Beyond

Recommendations for Offshore CO_2 Storage

Improving Outcomes and Minimizing Negative Environmental and Social Impacts



November 2026

CONTENTS

3 **ACKNOWLEDGEMENTS**

4 **EXECUTIVE SUMMARY**

8 **APPLICABILITY TO DECARBONIZATION PATHWAYS**
Relevance to Decarbonization Goals
Applicability to CO_2 Reduction Pathways
Applicability to CO_2 Removal (CDR) Pathways
Offshore Storage Ecosystem

12 **CONTEXT ON OFFSHORE STORAGE**
Geological Storage Estimated Capacity
Current Geological Storage Hub Development
Offshore Storage Management Life Cycle

15 **REGULATORY AND CARBON MARKETS ALIGNMENT**
Overview of Regulatory Frameworks Applicable to Offshore Storage
Overview of Carbon Market Standards Applicable to Offshore Storage

19 **IMPACTS AND ASSOCIATED SAFEGUARDS**
Summary of Potential Impacts and Corresponding Safeguards
Understanding Impacts of CO_2 Leakage
Understanding Impacts of Active Seismic Geophysical Surveys

33 **RECOMMENDATIONS CHECKLIST**

37 **ACTIONABLE OPPORTUNITIES**

39 **CONCLUSION**

40 **APPENDIX**
Footnotes

ACKNOWLEDGEMENTS

The Beyond Alliance would like to thank and acknowledge the individuals and organizations below for their expert contributions in developing this report:

CONTRIBUTORS

Meta	Patrick Nease
Chlorophyll	Sarah Garic
Commonwealth Scientific and Industrial Research Organisation (CSIRO)	Mrinal Sinha Erdinc Saygin Andrew Ross Linda Stalker Charles Jenkins Tess Dance
Woods Hole Oceanographic Institution (WHOI)	Aran Mooney Matthew Long
Northern Lights	

ABOUT THE BEYOND ALLIANCE

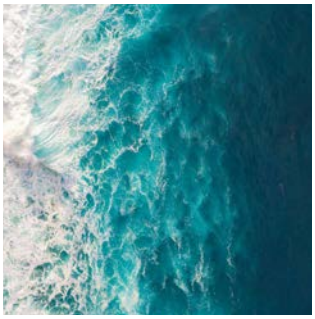
Beyond brings together leading companies, NGOs, and other expert partners to make corporate climate investment go further. Founded in 2020 and hosted by the We Mean Business Coalition, we are an independent platform that helps companies move from climate commitment to climate action.

We equip companies with the knowledge and tools to invest with confidence, bring members together for trusted peer exchange, and help shape the voluntary standards and policies that make market-based climate investment possible — moving further and faster toward a net zero future.

Learn more at beyond-alliance.org.

EXECUTIVE SUMMARY

Public and private actors are likely to encounter carbon reduction and removal opportunities that leverage geological offshore storage pathways. This report assesses the potential environmental and social impacts of dedicated offshore carbon dioxide (CO_2) storage projects and describes existing and potential strategies for safe and secure operation in a decarbonization context.







CO_2 STORAGE SCOPE

Dedicated geological offshore CO_2 storage represents a scalable storage pathway aligned with decarbonization and net zero goals. The term "dedicated" is indicative of utilization of saline or depleted hydrocarbon reservoirs solely for storage purposes rather than in combination with enhanced oil recovery (EOR). This report exclusively addresses dedicated geological offshore CO_2 storage, which is hereby referred to as offshore storage.

ROLE

This report summarizes perspectives from international regulatory bodies and standard organizations, the scientific community, the industry, and end buyers in a condensed and accessible review of offshore storage impacts. The report then presents actionable recommendations to maximize positive outcomes and minimize negative impacts. The integration of multidisciplinary perspectives is described below:

Regulatory bodies and standard organizations > *Recommendations build upon regulatory frameworks and standards and identify opportunities to improve environmental and social outcomes:* Existing and developing global and national regulatory frameworks as well as modules and methodologies from Isometric and Verra applicable to offshore storage are summarized in this report. All recommendations in this report build upon requirements of the identified existing offshore storage regulatory frameworks and standards.

Scientific community > *Recommendations integrate lessons from a comprehensive literature review and support the development of field trials of low-impact monitoring technologies:* There is a significant body of scientific literature evaluating potential impacts, mitigation strategies, and proven and emerging monitoring approaches and technologies related to offshore storage. Through contributions from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Woods Hole Oceanographic Institution (WHOI), the report provides a literature review and highlights the recurrent theme of supporting further site-specific, species-specific field research.

Industry > *Recommendations integrate lessons from and are designed to be actionable in commercial project contexts:* Through contributions from Northern Lights, a global leader in commercial offshore storage, all recommendations are designed to be actionable and practical in commercial contexts.

End-buyers > *Recommendations integrate lessons from and are designed to be a support tool in due diligence processes:* Contributions from corporate buyers of carbon removal credits enable the recommendations to respond to open buyer questions and provide a checklist tool for due diligence processes.

EXECUTIVE SUMMARY

CONTENT

The report addresses the following subjects:

Applicability: Explores the applicability of offshore storage to carbon reduction and removal pathways

Context: Provides context on offshore storage capacity and project development

Regulatory frameworks and standards: Summarizes existing regulations and carbon market standards applicable to offshore storage

Environmental and social impacts and safeguards: Builds awareness of environmental and social impacts and the strategies to maximize positive outcomes and minimize negative impacts

Recommendations Checklist: Delivers a Recommendations Checklist to guide responsible investment in and scaling of offshore storage projects

FINDINGS

Overall, this report identifies environmental and social recommendations that can support the development and operation of offshore storage projects. Key findings and associated opportunities presented in this report are:

Offshore storage projects are highly site-specific: The development of the subsurface assessment, understanding of potential impacts on the ecosystem and communities, CO_2 and environmental monitoring plan, and design of safeguards must be highly site-specific. There is an opportunity to foster increased sharing of project lessons, including lessons specific to individual project sites and common across all projects, through cross-sector collaboration.

Existing and developing regulations provide a foundation for improving outcomes and minimizing potential negative impacts: Existing offshore storage regulatory frameworks generally require site-specific subsurface and operations plans, environmental and social impact assessments, demonstration of financial accountability, and CO_2 and broader environmental monitoring. These frameworks and associated regulatory enforcement provide the foundation to maximize environmental, social, and economic outcomes and mitigate risks. It is expected that existing national frameworks will shape the development of regulations in countries that do not currently have regulatory schemes applicable to offshore storage.

Several factors contribute to safe storage: Overlapping factors and activities tailored to the unique project site contribute to safe CO_2 sequestration. These include project operational expertise and accountability, subsurface physical and chemical processes, risk and impact assessments, and risk-optimized monitoring. Storage integrity and safe operations can be maintained through appropriate project management of these factors and collaboration with regulatory, community, and other offshore storage stakeholders.

Integration of low-impact, risk-optimized monitoring technologies and approaches in the field will support benchmarking and advance understanding of impacts and the design of effective safeguards: There is a need to test emerging CO_2 and environmental monitoring techniques in field trials, preferably in commercial offshore storage project settings, alongside the deployment of proven techniques. Such monitoring technologies, examples of which are provided in ***Table 7***, have the potential to further prevent unexpected CO_2 behaviors, reduce potential negative environmental and social impacts, and optimize costs.

EXECUTIVE SUMMARY

RECOMMENDATIONS CHECKLIST

A proposed checklist of key elements of storage, environmental, and social safety for offshore storage projects at or near operational phase is provided below. These recommendations build upon existing regulatory frameworks and standards applicable to offshore storage. Importantly, each recommendation is presented in the format of a question with accompanying example documentation that operators could develop to address each topic. Please reference ***Table 8*** for a detailed version with resource examples and frameworks.

PROJECT PLAN COMPONENT	RECOMMENDATIONS CHECKLIST - QUESTIONNAIRE
1 **Project Expertise and Accountability**	☐ **Project expertise:** Does the project have the appropriate cross-sector expertise to manage onshore and offshore project parameters over the lifetime of the project? ⏩ ***Example Documentation:*** *Applicable licenses and permits; cross-sector team profile; previous offshore storage experience* ☐ **Financial accountability:** Does the project demonstrate financial accountability for the lifetime of the project, including capital to integrate any remediation measures? ⏩ ***Example Documentation:*** *Demonstration of sufficient financial capital*
2 **Subsurface Assessment**	☐ **CO_2 containment:** Did the project assess CO_2 containment integrity through a site-specific subsurface assessment of geological and well-related potential leakage paths? ⏩ ***Example Documentation:*** *Geological models and reservoir simulations that predict the movement of CO_2 and demonstrate containment* ☐ **Potential for induced seismicity:** Did the project assess the potential for induced seismicity or earthquakes in the impacted area due to pressure changes associated with CO_2 injection in the reservoir? ⏩ ***Example Documentation:*** *Baseline and expected seismicity for the impacted area; pressure and microseismic management programs* ☐ **Risk management:** Did the project assess site-specific CO_2 leakage and other subsurface risks, potential consequences, and the likelihood of occurrence and implement corresponding risk mitigation strategies? ⏩ ***Example Documentation:*** *Risk management plan for CO_2 leakage and other subsurface hazards*
3 **Environmental and Social Impacts**	☐ **Regulatory jurisdiction:** Is the project operating within a jurisdiction characterized by robust and enforceable safety regulations for offshore storage? ⏩ ***Example Documentation:*** *Relevant regulatory frameworks* ☐ **Stakeholder engagement:** Does the project integrate stakeholder engagement with all impacted communities, notably Indigenous communities and vulnerable groups, over the lifetime of the project? ⏩ ***Example Documentation:*** *Stakeholder engagement mechanism* ☐ **Environmental and social baseline assessment:** Did the project conduct a site-specific assessment of baseline environmental and community parameters in the impacted area? ⏩ ***Example Documentation:*** *Environmental and social baseline assessment* ☐ **Environmental and social impacts & safeguards:** Did the project assess site-specific, potential environmental and social impacts associated with the lifetime of the offshore project (e.g., site assessment and development, CO_2 injection and associated monitoring, and post-injection monitoring activities), identify the likelihood of occurrence, and implement safeguards for all potential negative impacts, notably potential negative impacts related to anthropogenic sound and impacts to endangered species? ⏩ ***Example Documentation:*** *Environmental and social impact assessments with actionable safeguards*

Continued on next page

PROJECT PLAN COMPONENT	RECOMMENDATIONS CHECKLIST - QUESTIONNAIRE
4 **CO_2 and Environmental Monitoring**	☐ **CO_2 & environmental monitoring plan:** Does the project have a site-specific, risk-optimized CO_2 and environmental monitoring plan that has been approved by the relevant national authorities and/or verified by relevant third party auditors? ⏩ ***Example Documentation:*** *CO_2 and broader environmental monitoring plan with proof of approval and/or verification* ☐ **Maintenance & leakage response plans:** Does the project integrate site-specific maintenance and leakage response plans (inclusive of onshore and offshore infrastructure)? ⏩ ***Example Documentation:*** *Maintenance and leakage response plans*
5 **Drilling and Wells**	☐ **Drilling permits and licenses:** Has the project secured the required competence to safely plan and drill wells into the storage site, including well control procedures in the case of unexpected behavior? ⏩ ***Example Documentation:*** *Relevant permits and licenses* ☐ **Well architecture and barriers:** Has the project selected a fit-for-purpose well architecture that achieves project targets and ensures that barriers to vertical CO_2 migrations are in place? ⏩ ***Example Documentation:*** *Relevant permits and licenses* ☐ **Well abandonment:** Does the project have criteria for well abandonment that ensures long-term stability? ⏩ ***Example Documentation:*** *Relevant permits and licenses*
6 **Continuous Improvement**	☐ **Monitoring plan updates:** Does the project regularly assess the effectiveness of its site-specific, risk-optimized CO_2 and environmental monitoring plan? ⏩ ***Example Documentation:*** *Regular process to update the monitoring plan* ☐ **Feedback and adjustment mechanisms:** Does the project integrate continuous improvement mechanisms with regards to environmental and social impacts? ⏩ ***Example Documentation:*** *Community feedback integration mechanism(s); process to monitor for unintended environmental and social impacts and adjust operations accordingly* ☐ **Field trials:** Does the project's CO_2 and environmental monitoring plan integrate field trials of emerging, low-impact monitoring technologies? ⏩ ***Example Documentation:*** *Process to identify and field test emerging, low-impact monitoring technologies as research develops*

APPLICABILITY TO DECARBONIZATION PATHWAYS

RELEVANCE TO DECARBONIZATION GOALS

Emissions reduction and CO_2 removal projects play a crucial role in supporting net zero goals aligned with the international Paris Agreement.[1] The Intergovernmental Panel on Climate Change (IPCC) identifies carbon removal paired with sequestration in geological reservoirs as a key lever in limiting warming to 1.5°C.[2] Fundamentally, both reduction and removal pathways can involve the durable storage of the resulting CO_2. Examples include: **(i)** point-source or flue gas capture and storage of petroleum-derived CO_2 in a reduction project and **(ii)** bioenergy with carbon capture and storage or direct air capture and storage in a removal project. The dominant storage approach is storage in subsurface geological reservoirs, either saline aquifers or depleted hydrocarbon fields. A summary of the relevance of offshore storage to decarbonization investments is summarized below:

1

Geological storage is a pivotal part of limiting warming to 1.5°C and Net Zero Emissions by 2050: As the IPCC identifies in their Global Warming of 1.5°C report, "All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1,000 Gt CO_2 [gigatonnes of CO_2] over the 21st century."[2] The International Energy Agency (IEA) estimates that 95% of the 7.6 gigatonnes/year (Gt/yr) of captured CO_2 will need be stored in onshore and offshore geological storage in the *IEA Net Zero Emissions by 2050 Scenario*.[3]

2

The first dedicated storage hub is in operation and additional are under development: There is active development of dedicated onshore and offshore storage hubs. These hubs enable economies of scale by aggregating CO_2 from multiple suppliers and aiming for the injection of stable volumes year-round. For example, Northern Lights, located on the western coast of Norway, commenced operations in 2025 and collects marine shipments of CO_2 prior to storage in a North Sea reservoir.[4] Additional hubs are expected to launch operations in the upcoming years.[5] ***Figure 2*** in Section 4 provides examples of active and planned dedicated offshore storage hubs.

