by EU member states. Additionally, the EU Commission is developing GHG accounting regulation for CCS and attempting to bring the EU legislation and regulation in line with international GHG accounting[121] and emissions trading schemes. This requires reform because current GHG accounting (the "reporting") rules by private institutions, notably corporations, are incompatible with how countries currently account for emissions in their GHG inventories in the EU[122].

The EU is currently attempting to solve these carbon accounting challenges. They are proposing a framework for certifying carbon removal offsets called the EU carbon removal certification Framework (EU CRCF)[123]. This aims to set standards to account for the permanence of CO_2 storage, life-cycle emissions and other MRV issues. Currently, the UK government is not conducting similar reforms. It is likely that the UK may go through a subsequent review of its GCS legislation after the EU reforms are complete, in order to integrate and comply with the new European legislation. This further emphasises the dynamic nature of UK carbon storage policy.

5.4 Considerations for UK future policy

Box 5.2: Key UK policy reports related to CCS and GCS

"Ten Point Plan for a Green Industrial Revolution" published November 2020[124]
"Industrial Decarbonisation Strategy" (IDS) published March 2021[50]
"Net Zero Strategy: Build Back Greener" published October 2021[125]

5.4.1 Monitoring, reporting, and verification

MRV is critical to establish public trust in CCS technologies and their governance, by ensuring that companies are operating with integrity, and enabling verifiable carbon emissions accounting[126]. There are currently no national MRV standards for onshore CDR and CCS in the UK, although the Task and Finish Group report commissioned by BEIS has outlined policy recommendations on the function of a UK MRV regulator[127]. CCS and CDR technologies are heterogeneous, and so MRV standards will have to account for a wide range of CCS and CDR methods, as well as translate mitigations and removals into pre-existing carbon accounting frameworks and economic regimes. A voluntary regulatory MRV framework for CDR is currently under proposal by the European Commission[128]. It is unclear how this will affect current plans for offshore GCS.

5.4.2 Climate policy and decarbonisation

There is a lack of coordination with regard to climate policy and ambitions to deploy CCS. The UK government published 3 key policy reports on CCS and GCS (Box 5.2). The "Net Zero Strategy" assesses CCS in relation to decarbonising industries, although it does not explicitly focus on climate mitigation and stabilising atmospheric CO_2 emissions[125]. Action on climate change and CCS are inherently linked and thus should be coupled, both in the implementation of climate policies and in political rhetorics to communicate a consistent, effective pathway to net zero by 2050. CDR as a whole is also under-developed in the UK, falling behind targets in several areas[129].

Public perceptions and acceptance

A successful CO_2 storage project will need to have a social licence to operate, something which has proved challenging for some (although not all) onshore storage projects in other countries in the past. Obtaining public support is crucial for the ethical and effective development of new technologies. However, the circumstances in which public support can be gained are also highly context-dependent, varying from place to place and depending on cultural, political, and social factors. One aspect of this challenge is that these onshore GCS could be perceived as allowing large polluters to "dump" waste CO_2 on other, distant communities. Public acceptance has proved difficult in a few high-profile onshore cases ending in project cancellation, notably in the Netherlands and Germany[130,131]. Although there are also a number of successful cases which can provide lessons for communication and engagement approaches.

6.1 Geological carbon storage

The geological storage of CO_2, whether onshore or offshore, is perceived amongst the other aspects in the wider CCS chain. Schumann et al.[132] found the storage component to be more contentious and perceived more negatively than the capture and transport of CO_2. Perceptions of geological storage are also inherently related to climate change and the climate concern of the respondents. As such, some respondents demonstrated support on the condition that it is part of a portfolio of climate measures[133,134]. Public awareness and understanding of CCS is low across Europe[135]. In the Netherlands, Huijts found the public to have little knowledge of CO_2 storage and little interest in finding out more[136].

The perception of personal and societal risks and benefits is deemed a critical factor in determining public attitudes and acceptability of CO_2 pipelines and storage[132]. It is so foundational that Sharp et al.[137] concluded that public opposition should be interpreted as concern over risks rather than fundamental opposition. In the UK, ripple effects from the risk perception of fracking were found to impact the public's view of carbon removal more widely[138]. The authors found a discourse surrounding the narrative of "*but they told us it was safe*" which points to the loss of trust in governing bodies over the safety of fracking, which then ripples over to perceptions of CO_2 storage, as both involve operations in the subsurface.

