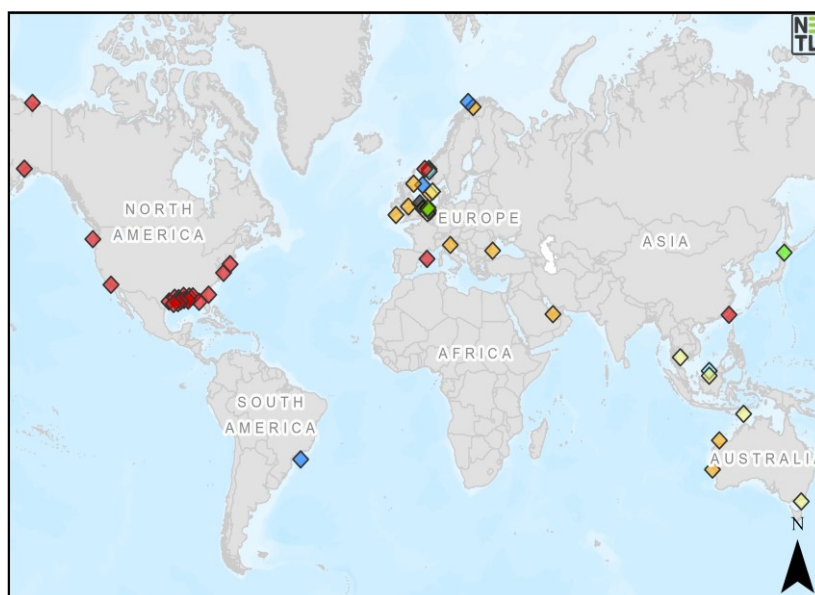




Scoping Review of Global Offshore Geologic Carbon Storage Activities

5 December 2023



U.S. DEPARTMENT OF
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**Office of Fossil Energy and
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Cover Illustration: Global offshore geologic carbon storage locations.

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Scoping Review of Global Offshore Geologic Carbon Storage Activities

Abigail Choisser^{1,2}; MacKenzie Mark-Moser¹; Julia Mulhern^{1,2}; Kelly Rose¹

¹National Energy Technology Laboratory, 1450 Queen Avenue SW, Albany, OR 97321, USA

²NETL Support Contractor, 1450 Queen Avenue SW, Albany, OR 97321, USA

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5 December 2023

NETL Contacts:

MacKenzie Mark-Moser, Principal Investigator

Kelly Rose, Technical Portfolio Lead

Bryan Morreale, Associate Laboratory Director for Research & Innovation, Research & Innovation Center

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Acronyms, Abbreviations, and Symbols

Term	Description
BOEM	Bureau of Ocean Energy Management
BSEE	Bureau of Safety and Environmental Enforcement
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization and storage
CIM	Brazilian Inter-Ministerial Committee on Climate Change
CO ₂	Carbon dioxide
CRUST	CO ₂ Re-Use Underground Storage under the Dutch Climate Policy Implementation Plan
CS	Carbon storage
CSLF	Carbon Sequestration Leadership Forum
DOE	U.S. Department of Energy
DTU	The Technical University of Denmark
DUC	Danish Underground Consortium
EBN	Energie Beheer Nederland B.V.
EC	European Commission
EDX	NETL's Energy Data eXchange
EEZ	Exclusive economic zone
EOR	Enhanced oil recovery
EPA	U.S. Environmental Protection Agency
ETI MMV	Energy Technologies Institute Measurement, Monitoring and Verification of CO ₂ Storage
EU	European Union
EUDP	Energy Technology Development Program
FEED	Front-end engineering design
FPSO	Floating production storage and offloading
ft	Feet
GCS	Geologic carbon storage
GHG	Greenhouse gas
GoM	Gulf of Mexico
GoMCarb	Offshore Gulf of Mexico Partnership for Carbon Storage
Gt	Billion Metric Tons
IEA	International Energy Agency

Acronyms, Abbreviations, Symbols (cont.)

Term	Description
JCCS	Japan CCS Co., Ltd.
km	Kilometer
km ²	Square kilometer
Km ³	Cubic kilometer
LNG	Liquid natural gas
m	Meter
m ³	Cubic Meter
mD	Millidarcy
METI	Ministry of Economy, Trade and Industry
mi	Mile
mi ²	Square Mile
Mt	Million Metric Tons
MW	Megawatt
NATCARB	National Carbon Sequestration Database
NCCC	National Committee on Climate Change Policy
NEATS	National Electronic Approvals Tracking System
NETL	National Energy Technology Laboratory
NOPSEMA	National Offshore Petroleum Safety and Environmental Management Authority
NPD	Norwegian Petroleum Directorate
NSTA	North Sea Transition Authority
OCS	Outer Continental Shelf
PTTEP	PTT Exploration and Production PCL of Thailand
QICS	Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage
RCSP	Regional Carbon Sequestration Partnership
SECARB	Southeast Regional Carbon Sequestration Partnership
SOSRA	Southeast Offshore Storage Resource Assessment
SSAP	Strategic UK Carbon Capture and Storage Appraisal Project
SSEB	Southern States Energy Board
STEMM-CCS	Strategies for Environmental Monitoring of Marine CCS
Tcf	Trillion cubic feet

TVD	True vertical depth
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Acronyms, Abbreviations, Symbols (cont.)

Term	Description
UAE	United Arab Emirates
UK	United Kingdom
UKCS	United Kingdom Continental Shelf
U.S.	United States of America
yr	Year

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EXECUTIVE SUMMARY

This technical report documents an inventory of offshore geologic carbon storage (GCS) sites globally, with a focus on existing, operating international sites and those characterized in the United States, indicating the type and variety of GCS efforts. Regional overviews provide a high-level understanding of basin-scale geology and history of GCS globally. Key aspects documented in this review include geological formation types, depth, play style, project size, timeline, existing infrastructure, environmental challenges, and potential risks. This review also includes a summary of the regulatory frameworks globally, as well as environmental, social, and commercial considerations.

1. INTRODUCTION

As technologies, infrastructure, and interest increase in the realm of carbon capture and storage (CCS), industry and governments are exploring opportunities for the expansion of CCS into offshore sedimentary basins. The United States (U.S.) offshore regions are a focus of emerging CCS potential, including in federal waters.

Presently, few resources exist that focus on concatenating global offshore CCS efforts. Gathering information on global geologic carbon storage (GCS) sites allows researchers and operators of potential carbon storage (CS) projects to identify analogous site characteristics, existing subsurface models, and select appropriate workflows to efficiently and safely enact GCS. This report aims to document the current state of offshore GCS globally and domestically as of March 2023 through a review of project stages, site geology, data availability, and regulatory considerations. This report leverages literature, data, event proceedings, and web resources to delineate international and domestic offshore GCS regions and capture geologic and operational information for global GCS sites. This report summarizes a scoping literature review of CS potential in U.S. and international offshore regions; 20 offshore U.S. locations characterized for CS; and 31 international offshore GCS projects ranging in maturity from initial site characterization to completed CS operation. This literature review may provide insights for storage resource, risk assessment, hazard mitigation, operational information, and regulatory potential across offshore U.S. domestic GCS projects. Additional products associated with this report include an ArcGIS Story Map web application (Choisser et al., 2023) and offshore GCS resources inventory (NETL, 2023).

2. METHODS

Significant yet disparate information exists regarding global offshore GCS efforts. To initiate an organization of these resources, a scoping literature review process was conducted to rapidly collect literature, data, event proceedings, and web resources capable of providing insights regarding extent, quantity, and maturity of information available for global offshore GCS (Munn et al., 2018).

Guidelines for site inclusion are defined to inform the scoping review process. Potential CS reservoirs or locations previously assessed and determined to present critical risks or non-viability due to geologic constraints, and are therefore not considered for future project development, are considered outside the scope of this review and have not been included. If during a characterization study a reservoir or location was recommended or considered optimal for future development, it has been included in this report where information was available. Some information may be incomplete due to late-breaking project identification in the review process; those projects not fully reviewed are mentioned in the appropriate regional section with references. Development and implementation of a progression framework capable of identifying consistent milestones shared across both domestic and international projects facilitated clarity in language and consistency in expectations when evaluating project progression.

Once distinction regarding potential viability of a project was made, further efforts were directed towards purposeful data organization. To contextualize the array of projects and their varying geologic characteristics, degrees of progression and organizational groupings are defined to assist in the extraction of meaningful comparisons. Initial observations related to geography and geologic context are used to categorize projects and assist in highlighting social, regulatory, and geologic issues that may have a notable influence on viability of offshore GCS projects.

Utilizing spatial, geologic, and progression-related designations, offshore GCS projects are presented in a manner that facilitates an organized and comprehensive approach. For U.S. domestic projects, focused efforts were extended towards presenting research and resources associated with past characterization efforts with publicly available information such as those performed through Regional Carbon Sequestration Programs (RCSP), the CarbonSAFE initiative, GoMCarb, and Southeast Regional Carbon Sequestration Partnership (SECARB) evaluations.

2.1 REGIONAL DIVISIONS

Domestic and global offshore GCS project reviews are categorized by geographic proximity, geologic context, and project density. Within global offshore regions, the spatial distribution of projects spans far greater distances compared to those present within the U.S. domestic offshore regions. A single sedimentary basin may be subdivided between regulatory authorities based on exclusive economic zone (EEZ), while alternately a few countries across a large geographic area may have one or two prospective storage projects yet benefit from similar technological and financial investment strategies (i.e., underlying socio-economic frameworks) implemented across a larger geographic region.

Therefore, global offshore GCS projects are grouped into three regions including the North Sea Storage Region, a well-known and active offshore CS project area; the Australia and Asia Pacific Storage Region, another active offshore GCS project area with a number of projects in relative

geographic proximity; and Other Regions for Consideration, containing more geologically and geographically disparate offshore GCS projects relevant for review.

Domestic offshore projects are likewise grouped into three regions based on geology and geographic region, with considerations for project density or lack thereof. Within sedimentary basins such as the Gulf of Mexico (GoM), the pursuit of GCS development has benefited from RCSP programs, CarbonSAFE, Offshore Gulf of Mexico Partnership for Carbon Storage (GoMCarb), and research efforts led by the Southern States Energy Board (SSEB) such as SECARB—undertakings that have provided data focused on reservoir characterizations.

Although extensively researched for hydrocarbon extraction, literature describing the Alaskan North Slope GCS characterization efforts are limited and will be discussed alongside the greater Pacific Margin and Alaskan Storage Region. The final region within the U.S. domestic offshore regions is defined based on the geographic and geologic context of the Atlantic Continental Margin and adjoining shelf. Although there are few characterization studies performed along the U.S. East Coast, three prospective reservoirs in this region were identified during collection of resources for this study. The prospective geologic storage reservoirs along the U.S. East Coast, their associated characterization studies, and data available will be discussed in sections referring to the “Atlantic Shelf Storage Region.”

2.2 GEOLOGIC CONSIDERATIONS FOR OFFSHORE CCS PROJECTS

Suitability of subsurface geology is critical to understanding both storage feasibility and operational viability for GCS locations. For this review, the following geologic data are gathered for each site: reservoir lithology, seal lithology, reservoir fluids (i.e., saline aquifer, depleted hydrocarbons, etc.), depth, and risks. When available, specific reservoir formations and characteristics are provided. Additional information for projects including potential geological risks such as fault reactivation, fault seal, pressure, surface risks (earthquakes, turbidity currents), and other factors are noted in the Offshore Geologic Carbon Storage Inventory (NETL, 2023).

Range and quality of data available varies for each prospective GCS location. This assessment focuses on sites with potentially viable “permanent storage” meaning those intended to store carbon dioxide (CO₂) commercially at geologic time scales. One of the challenges of this effort involved compiling information from a variety of spatial scales and model qualities before distilling relevant information into compatible formats for comprehensive review. Sources providing clear descriptions of modeling methods, data used, and associated uncertainties are leveraged preferentially when possible.

2.3 OFFSHORE GCS PROJECT LIFESPAN AND DEVELOPMENT STAGES

As part of developing this review, each prospective GCS location required categorization based upon factors independent of progress-related definitions put forth by disparate global regulatory authorities. This treatment of global project progression allowed accounting for potential discrepancies present across regulatory frameworks and their differing requirements and variable terminology.

Assignment of a project progression framework according to developmental stages requires identification of milestones consistent between GCS projects globally. Commonalities identified within initial stages of a GCS project included characterization or assessment studies of prospective geologic storage to determine reservoir location, lithology, quality, accessibility, and

identification of contingencies. These identified contingencies typically require resolution before commercialization can proceed and may include structural or environmental risks and location of logistically feasible CO₂ emissions and transport hubs necessary to support consistent CO₂ injection (SPE, 2017).

Attributes associated with the first stage of GCS project development are described as the “Characterization” stage and require a defined area of interest either through naming of a specific or set of reservoirs within the same sedimentary basin. Alternately, in the case of projects targeting depleted hydrocarbon reservoirs, oil field, gas field, or “play” names commonly associated with past operations are necessary.

To advance into “Early Development,” a front-end engineering design study (FEED) must be identified as in progress or permits have been reported as secured by initial interested parties to begin development of a FEED study. FEED studies are critical for gaining support of additional potential investors to begin the leasing or permitting process after securing a final investment decision. During the process of FEED development, risk mitigation studies, injection plans, details associated with ensuring environmental and personnel safety, operations and decommissioning, and fine points of infrastructure installation or well refitting plans can be identified according to requirements outlined by relevant regulatory authorities.

Establishing proof of financial security either through cooperation between industry partners or partial government funding is critical for permit and license approval before construction of GCS facilities can begin, at this stage projects are considered in “Advanced Development.”

Key distinctions between “Advanced Development” and the following stage “In Construction” rely upon identifying whether construction has purportedly begun at an identified GCS location. Construction could involve refitting offshore oil and gas platforms for CO₂ injection, installation of pipeline infrastructure or development of onshore facilities capable of facilitating transportation of CO₂ in a supercritical state to an offshore storage reservoir.

Once construction has been completed and initial injection begins, a GCS site is “In Operation” and has been authorized by the relevant regulatory authority to inject supercritical CO₂ into a subsurface reservoir at a set rate for a defined duration of time.

Projects considered “Complete” have ceased active injection operations, are in the process of site decommissioning, and may be actively implementing pre-approved long-term monitoring plans to track persisting CO₂ plumes through geophysical subsurface analyses to ensure any leakage risks are identified, monitored, and mitigated by responsible parties.

3. GLOBAL OFFSHORE GCS

Table 1: Regional Characteristics of International Offshore GCS Projects

	North Sea	Australia/Asia Pacific	Other Regions
Reservoir Type	Saline aquifers, depleted hydrocarbon	Saline aquifers, depleted hydrocarbon, depleted sour gas	Saline aquifers, gas condensate field, depleted hydrocarbon
Reservoirs	Sandstone, interbedded sandstones and shales	Sandstone, clastics and carbonates, volcanoclastic	Sandstone, clastics and carbonates, evaporites/salt
Caprocks / Seals	Shale, evaporites, salt tectonics, mud and claystone, carbonates	Shale, coal, mudstone	Anhydrite/limestone, shale, mudstone, salts/evaporites
Estimated Storage Resource	32 Mt–600 Gt	50 Mt–434 Gt	40 Mt–13.44 Gt
Depth	1,000 m–3,800 m	897 m–3,000 m	1,000 m–7,000 m
Tectonic Settings	Sedimentary basin with faulting, grabens, some salt tectonics	Australian shelf, near-subduction locations in some areas	Sedimentary basins, passive shelf margin, extensional fault zones
Infrastructure	Pipeline and ship transport mechanisms, projects in motion to improve transportation and lower logistics costs	Pipeline transport, ship transport	Pipeline, ship, and train transport
Environmental Challenges	Faulting, other commercial operations	Monsoons, cement carbonation	Ultradeep water, unconsolidated sediments, faulting
Expected Operation Date Range	2024–2030	2025–2029	2025–2028