3

Offshore is faring better than onshore in overcoming investment hurdles in the near-term: Currently, offshore hubs are generally progressing to operations commencement more rapidly than onshore hubs, particularly notable in the European context. Potential factors supporting this trend include: global acceptance from regulatory bodies and the United Nations; widely distributed offshore oil and gas infrastructure, geological data availability, and expertise that can be applied to CO_2 storage; and reduced land-permitting challenges as compared to onshore sites. Some countries, such as the United States and Australia, are pursuing a mixed onshore-offshore investment approach.

4

Current opportunity to shape risk-based approaches prior to scaling of offshore storage: Now is the pivotal moment to shape offshore storage approaches as global hubs are coming online and regulatory and voluntary schemes are developing. Given the economic environment for carbon capture and storage (CCS) projects, all parts of the CCS value chain must optimize cost to secure investable projects and limit reliance on public funding. Risk-based approaches enable developers to reduce potential negative environmental and social impacts while also maintaining focus on costs.

APPLICABILITY TO DECARBONIZATION PATHWAYS

APPLICABILITY TO CO_2 REDUCTION PATHWAYS

To achieve emissions reduction, CO_2 captured from natural gas plants or hard-to-abate industrial processes (e.g., cement or steel) requires subsequent CO_2 utilization and/or storage. The Sleipner and Snøhvit projects in the North Sea and Barents Sea, respectively, were the first dedicated offshore projects storing CO_2 separated from the production of natural gas. The CO_2 storage in saline aquifers began at Sleipner in 1996 and at Snøhvit in 2008.[6,7] These projects continue to support an offshore knowledge-base and facilitate technical benchmarking.

APPLICABILITY TO CO_2 REMOVAL (CDR) PATHWAYS

The Intergovernmental Panel on Climate Change (IPCC) defines carbon dioxide removal (CDR) as "deliberate technologies, practices, and approaches that remove carbon dioxide (CO2) from the atmosphere".[8] Importantly, CDR must complement and not replace emissions reductions. These projects inherently involve the durable storage of the resulting CO_2 in geological structures, manufactured products (e.g., mass timber), the ocean, and vegetation and soils.[8] Geological storage includes both onshore and offshore storage in subsurface geological reservoirs. Examples of CDR pathways and the related storage options are provided below in ***Table 1***. Overall, geological storage is applicable to both Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS) pathways.



TABLE 1: Mapping of CDR Pathways to Storage Options

CDR PATHWAY	DESCRIPTION	DURABILITY ESTIMATE	STORAGE OPTIONS
Afforestation, reforestation, and revegetation; Improved forest management (ARR/IFM)	Store carbon in forest contexts and/or in related bio-based products (e.g., mass timber)[4]	Decades to centuries[4]	Vegetation and soils Human products[4]
Soil carbon sequestration	Store carbon in soil contexts[4]	Decades to centuries[4]	Vegetation and soils[4]
Biochar	Pyrolyze biomass residues to store carbon as a soil amendment[4]	Centuries to millennia[5]	Vegetation and soils[4]
Bioenergy with Carbon Capture and Storage (BECCS)	Capture and store biogenic CO_2 from processes that convert biomass into biofuels or combust biomass for energy generation[2]	10,000+ years[4]	**Geological structures (onshore or offshore)[4]**
Direct Air Carbon Capture and Storage (DACCS)	Directly capture CO_2 from the air using liquid solvents or solid adsorbents for sequential CO_2 storage[3, 4]	10,000+ years[4]	**Geological structures (onshore or offshore)[4]**
Enhanced rock weathering	Spread crushed rock (e.g., limestone, basalt) on fields, which will in turn capture CO_2, enter the water system, and eventually enter the ocean where the CO_2 will be stored as carbonate[4,5]	10,000+ years[4]	Vegetation and soils Ocean minerals and sediment[5]
Peatland and wetland restoration	Restore degraded peatlands, which naturally capture and store CO_2, through rewetting and revegetation[5]	Decades to centuries[5]	Vegetation and soils[5]
Blue carbon	Store CO_2 in mangroves and other intertidal or marine flora[4]	Decades to centuries[5]	Vegetation and soils[4]
Ocean alkalinity enhancement	Increase localized alkalinity in the marine environment (e.g., by mixing crushed alkaline substrate) to reduce local acidity and increase the capacity to store CO_2, which will eventually be stored as carbonate[1, 4]	10,000+ years[4]	Ocean minerals and sediment[4]
Ocean fertilization	Fertilize the local marine environment with micronutrients (e.g., iron) and/or macronutrients (e.g., phosphorus, nitrogen, and silica) to increase the growth of phytoplankton and the consequential uptake of CO_2, which will eventually be stored as carbonate[1, 4]	Centuries to millennia[4]	Ocean minerals and sediment[4]

See Appendix for footnotes

APPLICABILITY TO DECARBONIZATION PATHWAYS

OFFSHORE STORAGE ECOSYSTEM

This report identifies offshore storage projects as existing within a broader offshore storage ecosystem, as represented in ***Figure 1***. Importantly, the recommendations developed in this report are geared toward enabling the ecosystem to collaboratively maximize positive outcomes and minimize negative impacts.

FIGURE 1: Offshore storage ecosystem

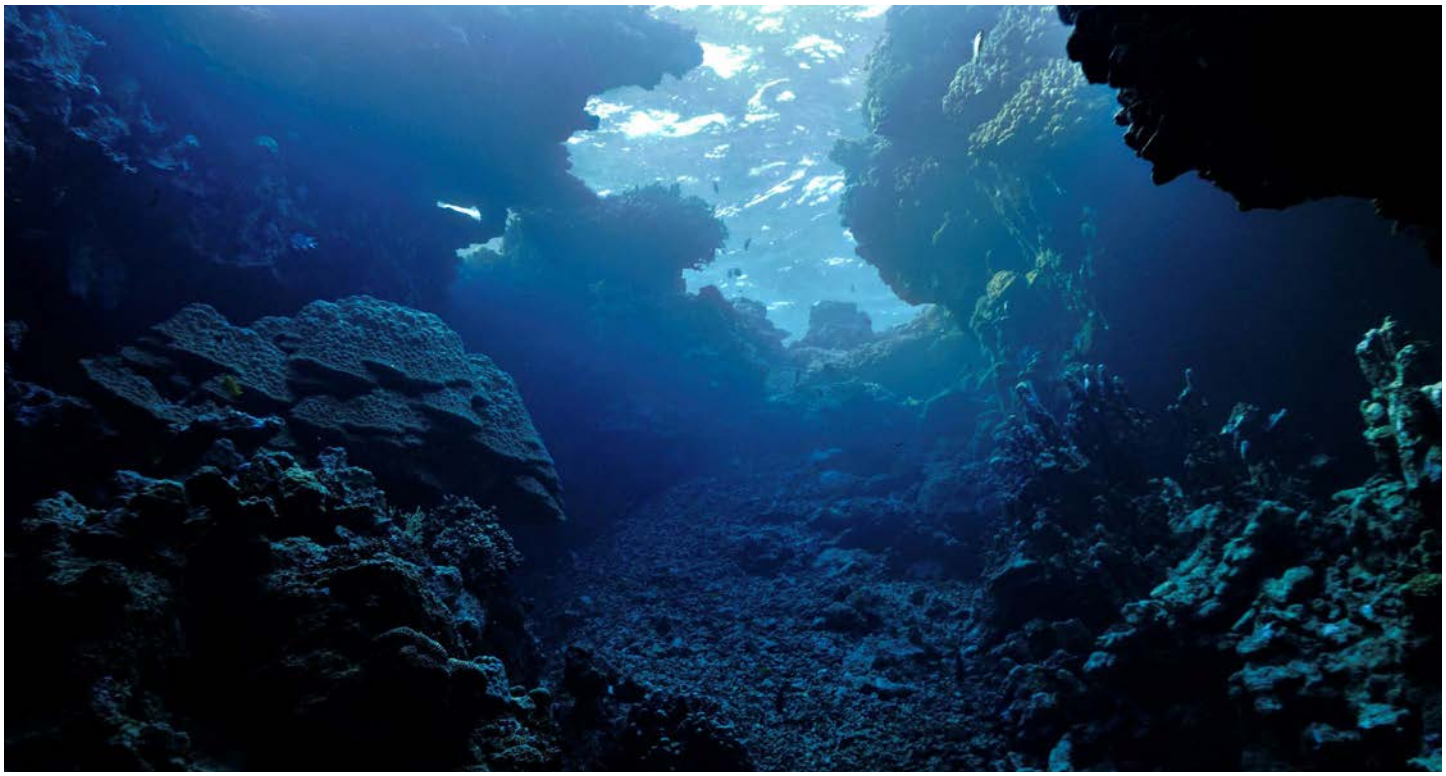


CONTEXT ON OFFSHORE STORAGE

GEOLOGICAL STORAGE ESTIMATED CAPACITY

Overall, the IEA's conservative estimate for the total geological storage complex volume of 8,000 Gt CO_2 far outweighs the 220 Gt predicted to be stored between 2020 and 2070 in the IEA Sustainable Development Scenario. Offshore capacity estimates range from 2,000 to 13,000 Gt. Conservatively, the IEA storage goal represents less than 3% of total geological storage and approximately 11% of total offshore storage.[9]

Care needs to be taken in the estimation of storage resources. Total resources typically consider **(i)** prospective storage resources and **(ii)** discovered storage resources. Discovered storage resources include commercial and sub-commercial resources. From a subsurface perspective, there is greater uncertainty on the prospective storage resources where: site-specific subsurface parameters (e.g., porosity, permeability, rock mechanics, structural features, geochemistry) and commercial feasibility have not been determined. For sub-commercial storage resources, cost reduction may occur with the development of hubs that facilitate scaled collection, transportation, and storage of CO_2, increasing the likelihood of moving this storage resource into the commercial capacity category.[9] The Society of Petroleum Engineers CO_2 Storage Resources Management System (SPE-SRMS) resource classification framework and the United Nations Framework Classification for injection projects are commonly used by storage proponents to categorize their CO_2 storage resources by project maturity and subsurface uncertainty.



CONTEXT ON OFFSHORE STORAGE

CURRENT GEOLOGICAL STORAGE HUB DEVELOPMENT

The development of storage hubs which store both CO_2 from industrial sources as well as removal sources (e.g., DACCS and BECCS) can leverage economies of scale, reducing costs of storage for all participants. ***Figure 2*** depicts examples of CO_2 storage hubs that are operational and planned. These hubs cluster CO_2 removal, infrastructure, and storage sites. Two active CO_2 storage hubs, Ravenna in the Mediterranean and Northern Lights in the North Sea, involve offshore storage.[10] References for more exhaustive maps of evolving storage hub projects include the Global CCS Institute and Scottish Carbon Capture and Storage.

FIGURE 2: Operational and planned CO_2 storage hubs



See Appendix for footnotes

Offshore Storage Hubs
- Operational
- Planned
- Planned w/delays

Onshore Storage Hubs
- Operational
- Planned

CONTEXT ON OFFSHORE STORAGE

OFFSHORE STORAGE MANAGEMENT LIFE CYCLE

Offshore storage requires a life cycle of development, transportation logistics, and reservoir management activities. The offshore reservoir is the subsurface geological storage compartment with barriers impermeable to the movement of CO_2. This report divides the offshore storage project life cycle into three broadly applicable phases, as outlined in ***Table 2***.

TABLE 2: Overview of the Activities Associated with Each Phase of the Offshore Management Life Cycle[1]

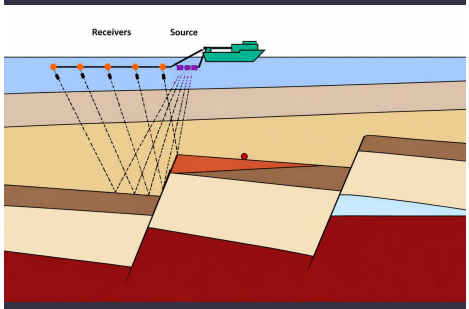
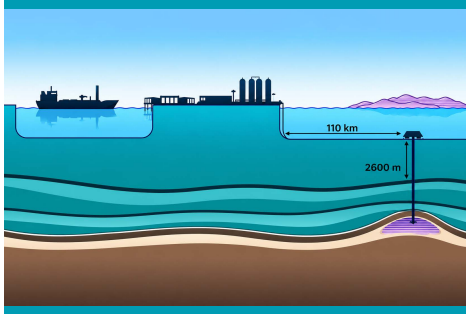
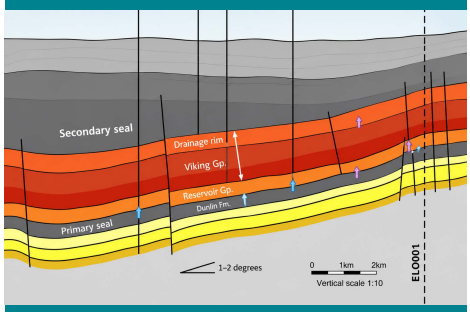
PHASE 1 SITE ASSESSMENT & DEVELOPMENT	PHASE 2 CO_2 INJECTION & ASSOCIATED MONITORING	PHASE 3 POST-INJECTION MONITORING
		
Subsurface site assessment Evaluate the potential offshore reservoir and associated cap rock. This exploration phase generally employs methodologies established in the oil and gas industry by leveraging active seismic geophysical surveys enduring several days to a few weeks and exploration well(s). **Site development (onshore and offshore)** Construct onshore collection and compression and offshore platform facilities, lay pipeline to the injection site, place templates on the seabed, and drill injection wells.	**Transport to onshore site** Transport CO_2 to the onshore facility via ships, pipeline, and/or trucks. **Transport to offshore site** Transport CO_2 to the offshore injection site via pipeline. **Offshore injection** Inject CO_2 into the offshore reservoir below the seafloor via a well. **Monitoring of immediate impacts** Leverage in-well and external (e.g., active seismic geophysical surveys) monitoring to detect potential immediate impacts.	**Monitoring of long-term impacts** Monitor for potential CO_2 movement into unanticipated subsurface compartments. **Transfer of offshore site from operator to state** After a sufficient monitoring interval (dependent on regulatory jurisdiction) and demonstration of a stable CO_2 plume, site ownership is generally transferred to the state.

Photo Source: National Science Foundation

Photo Source: Northern Lights

Photo Source: Northern Lights

See Appendix for footnote

REGULATORY AND CARBON MARKETS ALIGNMENT

An overview of existing requirements in selected offshore storage regulatory frameworks and standards is summarized in *Table 3* and *Table 4*, respectively. The recommendations in this report build upon these existing requirements.