Shackley et al.[134] found that the provision of reliable information can decrease risk perception, compared to the case where no information is provided. This was demonstrated through a comparison of the results of an initial questionnaire which found the leakage risk to be a major concern and a panel where additional information was provided, which lessened concerns over leakage risks[134]. However, a new meta-analysis has found that providing information about safety measures and monitoring may have a negative impact on public acceptance[139]. Other significant factors in the literature affecting public opinion include regulatory and legal uncertainty[118,133,134,140,141], trust in governing bodies, which is increased with the aforementioned certainty in regulatory and legal factors[133]. The assessment of public perceptions and acceptance must always be understood in relation to the place history and social context of the area studied, and not just reflect a purely techno-scientific assessment and communication of risks[142].

Box 6.1: Likely determinants of public opinion

Distance from people[136,141,143]
Communication and media response[134,137]
Ecological impacts[133,142]
Nationality of emissions and storage[144]
Societal and personal risks and leakage[132,140,142,145]
Societal and climatic opportunities[133,137,140–142]
Trust in governing bodies[133,136,140,145,146]
Uncertainties in regulatory and technical landscape[118,133,134,140,141]
Climate concern and associated policy[133,134,137,144]
Place history and wider social context[118,134,142]

6.2 Onshore and offshore

Few studies have analysed the perceptions of GCS alone, and even fewer have looked at the comparative differences between offshore and onshore GCS. Due to findings from analogous energy technologies depicting siting controversies as dependent on the proximity to people and communities[147], and a few high-profile onshore cases facing public opposition, industry attention and research has tended to focus on offshore storage alone. This is based on assumptions that it will be easier to garner public support and prevent the risk of project cancellation. While offshore storage may reduce some of the sources of public opposition seen onshore, there still remains significant risks and a need for adequate societal engagement.

Mabon, Shackley, and Bower-Bir[118] and Cox, Spence, and Pidgeon[114] both found that offshore GCS is not necessarily preferred to onshore GCS in the UK. Schumann et al.[132] found no difference in the overall perception of onshore and offshore storage in Germany

- concluding that both are hardly accepted. Similar results were again found in Germany and Norway by Merk et al.[144]. The authors argue that while there is no difference between onshore and offshore storage in either country, there is a disparity of perception over the nationality of where emissions are sourced, and where it is stored. While Norway is more open to CCS, the amount of positive responses dropped from 81% to 42% when Germany was the source country and with Norway as the storage country. Germany was not affected by this experimental manipulation[144]. Although the majority of studies find no significant differences in the preference and acceptance of onshore compared to offshore, Schumann et al.[132] found that the risk to people and society was perceived to be greater onshore. Similar findings were observed in the work of Terwal and Daamen[148], as respondents attached greater weight to the risks imposed on public safety when the proposed project was in their local area. Conversely, local safety became a lower priority to respondents when the project was located elsewhere.

The distance to people is widely researched to understand its capacity for influencing public acceptance. Huijts et al.[136] argues that public acceptance will be largely determined by the geographical distance to the planned facility. Using a within-subjects approach (posing two different scenarios to the same participants), the authors observed spatial effects due to the differential responses to GCS deployment when described generally (positive), or in their own residential area (negative). However, Terwel et al.[145] argues this approach can cause contrast effects. Another between-subjects study by Terwal and Daamen[148] observed no spatial effects (one condition contained two gas fields somewhere else; another contained two gas fields, with one in the local area). They also found that protest inclination did not differ between the two experimental conditions, which is a better measure of spatial effects than traditional social acceptance measures[145]. In Germany, Braun[141] found lower acceptance rates in areas that are close to potential CCS sites, while in Japan, public support of CCS faltered when discussing locally-situated CCS projects as compared to general deployment[143].

In studies regarding offshore or subsea carbon storage, differing deterministic factors emerge for public perceptions and perceived acceptance. Due to the low public awareness and knowledge of CCS in Sweden, Stigson et al.[133] used the O&G pipeline projects Nord Stream, SwePol Link, and OPAB as a proxy for predicting perceptions of GCS in the Baltic Sea. They found that there were significant concerns from fishing and shipping industries, and while they were not significant enough to cause the cancellation of a project proposal, they were recognised by developers and reconciled through monetary compensation[133]. Stigson et al.[133] argues that the ecological impacts in a marine environment perceived as 'precarious' are likely to be significant in the planning of offshore GCS. These factors were also observed in Scotland by Mabon et al.[118] - with one respondent quoted: “There are some studies that say we would basically completely acidify the sea if it leaked”.