3.1 THE NORTH SEA STORAGE REGION

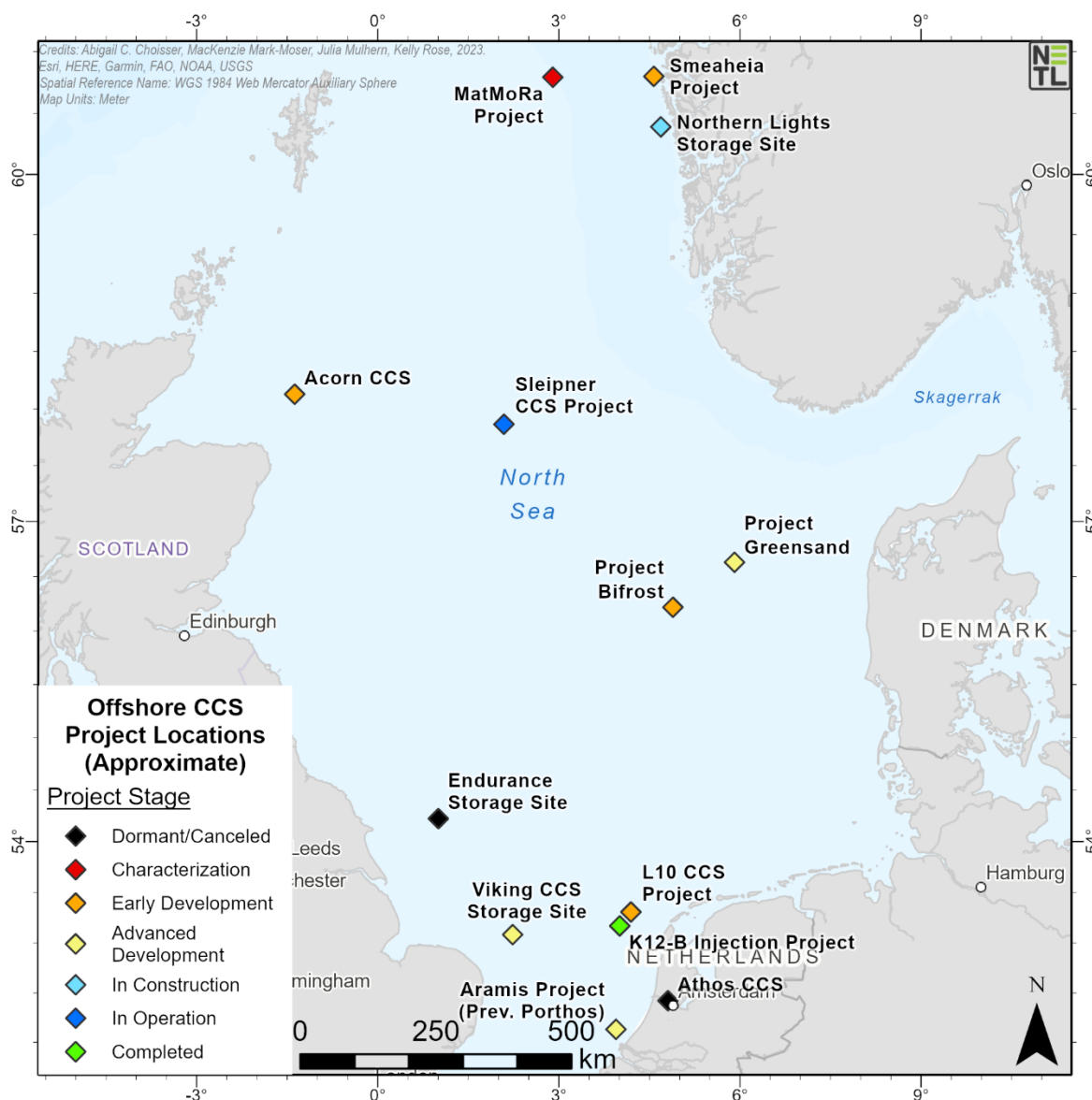


Figure 1: Offshore GCS projects in the North Sea Storage Region.

The North Sea has a long history of CS and currently has the highest concentration of existing GCS operations. The North Sea Storage Region encompassing the Netherlands, Norway, Denmark, and United Kingdom (UK) as shown in Figure 1 has a favorable sedimentary basin for GCS practices. In 1996, Sleipner set the stage as the first commercial-scale offshore CCS project (Arts et al., 2004). By capturing CO₂ scrubbed from natural gas streams extracted from the Norwegian Outer Continental Shelf (OCS), Sleipner has stored what would otherwise result in costly emissions within a reservoir in the nearby subsurface (Rennie et al., 2012). More recently, North Sea countries have increased GCS operations to meet net zero 2050 pledges and goals (Lee et al., 2023).

Since 1965, the North Sea has been a hub of oil and gas operations (Larminie et al., 1987), thus there is abundant existing infrastructure, active operations, and regulatory frameworks in place to facilitate subsurface operations. As a prolific oil and gas region proximal to dense population centers, the North Sea has potential for depleted hydrocarbon reservoirs to utilize GCS once available and long-term viability has been determined.

Extensive characterization efforts of the North Sea and its regional geologic characteristics provide data resources useful for identification of prospective storage resource locations (Furre, 2020; Gradstein et al., 2005). Within the North Sea Storage Region, more than twelve CCS projects are identified in varying stages of development with total storage resource ranging from 32 Mt to 600 Gt of CO₂ between 1,000 and 3,800 m depth as described in Table 1 (NETL, 2023; Wildenborg et al., 2022).

Infrastructure to support CO₂ transport through pre-existing pipelines and shipping networks within the North Sea are available and expansions are in progress. Projects such as the Langskip (or Longship) Project and Northern Lights Pipeline are currently in development and are expected to reduce barriers to CCS commercialization in the region by improving logistical costs for CO₂ transport (Equinor, 2023a; Lambton, 2022; OGCI, 2023).

Additional projects in the North Sea storage region besides those reviewed in this report include Errai CCS, Luna CCS, Poseidon Exploration, Stella Maris CCS, Trudvang Project, UKCS Poseidon CCS, EkoFisk EOR, and Bacton Thames NetZero (Carbon Capture Editorial Team, 2023; Procyk, 2023; Loizzo et al., 2022; Schünemann, 2023; Sval, 2023; Offshore Technology, 2023c; ConocoPhillips, 2013; Clark, 2022).

3.1.1 Acorn CCS

The Acorn CCS storage project located approximately 100 km offshore Aberdeen in the North Sea (Figure 1) is a commercial scale CCS project targeting offshore GCS within a combination of depleted hydrocarbon and saline reservoirs (Allen et al., 2020; Worden et al., 2020; Alcalde et al., 2021). The project is supported by multiple assessments performed over the past decade including the Strategic UK Carbon Capture and Storage Appraisal Project (SSAP) (James et al., 2016), the Goldeneye storage project (Tucker and Tinios, 2016) and the CO₂ MultiStore project (Akhurst et al., 2015). The associated area is also the location of two detailed studies on sealing shales (Worden et al., 2020) and the impact of rock mechanics on seal capacity (Allen et al., 2020).

Located at depths between 1,950–2,050 m and an approximate water depth of 115 m, the primary storage reservoir for the Acorn CCS project is comprised of the Cretaceous Captain sandstone and is sealed by interbedded Sola shales and overlying Rodby shales (Allen et al., 2020). The Captain sandstone has a thickness of 30–60 m depending on interbedding and is characterized with a porosity of 29–36% and permeability of 2,114 mD (Allen et al., 2020). Identified as a secondary storage location, backup, and upscaling option at depths between 1,800–2,100 m, the East Mey reservoir targets Paleocene Mey sandstones within the Lista Formation, with the Lista shale serving as seal (Worden et al., 2020; Alcalde et al., 2021).

The storage locations of both primary and secondary reservoirs are supported by existing hydrocarbon infrastructure of the Blake Development, Goldeneye Field, and Balmoral Oil Field (Alcalde et al., 2021; Worden et al., 2020). Anticipated to begin operation in 2026, the project intends on transporting CO₂ captured from the Scottish Cluster via the Goldeneye subsea

pipeline (Global CCS Institute, 2018). Currently in early development, the project anticipates a contingent storage resource of 840 Mt, with injection rates ranging from 5–10 Mt/yr (Allen et al., 2020).

3.1.2 Northern Endurance

The Northern Endurance storage project located approximately 96 km offshore Flamborough Head in the British North Sea (Figure 1) is a commercial scale CCS project targeting offshore GCS within a saline reservoir (Gluyas and Bagudu, 2020). Supported by the Northern Endurance Partnership—a collaboration between BP, Equinor, National Grid, Shell, and TotalEnergies—the project has maintained investor interest despite past economic uncertainties delaying commercial development (The CCUS Hub, 2023b; Bouffin, 2022; BP, 2022).

Located at an approximate depth of 1,020 m and a water depth of 60 m, the storage reservoir for the Northern Endurance project is comprised of the Triassic Bunter sandstones primarily sealed by the 100-m thick Rot Clay unit and a secondary seal of 90-m thick Rot Halite overlain by 900 m of Haisborough Group mudstones (Gluyas and Bagudu, 2020; Bouffin, 2022; BP, 2022). The Bunter sandstone has a thickness of 250 m and is characterized with a porosity of 16–24% and permeability of 100–500 mD (BP, 2022; Gluyas and Bagudu, 2020).

Previously anticipated to begin operation in 2026 before being assigned a dormant status, the project intends on transporting CO₂ captured from the East Coast Cluster facilities of Teeside and Humber (Bouffin, 2022; NETL, 2023). The project anticipates a contingent storage resource of 100–450 Mt, with an injection rate of 4 Mt/yr in Phase 1 (Bouffin, 2022; BP, 2022, CCUS Hub, 2023e).

3.1.3 K12-B CO₂ Injection Project

The K12-B CO₂ injection project located approximately 150 km offshore Amsterdam in the Dutch North Sea (Figure 1) was a pilot CCS demonstration project testing capture and reinjection of byproduct CO₂ into its source natural gas reservoir above the gas water (Neptune Energy, 2022; Vandeweyer et al., 2018, 2021; MIT, 2016). Supported by research associated with the CO₂ Re-use through Underground Storage under the Dutch Climate Policy Implementation Plan (CRUST) and funding from the Dutch Ministry of Economic Affairs, GDF Suez E&P Nederland B.V., and TNO (TNO, 2007; MIT, 2016) the project operated from 2004 to 2018 and is considered complete (Vandeweyer, 2016; Global CCS Institute, 2018).

Located at an approximate depth of 3,800 m and a water depth of 31 m (Offshore Technology, 2023a), the storage reservoir for the K12-B CO₂ injection project is between 92–522-m thick and comprised of Permian Slochteren Formation sandstones, conglomerates, and some subordinate claystones of the Upper Rotliegend Group (TNO-GDN, 2023). The Slochteren Formation is sealed by Silverpit Formation claystones or black bituminous Coppershale Member shales (TNO-GDN, 2023).

The anticipated total storage resource for the storage reservoir was 25 Mt, with an injection rate of 0.1 Mt of CO₂ per year over the duration of the project (Global CCS Institute, 2018; Vandeweyer et al., 2021).

3.1.4 L10 GCS Project

The L10 Central Development Area located approximately 62.5 km offshore from Den Helder in the Dutch North Sea (Neptune Energy, 2023) is a commercial scale CCS project targeting geologic storage within L10-A, L10-B, and L10-E areas of the depleted hydrocarbon Field L10-CDA (TNO, 2009; Global CCS Institute, 2018; NLOG, 2023). The L10 GCS project is supported by industry collaboration between Neptune Energy, EBN Capital B.V., Rosewood Exploration Ltd., and ExxonMobil subsidiary XTO Netherlands Ltd. (Neptune Energy, 2022).

The target storage reservoir for the L10 GCS project is comprised of the Permian Slochteren Formation sandstones, conglomerates, and some subordinate claystones of the Upper Rotliegend Group (TNO, 2009; Duin et al., 2016; TNO-GDN, 2023). The Slochteren Formation is sealed by the Silverpit Formation claystones or black bituminous Coppershale Member shales (TNO-GDN, 2023).

Anticipated to begin operations in 2026, collaborators on the project as of a 2022 presentation from Neptune Energy are finalizing assessment studies necessary to begin FEED development and submit a storage license application in 2023 (Neptune Energy, 2022). The project anticipates a contingent storage resource of 120-150 Mt, with an injection rate of 4-5 Mt per year (Global CCS Institute, 2018; NLOG, 2023).

3.1.5 MatMoRa Project

The MatMoRa project located approximately 60 km offshore Mongstad in the Norwegian North Sea (Figure 1) was a strategic research project aimed to determine suitability for large-scale GCS within the Johansen Formation (Dahle et al., 2022; Eigestad et al., 2009). Supported by Norsk Hydro, Equinor, Shell, and the Climit programme at the Research Council of Norway, the MatMoRa project is noted as an unrelated characterization study amongst others targeting the Johansen Formation (Dahle et al., 2022; Eigestad et al., 2009).

Located at an approximate depth of 2,200–3,100 m, the prospective storage reservoir characterized through the MatMoRa project was comprised of the 60–100-meter-thick sandstones and interbedded shales of the Johansen Formation (Eigestad et al., 2009). Positioned 500–600 m beneath the producing Troll Field, the Johansen Formation characterized with a porosity of 25% and permeability of 64–1660 mD is sealed by thick Dunlin Group shales with a permeability of 0.01 mD (Eigestad et al., 2009).

Initiated in 2007, the 4-year MatMoRa project calculated a contingent CO₂ storage resource of over 1 Gt within the Johansen Formation (Dahle et al., 2022; Eigestad et al., 2009).

3.1.6 Northern Lights “Aurora” GCS Site

The Northern Lights “Aurora” GCS site located approximately 110 km offshore in the Norwegian North Sea (OGCI, 2023) is a commercial scale geologic saline aquifer storage location for the integrated Longship (or Langskip) project (Equinor, 2023a; Meneguolo et al., 2021). Supported by Equinor, Shell, TotalEnergies, regulatory oversight of Norwegian Petroleum Directorate (NPD) licensing block EL001 is provided by Gassnova on behalf of the Norwegian government (Lambton, 2022; NPD, 2022; OGCI, 2023).

Located at an approximate depth of 2,600 m and a water depth of 300 m (Equinor, 2020), the storage reservoir for the Northern Lights “Aurora” GCS site is comprised of sandstones and

interbedded shales of the Johansen and Cook Formations within the lower Jurassic Dunlin Group (Eigistad et al., 2009; Equinor, 2023a; Lambton, 2022; Meneguolo et al., 2021; OGCI, 2023). The Johansen and Cook Formations are primarily sealed by the Drake Unit, while the Draupne Formation, Cromer Knoll, Shetland, and Rogaland groups provide a thick overlying secondary seal (Equinor, 2020).

Anticipated to begin injection in 2024, the project estimates a contingent storage resource of 37.5 Mt, with an injection rate of 1–1.5 Mt of CO₂ per year (Lambton, 2022; Offshore, 2022a; Acuna et al., 2023). Characterization well “31/5-7 Eos” drilled in early 2020 provided lithologic verification and detailed reservoir quality data necessary for storage resource capacity refinement (Equinor, 2020; Northern Lights, 2023).

3.1.7 Porthos Project

The Port of Rotterdam CO₂ Transport Hub and Offshore Storage, or “Porthos” located approximately 21 km offshore the Port of Rotterdam in the Dutch North Sea (Figure 1) is a commercial scale CCS project targeting GCS within the depleted P18 gas field cluster including P18-2, P18-4, and P18-6 fields (Zikovic et al., 2022; Neele et al., 2020). Supported by the Port of Rotterdam Authority, Energie Beheer Nederland B.V. (EBN), and Nederlandse Gasunie N.V., the project is a follow-on to the ROAD project previously cancelled in 2017 due to issues unrelated to reservoir suitability (Read et al., 2019; Arts et al., 2012; The CCUS Hub, 2023a, 2023d).

Located at an approximate depth of 3,500 m, the storage reservoir for Porthos is comprised of sandstones of the Triassic Buntsandstein Subgroup and is sealed by 450–750-m thick shale seal of the Upper Germanic Trias Group and Jurassic Altena Group, followed by a secondary seal comprised of the Vlieland Claystone Formation (Zikovic et al., 2022).

Anticipated to begin injection in 2026, the project is currently pending final investment decision in 2023 (Porthos, 2023). The Porthos project estimates a contingent storage resource of 32 Mt in the P18-2 field, with an injection rate of 2–4 Mt of CO₂ per year (Zikovic et al., 2022; Neele et al., 2020).

3.1.8 Athos Project

The Amsterdam-IJmuiden CO₂ Transport Hub & Offshore Storage (Athos) Project located offshore from the Port of Rotterdam in the Dutch North Sea Canal area (Figure 1) was designed as part of a large scale carbon capture, utilization and storage (CCUS) network targeting geologic saline aquifer storage (Athos, 2021b; Neele et al., 2020; EBN, 2020). This project was supported through a partnership between EBN, Gasunie, Havenbedrijf Amsterdam, and Tata Steel (Neele et al., 2020).

Located at an approximate depth of 3–5 km, the intended storage reservoir for Athos is largely undescribed by available literature, though an integrated transport network has been described as primarily focused on the region associated with the P18 Field Cluster (Neele et al., 2020).

Anticipated to begin operations in 2026 (Athos, 2021a), the project completed its feasibility study in 2019 before cancellation when a key investor and primary CO₂ source chose to pursue other CO₂ mitigation strategies (Athos, 2021b). The Athos project estimated an injection rate of 1.5–7.5 Mt of CO₂ per year (Neele et al., 2020).

3.1.9 Aramis Project

The Aramis project located in the Port of Rotterdam in the Dutch North Sea (Figure 1) is a collection hub and transportation network supporting the Porthos project and targeting additional offshore geologic storage in depleted gas fields of the South Permian gas basin L4-A offshore block (Tucker, 2022; The CCUS Hub, 2023a; Shotton et al., 2022). The Aramis project is supported by collaboration between EBN, Gasunie, Shell, and TotalEnergies, with a focus on upscaling capabilities for the associated CO₂ transport network (Tucker, 2022; Aramis, 2023).