OVERVIEW OF REGULATORY FRAMEWORKS APPLICABLE TO OFFSHORE STORAGE

Comprehensive frameworks to lease and regulate offshore storage on the ocean continental shelf are under development. Currently, the only global framework is the London Protocol's allowance of CO_2 injection in offshore geological reservoirs. This framework builds upon offshore waste disposal regulations and serves as a global baseline for offshore storage environmental and social safeguards. More robust and enforceable frameworks are being enacted at national and regional levels. A summary of these regulatory approaches and required environmental and social safeguards are provided in ***Table 3***.

TABLE 3: Overview of Regulatory Frameworks Applicable to Offshore Storage and the Associated Environmental and Social Safeguards

JURISDICTION	REGULATORY FRAMEWORK DESCRIPTION	ENVIRONMENTAL AND SOCIAL SAFEGUARDS
International	**London Protocol (2006):** Regulates waste materials disposed at sea and allows for the disposal of CO_2 if the following criteria are met: (i) the CO_2 is injected into a geological reservoir, (ii) the CO_2 stream maximizes purity with no threshold provided, and (iii) no additional waste types are injected with the CO_2[12] **London Protocol Risk Assessment and Management Framework for CO_2 Sequestration in Sub-Seabed Geological Structures (2006):** Provides guidance on meeting the requirements under the London Protocol, including problem formulation, site selection and characterization, exposure assessment, effects assessment, risk characterization, and management[12] **London Protocol Specific Guidelines for Assessment of Carbon Dioxide Streams into Sub-Seabed Geological Formations:** Guides national authorities in evaluating applications for offshore geologic storage[4]	**Establishes global operational baseline:** Provides an international, operational baseline that serves as an environmental and social safeguard in countries with developing offshore storage regulations; requirements include waste prevention and management, site-specific environmental characterization and impact assessment, field monitoring and assessment, and mitigation or remediation plans[4, 12]
Australia	**Offshore Carbon Capture and Storage Regulatory Approvals (2023) and associated legislation:** Provides guidance on the requirements and processes of permitting and environmental approvals established in the Offshore Petroleum and Greenhouse Gas Storage Act 2006, the Environment Protection (Sea Dumping) Act 1981, and the Environment Protection and Biodiversity Conservation Act 1999[6]	**Requires environmental plan and public consultation period:** Specifies that environmental plans must uphold ecologically sustainable development, minimize environmental impacts, and ensure that seismic surveys and exploration drilling be subject to a public consultation period[6]

See Appendix for footnotes

Table 3 continued on next page

TABLE 3: (Continued)

JURISDICTION	REGULATORY FRAMEWORK DESCRIPTION	ENVIRONMENTAL AND SOCIAL SAFEGUARDS
European Union	**European Commission CCS Directive 2009/31/EC (2009) and associated legislation:** Establishes a legal framework for the environmentally safe storage of CO_2 by preventing and eliminating, to the extent possible, negative impacts on the environment and human health within the territory of the member states, their exclusive economic zones, and the continental shelf[2] **Please note:** Associated legislation includes EC Monitoring and Reporting Guidelines (2010); CO_2 Storage Life Cycle Risk Management Framework (2011); Characterisation of the Storage Complex, CO_2 Stream Composition, Monitoring and Corrective Measures (2011); Criteria for Transfer of Responsibility to the Competent Authority (2011); and Financial Security and Financial Mechanism (2011)[2, 12]	**Mandates Environmental Impact Assessment:** Requires that a project conduct an Environmental Impact Assessment inclusive of population and human health, biodiversity, land, soil, water, air, climate, landscape, material assets, and cultural heritage[2] **Establishes project plan update cadence:** Requires project plan to be updated at a minimum of 5-year intervals to account for changes to CO_2 leakage risk, environment and human health risks, evolving scientific knowledge, and improvements in best available technology[2]
Malaysia	**CCUS Bill (2025):** Introduced initial federal framework for the entire CCUS value chain, including offshore storage[10, 11]	**Requires CO_2 plume monitoring but not environmental and social impact assessments and monitoring:** Requires that the operator monitors the storage complex, prepares a geological assessment, and owns responsibility for monitoring and remediation activities; further regulations will increase clarity on monitoring requirements[10, 11]
Norway	**Royal Decree on 5 December 2014 pursuant to Section 3 of Act No. 12 of 21 June 1963 relating to scientific research and exploration for and exploitation of subsea natural resources other than petroleum resources:** Regulates exploitation, transportation, and storage of CO_2 storage on the continental shelf to counteract climate change[5] **Pollution Control Regulations, Part 7A. Storage of CO_2 in Geological Formations:** Provides a legal framework for the environmentally safe storage of CO_2[1]	**Requires an environmental impact assessment:** Requires that the project assess the environment that may be significantly impacted and related consequences, monitoring, and mitigating measures[1, 5] **Requires risk characterization:** Requires that risks are categorized according to hazard, exposure, and effects assessments[1] **Requires demonstration of financial security:** Requires that operators put in place financial security throughout the lifetime of the project that integrates considerations of the risk of leakage and estimated costs[1] **Requires inspections by the relevant authority:** Requires regular inspections, including assessing impacts on the environment and human health, and public reporting by the Norwegian Environment Agency throughout the project lifetime[1] **Requires compensation for the fishing community:** Requires projects to compensate the fishing community for financial loss associated with the transport and storage of CO_2[5]

See Appendix for footnotes

Table 3 continued on next page

TABLE 3: (Continued)

JURISDICTION	REGULATORY FRAMEWORK DESCRIPTION	ENVIRONMENTAL AND SOCIAL SAFEGUARDS
United Kingdom	**Carbon Storage Stewardship Expectations:** Provides stewardship expectations, detailed roadmaps, and best practice suggestions[8] **The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010, No. 2221 Environmental Protection:** Establishes framework to ensure that the storage of CO_2 does not pose significant risk to the environment or human health[3]	**Requires identification of environmental and social risks:** Requires that operators identify all risks that could harm the environment and human health and update the risk assessment throughout the project lifetime[3, 8] **Requires stakeholder engagement:** Requires identification of impacted stakeholders, timely consultation, and broader collaboration (e.g., sharing of best practices, case studies, and lessons learned with industry)[8]
United States	**[Pending] Offshore Carbon Sequestration Program:** Expected to provide a framework to ensure the safe and effective storage of CO_2 on the U.S. Outer Continental Shelf (OCS)[7] **[Designed for onshore and state-submerged lands connected to underground sources of drinking water] Environmental Protection Agency Underground Injection Control Program:** Regulates geologic CO_2 storage via Class VI well permits with the goal of protecting public health and underground sources of drinking water[9]	**Requires demonstration of financial responsibility:** Requires operator to demonstrate financial responsibility to cover operations and any corresponding corrective actions throughout the lifetime of the project, inclusive of the post-injection phase[9] **Requires public participation and transparency in the permitting process:** Requires that a project's draft permit is open for public review, including comments and public hearings, prior to finalization[9] **Recommends community engagement:** Recommends engagement with local communities early in the permitting process; this engagement should integrate community concerns and utilize accessible engagement mechanisms, such as offering materials in multiple languages and proposing meeting times that accommodate work schedules[9]

See Appendix for footnotes

REGULATORY AND CARBON MARKETS ALIGNMENT

OVERVIEW OF CARBON MARKET STANDARDS APPLICABLE TO OFFSHORE STORAGE

Storage operations build on well-established methodologies and infrastructure from the oil and gas sector. This includes infrastructure (e.g., offshore platforms, pipelines, umbilicals) as well as monitoring approaches (e.g., active seismic geophysical surveys). The decarbonization context provides the opportunity to align legacy and new operational practices with overall sustainability, carbon market, and decarbonization goals. An overarching aim is to pursue decarbonization strategies that safeguard against negative environmental and social impacts.

This report builds upon existing carbon market safeguards, with examples provided in ***Table 4***, and provides additional guidance to ensure the sustainable scaling of offshore storage project types.

TABLE 4: Overview of Isometric and Verra Methodologies Applicable to Offshore Storage

Please Note: This evaluation considered the following internationally-recognized methodologies:
Isometric: CO_2 Storage in Depleted Hydrocarbon Reservoirs, CO_2 Storage in Saline Aquifers, and the Isometric Standard
Verra: VMD0058 CO_2 Storage in Saline Aquifers and Depleted Hydrocarbon Reservoirs

REQUIREMENTS	DESCRIPTION	ADDITIONAL GUIDANCE PROVIDED BY THIS REPORT
Comply with country- and region-specific permitting requirements	Isometric: "The injection site shall be monitored in accordance with the country/region specific well permitting requirements as specified in the operating permit for the injection site issued."[2, 3]	Provides examples of regulatory frameworks applicable to offshore storage and the associated environmental and social safeguards (Please reference ***Table 3***)
Develop a site-specific project plan	Isometric: "Each site should create a "testing and monitoring plan" which incorporates available, site-specific techniques..."[2, 3]	Provides guidance on site-specific parameters to consider
Integrate environmental and social safeguards	Isometric: "Comply with all applicable local environmental, ecological and social requirements as well as those set out in the relevant protocol and Section 3.7 of the Isometric Standard."[2, 3] This Section 3.7 states: "Projects must consider the material environmental and social impacts that could potentially arise as a result of their activities, both within and beyond its boundary, and at minimum must do no net environmental or social harm."[4]	Summarizes potential environmental and social impacts and corresponding safeguards in the context of an offshore storage project (Please reference ***Table 5***)
Assess appropriate system parameters at a regular cadence to monitor for CO_2 plume stabilization	Isometric & Verra: Both Isometric and Verra define parameters that should be assessed within the project boundary through regular monitoring.[1, 2, 3] Isometric requires that monitoring plans include direct (e.g., fluid pressure and temperature monitoring, groundwater geochemical monitoring) and indirect (e.g., geophysical monitoring, computational modeling) strategies. Isometric also requires that these plans are updated every 5 years, or at a shorter interval recommended by regulatory bodies, to integrate updates to potential risks (e.g., CO_2 storage integrity, social and environmental impacts) as well as to integrate best available technologies and new scientific findings.[2, 3]	Explores existing and developing CO_2 plume monitoring technologies and risk-based strategies that maintain and/or increase integrity of plume monitoring while minimizing negative environmental and social impacts

See Appendix for footnotes

IMPACTS AND ASSOCIATED SAFEGUARDS

SUMMARY OF POTENTIAL IMPACTS AND ASSOCIATED SAFEGUARDS

Table 5 summarizes the potential environmental and social impacts of offshore storage. The table also provides strategies to maximize positive outcomes and minimize negative impacts.

TABLE 5: Summary of the Primary Potential Environmental and Social Impacts of Offshore Storage and the Associated Safeguards

POTENTIAL IMPACTS	IMPACTED GROUPS = Social = Environmental	DESCRIPTION	LIKELIHOOD OF OCCURRENCE	SAFEGUARDS* (Integrated into Recommendations Checklist)
POTENTIAL POSITIVE IMPACTS OF OFFSHORE STORAGE PROJECTS				+
Decarbonization	Public and private actors with decarbonization goals	Offshore storage projects can provide durable, long-term storage aligned with the IEA Sustainable Development Scenario.[11] Offshore storage projects can enable economies of scale given significant storage volume capacity.	**High** likelihood of supporting decarbonization goals	**CO_2 hubs:** Prioritize projects linked to CO_2 hubs to support the efficient development and utilization of CO_2 infrastructure; increased opportunities for regulatory alignment and enforcement; and the scaling of carbon removal and storage pathways.
Economic opportunities	Local communities and broader carbon sector workforce	Offshore storage projects can maintain and create local jobs and broader contracting opportunities. Offshore storage projects can support the development of local storage hubs and the broader decarbonization economy.	**High** likelihood of driving local economic opportunities	**Social Impact Assessment:** Prioritize projects that integrate a community or social impacts assessment. **Local workforce:** Prioritize projects that maximize hiring of the local workforce, including contractors, where feasible.
Energy industry diversification	Local and broader energy sector workforce	Offshore projects can build upon existing knowledge and infrastructure capacity of the energy sector. Offshore projects can aid transition of jobs and skills from the oil and gas sector to new roles in carbon management.	**High** likelihood of supporting energy industry diversification given the high degree of overlap between offshore storage actors and energy actors	**Energy sector knowledge:** Prioritize projects that build upon local and regional oil and gas sector knowledge, where feasible.

Table 5 continued on next page

*Included in Recommendations Checklist

See Appendix for footnotes

TABLE 5: (Continued)

POTENTIAL IMPACTS	IMPACTED GROUPS ✋ = Social 🌊 = Environmental	DESCRIPTION	LIKELIHOOD OF OCCURRENCE	SAFEGUARDS*
POTENTIAL NEGATIVE IMPACTS OF OFFSHORE STORAGE PROJECTS				X
Site-specific risks	✋ Coastal communities and Indigenous groups 🌊 Onshore and marine flora and fauna	Offshore projects pose site-specific risks influenced by a distinct composition of onshore and offshore geological, geophysical, environmental, and social parameters. Examples of site-specific risks include (i) conflicts with fishing grounds and other coastal and Indigenous community resources and activities and (ii) negative impacts on local biodiversity and endangered species.	**Low to High** likelihood of occurrence of site-specific risks that will require site-specific mitigation measures	**Site-specific baseline assessment and monitoring plans:** Require that projects evaluate the baseline community and eco-system parameters and design site-specific monitoring plans. **Site-specific social and environmental impact assessments:** Require that projects conduct site-specific social and environmental impact assessments in collaboration with impacted communities (e.g., coastal communities and Indigenous groups). The assessment should include plans to mitigate negative impacts. **Stakeholder engagement:** Require that projects implement recurrent formal and informal stakeholder engagement mechanisms with all impacted communities, notably Indigenous communities and vulnerable groups, throughout the project lifetime. **Continuous improvement:** Require that projects regularly assess for site-specific impacts during the lifetime of the project and update operations accordingly.
Earthquakes	✋ Communities near CO_2 injection site 🌊 Onshore and marine flora and fauna near CO_2 injection site	Subsurface pressure changes associated with CO_2 injection pose the risk of triggering earthquakes, submarine landslides, and other geohazards[12]	**Low to Medium** likelihood of earthquake events given that the mitigation measures are required by regulatory and standards bodies	**Site-specific pressure and microseismic monitoring and management plan:** Require that projects avoid operations in areas that pose a higher risk of seismic activity and integrate pressure and microseismic management programs.