Mabon et al.[118] argues that a greater awareness on the importance of place, history and social context should be embedded in work on public perceptions and acceptance. The history of offshore activities in the North Sea mean that CCS is viewed as one development of many in a long history of marine development and one which, in its infancy, is not a major concern[118]. The concern over the associated risks of leakage to the marine environment was also found to be present in a UK study by Shackley et al.[134] who argued that the role of communication and the media is of critical importance to public acceptance. This was demonstrated in the case of the Brent Spar platform, whereby Greenpeace labelled it as unacceptably dangerous and convinced the media and the public that it was setting a precedent for waste disposal in ocean environments[134].

Box 6.2: Barendrecht, Netherlands

In 2006, Shell Storage B.V. started plans for an onshore CCS project in two depleted gas fields under the town. Shell informed the Municipal government in 2007 and led public engagement in 2008. The Local Government then stated their opposition to the project while the National Government supported the project development. In mid-2009, citizens formed an activist group called "Stichting CO2 ist nee" ('CO_2 is no') and the national government published three reports addressing possible alternative locations, safety, and the psychosomatic impacts of the project, based on the primary concerns of the municipality and the public. The project was running two years behind schedule at the end of 2009. In 2010, the Dutch Government shelved the project, citing public opposition as the main reason[130,131,149].

Main concerns: other locations were not initially considered properly; first onshore CCS project placed in a densely populated area; legal frameworks and safety of monitoring the stored CO_2; impact on property prices; unfairness of government funding deviating from ‘the polluter pays’ principle[130,131].

Lessons: contextualise CCS in a portfolio of climate solutions; engage and grant agency to stakeholders and the public as early on as possible; be transparent over costs and benefits and build trust before communication[130,131]. Project developers and local and national permitting authorities should familiarise themselves with previous cases of successful and unsuccessful deployment, so that lessons can be learnt. It is notable that many of the problems of the Barendrecht controversy were repeated in the UK just 5 years later, with fracking.

Cost and economics

7.1 Estimated costs of onshore and offshore GCS

The following examples are based on projects utilising a $\sim$2000 m deep injection well. The cost estimates do not include the legal and social engagement expenses, the costs of exploration licensing, 3D seismic assessment, and operational costs including CO_2 capture and transport[150].

7.1.1 Onshore UK drilling

Over the past century, hundreds of wells have been drilled in onshore UK basins primarily for hydrocarbon exploration, development, production, and geothermal exploration. To date, no wells have been drilled onshore for GCS. As is the case for offshore GCS, licenses for exploration, drilling, development and injection are individually required if onshore prospecting were to be conducted. The regulatory and approval process for onshore storage is likely to involve extensive public consultations. This means that the development of a GCS project could have long lead times (+5 years)[151]. At present, there is no licensing or permitting framework for onshore carbon storage (see Chapter 5). The process of acquiring these licences and permits naturally adds significant costs to a project, and it is not known exactly how much this would add to the cost of an onshore development.

A detailed well plan and costing is outside the scope of this report, however basic costs can be assessed from inactive and currently operating wells. The following cost estimates are based on discussions with operators who are currently active in the UK. The most significant costs are associated with the following categories: initial setup costs; operational costs maintenance and environmental considerations; operating considerations; community engagement, impact, and land use; and technological requirements. It is estimated that an onshore well would cost around $\sim$£7-8m to construct[150]. This includes a contingent amount of around £1m for CO_2 injection equipment and testing.

7.1.2 Offshore UK Drilling

There is an offshore GCS licensing and permitting system in the UK (see Chapter 5) which enables development of offshore GCS. Storage operators predominantly comprise of existing energy companies, such as BP, and to a lesser extent new commercial storage-focused companies, such as Storegga. Thousands of wells have been drilled on the UK continental shelf for oil and gas exploration and production. Offshore drilling requires an offshore exploration licence, exploration permit, drilling licence, and drilling permit. This permitting and licensing process is not as protracted as the onshore process because the public engagements requirements are less stringent.

An offshore well could cost around $\sim$£12-15 million. These costs include operational and logistical expenses; environmental impact considerations; operating considerations (regulatory challenges, technological requirements); regulatory, technological, and safety requirements (coring, injectivity tests, CO_2 reactivity tests; and environmental protection measures. This means that it is likely over 50% cheaper to drill onshore rather than offshore[150]. However, as stated, this does not capture the costs required to licence and permit an onshore well, or the more extensive public consultations that would be required to gain social licence to operate. These are currently unknown, and are a significant source of uncertainty in the above costs.