Located approximately 200 km offshore at depths of 3–4 km and water depth of 40 m, the storage reservoir for Aramis is composed of 80-m thick sandstones of the Slochteren Formation characterized with an average porosity of 10% and permeability of 86 mD confined by a sealing unit of 200-m thick claystones of the Silverpit Formation and a secondary seal of Zechstein Salt (Aramis, 2023; TNO-GDN, 2023; Shotton et al., 2022; Tucker, 2022; The CCUS Hub, 2023a).

Anticipated to begin operations in 2026–2027, the project aims to facilitate commercial demand for offshore GCS with an initial transportation capacity of 22 Mt/year from the onshore collection hub located on the Maasvlakte in the Port of Rotterdam (Aramis, 2023; Tucker, 2022; The CCUS Hub, 2023a). The Aramis project estimates a contingent storage resource of 400 Mt at its offshore storage reservoir location, with an injection rate of 4–5 Mt/yr (Tucker, 2022; The CCUS Hub, 2023a; Aramis, 2023).

3.1.10 Bifrost Project

The Bifrost Project located 260 km off the coast of Denmark in the North Sea (Figure 1) is a CCS demonstration project targeting GCS in the depleted Harald West gas field (Hajiabadi et al., 2022; Prevost et al., 2022). Supported by the Danish Underground Consortium (DUC), TotalEnergies, Noreco, Nordsøfonden, Ørsted, BlueNord, and The Technical University of Denmark (DTU), the project aims to estimate viability of supporting full-scale CCS with room to expand to secondary storage targets in the Harald East depleted gas field and through partnerships with Aramis and the Northern Lights projects (Prevost et al., 2022; Bifrost, 2023).

Located at an approximate depth of 3,650 m and water depth of 64 m, the target storage reservoir is comprised of the Harald sandstones with an overlying shale seal (Bifrost, 2023; Hajiabadi et al., 2022). The secondary target reservoir in the Harald East field is comprised of the Tor and Ekofisk Formations, characterized with an average porosity of 28–32.7% and permeability of 2.2 mD (Hajiabadi et al., 2022). The Våle Formation mudstones overlying the Ekofisk formation would likely serve as the confining unit for the secondary storage target (Prevost et al., 2022; Tellefsen et al., 1989).

The Bifrost project completed its conceptual design in 2022, aiming to estimate viability of transportation, injection, and storage of CO₂ at a rate of 3 Mt/yr over a 15-year injection period (Prevost et al., 2022).

3.1.11 Project Greensand

Project Greensand located offshore Denmark in the North Sea (Figure 1) is a CO₂ transport and storage project aimed at turning the depleted Nini Main gas field of the Siri area into a CO₂ storage hub (Poulsen, 2022). The project is supported by a consortium of 23 partners and the

Danish government through the Energy Technology Development Program (EUDP) (Global CCS Institute, 2018).

Located at approximate depths of 1,700–1,800 m, the target reservoir is comprised of 12–30 m thick Hefring Member sandstones of the Horda Formation with a characterized permeability of 100–300 mD along the western flank of the Nini salt dome with over 300 m of Horda Formation and lower Lark Formation shales as an overlying confining layer (INEOS Oil & Gas Denmark, 2021).

Currently in its second pilot phase, project Greensand is anticipated to begin full operation by 2025, aiming to reach an injection rate of 1.5 Mt/yr utilizing dedicated tankers for transport from the INEOS Oxide factor and CO₂ capture facility in Antwerp, Belgium (Poulsen, 2022; Global CCS Institute, 2018; INEOS Oil & Gas Denmark, 2021). Future expansion of operations to other fields in the Siri area through project Greensand focus on facilitating a commercial target injection rate of 8 Mt/yr (Poulsen, 2022; INEOS Oil & Gas Denmark, 2021; Global CCS Institute, 2018).

3.1.12 Sleipner

The Sleipner site located 200 km offshore Norway in the North Sea (Figure 1) was the first offshore GCS project and both captured CO₂ separated from coincidentally produced natural gas and stored the would-be emissions into a local geologic saline storage reservoir (Global CCS Institute, 2018; Akerboom et al., 2021; Zhang et al., 2022). The implementation of CCS capabilities at the Sleipner Vest field provided a financially feasible way of reducing the impact of the carbon tax implemented by Norway in 1991 (Rennie et al., 2012).

Located at an approximate depth of 800–1,000 m and a water depth of 110 m, the target storage reservoir is comprised of 200–250-m thick Utsira Formation sandstones with intercalated claystones and a thick confining shale seal (Arts et al., 2004; Rundberg and Eidvin, 2005; MIT, 2016; Ringrose, 2018; Zhang et al., 2022).

In operation since 1996, over 20 Mt had been injected for permanent geologic storage as of 2018 (Global CCS Institute, 2018). Currently, injection at Sleipner's 15/9-A-16 well has been reported at a rate of 1 Mt of CO₂ per year (Eiken, 2009).

3.1.13 Smeaheia Project

The Smeaheia project located 50 km west of Mongstad in the North Sea (Figure 1) is a CCS project targeting offshore geologic saline aquifer storage within blocks 32/4 and 32/1 just east of the Troll Field on the Horda Platform (NPD, 2020, 2022; Ringrose, 2018). Supported by Equinor and through collaboration with the Northern Lights Project, exploration license EXL002 was awarded to Equinor in 2022 to expand upon and verify previous research performed in association with Gassnova's former "Troll Kystnær" storage prospect in the same area (Equinor, 2022; Dahle et al., 2022; Equinor, 2023b).

Located at an approximate depth of 1,200–1,700 m and water depths of 300–350 m, the target storage reservoir is comprised of Viking Group sandstones with an overlying confining unit of Draupne Formation shales (Ringrose, 2018; Equinor ASA and Gassnova SF, 2021; NPD, 1984).

Anticipated to begin operations by 2028, the Smeaheia project aims to begin with a starting injection rate of 5 Mt of CO₂ per year before increasing to an injection rate of 20 Mt/yr (NPD, 2022; Equinor, 2023b).

3.1.14 Viking CCS Project

The Viking CCS project located 140 km east of Humber in the North Sea (Figure 1) is the GCS element of the larger Viking CCS Network (or Cluster) formerly known as V Net Zero (Viking CCS, 2023; Harbour Energy, 2022). Supported by Harbour Energy, BP, and CO₂ sourced from Phillips 66 Ltd., VPI Immingham LLP, RWE, and West Burton Energy, the project aims to store collected CO₂ in depleted Viking hydrocarbon reservoirs (Viking CCS, 2023; Harbour Energy, 2023).

Located at an approximate depth of 2,700 m and water depths of 30 m, the target storage reservoirs are comprised of the depleted Viking Fields overlain by a thick salt confining layer (Anston-Race, and Ganesh, 2020; Viking CCS, 2023).

Anticipated to begin operation by 2030, the project estimates a contingent storage resource of 300 Mt with a starting injection rate of 10 Mt/yr before increasing to 14 Mt/yr by 2035 (Harbour Energy, 2022; Viking CCS, 2023).

3.2 AUSTRALIA AND ASIA PACIFIC STORAGE REGION

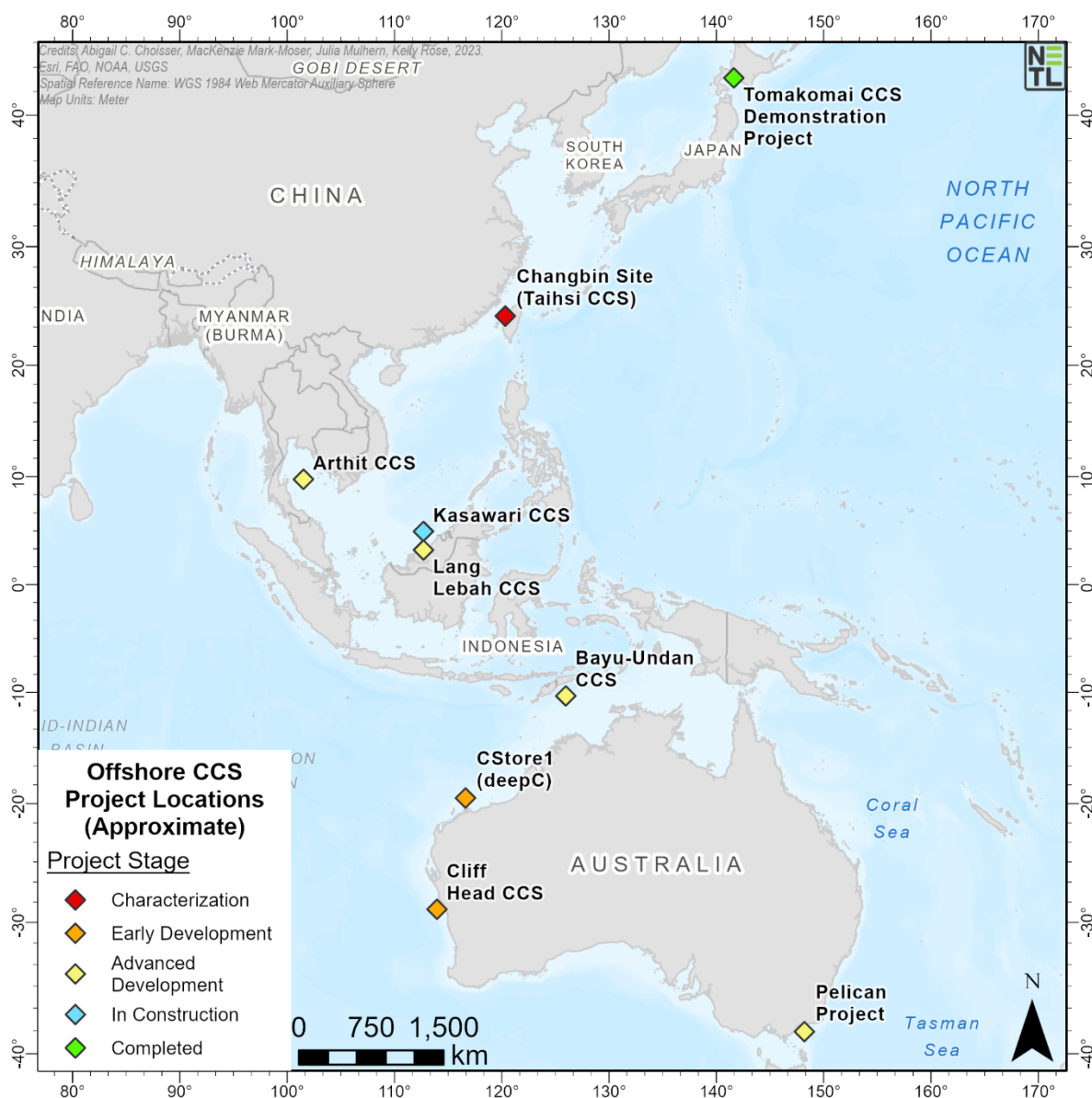


Figure 2: Offshore CCS projects in the Australia and Asia Pacific Storage Region.

Offshore GCS project operations have been expanding steadily in the Australian and Asia Pacific Storage Region (Figure 2). The offshore sedimentary basins surrounding Australia and located throughout Asia Pacific are host to nine identified GCS projects with expected operation starting within the next 2–6 years (2025–2029). Contingent storage resource estimations are high despite the sometimes-complex tectonic regimes and range from 50 Mt to 434 Gt at depths between 897 and 3,000 m (Table 1).

Due to the size of this region, prospective locations and projects are unsurprisingly varied in scale, scope, and geology. Australia is a notable carbon management leader in the region, with large scale projects in development both onshore (Gorgon and others) and offshore (deepC and

CarbonNet). The Australian government committed \$263 million Australian for CCS, including projects on the Northwest Shelf and the Bonaparte Basin, both located in the offshore basins of West Australia (as well as other onshore projects) (Morrison, 2021).

Further north, sour gas has been the catalyst for GCS development around Malaysia with the advancement of the Kasawari and Lang-Lebah projects (Pandey, 2022). Site characterization for offshore Taiwan is ongoing with new seismic data acquisitions expected to facilitate final site selection by 2023 (Yang, 2022). In China, characterization assessments of existing basins for CO₂ injection are still an ongoing process (Li et al., 2023). The successful Tomakomai demonstration in Japan, completed in 2019, demonstrated successful offshore injection into volcanoclastic reservoirs.

Infrastructure necessary for supporting CO₂ transport through pipelines is available where several prospective storage resources are also anticipated. However, ship transport infrastructure through the development of floating multi-user injection hubs aim to support international collaboration within the northern Carnarvon Basin, offshore Australia (Cavicic, 2022). One challenge for this region may be regulatory guidance, as there are a limited number of regulatory frameworks clearly defined for new carbon management projects outside of Australia and Japan.

Additional projects or prospective projects in the Australia and Asia Pacific storage region besides those reviewed here include Bonaparte Basin CCS, Browse Basin LNG, JDA Block A-18 Expansion, and Enping 15-1 (INPEX, 2022; Seggie et al., 2019; Norwegian Energy Partners, 2023; CNOOC, 2023).

3.2.1 Arthit CCS

The Arthit CCS project located 230 km offshore Songkhla within the Malay Basin in the Gulf of Thailand (Figure 2) is a CCS project targeting deep offshore geologic saline aquifer storage in the Arthit Offshore Gas Field (Global CCS Institute, 2018; Hasbollah et al., 2020). Supported by PTT Exploration and Production PCL of Thailand (PTTEP), Petronas, Thai Oil Public Company Ltd., Global Power Synergy Public Co. Ltd., SCG Cement Company Ltd., Bangkok Industrial Gas Co. Ltd., and Sahaviriya Steel Industries PCL along with past characterization efforts of the Malay Basin by the Carbon Sequestration Leadership Forum (CSLF) (Global CCS Institute, 2018; Hasbollah et al., 2020).

The intended storage reservoir for the Arthit CCS project is largely undefined by available literature, though past CSLF studies using the U.S. Department of Energy's (DOE) methods to evaluate prospective storage resource have provided a regional estimation of near 114 Gt (Hasbollah et al., 2020).

In FEED study development as of 2022, the Arthit CCS project is anticipated to begin operation by 2026 with an injection rate of 0.7–1 Mt/yr (PTTEP, 2022; Global CCS Institute, 2018).

3.2.2 Bayu-Undan CCS

The Bayu-Undan CCS project located 250 km offshore to the south of East Timor (Figure 2) in blocks 91-12 and 91-13 (Offshore Technology, 2016; Wilkinson, 2022). The project is supported by Santos for facility operations and Worley out of Perth, Australia for management and planning services (Offshore, 2022b; Wilkinson, 2022; Global CCS Institute, 2018).

Located at an approximate water depth of 80 m, details regarding the intended storage reservoir for the Bayu-Undan project are largely undefined by available literature resources (Offshore Technology, 2016; Wilkinson, 2022).

Anticipated to begin operation in 2027, the project is currently awaiting final investment decision in 2023 (Global CCS Institute, 2018; Wilkinson, 2022). The project anticipates an injection rate of up to 10 Mt/yr with future plans to expand into the Barossa field to the East (Wilkinson, 2022; Offshore Technology, 2016).

3.2.3 Changbin Site (Taihsi CCS)

The Changbin Site located offshore Western Taiwan (Figure 2) is a prospective storage target for Taihsi CCS, aiming to utilize deep offshore geologic saline aquifer storage in the Taihsi Basin (Chiao et al., 2013; Yang, 2022). The project is supported by favorable proximity to CO₂ sources in Taichung and effective storage capacity calculation methodology derived from the U.S. DOE, CSLF, Australia (CO₂CRC), and Japan RITE (Chiao et al., 2013).

Located at an approximate depth of 1,000 m, three prospective target sandstone reservoir lithologies were identified through an onshore confirmation well TPCS-M1 which identified favorable GCS conditions in the lower Cholan Formation capped by the Dalu shale and the Kueichulin and Nanchuang sandstones capped by the Chingshui shale (Yang, 2022; Hsu and Lin, 2012).

With seismic studies ongoing, a decision for final site selection and identification of any additional characterization requirements is anticipated for 2023 (Yang, 2022).

3.2.4 Cliff Head CCS

The Cliff Head CCS project located 10 km offshore Western Australia in the Perth Basin (Figure 2) is a CCS project targeting the near-depleted Cliff Head oil field (Varma et al., 2012; Global CCS Institute, 2018; Offshore Staff, 2023). Supported by collaboration with the Mid-West Clean Energy Project (CarbonNet) and Triangle Energy (Global) Ltd. and Pilot Energy Ltd. through a joint venture, the WA 31-L active oil field production license held by Triangle Energy is anticipated to expand the adjacent greenhouse gas (GHG) exploration license WA-481-P held by Pilot Energy to facilitate FEED development studies (Triangle Energy Ltd. and Pilot Energy Ltd., 2022).

Located at a water depth of 15–20 m, the target reservoir within the Cliff Head CCS project is the High Cliff sandstone with a confining unit represented by the Irwin River Coal measures (Varma et al., 2012).