Table 5 continued on next page
See Appendix for footnotes

*Included in Recommendations Checklist

TABLE 5: (Continued)

POTENTIAL IMPACTS	IMPACTED GROUPS = Social = Environmental	DESCRIPTION	LIKELIHOOD OF OCCURRENCE	SAFEGUARDS*
POTENTIAL NEGATIVE IMPACTS OF OFFSHORE STORAGE PROJECTS				X
CO_2 leakage *(Further reference provided in "Understanding Impacts of CO_2 Leakage" section below)*	Communities in close proximity to CO_2 infrastructure Onshore and marine flora and fauna	Land leakage (e.g., onshore equipment and pipeline failure) and marine leakage (e.g., marine pipeline failure and subsurface leakage) pose the risks of (i) asphyxiation in onshore contexts and (ii) harm to flora and fauna sensitive to increased acidification in marine contexts. These risks are related to elevated, localized CO_2 concentration prior to dispersal.[2, 8]	**Low to Medium** likelihood of leakage events given that the mitigation measures are required by regulatory and standards bodies	**Robust safety regulations:** Prioritize projects operating in robust safety regulatory regimes, such as those provided in ***Table 3***. **Site selection:** Require that projects select storage reservoirs at an appropriate depth with suitable porosity, permeability, and sealing mechanisms. **Site-specific, risk-optimized CO_2 and environmental monitoring plan:** Require that projects integrate a site-specific, risk-optimized CO_2 and environmental monitoring plan, inclusive of land and marine contexts. Additional monitoring should be triggered if certain risk thresholds are exceeded.[7] **Site-specific maintenance and leakage response plans:** Require that projects integrate provisions to maintain pipelines and equipment as well as leakage response plans.

Table 5 continued on next page

See Appendix for footnotes

*Included in Recommendations Checklist

TABLE 5: (Continued)

POTENTIAL IMPACTS	IMPACTED GROUPS ✋ = Social 🌊 = Environmental	DESCRIPTION	LIKELIHOOD OF OCCURRENCE	SAFEGUARDS*
POTENTIAL NEGATIVE IMPACTS OF OFFSHORE STORAGE PROJECTS				X
Anthropogenic sounds from active seismic geophysical surveys *(Further reference provided in "Understanding Impacts of Active Seismic Geophysical Surveys" section below)*	✋ Fishing communities whose operational activities coincide with the area of the geophysical survey 🌊 Marine life within the water volume (depth and lateral distance) impacted by sounds from the geophysical survey	Anthropogenic sounds produced during geophysical surveys pose the risks of temporary or permanent physical (e.g., auditory and tissue damage), behavioral (e.g., avoidance of feeding and breeding areas), and physiological (e.g., stress indicators) impacts on marine life, including fish.[1, 3, 13, 10]	**High** likelihood of anthropogenic sound generation from active seismic geophysical surveys, given the current reliance on these surveys	**Site-specific, risk-optimized CO_2 and environmental monitoring plan:** Require that projects integrate a site-specific, risk-optimized CO_2 and environmental monitoring plan. This approach enables the balancing of risks with the need for geophysical surveys. **Site-specific assessment of anthropogenic sound impacts:** Prioritize projects that integrate an acoustic-biological model with site-specific parameters to assess sound propagation and biological impacts on the species in the affected area and minimize negative impacts on marine life and fishing communities. The model should leverage comprehensive acoustic source data for the specific geophysical survey system.[4, 5, 6, 9] **Recognized limitations of Protected Species Observers (PSOs) personnel, infrared systems, and the soft-start method:** Prioritize projects that are not solely reliant upon PSOs or infrared on ships as well as the soft-start of active seismic geophysical surveys as mitigation strategies. These strategies are not effective at preventing negative impacts to marine life and human communities dependent on marine life. **Low-impact monitoring technologies:** Prioritize projects that integrate proven and emerging low-impact CO_2 and environmental monitoring approaches that minimize negative environmental and social impacts.

See Appendix for footnotes

*Included in Recommendations Checklist

IMPACTS AND ASSOCIATED SAFEGUARDS

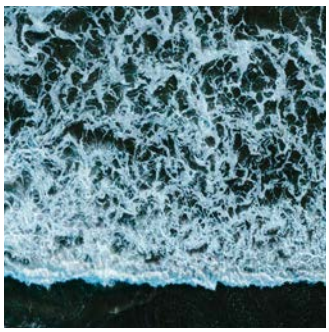
UNDERSTANDING IMPACTS OF CO_2 LEAKAGE

How does CO_2 leakage occur?

CO_2 leakage can occur at each phase of the offshore storage management life cycle. This report categorizes CO_2 leakage as occurring in a land or marine context.

Land leakage: Regarding land processes, CO_2 leakage can be a result of pipeline failure, equipment leakage, or equipment venting.[11, 12]

Marine leakage: CO_2 leakage in a marine environment can be a result of marine infrastructure failure, similar to the land context described above. It can also be due to offshore subsurface leakage that allows CO_2 to migrate up to the seafloor, impacting the deep seafloor or benthic ecosystem. In the subsurface, leakage can occur if CO_2 injection and the resulting increased fluid pressure activate natural channels (e.g., faults) or human-made pathways (e.g., poorly completed wells) that allow fluid transmission between the geological reservoir and seals.[13, 14]



What are the potential impacts of CO_2 leakage?

Land leakage: Regarding potential consequences of infrastructure failure in an onshore environment, leakage can result in a temporary imbalance of CO_2. Though CO_2 is not an explosive, it can act as an asphyxiant. The severity of the impact on an individual is dependent on the CO_2 concentration and the time-length of the exposure. CO_2 concentrations in air greater than or equal to 10% can lead to unconsciousness or death, while lower concentrations can result in headaches, sweating, elevated heart rate and breathing, shortness of breath, dizziness, depression, visual disturbances, or shaking.[15] Populations at risk of exposure are individuals and communities who work or live in close proximity to CO_2 infrastructure.

Marine leakage: Marine CO_2 leakage (be that from marine infrastructure failure or from subsurface leakage) increases the concentration of CO_2 and thus the acidity in the environment local to the emission site prior to dispersal. Additionally, in a deep seafloor or benthic ecosystem, the leakage of CO_2 may trigger the leakage of highly saline subsurface waters, subsurface hydrocarbons (applicable to depleted hydrocarbon reservoirs), and ocean floor sediment metals. Overall, leakage results in temporary chemical imbalances that can negatively impact organisms and the ecosystem as a whole. Marine life will respond and be impacted differently according to their organic structures and levels of mobility. Larger leaks may lead to the loss of biodiversity. Importantly, the time window required for marine dispersal is dependent on the release rate (large volume, short time interval for a pipeline leak vs. small volume, extended time interval for a subsurface leak) and site-specific parameters, including the hydrodynamic conditions and boundaries of the receiving environment. Generally, dispersion is likely to occur within the window of hours to weeks.[13, 16, 17, 18]

There have been a number of studies on the potential impacts of marine CO_2 leakage using natural analogs (e.g., natural CO_2 seeps) or biogeochemical modelling. Biogeochemical models assess site-specific length scales over which a pH drop is likely to be observed. A pH drop is a measurement that indicates increasing acidity. Typically these models and field analog observations show that large leakage rates are required to produce changes in pH that are

IMPACTS AND ASSOCIATED SAFEGUARDS

higher than the natural variance observed in the marine environment (e.g., seasonal changes in pH), beyond just a highly localized area.[17, 18, 19, 20, 21] These models have typically not included other substances that may be mobilized with CO_2 movement such as formation waters, hydrocarbons, and heavy metals, which may represent a higher environmental risk than the CO_2 itself.

What is the likelihood of occurrence?

Site selection and risk assessment and management are designed to manage and mitigate any leakage risk. In regions where offshore storage is well-regulated, the likelihood of CO_2 leakage is extremely low.[22]

What are the potential mitigation strategies for the negative impacts?

Robust safety regulations: Prioritize projects operating within robust safety regulatory regimes, such as those provided in ***Table 3***. The prime mitigation of risk is strong safety regulations. Robust and enforceable regulatory schemes, already operational in many jurisdictions, ensure that safety and prevention of CO_2 leakage is a planning, design, and operational requirement.



Site selection: Require that projects select storage reservoirs at an appropriate depth with suitable porosity, permeability, and sealing mechanisms. Primary reservoir sealing mechanisms include impermeable mudstone or sealing formations of appropriate thickness, extent, and rock mechanical properties. Evaluations may include cap rock geomechanics under increased pressure and thermal cooling. Additionally, the presence of secondary sealing and storage units in the overburden minimizes the risk of CO_2 leakage to the seabed.

Storage targets may either be depleted oil and gas reservoirs or saline aquifers. While depleted oil and gas reservoirs introduce risks and uncertainties regarding the effects on the reservoir, top seal, and legacy wells from previous operations, the data from those wells and any information available (e.g., rock and fluid samples) significantly reduce many geological uncertainties including how injection performance and pressure response might behave.[23] Saline aquifers tend to have far less data, as greenfield sites, and generally require new data acquisition. These uncertainties and risks should be taken into consideration when evaluating storage sites. Ultimately, the two key risks of note are **(i)** compromised well integrity and **(ii)** compromised subsurface integrity. The decision of whether to use depleted oil and gas reservoirs or saline aquifer storage will be made on a case-by-case basis and will be highly dependent on a cost-benefit estimation.

Site-specific, risk-optimized CO_2 and environmental monitoring plan: Require that projects integrate a site-specific, risk-optimized CO_2 and environmental monitoring plan, inclusive of land and marine contexts. For building, transportation, and storage infrastructure, projects should integrate CO_2 detection systems, alarms, and evacuation procedures. These evacuation procedures should be public, transparent, and accessible. Regarding potentially impacted areas, the project should monitor indicative environmental parameters. Regarding the subsurface, projects should use the latest and most appropriate available technologies that effectively monitor the CO_2 plume while minimizing negative environmental and social impacts. Additional monitoring should be required if certain risk thresholds are exceeded, such as if pressure does not conform with predictions or if the plume migrates into an unexpected reservoir compartment.[24]

IMPACTS AND ASSOCIATED SAFEGUARDS

Importantly, commercial-scale CO_2 storage projects are actively developing and monitoring technologies are likely to advance throughout a storage project lifetime. Offshore storage projects can support the development of less environmentally- and socially-intrusive monitoring approaches by field-testing these developing technologies as they become available. Testing ensures that monitoring technologies are safe, efficient, and adapted to operational contexts.[25] Overall, monitoring plans should be based on risk management approaches that maximize the value of information and safe operations, while reducing potential negative impacts. The business case for implementation of monitoring techniques should include the suitability, cost effectiveness, and evaluation of potential negative impacts.

Over the lifetime of CO_2 storage projects, land and marine environments and corresponding receptors will change. Dynamic baseline surveys enable a more robust understanding of impacts in the unlikely event of leakage.

Site-specific maintenance and leakage response plans: Require that projects integrate provisions to maintain pipelines and equipment as well as leakage response plans. Maintenance of pipelines and equipment prevents leaks, overpressure, and corrosion. Potentially impacted communities should be consulted with in the development of maintenance and leakage response plans. The project should also clearly communicate to immediate and broader communities the safety protocols and response measures that will be implemented if a leak occurs.

UNDERSTANDING IMPACTS OF ACTIVE SEISMIC GEOPHYSICAL SURVEYS



How are active seismic geophysical surveys utilized?

Active seismic geophysical surveys are employed to **(i)** characterize the subsurface geology prior to CO_2 injection and **(ii)** monitor the movement of the subsurface CO_2 plume in the storage complex during and after injection. The most time- and area-extensive survey occurs prior to injection and generally lasts between several days to a few weeks. It is important to note that this process may be less extensive if previous subsurface survey data is available for the area that can support geophysical modeling. Following CO_2 injection, it is expected that monitoring surveys will require a shorter time duration and survey a less extensive area.

These surveys use a diverse array of sound-source technologies that span frequencies, durations, applications, and sound levels to survey the seafloor and evaluate and quantify the subsurface storage compartment. These sound sources may include air-gun arrays, boomers, chirp sub-bottom profilers, side-scan sonars, sparkers, and swath bathymetric sonars.[26]

Among the most broadly employed survey sound sources are air-gun arrays. This technology builds upon the oil and gas industry's practice of leveraging active seismic acquisition for subsurface assessment and monitoring. In the acquisition process, a seismic vessel trails an array of air guns (approximately 6 to 40 air guns) and receivers over the area of the seafloor to be mapped and studied. The air guns are fired simultaneously every 10 to 12 seconds, resulting in a nearly nonstop, pulsing of pressurized air and intense sound to collect geophysical information about reservoir compartments and layers. They produce high amplitude, low frequency (approximately 20 to 1,500 Hz) sound, although most energy can be below 500 Hz.[27] These sounds can be detected up to 4,000 km from the source and may be heard without interruption during the survey activity. Thus,

IMPACTS AND ASSOCIATED SAFEGUARDS

this can result in intense sounds permeating a potentially large area of the ocean across days to weeks.[28] Importantly, these sounds add to existing anthropogenic sound impacts in the marine environment.

What are the potential impacts of active seismic geophysical surveys and the associated anthropogenic sounds?

Depending on distance from the source, the sounds associated with the technologies employed during active seismic geophysical surveys can cause diverse negative consequences upon marine life, including physical (e.g., auditory and tissue damage), behavioral (e.g., avoidance of feeding and breeding areas), and physiological (e.g., stress indicators) impacts.[29, 30] These anthropogenic sounds can also mask communication related to mating and alter fundamental activities such as feeding, predator evasion, and navigation.[31] Resulting consequences may be short- or long-term at the individual, population, and ecosystem levels, and sound impacts may also compound as one of multiple stressors animals face.

Animals vary substantially in sound-sensitivity and responses (e.g., squid may respond differently than cod or copepods). Furthermore, within a grouping, (e.g., fish) hearing mechanisms, abilities, and responses can differ substantially.[32] Thus there is a need to address species- and context-specific responses to the greatest extent possible. Nearly every taxon is understudied, notably ecologically key invertebrates and the deep sea fauna whose habitats overlap with these potential activities. There is a clear need to better understand these biological communities and the associated impacts of sound on the individuals and populations therein. The research that has been conducted for cetaceans, fish, sea turtles, and invertebrates demonstrates that the sound from active seismic geophysical surveys have demonstrable negative impacts. ***Table 6*** provides a literature review summary of the potential impacts on marine life.