There are other non-financial considerations to both onshore and offshore drilling. Direct well drilling costs are only one part. Skills and management are paramount. Drilling efficient wells into safe, effective traps and linking them to a capture, transport, injection, and storage system is a very significant engineering and logistic challenge. There are very few UK operators with experience. If this is to be explored further, partnerships with suitably experienced groups should be considered as the most efficient route.

7.1.3 Case study: Quest CCS project, Canada

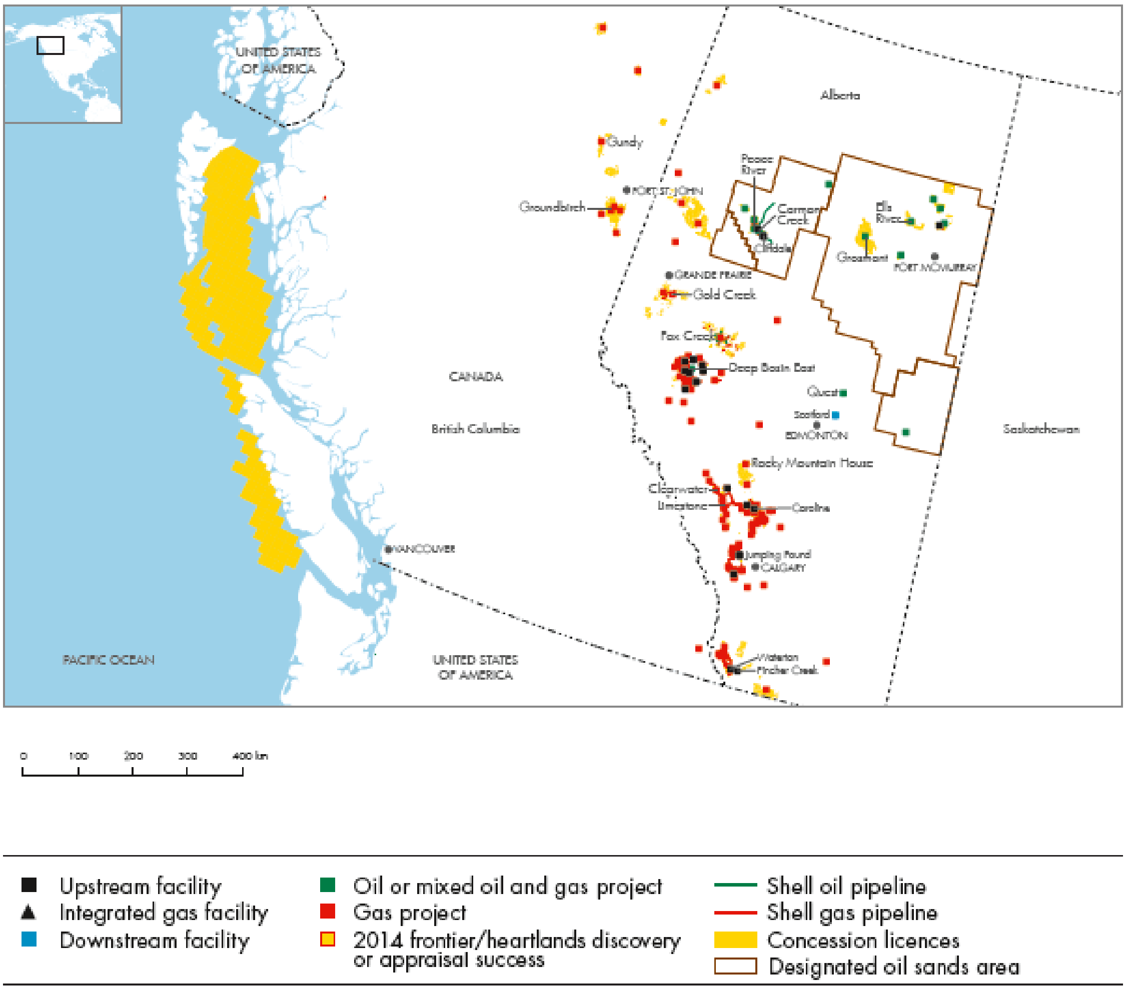

Figure 7.1: Map of the Quest CCS project in Alberta, Canada. Image reproduced from Shell[152]