Anticipated to begin operations in 2026, the Cliff Head CCS project estimates a contingent storage resource of 16 Mt with an injection rate of 1.1 Mt/yr (Triangle Energy Ltd. and Pilot Energy Ltd., 2022; Offshore Staff, 2023).

3.2.5 CStore1

The CStore1 project located 120 km North of Karratha within the Northern Carnarvon Basin (Figure 2) is the location for the deepC floating industrial multi-user injection hub within the GHG assessment permit G-10-AP associated with the depleted Angel Gas Field (Cavicic, 2023; deepC Store, 2023; NEATS, 2023). Supported through industrial collaboration between deepC

Store Ltd., Nippon Steel Corp., JX NOEX, BP Developments Australia, Chevron Australia, Japan Australia LNG (MIMI), Shell Australia, and Woodside the GHG assessment permit covers 22 blocks within the Northern Carnarvon basin (Offshore, 2022a; NEATS, 2023).

Currently in pre-FEED phase and anticipated to begin operation in 2029, the CStore1 project estimates a contingent storage resource of 434 Gt (Cha, 2022).

3.2.6 Kasawari CCS

The Kasawari CCS project located offshore Malaysia in the Sarawak Basin (Figure 2) is a CCS project aiming to utilize depleted sour gas reservoirs in the M1 field of Block SK 316 (Petronas, 2022; Battersby, 2022). Supported by Petronas, the project has plans to capture CO₂ from produced, high-CO₂ (up to 40%) natural gas, and pipe it 135 km to the M1 Platform for permanent offshore GCS (Global CCS Institute, 2018).

Located at water depths of 108 m, details regarding the intended storage reservoir for the Kasawari CCS project are largely undefined by available literature resources (Petronas, 2022).

Anticipated to begin operation in 2025, the Kasawari CCS project intends on storing 76 Mt of CO₂ in the M1 field of Block SK 316 with a target injection rate of 3.3 Mt/yr (Global CCS Institute, 2018; Battersby, 2022; Petronas, 2022).

3.2.7 Lang Lebah CCS

The Lang Lebah CCS project located 90 km offshore Malaysia in the Sarawak Basin (Figure 2) is a CCS project aiming to extract CO₂ from natural gas (17% CO₂) produced from block SK 410B before permanently storing it in the depleted Golok field (Battersby, 2022). Supported by PTTEP, Petronas Cargali, Kufpec, and Ranhill Worley, the project has the potential to re-use the Golok Go-Pa platform in the future (Battersby, 2022; Vahrenkamp et al., 2004).

The intended storage reservoir for the Lang Lebah CCS project are calcareous sandstones accessible through the depleted Golok field (Battersby, 2022; Vahrenkamp et al., 2004).

Currently in FEED development, the project is anticipated to begin operations in 2027 (Offshore Technology, 2023b).

3.2.8 CarbonNet “Pelican” Storage Site

The Pelican storage site located approximately 20 km offshore Victoria, Australia, in the Gippsland Basin (Figure 2) is the initial offshore geologic storage location for the CarbonNet project (Victoria State Government, 2023). The project is supported by CarbonNet, and CO₂ sourced from emitters from Loy Yang to Golden Beach (Gibson-Poole et al., 2008; Victoria State Government, 2023).

Located at an approximate depth of 1,500 m, the target storage reservoir consists of sandstones capped by the Traralgon Formation with a regional secondary seal consisting of overlying Lakes Entrance Formation (Gibson-Poole et al., 2008; Hoffman, 2022).

Anticipated to begin operations by 2027, the project is currently anticipating its Final Investment Decision in 2024. The Pelican site is expected to contain a contingent storage resource of at least 168 Mt with an injection rate of 6 Mt/yr (Victoria State Government, 2023).

3.2.9 Tomakomai CCS Demonstration Project

The Tomakomai CCS Demonstration project located beneath the Tomakomai Port, Japan (Figure 2), is a CCS demonstration project targeting permanent GCS within two volcanoclastic reservoirs (Abe et al., 2013; Tanase, 2022). The project was supported during its operation from 2012–2019 by the Ministry of Economy, Trade and Industry (METI), Japan CCS Co. Ltd. (JCCS), and CO₂ captured from the Idemitsu Kosan’s Hokkaido Refinery in Hokkaido Japan (Tanase, 2022; JCCS, 2020; Abe et al., 2013).

Located at approximate depths of 1,000–1,200 m and 2,400–3,000 m, the two reservoir targets consisted of Moebetsu Formation sandstones and Takinoue Formation volcanoclastics capped by mudstone seals (Abe et al., 2013; Tanase, 2022).

The project injected 0.3 Mt of CO₂ before its planned conclusion. Currently, the project has undergone four years of post-injection monitoring. Marine environmental surveys are conducted each season, and extensive onshore and offshore seismic monitoring systems are in place to evaluate potential micro seismicity and behavior of the CO₂ plume with respect to natural earthquakes. As of 2022, no seismicity from CO₂ injection has been detected (Tanase, 2022).

3.3 OTHER REGIONS FOR CONSIDERATION

Other GCS projects and assessments are in varying stages of progress and are considered in this section due to their varied global distribution outside of any common sedimentary basins or regional commonalities. These additional locations include projects in the following countries: Brazil, Bulgaria, Greece, Ireland, Italy, Norway, Spain, the United Arab Emirates (UAE), and the United Kingdom.

Projects from each of these countries are reviewed here with the exception of the Prinos Concession in Greece due to the recent nature of its announcement (Vujasin, 2023).

3.3.1 Barents Sea

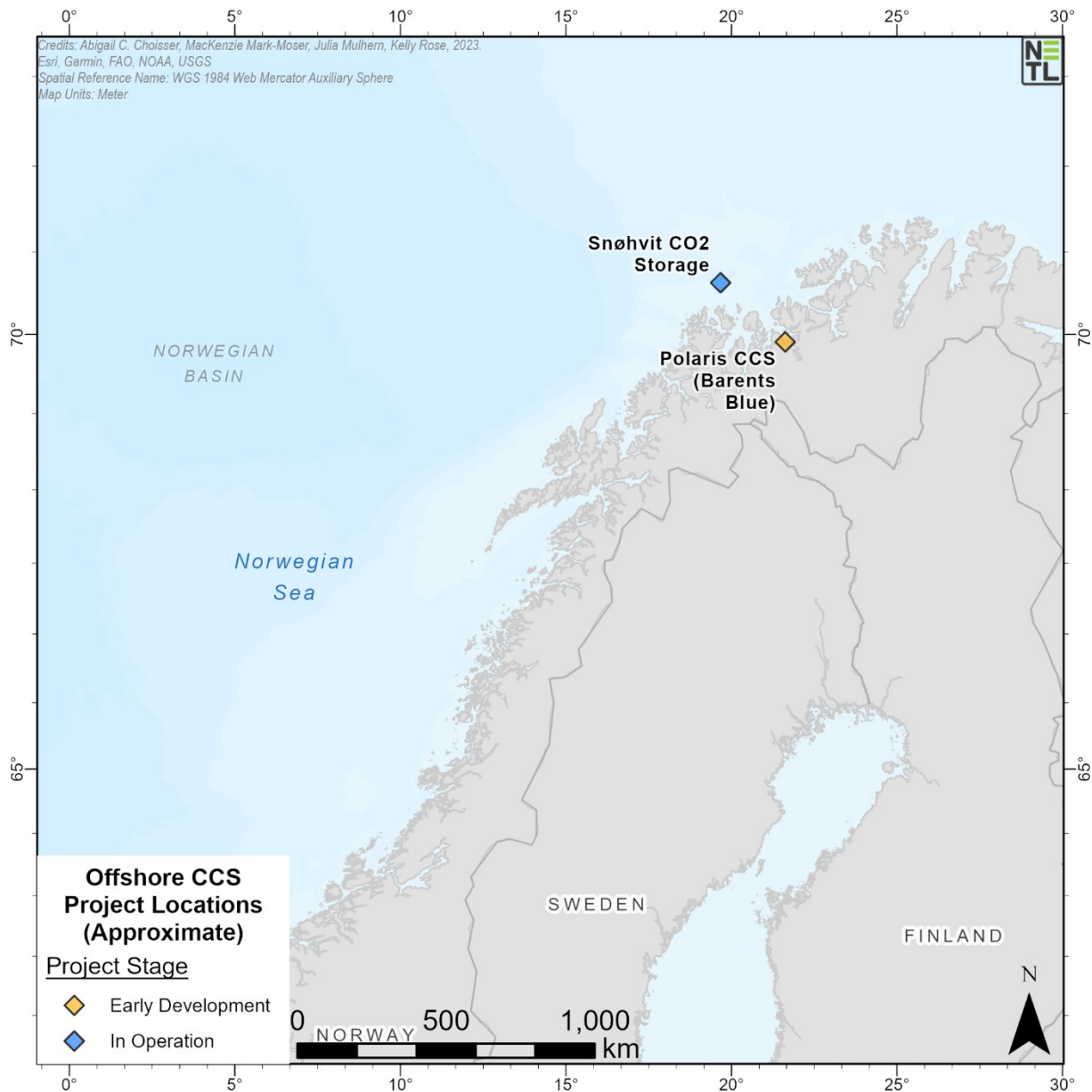


Figure 3: Offshore CCS projects in the Barents Sea.

3.3.1.1 Polaris (Barents Blue)

The Polaris Barents Blue storage project located 100 km off the coast of Finnmark, Norway (Figure 3), is the element of the Barents Blue project targeting permanent offshore geologic saline aquifer storage beneath the Barents Sea (Offshore, 2022a; Sola, 2022). The project is supported by collaborations between Horisont Energi, Var Energi, Equinor, and CO₂ captured from a local onshore ammonia plant (Offshore, 2022a; Sola, 2022).

Located at an approximate depth of 1,375 m and water depths of 252 m, the target storage reservoir for the Polaris storage location is comprised of sandstones overlain by a confining unit of 50-m thick black shale (Sola, 2022).

Anticipated to begin operations in 2026, the target injection rate is estimated at 2 Mt/yr for 25 years, for a total of 50 Mt of prospective storage resource (Offshore, 2022a; Sola, 2022).

3.3.1.2 Snøhvit CO₂

The Snøhvit project field located north of Hammerfest (Figure 3) is a CCS project targeting permanent offshore geologic saline aquifer storage beneath the Barents Sea (Ringrose, 2018; Global CCS Institute, 2018). Supported by collaboration between Equinor, Petoro, TotalEnergies, Neptune Energy, Wintershall Dea, and CO₂ extracted from locally produced natural gas (5–6% CO₂), the potential for project expansion has been indicated by the CO₂ exploration license EXL003 granted in 2022 to the Northeast of the Snøhvit unit (NPD, 2022; Akerboom et al., 2021).

The target storage reservoir for the Snøhvit project was initially the saline aquifer of the Tubåen Formation beneath the gas-bearing Stø Formation; however, complications arose due to unexpected pressure increases after the first three years of injection, causing a pause in operations in 2011 (Ringrose, 2018). The cause of the pressure differential was identified to be related to geologic baffles restricting access to available pore space. After modifications to the injection plan, operations resumed targeting the Stø Formation (Ringrose, 2018).

3.3.2 Black Sea



Figure 4: Offshore CCS projects in the Black Sea.

3.3.2.1 ANRAV

The ANRAV project located offshore Bulgaria (Figure 4) is targeting permanent offshore geologic saline aquifer storage beneath the Black Sea. Supported by the European Union (EU) Innovation Fund, HeidelbergCement, Petroceltic, Devnya Cement, Bulgaria Food, and CO₂ supplied by the Devnya cement plant, the project is considered the first full chain CCUS project in Eastern Europe (International Cement Review, 2023; IOGP Europe, 2022).

Although few details are yet available regarding the geologic storage unit target beneath the Bulgarian waters of the Black Sea, the Kamchia Trough, a small Eocene foreland basin located immediately north of the Balkanide thrust belt, contains the primary prospective reservoirs associated with this area (Robinson et al., 1996).

The ANRAV project is anticipated to begin operation in 2028 transporting CO₂ through pipeline to the target storage reservoir (IOGP Europe, 2022; International Cement Review, 2023).

3.3.3 Irish and Celtic Sea

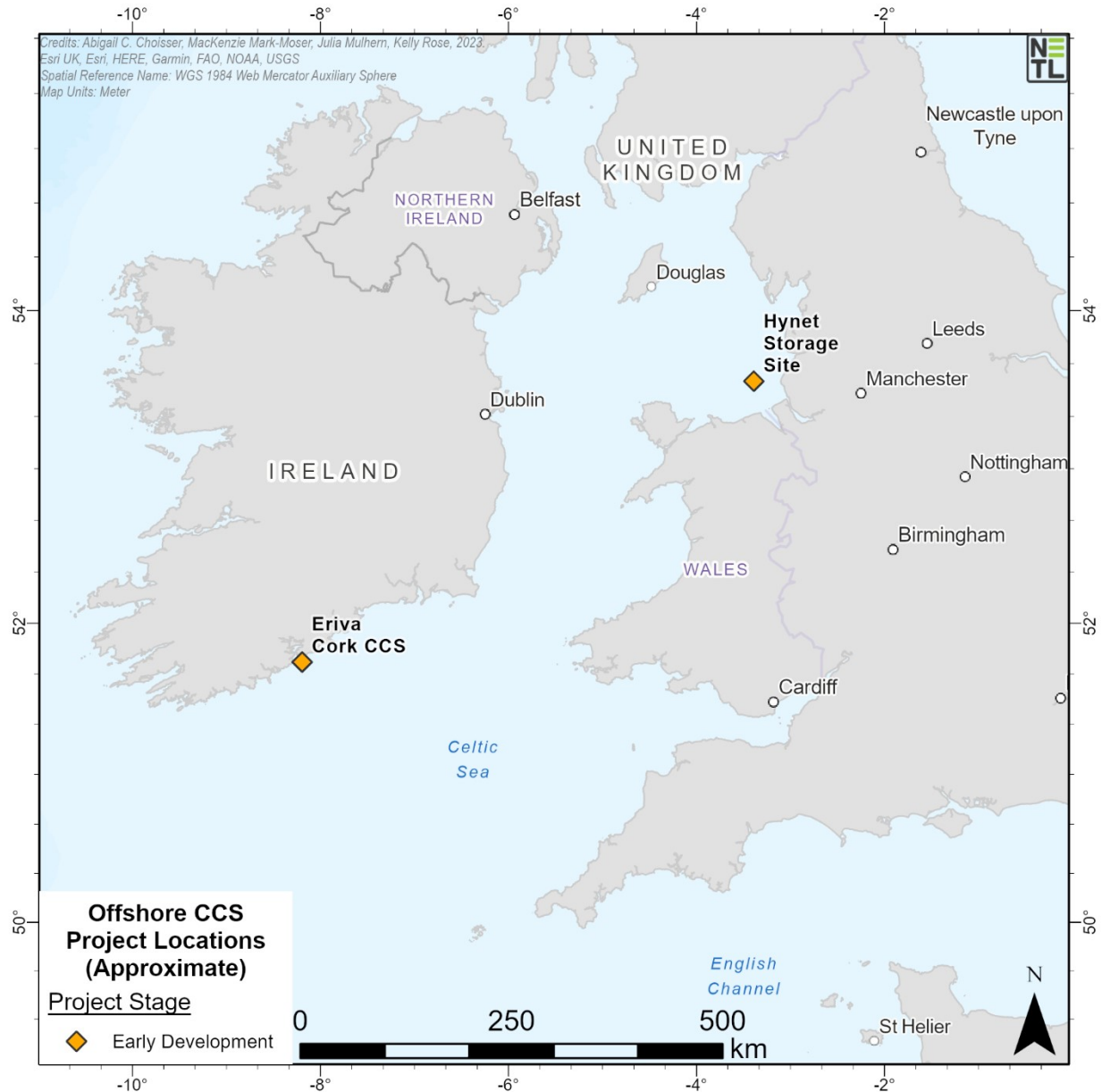


Figure 5: Offshore CCS projects in the Irish and Celtic Sea.

3.3.3.1 Ervia Cork

The Ervia Cork Project located 40–70 km offshore Ireland in the Celtic Sea (Figure 5) is a CCS project targeting permanent geologic storage in the soon-to-be depleted Kinsale Head Gas Field (Ervia, 2022; Offshore Technology, 2020). Current plans require an additional terminal (Inch Terminal) to be converted for CO₂ transport offshore via an existing 24-in. pipeline currently utilized for natural gas (Ervia, 2022).

The local storage site contains an estimated storage resource of 330 Mt within the Lower Cretaceous Walden and Greensand Sandstones which are regionally sealed by the Mercia Mudstone (Graham et al., 2014; Sustainable Energy Ireland, 2008).

According to a report published in 2022, the project is still in the early development stages and recently finished pre-FEED development (Ervia, 2022).

3.3.3.2 Liverpool Bay Storage Site (HyNet NorthWest Project)

The Liverpool Bay storage site located 29 km Northwest of Wales (Figure 5) is the storage element of the HyNet NorthWest CCS project targeting permanent geologic storage of CO₂ in the depleted reservoirs of Hamilton Main, Hamilton North, and Lennox (Aleandri, 2022; The CCUS Hub, 2023c).