TABLE 6: Literature Review of the Potential Impacts of Active Seismic Geophysical Surveys on Marine Life

KEY TAKEAWAYS

- **Impact Types:** Impacts can be divided into the following categories: (i) physical (e.g., auditory damage, tissue trauma, mortality); (ii) behavioral (e.g., avoidance of feeding and breeding areas); and physiological (e.g., stress markers, respiration rates) [5, 11]
- **Impact Degree:** Subtle changes in normal patterns to drastic reactions[1]
- **Impact Duration:** Temporary to permanent impacts, potentially linked to hearing ability and energy utilization [7, 11]
- **Broader Ecosystem Impacts:** Individual- and species-level impacts have broader ecosystem impacts, such as related to altered food availability (e.g., plankton loss can impact cetaceans and fish)[7, 11]



Photo: Vincent Kneefel Ocean Image Bank

IMPACTS ON MAMMALS

Impacts on cetaceans:

- Odontocetes:

- Dolphins can demonstrate a shift in auditory thresholds as well as behavioral changes [9, 10]

- Porpoises can show changes in movement patterns [3]

- Belugas can demonstrate behavioral disruptions [8]

- Pygmy or dwarf sperm whales can experience lower levels of harassment to serious injury [2]

- Mysticetes:

- Bowhead whales can decrease calls with increasing exposure levels and become silent after a certain threshold [4]

- Humpbacks can demonstrate avoidance, with increased responses for pods with cows [19]

- Rare taxa - There are a number of taxa, such as beaked whales, which are somewhat rare or difficult to observe and often considered 'sound sensitive' but there are fewer studies addressing these taxa so there is much greater uncertainty regarding potential impacts

Impacts on pinnipeds (seals):

- Pinnipeds - There are few data sources on sound impacts for pinnipeds; yet similar risks (hearing loss, disturbance and displacement) have been associated with geophysical sounds [13, 15]



Photo: Masayuki Agawa Ocean Image Bank

IMPACTS ON FISH

General impacts on fish:

- For those species studied, there is evidence of a variety of impacts, including: (i) physical (e.g., damaged hearing organs); (ii) behavioral (e.g., movement away from air-gun arrays, an increase in swimming activity, a decrease in feeding activity); and (iii) physiological (e.g., temporary threshold shifts [7, 18, 19, 21, 23]

- Degree of impact - The incidence of behavioral responses raises with increasing impulsive sound levels [7, 14]

- Research gaps - Fish constitute a diverse taxonomic group and sound-impact studies have focused on relatively few taxa. There is often far less known about demersal, benthic, deepwater, or high-latitude taxa

Impacts by example fish species:

- Cod - Cod can demonstrate disruption to diurnal feeding activities and a decrease in heart rate, with impacts increased at a range of 5-10 km [3, 6, 16]

- Saithe - Saithe can demonstrate increased dispersal [6]

See Appendix for footnotes

Table 6 continued on next page

TABLE 6: *(Continued)*



Photo: Emilie Ledwidge *Ocean Image Bank*

IMPACTS ON SEA TURTLES

General impacts on sea turtles:

- Turtle sound use - While generally less sensitive in hearing abilities than some other marine taxa, there is an increasing realization of turtle sound use and sensitivity, thereby causing concern.
- Impacts - Sea turtles can respond to high-amplitude, low-frequency anthropogenic sounds. Responses include increased swimming speed, change of swimming pattern and direction, alarm, and avoidance. [17, 19]
- Foraging impacts - Leatherback sea turtles can demonstrate significantly reduced foraging during exposure to impulsive sounds, such as those used in active seismic geophysical surveys. [20]
- Impacts on freshwater turtles that may be an analog to sea turtles - Impacts on freshwater turtles imply similar impacts on sea turtles. Freshwater turtles incur noise-induced hearing loss to broadband, low-frequency sound. Even a temporary decline in hearing sensitivity may have consequences on survival and fitness. [22]



Photo: Alex Tyrrell *Ocean Image Bank*

IMPACTS ON INVERTEBRATES

General impacts on invertebrates:

- Invertebrates can experience severe negative impacts which vary across species. Sound sensitivity studies for invertebrates are nascent and limited.

Impacts on squid:

- Squid - Squid can show alarm response, which increases as noise level increases. [7, 19]
- Giant squid - Giant squid have experienced organ and tissue lesions, which led to mortality. [12]

Impacts on plankton and krill:

- Zooplankton and krill can have immediate mortality and a decline in overall abundance. [3]

What is the likelihood of occurrence?

Active seismic geophysical surveys are a normative monitoring strategy for offshore storage projects. Often, these surveys are required by regulatory bodies. Thus, the risks associated with active seismic geophysical surveys have a high likelihood of occurrence.

What are the potential mitigation strategies?

Site-specific, risk-optimized CO_2 and environmental monitoring plan: Require that projects integrate a site-specific, risk-optimized CO_2 and environmental monitoring plan. This approach should appropriately balance the risks with the need for active seismic geophysical surveys, particularly comprehensive 3D and 4D (repeated 3D surveys over time) surveys. Monitoring plans should be commensurate to subsurface risks rather than a response to unfounded concern or project funding conditions. There is an opportunity for projects to utilize a hierarchy of controls to maximize the value of information through the implementation of a portfolio of monitoring methods, including lower impact monitoring methods further expanded upon below.[33]

IMPACTS AND ASSOCIATED SAFEGUARDS

Site-specific assessment of anthropogenic sound impacts: Prioritize projects that integrate an acoustic-biological model with site-specific parameters to assess sound propagation and biological impacts on the species in the affected area. This assessment is fundamental to understanding and minimizing negative impacts on marine life as well as human populations, such as fishing communities, that depend on marine life. As example, site-specific and context-based parameters enable the delineation of the radius at which sound is no longer causing acoustic masking for marine life. The site-specific parameters integrated into the assessment model include: behavioral and physiological responses of marine life to the anthropogenic sounds expected, relative sound levels and hearing thresholds, and acute and chronic sound exposure impacts. This final point considers the sounds of the active seismic geophysical survey as adding to ocean environments that are experiencing an increase in chronic and acute anthropogenic sound. Additionally, the model should leverage comprehensive acoustic source data for the specific geophysical survey system that will be utilized.[29, 31, 34]



Recognized limitations of protected species observers (PSOs) personnel, infrared systems, and the soft-start method: Prioritize projects that are not solely reliant upon PSOs or infrared on ships as well as the soft-start of active seismic geophysical surveys as mitigation strategies. During these surveys, the current practice of the energy industry is to leverage PSOs, individuals onboard seismic vessels who are tasked to monitor for the presence of marine life. However, PSOs are limited given that: **(i)** observations cover a relatively small portion of the impact area; **(ii)** observations may not detect all marine species and will even miss many individuals (e.g., those that are below the surface, animals surfacing in vision-limited scenarios at night or when it is raining); and **(iii)** there are minimal incentives to stop and start surveys given the significant associated costs of restarting. An additional current practice is to implement a soft-start, or ramp-up, of active seismic geophysical surveys, in which the sound impulses start at a lower sound level and then increase in amplitude in order to provide an early warning and potentially drive marine life aversion. Importantly, the U.S. National Oceanic and Atmospheric Administration (NOAA) notes that the soft-start practice may reduce injurious exposure (for some taxa) but not overall harassment.[35] Furthermore, it fails to take into account the context in which animals may or may not seek to avoid sound-exposure (e.g., whether a species actually shows horizontal displacement, taxa that are habituated to the sound) and assumes simple sound propagation, the assumption that sound levels decrease away from the source.

Low-impact monitoring technologies: Prioritize projects that integrate proven and emerging low-impact CO_2 and environmental monitoring approaches that minimize negative environmental and social impacts. These lower impact monitoring approaches are summarized in ***Table 7***. Emerging approaches will require field testing in an offshore storage project context in order to progress research and development. This enables the approval of emerging technologies by regulators.

Fundamentally, in a CO_2 and environmental monitoring plan, it is likely that a combination of monitoring technologies will be deployed in addition to conventional 3D and 4D active seismic geophysical surveys. Deployed in a risk-optimized hierarchy, lower impact monitoring techniques may reduce reliance upon 3D and 4D active seismic geophysical surveys. The frequency of the monitoring will be determined by the project risks and regulatory requirements. There are significant opportunities for marine monitoring activities to use existing infrastructure (e.g., fiber optic cables, existing wells) or make use of other operations (e.g., vessel infrastructure inspections) to deploy or retrieve monitoring equipment.

TABLE 7: Overview of Proven and Emerging Low-Impact CO_2 Monitoring Methods

TECHNOLOGY	METHODOLOGY	PROS & CONS	MATURITY FOR CARBON CAPTURE AND STORAGE (CCS)	OPTIMAL MONITORING USE CASE
CONTINUOUS LOW-IMPACT MONITORING METHODS				
Passive Seismic + Distributed Acoustic Sensing (DAS), Distributed Temperature Sensing (DTS), and Distributed Strain Sensing (DSS) Passive seismic and fibre optic sensing to continuously track subsurface changes [1, 2, 11, 12, 13]	**Passive**	**Pros** • Provides continuous, real-time monitoring either in the wellbore or on the seabed • Can leverage existing fiber optic infrastructure • Yields fine spatial sampling • Serves as a lower cost monitoring lever **Cons** • Has resolution limitations • Requires large data volumes due to fine spatial sampling • Depends on the architecture of the wells for utilization in wellbore	**Mature** • Utilization in wellbore: Mature • Utilization on seabed: Achieved proof of concept	• CO_2 plume • Induced seismicity • Fault reactivation • Pipeline and well • Marine life • Broader environmental parameters
PERIODIC LOW-IMPACT MONITORING METHODS				
Biological Monitoring Monitoring of biological communities to detect ecological impacts of CO_2 using microbial analyses, DNA fingerprinting, plant surveys, and sensor technologies[4]	**Observational**	**Pros** • Directly measures microorganisms and marine life that could be impacted by CO_2 leakage **Cons** • Faces challenge that highly localized impacts may not be easily sampled • Requires baseline monitoring and regional understanding of local species and potential overlapping impacts from climate change	**Mature**	• Baseline biological surveys of seabed and marine species • Post-leakage impact detection
Geochemical Monitoring Chemical measurements to detect CO_2- related anomalies in water or sediments[10]	**Observational**	**Pros** • Provides a relatively simple means of leakage detection in the seabed and seawater • Serves as a highly cost-effective monitoring lever **Cons** • Has susceptibility to false positives • Requires frequent maintenance for moored seabed systems • Faces the challenge of shifting seawater baselines due to climate change	**Mature**	• Marine environmental characterization • Localized leakage detection near wells • Ad-hoc data collection during risk escalation

See Appendix for footnotes

Table 7 continued on next page

TABLE 7: *(Continued)*

TECHNOLOGY	METHODOLOGY	PROS & CONS	MATURITY FOR CARBON CAPTURE AND STORAGE (CCS)	OPTIMAL MONITORING USE CASE
PERIODIC LOW-IMPACT MONITORING METHODS				
Marine Acoustic Methods: Hydrophone Arrays Underwater device to detect acoustic signals Please note: can be leveraged as periodic or continuous monitor[9]	**Passive**	**Pros** • Has the capacity to detect CO_2 bubbles **Cons** • Requires costly equipment and regular maintenance • Requires densely spaced sensors or close proximity to bubbles (co-located DAS cable may reduce this need)	**Mature** • Trial in Australia and overseas	• In-situ monitoring of CO_2 bubbles during severe leakage
Marine Acoustic Methods: Sonar Acoustic imaging to detect gas escape at or near the seafloor[6]	**Active**	**Pros** • Has sensitivity to detect low levels of CO_2 leakage **Cons** • Detects leakage only at or from seabed • Has susceptibility to false positives.	**Mature**	• Baseline characterization • Periodic surveys • Ad-hoc surveys during risk escalation
Marine Sparker/ Sub-bottom Profilers Uses sound to provide imaging of the shallow subsurface[6]	**Active**	**Pros** • Has sensitivity to detect low levels of gas in seabed (e.g., geohazards at 50–100 m) • Emits lower marine noise than other subsurface imaging methods **Cons** • Provides shallow imaging only that is dependent on the substrate • Emits anthropogenic sounds that can impact marine life	**Mature**	• Baseline characterization • Infrastructure hazard assessment • Ad-hoc surveys during risk escalation
Sparse Geophysical Data Acquisition Survey Uses fewer air guns than a conventional 3D active seismic geophysical survey, in combination with a ingle receiver, to map the deeper subsurface (e.g., reservoir)[8]	**Active**	**Pros** • Serves as a lower impact, short-duration geophysical survey for discrete location sampling in focused, high-risk locations **Cons** • Provides low spatial resolution • Requires active seismic sources that emit anthropogenic sounds that can impact marine life	**Low-High** • Initial testing performed; needs further demonstration	• Specific, high-risk areas • Ad-hoc surveys during risk escalation

See Appendix for footnotes

Table 7 continued on next page

TABLE 7: *(Continued)*

TECHNOLOGY	METHODOLOGY	PROS & CONS	MATURITY FOR CARBON CAPTURE AND STORAGE (CCS)	OPTIMAL MONITORING USE CASE
IN-WELL MONITORING METHODS (LEVERAGING EXISTING WELL INFRASTRUCTURE)				
Controlled Source Electromagnetic Method (CSEM) Electromagnetic measurements sensitive to fluid saturation variations[3]	**Active**	**Pros** • Provides sensitivity to CO_2 saturation changes **Cons** • Has subsurface depth limitations	**Low–Moderate** • Remains at the experimental phase for CCS	• CO_2 plume migration
In-well Sampling Direct sampling of reservoir fluids to verify CO_2 movement[14]	**Observational**	**Pros** • Directly measures reservoir fluids **Cons** • Can increase leakage risk for complex well completions (e.g., ADM leak at Decatur)	**High**	• Validation of CO_2 migration behavior
Pressure Tomography Pressure-based imaging to track CO_2 migration between wells[7]	**Active (Requires pressure change as a source)**	**Pros** • Provides high sensitivity to CO_2 plume presence and migration **Cons** • Has limited spatial coverage due to well geometry • Requires dense wells, which is costly	**Low** • Field-tested in pilot phase at Otway	• Early detection and tracking of migrated CO_2 plume

See Appendix for footnotes

Table 7 continued on next page

RECOMMENDATIONS CHECKLIST

A summary of recommendations for ensuring the containment integrity and environmental and social safety of an offshore storage project is provided in ***Table 8***. These recommendations support: **(i)** confidence in alignment of the project with decarbonization, environmental, and social goals, and **(ii)** the responsible investment of climate funding in offshore storage pathways.