The Quest CCS project, operated by Shell Canada, has stored around 1 $MtCO_2$ per year since it began operations in 2015, and cumulatively has stored 6.8 $MtCO_2$. Quest captures CO_2 from a bitumen upgrader, oil refinery, and chemical plant. The operating costs averaged \$66.50-\$88.50/tCO_2, with capture being \$60-80/tCO_2, transport \$0.5/tCO_2, and storage \$6-8/tCO_2 (including regulatory costs, and monitoring, reporting, and verification). The total costs, including capital costs, averages to \$130-150\$/tCO_2, with capture being \$110/tCO_2, transport \$10/tCO_2, and storage \$15/tCO_2[153]. The cost per tonne of avoided emissions (i.e. net CO_2 draw-down) is \$160/tCO_2 avoided.

The operating costs averaged \$66.50-\$88.50/tCO_2, with capture costs equating \$60-80/tCO_2, transport \$0.5/tCO_2, and storage \$6-8/tCO_2. The total costs, including capital costs, averages to \$130-150\$/tCO_2, with capture being \$110/tCO_2, transport \$10/tCO_2, and storage \$15/tCO_2[153]. These figures equate to OPEX comprising 51.1-59% of total costs.

The breakdown of OPEX as a percentage of total costs is: capture equates to 54.5-72.7% ; transport equates to 5%; storage equates to 40-53.3% of total costs. Learnings from the QUEST project have shown that CO_2 capture will represent the bulk of its OPEX. Funding models will have to be developed and tailored for a UK-specific context if onshore GCS were to be conducted. Deployment and operating costs could potentially be higher in the UK as monitoring, reporting and verification requirements may be much higher than in Canada's regulatory environment. Public consultations, financial planning and rigorous measurement, monitoring and verification measures are likely to be extensive as there is no precedence to onshore GCS in the UK.

7.2 Financing options

The total costs of an onshore GCS remain uncertain and politically sensitive. The costs of a CCS project are dependent on the type of CCS (point source capture, BECCS, or DACCS), the capture process technology, transport method, and storage location. The economic viability of onshore storage projects are often questioned in public discourse[114], as CCS projects currently rely on financial support from governments in the form of subsidies, low-interest loans, or contracts for difference.

The UK Government and DESNZ published the CCS Investment Road-map in April 2023[154]. This document outlines government plans to address CCS investment barriers and develop the market that could lead to a self sustaining CCS industry. However, this road-map is a high level overview, and provides no specific investment mechanisms or explicit plans to address the investment gap for CCS in the UK. The UK currently uses subsidies and direct government financing to stimulate the CCS industry. The UK government has warned investors and companies that these subsidies will taper off over the next 15 years[154]. Using this financing model, companies are able to gradually plan and adapt to changes, as the CCS industry develops. The UK government acknowledges that long-term subsidies are not financially viable, and detrimental to public spending. As a result, consultations are currently ongoing to pursue alternative modes of funding.

One possible solution may be derived from the US model. The US uses a tax alleviation model that provides subsidies to verified removals[155]. Under this system, operators only receive subsidies once CO_2 emissions are removed and verified. Other solutions to the investment gap may come from removals markets or voluntary carbon markets (VCM), however these markets are generally unstable, poorly regulated[156], or too small to be a viable long-term solution for the large costs associated with CCS[157].

Discussion and research gaps

8.1 Technical and geological viability

Relying exclusively on offshore GCS is associated with significant limitations. Dispersed sites, located at a significant distance from industrial clusters or transport hubs, may face difficulties in connecting to the infrastructure necessary for transporting and storing captured CO_2[52]. 136 industrial sites belonging in sectors with CCS potential, representing $\sim$8.64% of total point source emissions, would be unable to access CO_2 T&S infrastructure even if it were to be extensively implemented at a disproportionate distance of 100 km from industrial clusters (Table 3.1). The potential reduction in CO_2 transport distance from point sources through the use of onshore GCS could improve access to CCS for dispersed sites as an abatement option. Additionally, onshore GCS could enable a more localised approach to emissions management, and stimulate local economies[28].