The primary reservoir of the Hamilton Field is the Ormskirk Sandstone, with a potential secondary reservoir comprised of the St. Bees Sandstone Formation (Chedburn et al., 2022). Overlying the primary reservoir at the Hamilton Field is 60 m of the Ansdell Mudstone Member within the Mercia Mudstone Group, followed by a secondary seal of the Rossall Halite Member (Kirk, 2005).

Anticipated to begin operations in 2025–2026, the project estimates a combined contingent storage resource of 130–190 Mt with a starting injection rate of 4.5 Mt/yr before scaling up to 10 Mt/yr (Aleandri, 2022). Once proven, the HyNet NorthWest project has indicated the potential for future expansion into the nearby North and South Morecambe Bay gas fields, an additional prospective storage resource of 1.5 Gt (The CCUS Hub, 2023c).

3.3.4 Mediterranean Sea

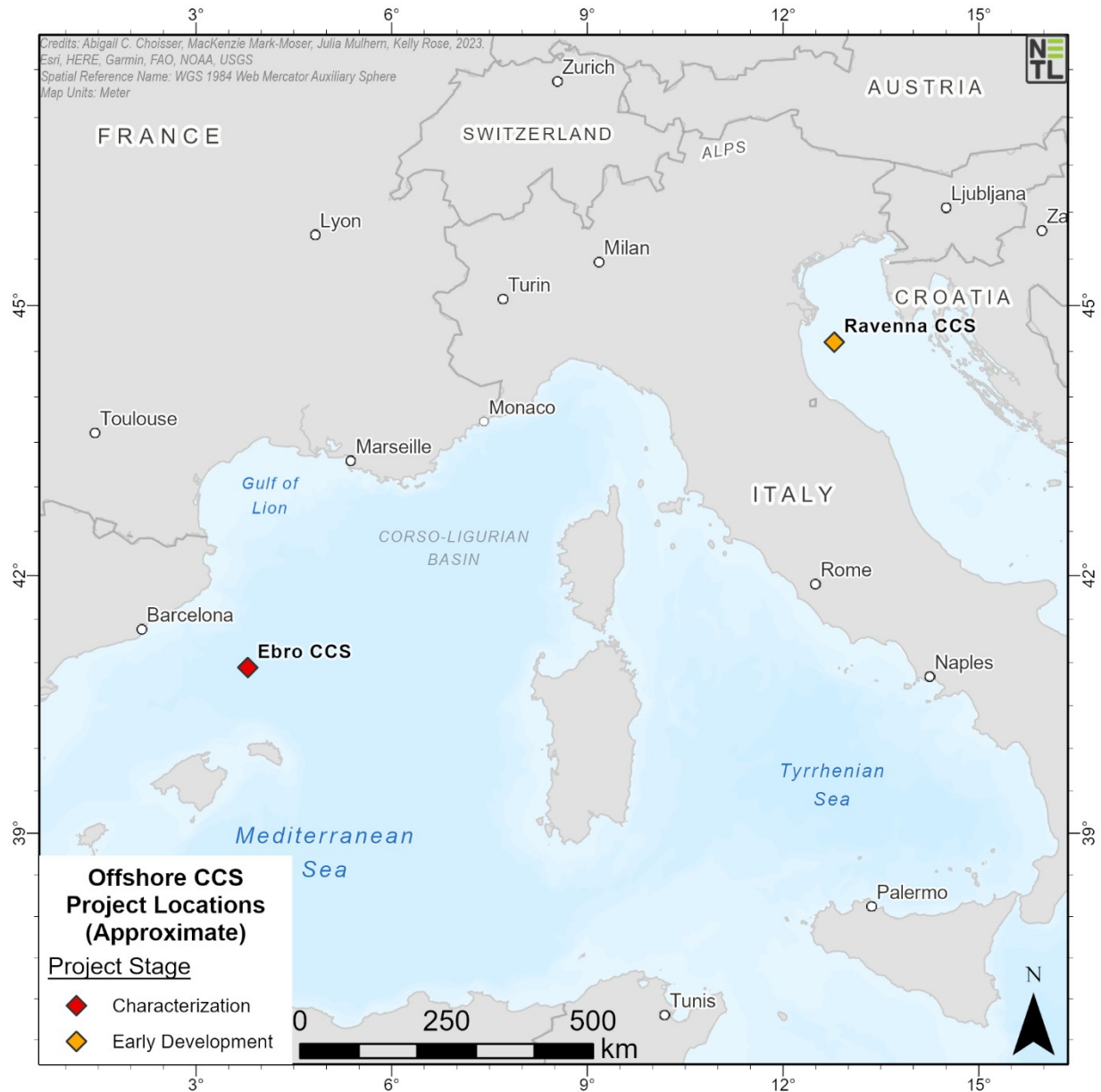


Figure 6: Offshore CCS projects in the Mediterranean Sea.

3.3.4.1 Ebro Basin - Offshore

The Ebro basin located offshore Barcelona, Spain (Figure 6), has been explored for potential GCS feasibility by Repsol in 2022 (Pángaro, 2022).

Prospective storage resources within the offshore Ebro basin are associated with sandstones of the Castellon and Salou Formations with an overlying primary confining unit of Ebro Shales and a potential secondary regional seal of Messinian salt deposits (Pángaro, 2022; Camerlenghi et al., 2022).

Initial characterization efforts estimate a prospective storage resource of over 40 Mt (Pángaro, 2022).

3.3.4.2 Ravenna

The Ravenna project located 20 km off the coast of Ravenna (Figure 6) is a CCS project targeting permanent geologic storage in the Porto Corsini Mare Ovest Field in the Adriatic Sea (Global CCS Institute, 2018; Donda et al., 2013). Supported by Eni, Snam, and CO₂ emissions sourced from the Po Valley, the project also benefits from past regional assessments of the Italian Adriatic Sea which identified an additional 14 deep saline aquifers within the region (Donda et al., 2011, 2013; Eni, 2023).

Located at an approximate depth of 2,000 m, additional details regarding the storage target have not yet been identified within available literature (Global CCS Institute, 2018).

Anticipated to begin pilot testing in 2023 before scaling to industrial development in 2027, the project expects an initial injection rate of 25 Kt/yr for 2 years before scaling up to 4 Mt/yr (Global CCS Institute, 2018; Aleandri, 2022). The total prospective storage resource for the Adriatic offshore basin from past regional assessments is estimated at 500 Mt (The CCUS Hub, 2023d).

3.3.5 Persian Gulf



Figure 7: Offshore CCS projects in the Persian Gulf.

3.3.5.1 Ghasha Concession Fields

The Ghasha Concession CCS project located near Dalma Island off the coast of the UAE (Figure 7), is a commercial CO₂ capture and reinjection project for the Ghasha, Dalma, and Hail Sour Gas and Oil fields within the Persian Gulf (Offshore Engineer, 2021). The project is supported by industry collaboration between ADNOC, Eni, Wintershall Dea, OMV, and LUKOIL, with Technip Energies NV currently undertaking the FEED development process to integrate CCS and optimize efficiency for the large ultra-sour gas project (Offshore Engineer, 2021).

3.3.6 Southern Atlantic



Figure 8: Offshore CCS projects in the Southern Atlantic.

3.3.6.1 Lula Petrobras

The Petrobras CCS project located 300 km offshore Brazil in the Santos Basin (Figure 8) is a pilot injection project targeting the Lula and Saphinoa fields (Seabra, 2020; da Silva Ribeiro, 2022). Supported by Petrobras and CO₂ sourced from locally produced natural gas, the project utilizes floating production storage and offloading (FPSO) units to treat and store CO₂ for injection in offshore geologic storage reservoirs (Seabra, 2020; da Silva Ribeiro, 2022).

Located at an approximate water depth of 2,000–2,500 m, implementation of nine FPSO units in 2020 allows for on-site separation of CO₂ from produced natural gas (8–80% CO₂) before reinjection into the subsurface (Seabra, 2020).

Pilot CO₂ injection (Figure 8) started in 2011 in the Lula field and 2013 in the Saphinoa field. In 2021 injection rates reached 8.7 Mt/yr and in 2022 Petrobras reinjected 10.6 Mt (da Silva Ribeiro, 2022). Cumulatively, 9.8 Mt CO₂ was stored between 2013 and 2018 and 30.1 Mt was stored between 2018 and 2021 (da Silva Ribeiro, 2022; Seabra, 2020). The initial injection target was 40 Mt by 2025 but Petrobras has increased that objective, now aiming to reach 80 Mt by 2025 (Global CCS Institute, 2018).

4. U.S. OFFSHORE CCS

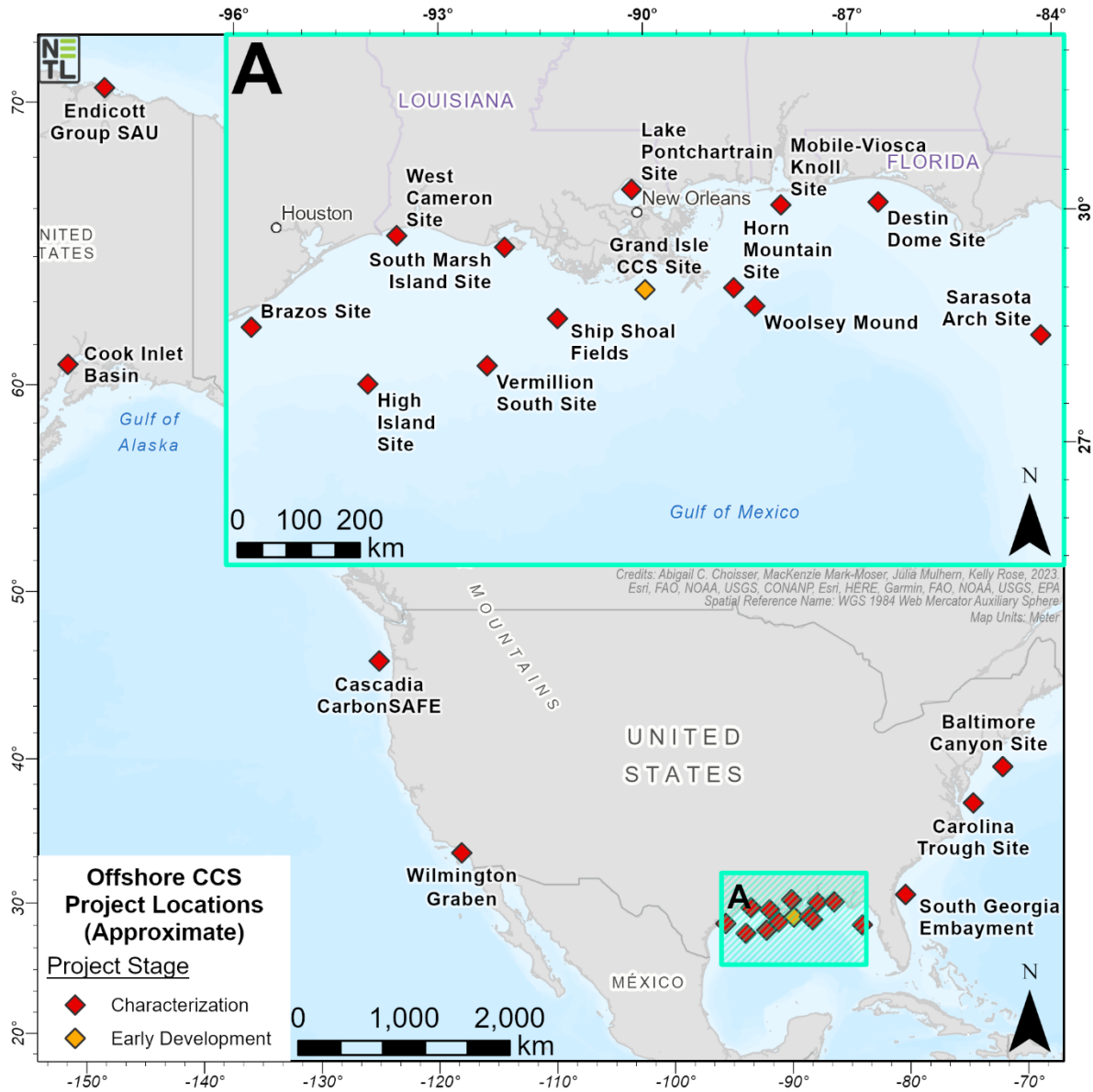


Figure 9: Offshore CCS projects in the U.S.

For the purposes of this review the offshore waters of the U.S. (Figure 9) have been divided into three regions: The Atlantic Shelf Storage Region, the GoM, and the Pacific Margin and Alaska Storage Region. Each of these three regions are described in the following sections.

4.1 ATLANTIC SHELF STORAGE REGION

Three areas along the Atlantic Margin are included in this assessment, from north to south they are the Baltimore Canyon Trough, the Carolina Trough, and the South Georgia Embayment. All three have promising storage potential but are under-studied and under-developed relative to counterparts in the GoM, likely due to the basin history within the Atlantic Margin.

The development of the Atlantic margin began with rifting of Pangea during the Triassic. By the middle Jurassic following formation of the Central Atlantic magmatic province, rifting had extended into the central Atlantic (Miall et al., 2008). Deposition of evaporites and carbonates initially followed rifting before transitioning into Cretaceous siliciclastic sediments (Jansa, 1981).

Typically, post-rift sedimentation creates packages 2–16-km (1–10 mi) thick within offshore basins which can reach up to 25-km thick (Fukai et al., 2020, Miall et al., 2008). Thinner sediment packages between 0–2.4 km (0–1.5 mi) comprise the margin along the Atlantic coastal plain (Fukai et al., 2020; Grow and Sheridan, 1988). Overall, the region is tectonically stable and geologic sequences can be mapped regionally with relative confidence.

The Atlantic Margin has remained largely closed to offshore development; therefore, existing subsurface data is limited. Some exploratory drilling took place in the late 1970s and early 1980s involving five offshore test wells and 46 industry wells drilled in the offshore with support from the U.S. Bureau of Ocean Energy Management (BOEM). Oil and gas were subsequently discovered and produced in the Great Banks area of Newfoundland, Canada. Further south, along the Northern U.S. Atlantic Margin limited gas shows in the offshore New Jersey area were identified, but these resources were never developed (BOEM, 2023).

These well data from legacy drilling operations provide the basis for several of the more recent GCS assessments. The Mid-Atlantic region was studied in a project referred to as the Mid-Atlantic U.S. Offshore Carbon Storage Resource Assessment led by the Battelle Memorial Institute and concluded in 2019 (Ripepi, 2018; Gupta, 2019). This assessment considered the Baltimore Canyon Trough, the Long Island Platform, and the Georges Bank Basin. The Long Island Platform and Georges Bank Basin were found to have insufficient sediment thickness and depth for effective storage (Gupta, 2019). Details about the specific study locations along the Atlantic Margin are summarized in Table 2.

The lack of drilling, both onshore and offshore in the Mid-Atlantic region has resulted in a limited understanding of regional geology and fluid flow in the reservoirs (Fukai et al., 2020). Additionally, limited regulatory and public familiarity with the offshore drilling process could hinder potential future projects (Fukai et al., 2020). Studies would need to be performed within local communities to better understand and create education opportunities for improved public understanding of GCS (Ashworth et al., 2019). Primary existing industries along the Atlantic Coastal Margin include fishing, commercial shipping, leisure, and recreation. Offshore wind power generation is in the nascent stages of development along the mid-Atlantic margin (Fernandez-Alvarez et al., 2023).

The Northeastern and Mid-Atlantic regions of the Atlantic Shelf contain over one thousand CO₂ emission sources and produce over 25 Gt of CO₂ per year (Fukai et al., 2020). For support of GCS commercial operation, these emission sources could provide the reliable CO₂ supply

necessary for large-scale injection (specifically if sourced from emitters in the range of the Baltimore Canyon Area) (Fukai et al., 2020).

Table 2: Summary of Geologic Storage Assessment Locations along the U.S. Atlantic Margin

Location	Reservoir/Seal	Reservoir Type	Estimated Storage Resource	Depth	References
Baltimore Canyon Trough	Sandstone/Shale	Unknown	37–59 Gt	800–4,000 m	Fukai et al., 2020; Gupta, 2019; Ripepi, 2018
Carolina Trough	Sandstone/Shale	Unknown	7–114 Gt	1,088 m	Berry et al., 2018; Ripepi, 2018
South Georgia Embayment	Carbonate/Shale	Unknown	852 Gt	1,200–1,800 m & 2,400–3,300 m	Berry et al., 2018; Buffler et al., 1979; Edsall et al., 1978; Ripepi, 2018; Almutairi, 2017

4.1.1 Baltimore Canyon Trough

Investigations of the Baltimore Canyon Trough were conducted during the Mid-Atlantic U.S. Offshore Carbon Storage Resource Assessment led by the Battelle Memorial Institute in 2019 (Ripepi, 2018; Gupta, 2019). The area was evaluated for CCS viability as part of a research effort aimed to improve efficiency estimates and identify any critical risk factors for future project implementation (Gupta, 2019). This extensive report includes seismic interpretations, rock property assessments, hydrologic properties and characterization, storage resource assessments, risk factor analysis, and a stakeholder engagement study (Gupta, 2019). Some historic drilling (COST program) allowed for direct assessments in this region.