TABLE 8: Offshore Storage Recommendations Checklist

PROJECT PLAN COMPONENT	RECOMMENDATIONS
1 Project Expertise and Accountability	**1.1 Project expertise:** Ensure appropriate cross-sector expertise to manage onshore and offshore project parameters over the lifetime of the project This expertise includes onshore and offshore operations, reservoir management, risk management, impact assessment, monitoring, and stakeholder engagement. **Example Documentation:** Applicable licenses and permits; cross-sector team profile; previous offshore storage experience
	1.2 Financial accountability: Demonstrate financial accountability for the lifetime of the project Financial accountability includes consideration of costs and associated financial capital to integrate any remediation measures over the lifetime of the project. **Example Documentation:** Demonstration of sufficient financial capital
2 Subsurface Assessment	**2.1 CO_2 containment:** Assess CO_2 containment integrity through a site-specific subsurface assessment This assessment should include: cap rock lateral continuity and permeability; effects of temperature and pressure change; geomechanical behavior of the overburden; potential geological and well-related leakage pathways; and secondary sealing mechanisms for the expected injection and post-injection periods. **Example Documentation:** Geological models and reservoir simulations that predict the movement of CO_2 and demonstrate containment
	2.2 Potential for induced seismicity: Assess the potential for induced seismicity or earthquakes in the impacted area due to pressure changes associated with CO_2 injection in the reservoir Projects should avoid operations in areas that pose a higher risk of seismic activity and should integrate pressure and microseismic management programs. These programs should be public, transparent, and accessible. **Example Documentation:** Baseline and expected seismicity for the impacted area; pressure and microseismic management programs
	2.3 Risk management: Assess site-specific CO_2 leakage and other subsurface risks, potential consequences, and the likelihood of occurrence and implement corresponding risk mitigation strategies. The risk management plan should be public, transparent, and accessible. **Example Documentation:** Risk management plan for CO_2 leakage and other subsurface hazards

See Appendix for footnotes

Table 8 continued on next page

TABLE 8: *(Continued)*

PROJECT PLAN COMPONENT	RECOMMENDATIONS
3 Environmental and Social Impacts	**3.1 Regulatory jurisdiction:** Ensure operation within a jurisdiction characterized by robust and enforceable safety regulations for offshore storage **Reference:** ***Table 3*** provides an overview of current selected regulatory frameworks applicable to offshore storage.
	3.2 Stakeholder engagement: Integrate stakeholder engagement with all impacted communities, notably Indigenous communities and vulnerable groups, over the lifetime of the project **Example Documentation:** Stakeholder engagement mechanism **Reference: Stakeholder engagement frameworks:** The Global Carbon Council Environment and Social Safeguard Standard provides a framework and certification process for the identification of impacted stakeholders, continuous and active engagement, and grievance mechanisms.[3] Additionally, the United Nations Department of Economic and Social Affairs provides an analytical framework to assess the quality of inclusion, participation, and accountability within stakeholder engagement.[1]
	3.3 Environmental and social baseline assessment: Conduct a site-specific assessment of baseline environmental and community parameters in the impacted area Broader datasets can be leveraged in combination with locally collected data. There is a strong preference for leveraging a minimum of 1 year of data prior to the start of project activities. This baseline assessment should be public, transparent, and accessible. **Example Documentation:** Environmental and social baseline assessment **References:** **Global data sources:** Global data sources include GEOTRACES, International Council for the Exploration of the Sea (ICES), Argo Program, national buoy networks, and fisheries and species databases. **Baseline assessment types:** Blackford et al. (2015) recommends a baseline survey that integrates temporal and spatial dynamics.[5] Methratta (2020) recommends a before-and-after gradient design to test parameters at increasing distance from the site of operation before and after development.[12]
	3.4 Environmental and social impacts & safeguards: Assess site-specific, potential environmental and social impacts associated with the lifetime of the offshore project, identify the likelihood of occurrence, and implement safeguards for all potential negative impacts The assessment should cover potential impacts related to site assessment and development, CO_2 injection and associated monitoring, and post-injection monitoring activities. An important consideration, particularly for marine life, is the consideration of impacts from anthropogenic sounds resulting from project activities. All impacts to critical species, including endangered species, fisheries taxa, ecosystem engineers and those playing a key role in the community, and species of concern, should be mitigated or demonstrated to be negligible. Offshore storage within critical ecosystems for biodiversity should be avoided. Importantly, the assessment should integrate stakeholder engagement and be public, transparent, and accessible. **Documentation:** Environmental and social impact assessments with actionable safeguards **References:** **Framework for social and environmental impact assessments:** The Global Carbon Council Environment and Social Safeguard Standard provides a framework and certification process for the assessment and management of environmental and social risks and impacts for CCS projects.[2]

See Appendix for footnotes

Table 8 continued on next page

TABLE 8: *(Continued)*

PROJECT PLAN COMPONENT	RECOMMENDATIONS
3 **Environmental and Social Impacts**	**3.4 Environmental and social impacts & safeguards** *(continued)* **Methods for species identification:** The Australian Government's Department of Climate Change, Energy, the Environment and Water provides guidance on methods for determining the presence or absence of threatened mammals.[4] **Methodologies to assess the impacts of anthropogenic sound on marine life:** To minimize negative impacts on marine life and fishing communities, projects should integrate an acoustic-biological model with site-specific parameters to assess sound propagation and biological impacts on the species in the affected area. The model should leverage comprehensive acoustic source data for the specific geophysical survey system.[6, 7, 8, 10] Regarding behavioral impacts, Southall et al. (2021) provides guidance on how to evaluate for behavioral impacts on marine mammals from sound exposure. The evaluation integrates variability across species, individuals, situational contexts, and temporal and spatial scales.[14] **Examples of critical ecosystems for biodiversity:** Examples of critical ecosystems include whale migratory routes or blue corridors, the U.S. Arctic, the Eastern Pacific, the Southwest Indian Ocean, and the Southwest Pacific and Indonesia.[3, 11]
4 **CO_2 and Environmental Monitoring**	**4.1 CO_2 & environmental monitoring plan:** Integrate a site-specific, risk-optimized CO_2 and environmental monitoring plan that has been approved by the relevant national authorities and/or verified by relevant third party auditors This site-specific, risk-optimized monitoring plan design should leverage best available technologies that effectively monitor prioritized risks concerning the CO_2 plume while minimizing negative environmental and social impacts. This will generally require a portfolio or multi-modal approach and broader environmental parameters in which a suite of monitoring technologies are used in proportion to the potential risk. Additional monitoring should be triggered if certain risk thresholds are exceeded. The monitoring plan should integrate stakeholder engagement and be public, transparent, and accessible. **Documentation:** CO_2 and broader environmental monitoring plan with proof of approval and/or verification **References:** **Illustration on a risk-optimized monitoring approach:** Sinha et al. (2024) provides an illustration on developing a risk-based or hierarchical monitoring approach which balances continuous and periodic monitoring approaches. Continuous, low-impact approaches are used to detect anomalies in the CO_2 plume and trigger periodic monitoring approaches.[13] Additionally, Furre et al. (2017) provides illustration on optimizing monitoring approaches (i.e., technology, timing, extent) to the project-specific risks.[9] **Examples of proven and emerging low-impact monitoring technologies:** ***Table 7*** provides examples of proven and emerging CO_2 and environmental monitoring technologies with lower impact potential compared to the potential negative impacts of conventional active seismic geophysical surveys. **4.2 Maintenance & leakage response plans:** Integrate site-specific maintenance and leakage response plans This includes provisions to maintain pipelines and equipment offshore and at the onshore facility. These plans should integrate stakeholder engagement and be public, transparent, and accessible. **Documentation:** Maintenance and leakage response plans

See Appendix for footnotes

Table 8 continued on next page

TABLE 8: *(Continued)*

PROJECT PLAN COMPONENT	RECOMMENDATIONS
5 Drilling and Wells	**5.1 Drilling permits / licenses:** Ensure competence to safely plan and drill wells and integrate well control procedures in the case of unexpected behavior This should include selection of corrosion-resistant material for the sections exposed to CO_2. **Documentation:** Relevant permits and licenses
	5.2 Well architecture and barriers: Select a fit-for-purpose well architecture that achieves project targets and ensures that barriers to vertical CO_2 migrations are in place **Documentation:** Relevant permits and licenses
	5.3 Well abandonment: Integrate criteria for well abandonment that ensures long-term stability **Documentation:** Relevant permits and licenses
6 Continuous Improvement	**6.1 Monitoring plan updates:** Regularly assess the effectiveness of the site-specific, risk-optimized CO_2 and environmental monitoring approach, including the consideration of climate change-related impacts on land and marine environments Risk assessments based on dynamic modelling should be used to update the risk-optimized CO_2 and environmental monitoring approach. Dynamic modelling assesses change over time by regularly evaluating environmental and social parameters in changing land and marine environments that may be affected by climate change. This allows the project plan to respond accordingly. Regarding risk-optimization, after injection has ceased, leakage risks typically decrease as pressures diminish, leakage pathways are removed (e.g., wells are plugged and abandoned), and more of the CO_2 dissolves or becomes residually trapped in the storage reservoir. Each CO_2 storage project will have its own specific post-injection risks that will need to be assessed. In some cases these risks may be deemed high enough for the proponent or regulators to continue monitoring activities. Within regulations globally there is a patchwork of time-based, post-injection monitoring requirements, which may predetermine some of the ongoing monitoring requirements. It is important to note that monitoring options become more limited once supporting infrastructure and access to the reservoir and overlying geology is removed (e.g., wells are plugged and abandoned). **Documentation:** Regular process to update the monitoring plan
	6.2 Feedback and adjustment mechanisms: Integrate continuous improvement mechanisms with regards to environmental and social impacts Projects should regularly assess for site-specific impacts during the lifetime of the project and update operations accordingly. Projects should work with experts, regulators, and local communities to proactively implement operational and monitoring tactics that manage the various environmental impacts (and related impacts on human communities such as fishing communities). **Documentation:** Community feedback integration mechanism(s); process to monitor for unintended environmental and social impacts and adjust operations accordingly
	6.3 Field trials: Integrate field trials of emerging, low-impact CO2 and environmental monitoring technologies where feasible Integrate monitoring technologies that reduce negative impacts on marine ecosystems wherever feasible. **Documentation:** Process to identify and field test emerging, low-impact monitoring technologies as research develops

See Appendix for footnotes

Table 8 continued on next page

ACTIONABLE OPPORTUNITIES

The emergence of offshore CO_2 storage as a novel approach to help achieve decarbonization goals presents opportunities for all actors to integrate practices that maximize positive outcomes and minimize negative impacts to people and the environment. Through contributions and review from both project operators and the scientific community, we summarize these opportunities, categorized by relevant actors:

ALL ACTORS

Foster And Participate In Cross-Sector Collaboration

Cross-sector communication and collaboration amongst regulatory bodies, standards bodies, project operators, scientists, carbon removal buyers, and relevant impacted communities serve as a foundation to increase awareness of opportunities, challenges, and mitigation strategies that support the scaling of offshore storage as a sustainable decarbonization lever. Each of these actors should seek increased collaboration as new projects are developed, engage in research opportunities, and participate in ongoing dialogue to advance the recommendations and opportunities surfaced in this paper.

REGULATORY BODIES

Translate safeguards into regulatory requirements

Integrate the following site-specific requirements into regulatory frameworks for offshore storage projects: project expertise and accountability, subsurface assessment, environmental and social impact assessments, risk-optimized CO_2 and environmental monitoring, drilling and well, and continuous improvement.

Support CO_2 and environmental monitoring technologies and approaches that have the potential to reduce negative environmental and social impacts

Support the utilization of proven and emerging low-impact CO_2 and environmental monitoring technologies and approaches. Examples of these monitoring technologies are provided in ***Table 7***.

STANDARDS ORGANIZATIONS

Integrate and strengthen offshore storage-specific environmental and social safeguards

Offshore storage-specific safeguards within CDR standards can serve as an international baseline alongside existing regulatory frameworks.

PROJECT OPERATORS

Implement the Recommendations Checklist in a project setting

Feedback on the strengths and gaps of this checklist will allow it to be a more practical and applicable tool in operational offshore storage projects.

ACTIONABLE OPPORTUNITIES

Integrate low-impact, proven and emerging CO_2 and environmental monitoring technologies and approaches

Field testing and communication about the performance of CO_2 and environmental monitoring technologies and approaches that have the potential to reduce environmental and social impacts is a crucial step in enabling broader operational and regulatory adoption.

SCIENTIFIC COMMUNITY

Advance research to field trials

The advancement of research to field settings progresses the understanding of low-impact CO_2 and environmental monitoring technologies and approaches, marine and broader environmental impacts, and social impacts in active project contexts.

Engage with broader communities

Engagement across the sciences (e.g., geoscientists, marine scientists, environmental scientists, social scientists) as well as beyond the scientific community (e.g., regulatory bodies, standards organizations, project operators, investors, and impacted communities) ensures that scientific findings serve as the basis for decision-making in the broader offshore storage ecosystem.

CARBON REMOVAL BUYERS AND BROADER DECARBONIZATION INVESTORS

Prioritize investment in projects that align with the Recommendations Checklist

Integration of the Recommendations Checklist in project assessment and diligence processes increases adoption of recommendations that maximize positive outcomes and minimize negative impacts. Buyers may also seek opportunities to signal to the market, through investment decisions and public communications, their preference for projects that adhere to these recommendations and higher-quality outcomes.

IMPACTED COMMUNITIES

Engage with offshore storage projects through stakeholder consultation

Fundamentally, these projects occur within environment and community-rooted contexts. Communities live and work within and adjacent to potentially impacted project areas. This creates an opportunity to share these site-specific perspectives in developing and shaping stakeholder engagement mechanisms, social and environmental impact assessments, and resulting project operations and monitoring plans.

CONCLUSION

As dedicated geological offshore CO_2 storage becomes an increasingly viable option for both public and private actors to reach decarbonization goals, it is critical for all actors to understand how these offshore storage projects and associated monitoring technologies can be designed to improve outcomes. As new projects come online, regulatory bodies, standards organizations, project operators, scientists, carbon removal and broader decarbonization investors, and communities alike will shape the evolving regulatory policies, carbon market frameworks, and technologies that will help ensure safer operations.