Furthermore, hard-to-abate sectors such as the UK aviation sector are unlikely to fully decarbonise through emissions reductions alone. The Jet Zero government public consultation has shown that CDR will be necessary, with offsetting being a mechanism enabling its use. The Fly Zero technical report has shown that the TRLs for sustainable aviation fuels are still at demonstration phases and won't enter commercial-use until the 2030s[158,159]. Since GCS development in the UK is largely tied to CCS in the UK, synergies between DACCS and BECCS with CCS should be further explored as hard-to-decarbonise sectors such as aviation would require GCS to achieve a durable decarbonisation. Sacchi et al.[76] further underlines that demand reduction, climate neutral jet fuels, and CDR will all be needed to durably decarbonise the aviation sector. The authors highlight that CO_2 storage capacity may be a limited resource due to scale-up constraints and competition for storage space. Given our results, this competition may occur between dispersed point sources, distributed sources of emissions in hard-to-abate sectors (i.e., aviation) and point sources at industrial clusters. Implementing CDR with onshore GCS to offset emissions from the aviation sector, even at small-scale, could ease competition for offshore CO_2 storage space. However, demand-side reductions will remain essential, as offsetting the climate impacts of aviation would require substantial resource use[76].

Based on assessments by Holloway et al.[101], hydrocarbon fields could serve as readily-available small-scale onshore storage sites. However, the availability and safety of hydrocarbon fields remain to be determined. In the case of natural gas fields, underground reservoirs and infrastructure may already be developed for natural gas storage[101]. In addition, the use of saline aquifers for onshore storage would require further research as stratigraphic traps were not considered in their analysis. Given that recent work on the use of legacy wells in Liverpool Bay for offshore GCS highlighted the issue of CO_2 leakage, the use of onshore depleted hydrocarbon fields may encounter the same problem[83].

The risks of fault reactivation and induced seismicity are greater in an onshore setting when compared to the offshore, and thus come with increased monitoring requirements. This is due to higher risks and greater proximity of GCS operations from population centres[160]. CO_2 leakage from storage sites are risks that are not unique to onshore GCS[84]. Findings from the European Zero Emissions Platform concluded that high rates of CO_2 leakage to the sea floor are highly unlikely and would be highly localised, as the CO_2 would be trapped in the subsurface or dissolved in waters before reaching the seafloor. Marine ecosystems are also resilient to CO_2 fluctuations[161]. In contrast to offshore GCS, onshore GCS does not have the ocean to act as a "buffer" that prevents CO_2 from being re-emitted into the atmosphere[162]. Environmental baseline studies, comprehensive risk assessment schemes and long-term monitoring plans will have to be implemented to ensure the safety of operations if onshore GCS were to be conducted[163].

Due to varying risk profiles, trade-offs between onshore and offshore GCS should be further explored. Opting for onshore GCS could benefit from reduced transport distance and lower transport risks[28]. Risks associated with onshore GCS site decommissioning should also be accounted for, considering that the decommissioning regime for T&S infrastructure developed by the government are separated between onshore and offshore contexts[164,165]. Assuming that CO_2 streams would be primarily transported using pipelines due to its cost-effectiveness[52], the deployment of an extensive onshore CO_2 pipeline network to access offshore GCS sites requires the effective management of transport risks along the pipeline. This would involve managing the pipeline flow rate, the presence of impurities in the CO_2 stream, pipeline corrosion, and the prevention of fractures and leakage[166].

Evaluating the onshore storage capacity and storage viability is crucial to assess the trade-offs between onshore and offshore GCS in the UK. Due to the lack of geological data, the locations where onshore GCS can be safely conducted are currently unknown, thus requiring further research. If suitable GCS sites were found to be at closer proximity to industrial point sources where CCS could be deployed, dispersed industrial sites would benefit from an additional abatement option. The use of CDR with onshore storage even at small scale ($ktCO_2$) would allow a more localised management of CO_2 emissions, and enable the decarbonisation of distributed sources of emissions (i.e., aviation) in hard-to-abate sectors, thus reducing residual emissions.