Regionally, storage was assessed for a range of reservoirs: The Upper Jurassic, Lower Cretaceous, Middle Cretaceous, Upper Cretaceous, and the Oligocene (Fukai et al., 2020, Ripepi et al., 2018). Overall, reservoir quality was deemed viable, with porosities ranging from 21–29% and mean permeabilities ranging from 45–339 mD (Fukai et al., 2020).

The Baltimore Canyon assessment included dynamic modeling of a notable regional four-way closure anticline, the Great Stone Dome, with a prospective storage resource of 45–51 Mt (Fukai et al., 2020).

4.1.2 Carolina Trough

The Carolina Trough was characterized through SSEB Southeast Offshore Storage Resource Assessment (SSEB-SOSRA) studies in 2018. There is no well control in the Carolina Trough, therefore assessments relied on sequence stratigraphy and extrapolation (Ripepi et al., 2018). The target reservoirs within this area are comprised of Early Cretaceous sandstones with shale seal; regional salt tectonics require further investigation to determine potential influence on these reservoirs (Nemeth et al., 2019).

4.1.3 South Georgia Embayment

The South Georgia Embayment, also characterized through SSEB-SOSRA, was the research focus of a thesis of the University of South Carolina (Almutairi et al., 2017; Nemeth et al., 2019). Likely due to data availability and variations in study area extent between projects, there is some variety in estimated storage resource calculations.

A detailed assessment of the South Georgia Embayment found 9 Gt of storage locally and 32 Gt regionally (Almutairi, 2018; Almutairi et al., 2017; Berry et al., 2018).

4.2 GULF OF MEXICO STORAGE REGION

The GoM is a focal point of offshore oil and gas operations in the U.S. with a long and extensive history of drilling and production. As a result, there is abundant data available, existing regulatory bodies for oversight, and extensive drilling and pipeline infrastructure.

Early GCS assessments for the GoM involved an approximately 10,000 mi² area analysis of the offshore region between Alabama and the western Florida Panhandle. The study suggested a prospective storage resource of 170 Gt in Miocene Sandstones and approximately 30 Gt in deeper Cretaceous formations (Hills and Pashin, 2011; Almutairi et al., 2017). Since then, the eastern region of the GoM has had some development, but the far eastern areas of the basin have been historically closed to drilling.

The complex geologic history of the GoM is central to understanding the opportunities and challenges for GCS viability. Despite being a passive margin, the GoM basin is geologically unique and differs from other passive margins due to the thick package of Louann Salt deposited during clockwise rotational extension in the Jurassic (Salvador, 1991; Pilcher et al., 2014). Subsidence rates remained high during the rifting process, resulting in syn-depositional sediment packages such as the eolian Norphlet Formation which rims the basin on the eastern and western margins (Snedden et al., 2020). A thick sedimentary package of shallow water carbonates, ramp carbonates, deep basin shales, and mixed clastics were then deposited over the Louann Salt throughout the later Jurassic, Cretaceous, and into the Tertiary (Snedden et al., 2016). In the Oligocene and Miocene, sedimentation was dominated by turbidity currents, resulting in thick, extensive, turbidite packages. These thick packages of stacked units ranging from clastic to carbonate are a key research focus for prospective storage resource evaluations in the GoM.

Following deposition in the Jurassic, the Louann Salt began moving and deforming to give the GoM its complex salt tectonic history. As the salt was buried through sedimentation it began to flow due to its lower relative density, rafting initial sedimentation, initiating diapirism, creating decollements, and forming mini basins (Galloway, 2008). The impermeable nature of salt, as well as the complex structures created from its movement, result in the formation of a wide variety of structural traps and associated seals. Due to the abundance of reservoirs, traps, and seals, the GoM is a primary interest for GCS feasibility. The presence of salt diapirs, rollers, and giant salt pillows may present both challenges and advantages for GCS (Nemeth et al., 2019).

Environmental hazards can pose risks to drilling and industrial operations in the GoM. However, the extensive development of the offshore drilling industry has led to a variety of processes and procedures that allow companies to safely mitigate and avoid these natural hazards. These hazards include turbidity currents, unconsolidated sediment transport, instability due to rapid sedimentation, submarine landslides, hurricanes, tropical storms, and unpredictable currents.

In addition to being an epicenter of hydrocarbon production, the GoM is a hub for critical shipping operations, commercial and recreational fishing, tourism, cruises, and other leisure activities.

Within the GoM, site-specific GCS assessments have included a mix of depleted hydrocarbon fields and saline reservoirs in federal waters. Tools such as NETL's Offshore CO₂ Saline Storage have been created to conduct regional offshore GCS resource potential in saline reservoirs with a test application conducted in the GoM (Romeo et al., 2022). Data associated with oil and gas exploration within the GoM is typically proprietary (e.g., well, seismic), though some data resources are publicly available through the Bureau of Safety and Environmental Enforcement (BSEE) Data Center, BOEM Resource Evaluation Program, National Carbon Sequestration Database (NATCARB), The National Archive of Marine Seismic Surveys, GoMCarb, SECARB, and SSEB-SOSRA. GIS data available through BOEM and USGS includes bathymetric surveys, geographic grids, lease maps, infrastructure, and well location databases (Nemeth et al., 2019).

While large-scale regional assessments have been done for the GoM regionally, this study focused on specific site assessments. The sites reviewed come from a variety of sources. One key source was the validation portion of a study done by NITEC LLC in 2017 which assessed 675 depleted oil and gas fields in the GoM and considered 3,514 reservoirs for potential CO₂ storage (Savage and Ozgen, 2017). Of those, five fields were chosen for a more detailed validation study: Brazos, High Island, West Cameron, Vermillion, and Grand Isle, each of which are included as sites in this inventory and described in detail in the following sections. Data for the NITEC study was originally gathered from the BOEM Reserve Database and includes detailed well and reservoir information—specific attention to reservoir volumetric, rock properties, and production parameters were considered of primary importance. These validations used the height of the hydrocarbon column to calculate storage volume, ignoring any potential storage in underlying saline bearing reservoir.

Another study of interest by Treviño and Meckel (2019) as part of a U.S. DOE National Energy Technology Laboratory's (NETL) assessment of the Northern GoM in which they developed a model spanning ~70 mi off the coast between Texas and Louisiana. While they did not provide site specific information, their assessment aggregated and reviewed seismic data which included updating processing, mapping multiple flooding surfaces (including MFS09 which is a regional seal), and mapping closures with maximum column heights of 50 m. They considered Miocene reservoirs in the High Island area with porosity of 28%, depth 8,348 ft, and temperatures of 178 °F as well as the Galveston lease area which has porosity of 29%, depth of 6,900 ft, and temperatures at approximately 164 °F (Treviño and Meckel, 2019). Overall, they modeled a total area of 5,575 km², and sandstone net volume of 1,476 km³, and porosity of 30–33%, resulting in a static capacity 7.15 Gt for Miocene reservoirs (Treviño and Meckel, 2019).

Table 3: Summary of Geologic Storage Assessment Locations in the GoM

Sub-Region	Location	Reservoir/ Seal	Type	Estimated Storage Resource	Depth	References
Texas & LA Coast	Brazos	Sandstone/ Shale	Depleted Gas	2.9–14.6 Mt	4,414 m	Savage and Ozgen, 2017
Eastern GoM	Destin Dome	Sandstone/ Shale	Unknown	99 Gt	2,000 m	Gray et al., 2019b; Nemeth et al., 2019
Western GoM	Grand Isle CCS	Sandstone/ Shale	Depleted Gas	0.6–2.8 Mt	3,780 m	Savage and Ozgen, 2017; Crescent Midstream, 2022; Davis, 2022a
Eastern GoM	Sarasota Arch	Carbonate/ Anhydrite	Saline	658–1,108 Gt	800– 2,200 m	Charbonneau II, 2018; Nemeth et al., 2019; Gray et al., 2019a, 2019b
Eastern GoM	Mobile-Vioca Knoll	Sandstone/ Shale	Unknown	133 Gt	4,000 m	Berry et al., 2018; Nemeth et al., 2019; Gray et al., 2019a, 2019b; Hills et al., 2019
Eastern GoM	Woolsey Mound	Solid CO ₂ hydrate	Gas-hydrate	Unknown	200 m	Knapp et al., 2022; Xu et al., 2015
Eastern GoM	Horn Mountain	Sandstone/ Shale	Depleted Oil	114 Mt	4,191 m	Oudinot, 2022
Texas & LA Coast	Lake Pontchartrain	Sandstone/ Shale	Unknown	30 Mt	1,830 m	Zeidouni et al., 2022
Western GoM	Ship Shoal	Sandstone/ Shale	Depleted Hydrocarbon	2.88–38.2 Mt	2,300 m	Russel, 1973; Roux, 1987; Bruno et al., 2017; Alonso et al., 2022
Texas & LA Coast	South Marsh Island	Sandstone/ Shale	Unknown	285 Mt	2,987 m	Zeidouni et al., 2022
Western GoM	High Island	Sandstone + Shale Interbeds/ Shale	Depleted Hydrocarbon	0.4–1.8 Mt	2,421 m	Savage and Ozgen, 2017; Treviño et al., 2018; Treviño and Meckel, 2019
Western GoM	Vermillion South	Sandstone/ Shale	Depleted Hydrocarbon	1.1–5.3 Mt	1,005– 1,504 m	Savage and Ozgen, 2017; Treviño and Meckel, 2019
Texas & LA Coast	West Cameron	Sandstone/ Shale	Depleted Hydrocarbon	225–275 Mt	2,133 m	Savage and Ozgen, 2017; Treviño and Meckel, 2019; Zeidouni et al., 2022; Davis, 2022b

4.2.1 Brazos

Characterized by NITEC in 2017, the Brazos location in the GoM is comprised of depleted gas-bearing sands within the BA020A field (Savage and Ozgen, 2017). Two sands were assessed, the T and the AA which cover 1,674 and 482 acres, have a gas column of 67 and 61 ft, and reservoir thicknesses of up to 200 and 128 ft, respectively. These reservoirs are at 4,414 m true vertical depth (TVD) (Savage and Ozgen, 2017), the water depth is ~130 ft (BOEM, 2023) and estimated storage is 2.9–14.6 Mt. The AA sand has a 28% porosity and 1,003 mD permeability, and water saturation of 0.2; while the T sand has 25% porosity, 140 mD permeability, and water saturation of 0.3 (Savage and Ozgen, 2017).

4.2.2 Destin Dome

The primary target reservoir within the DeSoto Canyon Salt Basin surrounding Destin Dome is the Paluxy sandstone at approximately 2,000 m depth (Nemeth et al., 2019). The Paluxy sandstone increases to roughly 550 m within the salt withdrawal synclines surrounding Destin Dome, creating a stratigraphically sealed CCS reservoir. Porosity of the Paluxy sandstone in the Destin Dome area averages at approximately 21.5% according to geophysical logs associated with well G02468 (Nemeth et al., 2019; Berry et al., 2018).

4.2.3 Grand Isle CCS Site

Grand Isle is located in offshore Louisiana in 40–70 ft water depth (BOEM, 2023). Characterized by NITEC in 2017, the Grand Isle site in the GoM is comprised of depleted hydrocarbon sands within the GI020 field specifically the GI20_X sand which has a column height of 52 ft, porosity of 30%, permeability of 405 mD, and water saturation of 0.3 (Savage and Ozgen, 2017).

Grand Isle is the location of a CCS hub operated by Cox Operating LLC; a Dallas-based company expanding operations to include CCS (Fitzgerald, 2023). Repsol SA, Crescent Midstream, and Carbon-Zero US LLC are all partnering on the project.

4.2.4 High Island

High Island is located offshore Texas in the western GoM in 222 ft water depth (BOEM, 2023). Characterized by NITEC in 2017, the High Island site in the GoM is comprised of depleted hydrocarbon sands within the HI519A field. This field has four reservoir sands on two different closures at different depths with spatial complexity which made interpretation difficult (Savage and Ozgen, 2017). Low resistivity reading in the pay bearing sands resulted in low contrast, meaning that standardized resistivity cut offs used for interpretation were not effective in this location.

4.2.5 Horn Mountain

Horn Mountain is an active oil producing field 80 mi offshore of Louisiana in Mississippi Canyon Block 126 (Figure 9). Roughly 40% of the original oil in place was produced as of February 2022. The reservoir includes two stacked Middle Miocene sands labeled J and M, with M as the primary reservoir in an anticlinal structure with bounding faults on the north and east sides and an oil water contact at 14,300 ft. The M sandstone has a porosity of 27%, a permeability of 250 mD, and a net thickness of 132 ft. The J sandstone is a smaller reservoir.

The storage potential was assessed with a model that converted four production wells to CO₂ injection wells. The injection area was modeled at 31 mi² and the plume extended 11 mi². The assessment included uncertainty analysis for permeability, anisotropy, and injection rates (Oudinot, 2022).

4.2.6 Lake Pontchartrain

The Lake Pontchartrain site, located on the eastern side of the lake near Slidel (Figure 9), proposes to inject CO₂ into Lower Miocene shoreface sands that are 207-ft thick and sealed by overlying mudstones 132 ft (Zeidouni et al., 2022 within Wernette et al., 2022). Well logs show the storage zone at approximately 6,000 ft depth with a temperature of 144 °F and located between two bounding faults located in the northeast quadrant of the lake. The shoreface sands have a net-to-gross of 0.76, and a porosity of 33%. Injection was modeled in Petrel both statically and dynamically, the injection area proposed is 380 mi² and the resulting plume is 4.8 mi in diameter for the injection of 1 Mt/yr for 30 years (Zeidouni et al., 2022).

4.2.7 Mobile-Viosca Knoll

Initial assessment shows possible storage in the Paluxy Formation and the Tuscaloosa Group within the Mobile-Viosca Knoll area (Berry et al., 2018). Further assessment by Nemeth et al. (2019) described in the final SOSRA report by the SSEB that the ideal target formations for geologic storage of CO₂ in the Mobile-Viosca Knoll area would be the Washita-Fredricksburg interval and Lower Tuscaloosa Group. The Upper Tuscaloosa Group is a seal and is the same confining layer for nearby petroleum reservoirs.

4.2.8 Sarasota Arch

The Sarasota Arch area is located in the eastern GoM along the western Florida coast just south of the Tampa Embayment (Figure 9). The axial trace of the Sarasota Arch is northeast-southwest at approximately 210-km wide with a westward plunge of unconfirmed angle. The Sarasota Arch site contains some gaps in seismic data coverage, although information available was still considered sufficient for useful identification of geologic structures and basic reservoir estimations (Nemeth et al., 2019).

Assessment units include the porous dolomites of the Punta Gorda Formation (25% porosity; 87 m thickness) and Lehigh Acres Formation (18.5%; capped by Punta Gorda anhydrite top seal) in addition to limestones of the Cedar Keys (lower is dolomite reservoir, upper serves as anhydrite seal; depth 1,220 m), Lawson, and Upper Pine Key Formations. The Cedar Keys assessment unit comprised of porous carbonate has an average thickness of 610 m, the greatest thickness of any potential storage unit in the Sarasota Arch area (Nemeth et al., 2019).

Assessment by Gray et al. (2019a) considered five different units (Upper Cedar Keys, Lower Cedar Keys, Panther Camp, Gordon Pass, and Punta Gorda) for an overall regional estimated storage resource in the Sarasota Arch of 879 Gt CO₂ (Gray et al., 2019a). The reservoir cited as optimal for future development was the Lehigh Acres Formation dolomite reservoir at 3,200 m depth near the OCSG-3912 well with a p50 storage capacity of 5 Mt/km² (Gray et al., 2019a).

4.2.9 Ship Shoal Fields

Ship Shoals is located offshore Louisiana in the central part of the GoM. Assessment and modeling was completed for Miocene and Pliocene sandstones in the depleted Ship Shoals Fields 84 and 107, which have 20 and 77 wells, respectively. Storage was modeled for each of the fields independently for a 30-year injection timeframe with a p50 result of 47 Mt (Bruno et al., 2018). Risks for this site include three potential leakage mechanisms: tensile fracturing of the caprock, fault activation, and well damage.

4.2.10 South Marsh Island

South Marsh Island is located along the central Louisiana coast. The South Marsh Island Site has a Middle Miocene aged sandstone reservoir 262-ft thick paired with a 336 ft shale seal (Zeidouni et al., 2022). The reservoir is composed of fluvial sandstone with a net-to-gross ratio of 0.6, a temperature of 190 °F, and a porosity of 30%. The reservoir is 9,800-ft deep, and the injection area is 165 mi² (Zeidouni et al., 2022).