Building upon existing scientific research and technical experience, this report identifies an initial set of recommendations and areas for these operational actors to consider as they participate in the market for offshore CO_2 storage. Importantly, these participants must consider that all projects are highly site-specific based on varying ecosystems— from geological basins to the adjacent ocean water columns — as well as proximity to communities whose livelihoods are supported by these ecosystems. Nonetheless, existing regulatory frameworks highlighted in this report provide some foundation for market participants to approach new projects. As projects become operational, these participants can demonstrate best practices to help inform and further develop these frameworks.

It is also critical to consider that several factors contribute to a project's safe operation, and these factors overlap and differ across project sites. Conducting risk and impact assessments that consider the recommendations in this report can help mitigate risks to communities and ecosystems. In particular, these assessments should be conducted proactively with the full participation of all stakeholders, inclusive of local and Indigenous communities as well as scientific experts across geophysical, biological, and engineering-related disciplines.

Offshore CO_2 storage actors should aim to continuously improve projects and contribute to the knowledge-base that will help improve the likelihood that future projects will be conducted safely. Cross-sector collaboration in this regard is critical to inform nascent technologies and project requirements to improve outcomes in offshore CO_2 storage. For example, project buyers may support developers to deploy low-impact CO_2 and environmental monitoring technologies such as passive seismic with distributed acoustic sensing alongside proven technologies. A comparison of monitoring techniques can be shared with the broader sector to accelerate the adoption of safer monitoring methods.

As offshore CO_2 projects become operational and inform the collective knowledge-base, we invite all participants to consider their role to advance safeguards and improved approaches to project management. By following the recommendations checklist provided in this report, participants can help advance regulatory frameworks, accelerate the adoption of safer technologies, and demonstrate a higher bar for projects optimized to mitigate risks and improve outcomes for communities and ecosystems.

APPENDIX

FOOTNOTES TO TEXT

1 Grant, A., et al. (2025). Australian Carbon Dioxide Removal Roadmap. *Commonwealth Scientific and Industrial Research Organisation* https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/CDR-Roadmap ;

2 (2019). Global Warming of 1.5°C. *Intergovernmental Panel on Climate Change.* https://www.ipcc.ch/sr15/ ;

3 (2021). IEA Net Zero by 2050: A Roadmap for the Global Energy Sector. *International Energy Agency.* https://www.iea.org/reports/net-zero-by-2050 ;

4 *Accelerating Decarbonization.* Northern Lights. https://norlights.com/ ;

5 (2026). Hubs in Action. The CCUS Hub. https://ccushub.ogci.com/hubs-in-action/ ;

6 (2024). Carbon capture and storage: What can we learn from the project track record?. *Clean Air Task Force.* https://www.catf.us/resource/carbon-capture-storage-what-can-learn-from-project-track-record/ ;

7 Chadwick, R. A., & Eiken, O. (2013). Offshore CO_2 storage: Sleipner natural gas field beneath the North Sea. *Geological Storage of Carbon Dioxide (CO_2): Geoscience, Technologies, Environmental Aspects and Legal Frameworks,* 227-253. https://doi.org/10.1533/9780857097279.3.227 ;

8 IPCC AR6 WGIII: CDR Factsheet. *Intergovernmental Panel on Climate Change.* https://www.ipcc.ch/report/ar6/wg3/resources/factsheets/ ;

9 Malischek, R., & McCulloch, S. (2021). *The world has vast capacity to store CO_2: Net zero means we'll need it.* International Energy Agency. https://www.iea.org/commentaries/the-world-has-vast-capacity-to-store-co2-net-zero-means-well-need-it ;

10 (2026). *Hubs in action.* The CCUS Hub. https://ccushub.ogci.com/hubs-in-action/ ;

11 Steven M., et al. (2010). Environmental risks and impacts of carbon dioxide (CO_2) leakage in terrestrial ecosystems, In M. Maroto-Valer (Ed.), *Developments and Innovation of CO_2 capture and storage, 2,* Woodhead Publishing, Cambridge. https://doi.org/10.1533/9781845699581.3.324 ;

12 (2010). Economic Impact Analysis for the Mandatory Reporting of Greenhouse Gas Emissions Subpart RR and Subpart UU: Injection and Geologic Sequestration of Carbon Dioxide. *U.S. Environmental Protection Agency.* https://www.cbd.int/impact/documents.shtml ;

13 (2015). Sub-seabed CO_2 Storage: Impact on Marine Ecosystems (ECO2). *European Commission.* https://cordis.europa.eu/project/id/265847/reporting ;

14 González-Nicolás, A., et al. (2019). Pressure management via brine extraction in geological CO_2 storage: Adaptive optimization strategies under poorly characterized reservoir conditions. *International Journal of Greenhouse Gas Control, 83,* 176-185. https://doi.org/10.1016/j.ijggc.2019.02.009 ;

15 Mallinger, S. (1996). OSHA Hazard Information Bulletins Potential Carbon Dioxide (CO_2) Asphyxiation Hazard When Filling Stationary Low Pressure CO_2 Supply Systems. *U.S Department of Labor: Occupational Safety and Health Administration.* https://www.osha.gov/publications/hib19960605 ;

16 Blackford, J., et al. (2015). Marine baseline and monitoring strategies for carbon dioxide capture and storage (CCS). *International Journal of Greenhouse Gas Control, 38,* 221-229. https://doi.org/10.1016/j.ijggc.2014.10.004 ;

17 Blackford, J., et al. (2008). Regional scale impacts of distinct CO_2 additions in the North Sea. *Marine Pollution Bulletin, 56*(8), 1461-1468. https://doi.org/10.1016/j.marpolbul.2008.04.048 ;

18 Blackford, J., et al. (2010). Chapter 13: Environmental risks and performance assessment of carbon dioxide (CO_2) leakage in marine ecosystems. *Developments and Innovation in Carbon Dioxide (CO_2) Capture and Storage Technology, 2,* 334-373. https://doi.org/10.1533/9781845699581.3.344 ;

19 Blackford, J., et al. (2017). Monitoring of offshore geological carbon storage integrity: Implications of natural variability in the marine system and the assessment of anomaly detection criteria. *International Journal of Greenhouse Gas Control, 64,* 99-112. https://doi.org/10.1016/j.ijggc.2017.06.020 ;

20 Gros, J., et al. (2019). Simulating and Quantifying Multiple Natural Subsea CO_2 Seeps at Panarea Island (Aeolian Islands, Italy) as a Proxy for Potential Leakage from Subseabed Carbon Storage Sites. *Environmental Science & Technology,* 53(17), 10258–10268. https://doi.org/10.1021/acs.est.9b02131 ;

21 Stalker, L., et al. (2025). Reviewing the implications of unlikely but potential CO_2 migration to the surface or shallow subsurface. *IEAGHG.* https://doi.org/10.62849/2025-01 ;

22 Alcalde, J., et al. (2018). Estimating geological CO_2 storage security to deliver on climate mitigation. *Nature Communications, 9,* 2201. https://doi.org/10.1038/s41467-018-04423-1 ;

23 Smyth, R. C., & Hovorka, S. D. (2017). Best Management Practices for Offshore Transportation and Sub-Seabed Geologic Storage of Carbon Dioxide. *U.S. Department of the Interior: Bureau of Ocean Energy Management,* 004. https://espis.boem.gov/final%20reports/5663.pdf ;

24 Furre, A., et al. (2017). 20 years of monitoring CO_2-injection at Sleipner. *Energy Procedia, 114,* 3916–3926. https://doi.org/10.1016/j.egypro.2017.03.1523 ;

25 Dean, M., et al. (2020). Insights and guidance for offshore CO_2 storage monitoring based on the QiCS, ETI MMV, and STEMM-CCS projects. *International Journal of Greenhouse Gas Control, 100,* 103120. https://doi.org/10.1016/j.ijggc.2020.103120 ;

26 Crocker, S.E., & Fratantonio, F. D. (2016). Characteristics of Sounds Emitted During High-resolution Marine Geophysical Surveys. *U.S. Department of the Interior: Bureau of Ocean Energy Management, 12,* 203. https://espis.boem.gov/final%20reports/5551.pdf ;

27 Weilgart, L. (2016). Alternative Quieting Technology to Seismic Airguns for Oil & Gas Exploration and Geophysical Research. *UN Global Sustainable Development Report.* https://sdgs.un.org/documents/brief-gsdr-alternative-quieting-technology-t-21543 ;

28 Fewtrell, J. L., & McCauley, R. D. (2012). Impact of air gun noise on the behaviour of marine fish and squid. *Elsevier: Marine Pollution Bulletin, 64,* 984-993. https://doi.org/10.1016/j.marpolbul.2012.02.009 ;

29 Carroll, A. G., et al. (2017). A critical review of the potential impacts of marine seismic surveys on fish & invertebrates. *Elsevier: Marine Pollution Bulletin, 114*(1), 9-24. https://doi.org/10.1016/j.marpolbul.2016.11.038 ;

30 (2014). Background Document on the Development of Practical Guidance and Toolkits to Minimize and Mitigate the Significant Adverse Impacts of Anthropogenic Underwater Noise on Marine and Coastal Biodiversity. *Convention on Biological Diversity,* UNEP/CBD/SBSTTA/18/INF/11. https://www.cbd.int/impact/documents.shtml ;

31 Ellison, W. T., et al. (2011). A new context-based approach to assess marine mammal behavioral responses to anthropogenic sounds. *Conservation Biology, 26*(1), 21-28. https://doi.org/10.1111/j.1523-1739.2011.01803.x ;

32 Popper, A. N., et al. (2022). Fish hearing "specialization" - a re-evaluation. *Hearing Research, 425.* https://doi.org/10.1016/j.heares.2021.108393

33 Sinha, M., et al. (2026). Low-Impact Monitoring Approaches for Offshore CCS Projects . *CSIRO,* EP2026-2213. https://doi.org/10.25919/3xbb-p853

34 Hovem, J. M., et. al. (2012). Modeling Propagation of Seismic Airgun Sounds and the Effects on Fish Behavior. *IEEE Journal of Oceanic Engineering, 37*(4), 576-588. https://doi.org/10.1109/JOE.2012.2206189 ;

35 (2024). Taking and Importing Marine Mammals; Taking Marine Mammals Incidental to Geophysical Surveys in the Gulf of Mexico. *U.S. National Oceanic and Atmospheric Administration,* Docket No. 240410-0195, 31488. https://www.federalregister.gov/documents/2024/04/24/2024-08257/taking-and-importing-marine-mammals-taking-marine-mammals-incidental-to-geophysical-surveys-in-the

APPENDIX

FOOTNOTES TO TABLES AND FIGURES

TABLE 1: MAPPING OF CDR PATHWAYS TO STORAGE OPTIONS

1 (2021). A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration. *National Academies of Sciences, Engineering, and Medicine; Division on Earth and Life Studies; Ocean Studies Board; Committee on A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration, 3.* https://www.ncbi.nlm.nih.gov/books/NBK580042/ ;
2 (2024). *Carbon Dioxide Removal (CDR).* Grantham Institute: Climate Change and the Environment. https://www.imperial.ac.uk/grantham/publications/background-briefings/carbon-dioxide-removal-cdr/ ;
3 (2026). *Enhanced Weathering.* Yale Center for Natural Carbon Capture. https://naturalcarboncapture.yale.edu/research/geological-ocean-capture/enhanced-weathering ;
4 IPCC AR6 WGIII: CDR Factsheet. *Intergovernmental Panel on Climate Change.* https://www.ipcc.ch/report/ar6/wg3/resources/factsheets/

TABLE 2: OVERVIEW OF THE ACTIVITIES ASSOCIATED WITH EACH PHASE OF THE OFFSHORE MANAGEMENT LIFE CYCLE

1 (2021). *About CCUS.* International Energy Agency. https://www.iea.org/reports/about-ccus

FIGURE 2: OPERATIONAL AND PLANNED CO_2 STORAGE HUBS

1 (2023). *Porthos CO_2 Transport & Storage.* Porthos. https://www.porthosco2.nl/en/ ;
2 (2024). *Moomba Carbon Capture and Storage.* Santos Ltd. https://www.santos.com/moombaccs/ ;
3 (2024). *PETROS, PETRONAS, and Japanese Consortium Parties Sign Landmark Storage Site Agreement.* Petroliam Nasional Berhad (PETRONAS). https://www.petronas.com/media/media-releases/petros-petronas-and-japanese-consortium-parties-sign-landmark-storage-site ;
4 (2026). *A Large-scale CO_2 Transport and Storage Service.* Aramis. https://www.aramis-ccs.com/ ;
5 (2026). *A project seeking to store carbon dioxide emissions to help lower the carbon intensity along the Texas Gulf Coast: Aiming to lead carbon dioxide (CO_2) transport and storage in Southeast Texas.* Bayou Bend CCS. https://bayoubend.com/ ;
6 (2026). *Carbon capture, utilization, and storage.* Saudi Arabian Oil Company. https://www.aramco.com/en/what-we-do/energy-innovation/ ; advancing-energy-solutions/carbon-capture-utilization-and-storage ;
7 (2026). *EAST CO_2AST* CLUSTER. EAST CO2AST CLUSTER. https://eastcoastcluster.co.uk/ ;
8 (2026). *Hubs in action.* The CCUS Hub. https://ccushub.ogci.com/hubs-in-action/ ;
9 (2026). *Northern Territory Low Emission Hub (NT LEH) Carbon Capture Storage and Utilisation (CCUS) business case project.* Commonwealth Scientific and Industrial Research Organisation (CSIRO). https://www.csiro.au/en/research/technology-space/energy/carbon-management/nt-low-emissions-hub/leh ;
10 (2026). *Ravenna CCS Project.* Ravenna CCS. https://ravennaccs.com/en-IT/project ;
11 (2026). *Scotland's CO_2 transport and storage network.* The Acorn Project. https://theacornproject.uk/ ;
12 (2026). *Unlocking a Low Carbon Future.* HyNet North West. https://hynet.co.uk/ ;
13 *Accelerating Decarbonization.* Northern Lights. https://norlights.com/

TABLE 3: OVERVIEW OF REGULATORY FRAMEWORKS APPLICABLE TO OFFSHORE STORAGE AND THE ASSOCIATED ENVIRONMENTAL AND SOCIAL SAFEGUARDS