Box 8.1: Research gaps - Technology and geology

- Decarbonisation support and T&S infrastructure access for dispersed sites
- Environmental impacts from large-scale T&S network implementation: leakage risks; viability of road and rail transport; pipeline construction and maintenance; impacts on population centres
- Integration between CCS and engineered CDR with GCS (onshore and offshore)
- Onshore GCS site prospecting:
  storage capacity; injectivity; integrity of legacy wells; structural and stratigraphic traps
- Surface and subsurface environmental impacts from onshore GCS:
  induced seismicity; fault reactivation; CO_2 migration dynamics; leakage risks; potable groundwater contamination risks
- Monitoring, reporting and verification framework for onshore GCS

8.2 Economic and regulatory viability

Currently, there are no frameworks for safe, secure and financially sustainable onshore CO_2 storage. Given the lack of regulation, MRV, legislation, permitting and licensing frameworks, and governance structures for onshore CO_2 storage, there are significant economic and legal barriers to onshore GCS development. The UK has no clear business model, investment model, or investment pathways for onshore CO_2 storage, which naturally create financial challenges. CO_2 storage projects are large infrastructure projects, requiring significant capital expenditure – even small scale projects are estimated to cost in excess of £10m. Therefore, the financing for an onshore storage project is likely to be an obstacle for the first projects proposed.

There are unresolved questions over legal liability and fungibility for onshore storage projects. Since there have been no legal court cases or legal precedent for onshore storage, potential development onshore GCS projects would have considerable legal exposure[167]. In the case where an onshore project is underperforming or is too risky to undertake, liabilities concerning surrounding properties and people still remain undefined in law. Any onshore storage operator would require insurance for infrastructure, leakage, and carbon. However, the insurance industry would be creating a novel product for this type of operator. This means that the insurer is likely to charge higher rates because they cannot model the potential risks, and costs. Many of these issues are also true for the largest offshore project, although it remains to be seen to what effect they may have on their development.

Given the current legal and regulatory hurdles, an onshore CO_2 storage project could be deemed untenable. However, as the DESNZ would regulate on a needs-case basis, there could also be opportunities in developing an onshore project, given enough pressure for the UK to meet its international climate targets. For instance, by creating investment and job opportunities, and improving the UK's international reputation for GCS implementation and climate action more widely. The onshore policy and regulatory space is highly dynamic, and so there are opportunities for innovation and novel policy approaches, thus Onshore GCS will have to be assessed in relation to the alternatives over time.

Box 8.2: Research gaps - Economy and regulation

- Onshore legal liability, permitting, licensing and governance structures; determining which government departments or non-governmental agencies take responsibility for different aspects
- Pinpointing sources of uncertainty in the governance, regulatory, and economic regimes in CCS
- Synchronisation of the UK ETS with the EU ETS, the effects of EU legislative changes on the UK legal regime for CCS post-Brexit, and the implications of the EU CBAM and the London Protocol and liabilities relating to sub-surface pressure regimes
- Long-term financial investment models, including removals markets, and how capital accrued in those markets can be re-invested into onshore storage projects

8.3 Social acceptability

The public acceptance of an onshore CO_2 storage project is a key requirement for project development. Many have assumed that garnering support for onshore storage will be more difficult than offshore based on analogous energy projects, citing distance to people as a key factor in siting controversies[147]. Furthermore, some early high-profile instances receiving significant public opposition, culminating in project cancellations and moratoriums, led to a focus primarily on offshore GCS[130,131].

Two UK-specific studies have found that offshore is not necessarily preferred to onshore GCS[114,118]. Significant contributing factors are the low level of CCS awareness among the UK public and low acceptance of both onshore and offshore GCS[132,144]. There have been mixed results in studies evaluating the dependence of public acceptance and risk perception on proximity to people. Whereby two studies found that risk perception is proximate to people, and therefore heightened onshore[132,148]. Huijts et al.[136] and Braun[141] found that proximity is the primary determinant of public acceptance, while Terwal and Daamen[148] dispute this and argue that the result is more nuanced and protest inclination, an indicator of societal acceptance, is not affected by geographical distance.

Regulatory and legal certainty and trust in governing bodies are significant determinants of public opinion. There are concerns among the public that allowing projects with uncertainty and distrust to go ahead could lead to health and safety ramifications for communities further down the line[118,133,134,140,141]. Specific factors affecting the perception and acceptability of offshore GCS should not be overlooked. Marine environments are often perceived as 'precarious' and perceptions of offshore activities are affected by the contextual history of marine activities in that area[118,133]. Due to the nascency and size of the CCS industry relative to other offshore activities in the North Sea, offshore GCS is not a major concern in Scotland[118].

Public perceptions and social acceptability are highly dependent on the place, history, and social context. Research into improving the knowledge space and addressing the regulatory uncertainties outlined in Chapter 5 could develop greater certainty for policy-makers and practitioners, and in turn improve the likelihood of public acceptance. The provision of reliable information and effective communication from the onset of projects can decrease the risk perception of the public[134]. As such, large-scale public engagement consultations in specific contexts and jurisdictions are needed for any onshore and offshore CO_2 storage project development. Offshore GCS storage should not be assumed to be capable of gaining a social licence, purely through techno-economic analyses[118].