4.2.11 Vermillion South

Vermillion South is located in the central to western GoM in 240 ft water depth (Figure 9, BOEM, 2023). Characterized by NITEC in 2017, the Vermillion South site in the GoM is comprised of depleted hydrocarbon sands within the VR348 field (Savage and Ozgen, 2017). The field has five sands on two separate closures with column heights ranging from 13–33 ft (Savage and Ozgen, 2017).

4.2.12 West Cameron

The West Cameron Site is located in the southwest corner of Louisiana and the eastern corner of Texas near Beaumont and Port Arthur along the GoM coastline in 100 ft of water (Figure 9). It was characterized by NITEC in 2017 and is comprised of depleted hydrocarbon bearing sandstones within the WC420 field (Savage and Ozgen, 2017). Gas has been produced from six sands from two separate closures with column height thicknesses of 26, 6, 6, and 45 ft, respectively (Savage and Ozgen, 2017).

In addition to the NITEC assessment, the site was modeled in Petrel for storage potential (Zeidouni et al., 2022). The identified reservoir is Lower Miocene fluvial-dominated delta deposits at a depth of 1,000 ft. These shorefaces sandstones are 2,930 ft thick, have a net-to-gross of 0.62, and a porosity of 33%. The reservoir is 170 °F and the overlying Miocene shales that form the seal are 135-ft thick. Overall, the injection area is 39 mi² but has significant storage potential due to the reservoir sandstone thickness (Zeidouni et al., 2022).

Core samples (well OCS-G-3496#A-3) were analyzed for seal capacity and lithology and measured porosity ranging from 9.5–11.9% porosity, 0.0007–0.0001 mD permeability, and 2.14–2.69 g/cc grain density (Treviño and Meckel, 2019).

4.2.13 Woolsey Mound

The Woolsey Mound is roughly 1 km in diameter and located in Mississippi Canyon Block 118, along the slope transition, in an area with significant seafloor topography and rugosity due to underlying salt diapirism (Xu et al., 2015). Water depth in the area is 900 m (Knapp et al., 2022).

The Woolsey Mound differs significantly from other characterization sites because rather than storing CO₂ as a super critical fluid the potential storage would be as a solid CO₂-hydrate (Knapp et al., 2022). The CO₂ would be fixed in the sediment matrix, therefore theoretically there is no risk of leakage and no sealing mechanism required. Instead, the CO₂ is injected into the pore space previously filled with methane hydrates, allowing the seafloor to remain stable (Knapp et al., 2022).

Woolsey Mound differs from other gas hydrate occurrences because the basal stability depth of the methane hydrates is relatively shallow (~100 m) due to increased heat flow from an underlying salt dome (Xu et al., 2015).

Table 4: Summary of Reservoir Properties Associated with Geologic Storage Assessment Locations in the GoM

Location	Reservoir Name	Porosity (%)	Permeability (mD)	Water Saturation	Data Source
Brazos	AA	28	1,003	0.2	BA020A Field from Savage and Ozgen, 2017, Appendix 2 Depleted Fields Database
Brazos	T	25	140	0.3	BA020A Field from Savage and Ozgen, 2017, Appendix 2 Depleted Fields Database
Destin Dome	Paluxy Sandstone	21.5	No Data	No Data	Well G02468 from Nemeth et al., 2019; Berry et al., 2018
Grand Isle	GI020_X	30	405	0.3	GI020 Field from Savage and Ozgen, 2017, Appendix 2 Depleted Fields Database
High Island	ANG_B1	37	1655	0.1	HI519A Field from Savage and Ozgen, 2017, Appendix 2 Depleted Fields Database
High Island	TA1	34	51	0.5	HI519A Field from Savage and Ozgen, 2017, Appendix 2 Depleted Fields Database
High Island	TA2	36	372	0.3	HI519A Field from Savage and Ozgen, 2017, Appendix 2 Depleted Fields Database
High Island	SAR_H	34	1,429	0.1	HI519A Field from Savage and Ozgen, 2017, Appendix 2 Depleted Fields Database
Horn Mountain	M	27	250	No Data	Oudinot, 2022

Location	Reservoir Name	Porosity (%)	Permeability (mD)	Water Saturation	Data Source
Lake Pontchartrain	Lower Miocene	22	No Data	No Data	Zeidouni et al., 2022
Sarasota Arch	Punta Gorda	25	No Data	No Data	Nemeth et al., 2019
Sarasota Arch	Lehigh Acres	18.5	No Data	No Data	Nemeth et al., 2019
South Marsh Island	Middle Miocene	30	No Data	No Data	Zeidouni et al., 2022
Vermillion South	AB2	33	256	0.3	VR348 Field from Savage and Ozgen, 2017, Appendix 2 Depleted Fields Database
Vermillion South	AB3	30	55	0.5	VR348 Field from Savage and Ozgen, 2017, Appendix 2 Depleted Fields Database
Vermillion South	AB4	30	34	0.5	VR348 Field from Savage and Ozgen, 2017, Appendix 2 Depleted Fields Database
Vermillion South	F	28	302	0.2	VR348 Field from Savage and Ozgen, 2017, Appendix 2 Depleted Fields Database
Vermillion South	K	29	989	0.2	VR348 Field from Savage and Ozgen, 2017, Appendix 2 Depleted Fields Database
West Cameron	1700	36	1,708	0.2	WC420 Field from Savage and Ozgen, 2017, Appendix 2 Depleted Fields Database
West Cameron	6000	28	220	0.3	WC420 Field from Savage and Ozgen, 2017, Appendix 2 Depleted Fields Database
West Cameron	LENT1	27	718	0.2	WC420 Field from Savage and Ozgen, 2017, Appendix 2 Depleted Fields Database
West Cameron	PL_1	33	1,454	0.2	WC420 Field from Savage and Ozgen, 2017, Appendix 2 Depleted Fields Database

Location	Reservoir Name	Porosity (%)	Permeability (mD)	Water Saturation	Data Source
West Cameron	Lower Miocene	33	No Data	No Data	Zeidouni et al., 2022

4.3 PACIFIC NORTHWEST AND ALASKAN STORAGE REGION

The Pacific Northwest and Alaska are grouped for their locational proximity. However, the two regions have distinctly different geology and developmental histories, which will dictate their CCS perspectivity. While the North Slope of Alaska has well studied sedimentary basins, the Pacific Northwest margin is a narrow, young, continental shelf overlying basalt, with a limited and poorly developed sediment column.

While significant CO₂ storage potential has been suggested from a wide variety of offshore basins around Alaska (Shellenbaum and Clough, 2010), more detailed characterization has been performed for some possible reservoirs on the North Slope as well as the Cook Inlet Basin, both of which are historically prolific hydrocarbon producing regions (Craddock et al., 2014; Panteleone and Bhattacharaya, 2021). The North Slope has a long, complicated, and controversial history of oil and gas development. Extensional followed by compressional tectonics led to the deposition of eight mega-sequences making up the stratigraphy of the North Slope, of which the lower three, called Ellesmerian, are the focus of most oil and gas development (Hubbard et al., 1987). Consequently, they have the most data available for possible CCS assessments (Craddock et al., 2014). Alaska has a complex geologic history and is undergoing active plate subduction as well as extension at divergent plate boundaries. These ongoing tectonic activities could pose both challenges and benefits to potential CSS projects. Alaska is also home to an extensive fishing industry as well as commercial shipping, and tourism. These industries would be impacted by CCS development.

The Pacific Northwest region is tectonically young and composed of various igneous provinces, including large swaths of basalt, both onshore and offshore. As a result, the region has become a focus area for understanding and assessing potential CO₂ storage within basalts. The Cascadia CarbonSAFE project, described in detail in the following sections, is a detailed assessment of storage potential in offshore Washington State. Characterization efforts along other parts of the offshore Pacific coast have been limited. However, there was one detailed modeling assessment done in the offshore Los Angeles basin by SoCalCarb which is described in detail in the following sections.

Table 5: Summary of Geologic Storage Assessment Locations along the Pacific Margin and Alaskan North Slope

Sub-Region	Location	Reservoir/ Seal	Reservoir Type	Estimated Storage Resource	Depth	References
Southern California	Wilmington Graben	Sandstone/ Shale	Unknown	549 Mt	1,524 m	Childers, 2012; Bruno et al., 2014
Pacific Northwest	Cascadia CarbonSAFE	Basalt/ Shale	Basalt	50 Mt	470 m	Goldberg et al., 2018
Alaskan North Slope	Endicott Group	Conglomerate + Sandstone/ Shale	Depleted Oil	Unknown	3,412 m	Wicks et al., 1991; Craddock et al., 2014
Alaska	Cook Inlet Basin	Sandstone/ Shale	Depleted Hydrocarbon	0.91-16.61 Gt	3,078 m	Craddock et al., 2014; Panteleone and Bhattacharya, 2021

4.3.1 Wilmington Graben

The Wilmington Graben, offshore Los Angeles, California was assessed for CO₂ storage potential as part of the SoCalCarb project, which also looked at other prospects, primarily onshore in Southern California (Childers, 2012). The Los Angeles Basin historically has had prolific oil production and there are abundant CO₂ sources available with more than a dozen refineries and power plants in the area. Miocene and Pliocene interbedded sands and shales are proven reservoir-seal pairs for several billion-barrel oil fields, including the Wilmington Field in Long Beach which had produced more than two billion barrels in 2012. The same reservoir-seal pairs have been used for the underground storage of natural gas. The fault-bound Wilmington graben is located just offshore of Long Beach and makes a distinct trap, separating this storage play for other fields, including the Wilmington Field. The reservoir sands have a gross thickness of 3,000–3,500 ft and are modeled to store 549 Mt (Childers, 2012). An assessment in 2014 suggested 100 Mt storage (Bruno et al., 2014).

4.3.2 Cascadia CarbonSAFE

The feasibility of industrial-scale CCS in the Cascadia region was assessed in detail in 2018 and is one of the most comprehensively studied oceanic crust injection sites, the Cascadia Site, assessed as part of CarbonSAFE (Goldberg et al., 2018). Injection is proposed into basalts with permeabilities of 0.1 to 1 darcies and porosities of 10–20%. The target reservoir is the upper 600 m of the crust which has a lateral extent of 50–100 km. These basalts are sealed by a thin layer of fine-grained sediments composed of pelagic and turbidite sediments, varying in thickness based on the subsidence and the age of underlying crust. Laboratory testing indicates that carbonate mineralization occurs within these oceanic basalts in a similar manner to onshore basalts, with mineralization forming in dead-end fractures (Goldberg et al., 2018). CO₂ sources

and transport pathways have been mapped and described in detail for the region (Goldberg et al., 2018).

Existing data on this resource can be found on NETL's Energy Data eXchange (EDX): <https://edx.netl.doe.gov/dataset/cascadia-carbonsafe-data-inventory-list>.

4.3.3 Endicott Group (Alaska North Slope)

Lower Carboniferous in age, the Endicott Group is the basal unit in the Ellesmerian sequence that overlies basement on the North Slope of Alaska (Craddock et al., 2014). The succession was deposited in fault bound extensional basins (Hubbard et al., 1987; Wicks et al., 1991). The potential CCS reservoir for the Endicott Group is the basal Kekiktuk Conglomerate which is composed of braided fluvial sandstones as well as some other mixed, finer-grained siliciclastic material and coals (Craddock et al., 2014). Two play types/areas have been characterized for the Endicott Group on the North Slope, both of which target the Kekiktuk Conglomerate reservoir but have different sealing mechanisms.

The first play targets the Kekiktuk Conglomerate reservoir truncated by the overlying Lower Cretaceous Unconformity which eroded structural highs. In this play type, the seal is the Pebble Shale and the Itkilyariak Formation. (Craddock et al., 2014). The play area is 54,000 acres and with a reservoir depth of 11,200 ft with a gross reservoir thickness of 1,000 ft, and net-to-gross ratio of 0.35 resulting in ~350 ft of reservoir. The conglomerate is thought to be prospective due to secondary porosity from the overlying unconformity. The conglomerate has an average porosity of 12–25% and permeability measurements range from 0.02–10,000 mD. Salinity has been measured to 10,000 milligrams per liter (mg/L) (Wicks et al., 1991; Craddock et al., 2014).

The other play consists of the Kekiktuk Conglomerate reservoir paired with the overlying seal of the Kayak Shale which is a regional caprock (Craddock et al., 2014). Areas with greater than 100 ft of Kayak Shale were considered prospective. The extent of the play is limited to areas where the conglomerate may have secondary porosity, making up 365,000 acres of the North Slope. The reservoir is at 11,500 ft depth and has a general thickness of 460 ft. Net-to-gross is 0.38 resulting in 175 ft of reservoir. Porosity ranges from 8–18% and permeability ranges from 0.02–1,200 mD. Salinities have been measured at 10,000 mg/L but may be higher or lower locally (Wicks et al., 1991, Craddock et al., 2014).

4.3.4 Cook Inlet

The Cook Inlet is a non-marine forearc basin within an intermontane graben trending north-northwest (Craddock et al., 2014). The basin fill is composed of a Tertiary sedimentary succession including the Hemlock Conglomerate and siltstones of the West Foreland formation, as well as other sandstones, siltstones, and shales from the Tyonek, Beluga, and Sterling Formations (Magoon, 1994, Craddock et al., 2014). The Cook Inlet has been actively developed for both oil and gas for five decades (Panteleone and Bhattacharrya, 2021). These hydrocarbon systems have Tertiary-aged reservoirs and are sourced from the Middle Jurassic Tuxedni Group (Magoon, 1994, Craddock et al., 2014). Many of these fields are in decline and already undergoing enhanced oil recovery (EOR). There are several point sources of CO₂ near the basin including refineries and other industrial facilities in the Anchorage area (U.S. Environmental Protection Agency (EPA) Flight Data).

The basin contains a series of en echelon anticlines which have been identified as potential structural traps for CO₂ at 3,078-m depth (Craddock et al., 2014). Detailed characterization of eight oil fields suggests 0.91–16.61 Gt of potential storage (Pantaleone and Bhattacharrya, 2021). The Hemlock sandstone reservoir has a 14.3% porosity and a permeability of 0.18 mD (Pantaleone and Bhattacharrya, 2021).

5. INTERNATIONAL REGULATORY FRAMEWORKS FOR OFFSHORE CCS

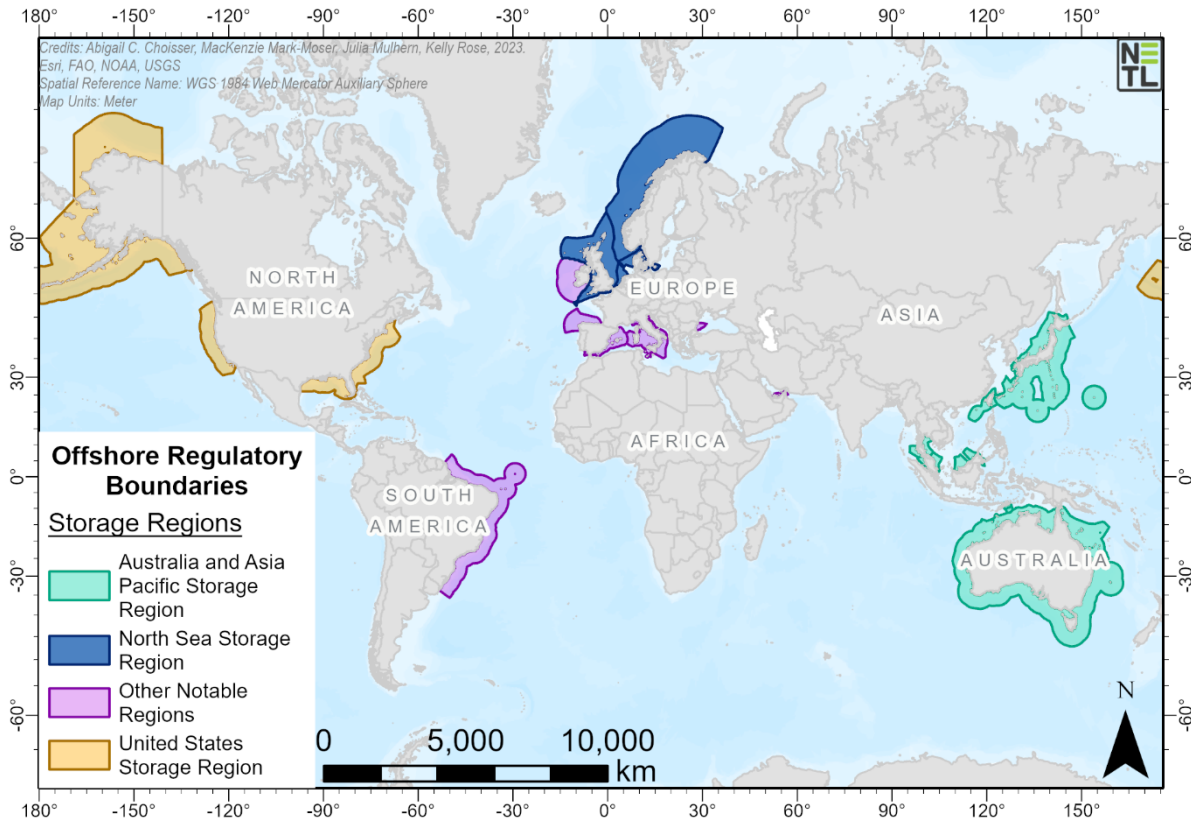


Figure 10: International regulatory boundaries for offshore CCS projects.

5.1 GLOBAL REGULATORY ENTITIES

To facilitate the process of exchanging information resources, organizations have been established over the years to assist with the development of GCS projects and provide insight on global regulatory progression through publication of annual reports, data repositories, and public registers. The International Energy Agency (IEA) provides one such data resource where connections to existing regulatory documentation are organized by issue and country, with a brief summary of each regulation provided (IEA, 2022a). Efforts to accelerate the global development of CCS technology have led to the establishment of the Global CCS Institute and the subsequent compilation of the CO₂RE Database which provides a valuable resource that includes updates on policy, legal, and regulatory information relating to CCS activities (Global CCS Institute, 2018). For the purposes of this review, regulatory frameworks are discussed in regard to organizations and regulatory authorities with the most prolific offshore CS portfolios in their respective regions.

Adherence to restricting authority to a country's EEZ is consistently established by regulators globally. Boundaries recognized by international regulatory authorities are similar to specifications followed by BOEM and BSEE in the U.S. as OCS Federal jurisdiction. Within the U.S., offshore federal jurisdiction is bound between coastal states' submerged land and the seaward extent of the U.S. EEZ. BOEM has released a Best Practices Manual on the topic of

offshore CCS and is in the process of developing regulations for offshore CCS operations per the U.S. Infrastructure Investment and Jobs Act (Smyth and Havorka, 2018; Infrastructure Investment and Jobs Act, 2021).

5.1.1 The North Sea

GCS projects within the North Sea are governed by the country possessing regulatory authority within the EEZ of that location. The United Kingdom Continental Shelf (UKCS) exists within the perimeter of the UK's EEZ, and UK GCS regulations are enforced by the North Sea Transition Authority. The Norwegian North Sea is similarly defined by Norway's EEZ, and regulatory issues are handled by the Norwegian Petroleum Directorate. Denmark and The Netherlands have regulatory authority over the Danish and Dutch North Sea according to their respective EEZ boundaries, though as members of the EU, regulatory guidance is provided through the European Commission (EC).

5.1.1.1 European Commission

Several regulatory frameworks have been developed based upon the *EU Directive 2009/31/EC on the geological storage of carbon dioxide*. The directive allows adjustments to be made as local regulatory authorities see fit. Such changes as those allowed by flexibility in the EU Directive 2009/31/EC are specifically focused on permitting regulators to restrict CCS projects more heavily as they deem appropriate.

EU Directive 2009/31/EC amended several pre-existing directives in force to include considerations for CCS implementation and regulation such as: *EU Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment* to include—through amendment of EU Directive 85/337/EEC—considerations for offshore infrastructure and pipeline standards; *EU Directive 2000/60/EC establishing a framework for Community action in the field of water policy* specifying CO₂ injection should follow guidelines included within EU Directive 2009/31/EC; and *EU Directive 2010/75/EU on industrial emissions (integrated pollution prevention and control)* by way of amendment to *EU Directive 2001/80/EC* – to require combustion plants producing over 300 MW to assess the economic feasibility of implementing CCS practices. Amendments from the EU Directive 2009/31/EC also included changes to *EU Directive 2004/35/EC on environmental liability with regard to the prevention and remedying of environmental change* to include language describing operation of GCS sites should be managed according to the EU Directive 2009/31/EC, *EU Directive 2008/1/EC on ambient air quality and cleaner air for Europe* to include CCS regulations are according to EU 2009/31/EC, and to *Regulation (EC) No 1013/2006 on shipments of waste* excluding shipments of CO₂ meant for GS from the regulation.

Maintenance of permanent registers detailing locations of closed storage sites, surrounding prospective storage complexes, maps, and information necessary to assess the security of permanently stored CO₂ must be retained and updated by national authorities (EU, 2009).

5.1.1.2 North Sea Transition Authority

Terminology within *The Storage of Carbon Dioxide (Licensing, etc.) Regulations 2010* aligns closely with definitions contained within the EU Directive 2009/31/EC, except for where references of the Exploration Permit are described as the “Appraisal Term.” This Appraisal Term is optional if sufficient assessments have been performed, being replaced by an “Initial Term”

where waived. An application for a storage permit must be submitted before the Appraisal or Initial Terms have ended. Requirements for environmental impact assessments and monitoring standards within UK Legislation (UK Statutory Instruments, 2010) defer to the guidelines outlined within the EU Directive 2009/31/EC and include considerations for land protection and sustainable development (IEA, 2022b).

The North Sea Transition Authority (NSTA), appointed as regulatory authority within the UK, has maintained public registers containing detailed CS permit information. This public register resource provides details relating to storage sites, permit terms and conditions, all past and present license holders and supervisors, any modifications made to the terms and conditions, and license termination/revocation dates and associated rationale as is required within register documentation (NSTA, 2022; UK Statutory Instruments, 2010).

5.1.1.3 Norwegian Petroleum Directorate

The NPD handles regulatory matters within the Norwegian EEZ according to *Regulations relating to materials and documentation in connection with surveys for and utilization of subsea reservoirs on the continental shelf to store CO₂* (NPD, 2018 English Translation). This regulation identifies requirements for surveys, drilling and well activity, material and documentation handling, notification, and reporting.

The Diskos online database is maintained by the Norwegian Petroleum Directorate to facilitate report submission, data transfer, and public access. Types of data contained within the Diskos online repository include approximately 11.5 petabytes of seismic, well, and monthly production data as it relates to the Norwegian Continental Shelf. It is noted that raw or composite data is not made publicly available for two years, and interpreted data is not to be released for 20 years due to confidentiality (NPD, 2022).

5.1.2 Australia and Asia Pacific

Regulatory frameworks within the EEZ of Australia are enforced by the National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA) (Commonwealth of Australia, 2023). Coastal waters within 3 nautical miles of Australia are regulated by local governing bodies through legislation such as the *Barrow Island Act 2003* in Western Australia (Western Australia, 2016), the *Greenhouse Gas Geological Sequestration Act 2008* in Victoria (Chief Parliamentary Counsel, 2021), and the *Greenhouse Gas Storage Act 2009* in Queensland (State of Queensland, 2022).

Other regulatory authorities in this region, such as those within the Taiwan Province of China, have been in the process of developing the *Climate Change Response Act* (EPA, 2023) through an interdepartmental effort, while Thailand has established the National Committee on Climate Change Policy (NCCC) to focus their integration of climate change policies and legal regulations (Office of Natural Resources and Environmental Policy and Planning, 2022). Meanwhile, Japan and Malaysia have utilized or modified pre-existing regulatory infrastructure to accommodate CCS operations until more specific laws can be established (JCCS, 2020).

5.1.2.1 NOPSEMA

The Australian Government requires that a sea dumping permit be acquired before CO₂ can be stored through CCS operations according to the *Environment Protection (Sea Dumping) Act 1981*, which regulates storage of CO₂ in offshore subsurface reservoirs. Additional regulation of

GCS operations can be found in the *Offshore Petroleum and Greenhouse Gas Storage Act 2006* (Office of Parliamentary Counsel, 2019).

Supporting the 2006 Act, five regulations were compiled to address specific matters with additional detail. The *Offshore Petroleum and Greenhouse Gas Storage (Greenhouse Gas Injection and Storage) Regulations 2011* include specification of details required when applying to declare part of a storage formation as suitable for GCS, site planning information, incident reporting direction, and decommissioning requirements (Office of Parliamentary Counsel, 2020). The *Offshore Petroleum and Greenhouse Gas Storage (Resource Management and Administration) Regulations 2011* discuss the process for assessment reports and required information, development of well operation and management plans, data management expectations and handling of technical data (Office of Parliamentary Counsel, 2023b). Within the *Offshore Petroleum and Greenhouse Gas Storage (Environment) Regulations 2009*, direction is given regarding the project proposal process, requirements for environment plan development and submission, expectations for financial assurance, incident reporting and record keeping as it relates to plan execution (Office of Parliamentary Counsel, 2023a). The *Offshore Petroleum and Greenhouse Gas Storage (Safety) Regulations 2009*, provides information regarding operator nomination and registration procedures, required considerations for development of a safety management system including safety standards to be applied, emergency handling information, validation process for facility design and management, and record-keeping requirements (Office of Parliamentary Counsel, 2023c). The *Offshore Petroleum and Greenhouse Gas Storage (Regulatory Levies) Regulations 2004* handles issues relating to fees associated with safety investigations, safety management system applications, wells and well activity, annual titles, and environment plans (Office of Parliamentary Counsel, 2022).

Regulatory functions associated with titling and resource management are conducted by the National Offshore Petroleum Titles Administration, which handles the application and titling process for GHS storage activities and publishes information to the online National Electronic Approvals Tracking System (NEATS) where title and application information is publicly available (NEATS, 2023).

5.1.2.2 Climate Change Response Act

Revised in 2023 and previously known as the *Greenhouse Gas Emission Reduction Act of Taiwan*, the *Climate Change Response Act* details the authority and responsibility of named government agencies towards the goal of meeting GHG reduction commitments including implementation of GHG reduction credits, and the minimum requirements for CO₂ storage applications, operation, and monitoring. The regulating authority is noted as reserving the right to implement more detailed regulations upon consultation with industry regulators on a case-by-case basis as long as the minimum requirements described in the *Climate Change Response Act* are satisfied.

5.1.3 Other Regions for Consideration

Regulatory entities within other notable storage regions throughout the world vary greatly both spatially and in regulatory structure. Members of the EU with GCS projects outside the North Sea rely on the guidance provided in the EU Directive 2009/31/EC. One of the longest-running CO₂ storage efforts is located in the offshore Santos Basin of Brazil, wherein regulatory authority is handled by the Brazilian Inter-Ministerial Committee on Climate Change (CIM) as

described in the *Brazilian Atlas of CO₂ Capture and Geological Storage* from 2014 (Ketzer et al., 2015). In storage regions such as the Persian Gulf, existing hydrocarbon industry rules and regulations are still utilized by the Gulf Cooperation Council States, although it has been noted that CCS-specific regulations still require development (Global CCS Institute, 2018, 2022; Tsai, 2014).

6. ENVIRONMENTAL, COMMERCIAL AND SOCIAL CONSIDERATIONS

Implementation of offshore CCS interacts with numerous other environmental, commercial, and industry interests. This section reviews potential interactions amongst these sectors. Each subsection notes key references to publications or other resources regarding their topic. However, it should be noted that this is not a comprehensive review of these topics.

6.1 ENVIRONMENTAL MONITORING

Due to the similarities in operations and infrastructure, many of the potential environmental impacts of offshore CCS mirror those of petroleum operations such as hazardous fluid or gas release and ecological disturbances (Austell et al., 2013). A key concern for the environmental impact of CCS is the potential for CO₂ leakage during sequestration operations and after the project is completed. Characterizing the site to understand natural fluctuations and migrations of gases and fluids is key to detecting perturbations that may indicate CO₂ leakage (Blomberg et al., 2021). In the North Sea, monitoring may be required for 25 years post-injection which has led to significant CO₂ storage monitoring research and monitoring guidance (Furre et al., 2018). Numerous strategies involving seismic data acquisition can be used to monitor CO₂ leakage and induced seismicity, including onshore seismic networks that may detect offshore seismic activity, marine seismic survey via boat (streamer survey) to image acoustic contrast within CO₂-saturated reservoirs, acoustic surveillance to detect gas migration from the seabed, and ocean bottom nodes providing permanent seismic reservoir monitoring (Furre et al., 2018). Three projects known as QICS (Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage), ETI MMV (Energy Technologies Institute Measurement, Monitoring and Verification of CO₂ Storage), and STEMM-CCS (Strategies for Environmental Monitoring of Marine CCS) produced valuable insights from 12 years of offshore CO₂ storage monitoring, including experiments of controlled CO₂ release (Blackford et al., 2015; Dean et al., 2020). Additional monitoring techniques include sub-bottom profilers, passive acoustic sensors, chemical sensors, oceanographic and metocean sensors, in-situ wet lab procedures, and eddy covariance analysis (Blomberg et al., 2021). A recent study demonstrating monitoring techniques using an artificial CO₂ release detected non-catastrophic CO₂ leaks below levels of environmental damage (Connelly et al., 2022).

6.2 ENERGY INDUSTRY

The offshore environment has great potential to support multiple energy industries, including wind, wave, tidal, solar, and hydrogen in addition to petroleum and CCS activities (e.g., Zhang et al., 2022; Peters et al., 2020). Offshore areas that have produced petroleum such as the GoM are populated with energy infrastructure, including platforms, rigs, and pipelines. The advent of offshore renewable energy such as wind, wave, and tidal energy will continue to supply infrastructure to areas of economic interest in the offshore. Offshore CCS operations will require interaction with these industries, competition for offshore lease space, and potential co-use or reuse of infrastructure resources. Where CCS will be accomplished via CO₂ sequestration in depleted hydrocarbon reservoirs or stacked plays, infrastructure such as platforms, wells, and pipelines may be reused (e.g., Sachde et al., 2022, Dyer et al., 2022).

Establishment of offshore wind turbines and other energy infrastructure has the potential to interfere with site characterization and monitoring for offshore CCS due to obstruction of seismic survey transportation and noise interference (Furre et al., 2018). These interferences

could be reduced with the installation of ocean bottom nodes for monitoring, which are significantly more expensive than traditional seismic surveys conducted via boat.

6.3 TOURISM AND FISHING INDUSTRY

Potential impacts to the tourism and fishing industries are similar to those of offshore petroleum operations in terms of the visual presence, operational noise, physical deterrents to fish stock, and environmental dangers of chemical releases. Visual impacts of infrastructure upon ocean vistas are often a concern for coastal tourism, such as in the case of wind farms (Smythe et al., 2020); however, little research has been conducted regarding visual impacts of CCS operations.

The physical presence of new CCS infrastructure, their associated fishing exclusion zones, and the acoustic impacts of site characterization and operations may hinder offshore fishing efforts. In the U.S., the range of protected species, Marine Protected Areas, and access to traditional fishing areas by tribal and indigenous communities are considerations for offshore CCS siting.

Unintended releases of CO₂ or associated drilling fluids could impact fishing stock negatively. However, such releases in ongoing offshore operations have been rare and current studies indicate nominal impact when CO₂ leakages are small to medium compared to the impact of oil spills (Dean et al., 2020). Offshore energy infrastructure has proven to support colonies of fish, including species of commercial interest, and invertebrates as artificial reefs (e.g., Todd et al., 2020).

7. NEXT STEPS AND GAPS IN KNOWLEDGE

Offshore CS projects have been established worldwide to address the global need for decarbonization. International projects range from early site characterization, to injection, to post-injection monitoring stage, with the most mature projects found in the North Sea. Projects in the U.S. are nearly all in the characterization phase, with one site in the GoM that has advanced to early development. Data availability and offshore CS sites are most abundant in areas that have previously been explored for petroleum production, especially clastic sedimentary systems.

There are many potential configurations of offshore CS. Depending on industrial and regulatory needs, offshore CS may be utilized to reduce an entity's emissions via ship or pipeline transport, as an adjunct to other energy production, e.g., hydrogen and petroleum, and so on.

Internationally, offshore CS projects may stand alone as carbon sequestration sites or may have a multi-purpose or multi-user approach. Multi-user storage hubs such as those being developed in Australia as part of the deepC project (Cavcic, 2023) take the approach of international collaboration and leverage it as a valuable opportunity. Countries that may be looking to offset their emissions through cross-border ship or pipeline transport could be considered an effective redundancy plan for CCS or GCS in early and advanced planning stages. This collaboration internationally opens the door to offer CO₂ emission sources in regions where domestic emitters are less prevalent, but the needs of neighboring countries may be significant (Dickel, 2022).

The multi-purpose and multi-approach nature of offshore CS would benefit from additional comprehensive reviews and meta-analyses of each section of this report. Comparison of analogous subsurface and ecological systems models from mature offshore CS projects can inform regions and potential sites in the earlier characterization stage. Significant data gaps where target reservoirs are not located adjacent to active or depleted hydrocarbon systems could be addressed by using data science and analytics to update subsurface interpretations and characterize these regions.

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Sean I. Plasynski

Director, Acting
National Energy Technology Laboratory
U.S. Department of Energy

Mark McKoy

Advanced Carbon Technology Manager
National Energy Technology Laboratory
U.S. Department of Energy

William Aljoe

Carbon Storage Infrastructure Technology
Manager
National Energy Technology Laboratory
U.S. Department of Energy

Dawn Deel

Carbon Storage Project Manager
Technology Development Center
National Energy Technology Laboratory
U.S. Department of Energy

Darin Damiani

Carbon Storage Program Manager
Office of Carbon Management
U.S. Department of Energy

Bryan Morreale

Executive Director
Research and Innovation Center
National Energy Technology Laboratory
U.S. Department of Energy