Box 8.3: Research gaps - Social sciences

The following areas require further research:

- Public perceptions and social acceptance research on onshore and offshore GCS in relation to place history and social contexts
- Regulatory and legal certainty, trust in governing bodies, and effective means of communication of risks and opportunities to the public
- Holistic evaluative framework for the social considerations of GCS
- Transparent and trustworthy engagement framework to facilitate a standardised approach to public engagement

Conclusion

Whilst there are obstacles to onshore GCS development in the UK, there is evidence to suggest that it may be a necessary and more cost-effective storage option compared to offshore storage. Projects around the world over past decades have demonstrated the technical feasibility of capturing, transporting and storing CO_2 into geological formations in onshore contexts. However, the implementation of onshore GCS in the UK is constrained by other non-technical factors.

Dispersed industrial sites are granted limited access to CCS and T&S infrastructure due to their distance from industrial clusters and transport hubs situated near the coast, as a consequence of the UK's exclusive reliance on offshore GCS. The implementation of onshore GCS could allow operations to occur at closer proximity to emission point sources, reducing the need for an extensive T&S network. There is little geological data for potential onshore CO_2 reservoirs in the UK. Very few studies have examined their potential, and thus their capacity and injectivity remain unclear. Broad-scale analysis indicates that several geological formations could be suitable for relatively small-scale storage projects[101] when compared to the large offshore projects being proposed on the UK continental shelf. These rates of CO_2 injection could be suitable for some dispersed point sources. Given that there has been widespread extraction of conventional oil and gas onshore in the UK, there is potential to repurpose depleted fields and deep well infrastructure for small-scale GCS projects. However, more work assessing the suitability of specific sites will have to be conducted to accurately assess this potential.

The UK regulatory and legislative environment on GCS is nascent but rapidly developing. It is currently tailored towards offshore rather than onshore GCS. This is partly led by knowledge of offshore geology, and also political will. There is hesitancy surrounding onshore subsurface projects due to the controversies surrounding the use of fracking and its ripple effects of risk perception. The UK legislative environment is rapidly changing because of the EU Revocation and Reform Act 2023. This means that many of the EU Regulations that were enacted into UK law are in the process of being revoked. For example, the EU CCS Directive which enables research organisations to establish a CCS facility, provided that it stored under 100 $ktCO_2$, is currently being revoked in the UK regulation. The regulatory uncertainty shown in Chapter 5 can negatively impact public opinion and the likelihood of acceptance. There are also cost-saving opportunities compared to offshore, although these estimates do not account for additional costs linked to permitting and public engagement.

Public acceptance and attaining a social licence is critical for the ethical and effective development of onshore GCS in the UK. These factors are hugely dependent on place, history, and social context. As such, research and public engagement consultations will be necessary in specific contexts and jurisdictions prior to project development to shed light on the likelihood of certain outcomes. High-profile cases of public opposition have resulted in widespread scepticism of onshore storage. However, two UK-specific studies have suggested that offshore is not necessarily preferred to onshore GCS[114,118]. Other studies have found specific factors to influence the perception and acceptability of either onshore or offshore or both. Offshore storage is primarily impacted by the perception of the marine environment as precarious and the impact and histories of fishing and shipping industries[133,142]. Whereas onshore storage is primarily impacted by risk perception proximate to people, although the exact impact of this is disputed[136,141,143]. Both are affected by low public awareness, climate concern, regulatory and legal uncertainty, trust in governing bodies, and perception of the system as a whole.

This report has demonstrated significant political, legislative, regulatory, and policy obstacles, with substantial uncertainties concerning the geology and social acceptance of onshore GCS. Given that current GCS plans are exclusively offshore, onshore GCS could be a necessary and more cost-effective storage option if demand for CO_2 pore space were to greatly increase, although further resources should be dedicated to further assess its viability. Greater certainty could be ensured by funding work to close research gaps highlighted in this work, thereby improving our understanding of onshore GCS and to provide a definitive answer on the potential of onshore GCS in the UK. Furthermore, research and development of onshore GCS could also produce investment opportunities if the barrier-to-entry was lower than offshore GCS, thus widening the range of climate mitigation options available to emitters.

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