1 (2004). Pollution Control Regulations, Part 7A: Storage of CO_2 in Geological Formations. *Norwegian Ministry of Climate and Environment, 9.* https://lovdata.no/dokument/SF/forskrift/2004-06-01-931 ;
2 (2009). Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006. *Official Journal of the European Union, 140,* 114-135. http://data.europa.eu/eli/dir/2009/31/oj ;
3 (2010). The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010: No. 2221 Environmental Protection. UK *Statutory Instruments.* https://www.legislation.gov.uk/uksi/2010/2221/contents/2010-10-01 ;
4 (2012). 2012 Specific Guidelines for the Assessment of Carbon Dioxide for Disposal into Sub-Seabed Geological Formations. *International Maritime Organization, 34/15, Annex 8.* https://www.imo.org/en/ourwork/environment/pages/ccs-default.aspx ;
5 (2017). Regulations relating to exploitation of subsea reservoirs on the continental shelf for storage of CO_2 and relating to transportation of CO_2 on the continental shelf. *Norwegian Offshore Directorate.* EEA Agreement Annex XX Chapter III No. 21 (Directive 2009/31/EC). https://www.sodir.no/en/regulations/regulations/exploitation-of-subsea-reservoirs-on-the-continental-shelf-for-storage-of-and-transportation-of-co/#Chapter-9 ;
6 (2023). Offshore Carbon Capture and Storage Regulatory Approvals. *Commonwealth of Australia.;* https://www.nopsema.gov.au/offshore-industry/carbon-capture-and-storage ;
7 (2025). The United States Department of the Interior Budget Justifications and Performance Information: Fiscal Year 2025. *Bureau of Ocean Energy Management.* https://www.doi.gov/sites/default/files/documents/2024-03/fy2025-508-boem-greenbook.pdf ;
8 (2026). Carbon Storage Stewardship Expectations. *North Sea Transit Authority.* https://www.nstauthority.co.uk/regulatory-information/carbon-storage/carbon-storage-stewardship-expectations/ ;
9 (2026). *Class VI: Well used for Geologic Sequestration of Carbon Dioxide.* United States Environmental Protection Agency. https://www.epa.gov/uic/class-vi-wells-used-geologic-sequestration-carbon-dioxide ;
10 Nair, K. L. (2025). *Cover Story: Who benefits from CCUS in Malaysia?.* Institute of Strategic and International Studies Malaysia. https://www.isis.org.my/2025/05/09/cover-story-who-benefits-from-ccus-in-malaysia/ ;
11 Smith, B. (2025). Thought Leadership: Policy, Legal and Regulatory Review: Mid-2025 Update and Perspective on the IMO's Net Zero Framework. *Global CCS Institute.* https://www.globalccsinstitute.com/wp-content/uploads/2025/08/Policy-Legal-and-Regulatory-Review-Mid-2025-Update-.pdf ;
12 Smyth, R. C., & Hovorka, S. D. (2017). Best Management Practices for Offshore Transportation and Sub-Seabed Geologic Storage of Carbon Dioxide. *U.S. Department of the Interior: Bureau of Ocean Energy Management, 004.* https://espis.boem.gov/final%20reports/5663.pdf

TABLE 4: OVERVIEW OF ISOMETRIC AND VERRA METHODOLOGIES APPLICABLE TO OFFSHORE STORAGE

1 (2024). VMD0058: CO_2 Storage in Saline Aquifers and Depleted Hydrocarbon Reservoirs. *Verified Carbon Standard, v1.0.* https://verra.org/methodologies/vmd0058-co2-storage-in-saline-aquifers-and-depleted-hydrocarbon-reservoirs-v1-0/ ;

2 (2025). CO_2 Storage in Depleted Hydrocarbon Reservoirs. *Isometric, v1.0.* https://registry.isometric.com/module/depleted-hydrocarbon-reservoirs/1.0 ;

3 (2025). CO_2 Storage in Saline Aquifers. *Isometric, v1.1.* https://registry.isometric.com/module/saline-aquifer-storage/1.1 ;

4 (2025). Isometric Standard. *Isometric, v2.1.* https://registry.isometric.com/standard/2.1#environmental-and-social-impact

TABLE 5: SUMMARY OF THE PRIMARY POTENTIAL ENVIRONMENTAL AND SOCIAL IMPACTS OF OFFSHORE STORAGE AND THE ASSOCIATED SAFEGUARDS

1 (2014). Background Document on the Development of Practical Guidance and Toolkits to Minimize and Mitigate the Significant Adverse Impacts of Anthropogenic Underwater Noise on Marine and Coastal Biodiversity. *Convention on Biological Diversity,* UNEP/CBD/SBSTTA/18/INF/11. https://www.cbd.int/impact/documents.shtml ;

2 (2015). Sub-seabed CO_2 Storage: Impact on Marine Ecosystems (ECO2). *European Commission.* https://cordis.europa.eu/project/id/265847/reporting ;

3 Carroll, A. G., et al. (2017). A critical review of the potential impacts of marine seismic surveys on fish & invertebrates. *Elsevier: Marine Pollution Bulletin, 114*(1), 9-24. https://doi.org/10.1016/j.marpolbul.2016.11.038 ;

4 Crocker, S. E., et al. (2019). Measurement of Sounds Emitted by Certain High-Resolution Geophysical Survey Systems. *IEEE Journal of Oceanic Engineering, 44*(3), 796-813. https://doi.org/10.1109/JOE.2018.2829958 ;

5 Ellison, W. T., et al. (2011). A new context-based approach to assess marine mammal behavioral responses to anthropogenic sounds. *Conservation Biology, 26*(1), 21-28. https://doi.org/10.1111/j.1523-1739.2011.01803.x ;

6 Fewtrell, J. L., McCauley, R. D. (2012). Impact of air gun noise on the behaviour of marine fish and squid. *Elsevier: Marine Pollution Bulletin, 64*(5), 984-993. https://doi.org/10.1016/j.marpolbul.2012.02.009 ;

7 Furre, A., et al. (2017). 20 years of monitoring CO_2-injection at Sleipner. *Energy Procedia, 114,* 3916–3926. https://doi.org/10.1016/j.egypro.2017.03.1523 ;

8 Hall-Spencer, J., et al. (2008). Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. *Nature, 454,* 96-99. https://doi.org/10.1038/nature07051 ;

9 Hovem, J. M., et al. (2012). Modeling Propagation of Seismic Airgun Sounds and the Effects on Fish Behavior. *IEEE Journal of Oceanic Engineering, 37*(4), 576-588. https://doi.org/10.1109/JOE.2012.2206189 ;

10 Løkkeborg, S., et al. (2012). Sounds from seismic air guns: gear- and species-specific effects on catch rates and distribution. *Canadian Journal of Fisheries and Aquatic Sciences, 69*(8), 1278-1291. https://doi.org/10.1139/f2012-059 ;

11 Malischek, R., & McCulloch, S. (2021). *The world has vast capacity to store CO_2: Net zero means we'll need it.* International Energy Agency. https://www.iea.org/commentaries/the-world-has-vast-capacity-to-store-co2-net-zero-means-well-need-it ;

12 Nadim, F., & Kvalstad, T. J. (2007). Risk Assessment and Management for Offshore Geohazards. *First International Symposium on Geotechnical Safety & Risk.* https://www.geoengineer.org/geosnet/ISGSR2007/InivtedLecture6.pdf ;

13 Streever, B., et al. (2016). Changes in Fish Catch Rates in the Presence of Air Gun Sounds in Prudhoe Bay, Alaska. *The Arctic Institute of North America, 69*(4), 331-458. https://doi.org/10.14430/arctic4596

TABLE 6: LITERATURE REVIEW OF THE POTENTIAL IMPACTS OF ACTIVE SEISMIC GEOPHYSICAL SURVEYS ON MARINE LIFE

1 (2014). Background Document on the Development of Practical Guidance and Toolkits to Minimize and Mitigate the Significant Adverse Impacts of Anthropogenic Underwater Noise on Marine and Coastal Biodiversity. *Convention on Biological Diversity,* UNEP/CBD/SBSTTA/18/INF/11. https://www.cbd.int/impact/documents.shtml ;

2 (2024). Taking and Importing Marine Mammals; Taking Marine Mammals Incidental to Geophysical Surveys in the Gulf of Mexico. *U.S. National Oceanic and Atmospheric Administration,* Docket No. 240410-0195, 31488. https://www.federalregister.gov/documents/2024/04/24/2024-08257/taking-and-importing-marine-mammals-taking-marine-mammals-incidental-to-geophysical-surveys-in-the ;

3 Affatati, A., & Camerlenghi, A. (2023). Effects of marine seismic surveys on free-ranging fauna: a systematic literature review. *Frontiers, 10,* 3389. https://doi.org/10.3389/fmars.2023.1222523 ;

4 Blackwell, S., et al. (2015). Effects of Airgun Sounds on Bowhead Whales Calling Rates: Evidence for Two behavioral Thresholds. *PLoS ONE, 10*(6). https://doi.org/10.1371/journal.pone.0125720 ;

5 Carroll, A. G., et al. (2017). A critical review of the potential impacts of marine seismic surveys on fish & invertebrates. *Elsevier: Marine Pollution Bulletin, 114*(1), 9-24. https://doi.org/10.1016/j.marpolbul.2016.11.038 ;

6 Davidsen, J. G., et al. (2019). Effects of sound exposure from a seismic airgun on heart rate, acceleration and depth use in free-swimming Atlantic cod and saithe. *Conservation Physiology, 7*(1). https://doi.org/10.1093/conphys/coz020 ;

7 Fewtrell, J. L., & McCauley, R. D. (2012). Impact of air gun noise on the behaviour of marine fish and squid. *Elsevier: Marine Pollution Bulletin, 64,* 984-993. https://doi.org/10.1016/j.marpolbul.2012.02.009 ;

8 Finneran, J. J., et al. (2000). Auditory and behavioral responses of bottlenose dolphins (Tursiops truncatus) and a beluga whale (Delphinapterus leucas) to impulsive sounds resembling distant signatures of underwater explosions. *The Journal of the Acoustical Society of America, 108*(1), 417-431. https://doi.org/10.1121/1.429475 ;

9 Finneran, J. J., et al. (2015). Effects of multiple impulses from a seismic air gun on bottlenose dolphin hearing and behavior. *The Journal of the Acoustical Society of America, 137*(4), 1634-1646. https://doi.org/10.1121/1.4916591 ;

10 Finneran, J. J., et al. (2023). Dolphins reduce hearing sensitivity in anticipation of repetitive impulsive noise exposures. *The Journal of the Acoustical Society of America, 153*(6), 3372. https://doi.org/10.1121/10.0019751 ;

11 Gordan, J., et al. (2003). A Review of the Effects of Seismic Surveys on Marine Mammals. *Marine Technology Society Journal, 37*(4), 16-34. https://doi.org/10.4031/002533203787536998 ;

12 Guerra, A., et al. (2004). A review of the records of giant squid in the north-eastern Atlantic and severe injuries in Architeuthis dux stranded after acoustic explorations. *International Council for the Exploration of the Sea.* https://doi.org/10.17895/ices.pub.25349203 ;

13 Harris, R. E., et al. (2006). Seal Responses to Airgun Sounds during Summer Seismic Surveys in the Alaskan Beaufort Sea. *Marine Mammal Science, 17*(4), 795-812. https://doi.org/10.1111/j.1748-7692.2001.tb01299.x ;

14 Hawkins, A. D., et al. (2014). Responses of free-living coastal pelagic fish to impulsive sounds. *National Library of Medicine: National Center for Biotechnology Information, 135*(5), 3101-3116. https://doi.org/10.1121/1.4870697

15 Hermannsen, L., et al. (2015). Characteristics and Propagation of Airgun Pulses in Shallow Water with Implications for Effects on Small Marine Mammals. *PLoS.ONE, 10*(7). https://doi.org/10.1371/journal.pone.0133436 ;
16 Hovem, J. M., et. al. (2012). Modeling Propagation of Seismic Airgun Sounds and the Effects on Fish Behavior. I*EEE Journal of Oceanic Engineering, 37*(4), 576-588. https://doi.org/10.1109/JOE.2012.2206189 ;
17 Kastelein, R., et al. (2024). Atlantic Green Turtles and Hawksbill Turtles: Behavioral Responses to Sound. *Springer Nature: The Effects of Noise on Aquatic Life,* 1243-1261. https://doi.org/10.1007/978-3-031-50256-9_75 ;
18 Løkkeborg, S., et al. (2012). Sounds from seismic air guns: gear- and species-specific effects on catch rates and distribution. *Canadian Journal of Fisheries and Aquatic Sciences, 69*(8), 1278-1291. https://doi.org/10.1139/f2012-059 ;
19 McCauley, R. D., et. al. (2000). Marine Seismic Surveys - A Study of Environmental Implications. *APPEA Journal, 40*(1), 692-708. https://doi.org/10.1071/AJ99048 ;
20 Patel, S. H., et al. (2026). Leatherback sea turtles (Dermochelys coriacea) react to impulsive sounds. *Scientific Reports, 16,* 7372. https://doi.org/10.1038/s41598-026-38178-3 ;
21 Popper, A. N., et al. (2005). Effects of exposure to seismic airgun use on hearing of three fish species. *The Journal of the Acoustic Society of America, 117*(6), 3958-3971. https://doi.org/10.1121/1.1904386 ;
22 Salas, A., et al. (2024). Narrowband noise induces frequency-specific underwater temporary threshold shifts in freshwater turtles. *JASA Express Lett, 4*(8). https://doi.org/10.1121/10.0028321 ;
23 Streever, B., et. al. (2016). Changes in Fish Catch Rates in the Presence of Air Gun Sounds in Prudhoe Bay, Alaska. *The Arctic Institute of North America, 69*(4), 331-458. https://doi.org/10.14430/arctic4596

TABLE 7:
OVERVIEW OF PROVEN AND EMERGING LOW-IMPACT CO_2 MONITORING METHODS

1 Bremaud, V., et al. (2023). Capabilities of Fiber Optics Deployed at Seabed for Microseismic Monitoring: Northern Lights Case Study. *The Fourth EAGE Global Energy Transition Conference and Exhibition,* 1 – 5. https://doi.org/10.3997/2214-4609.202321016 ;
2 Caudron, C., et al. (2024). Monitoring underwater volcano degassing using fiber-optic sensing. *Sci Rep, 14,* 3128. https://doi.org/10.1038/s41598-024-53444-y ;
3 Barajas-Olalde, C., et al. (2023). Application of Electromagnetic Methods for Reservoir Monitoring with Emphasis on CCUS. *Minerals, 13*(10), 1308. https://doi.org/10.3390/min13101308 ;
4 Dale, A. W., et al. (2021). Defining a biogeochemical baseline for sediments at CCS sites: An example from the North Sea (Goldeneye). *International Journal of Greenhouse Gas Control, 106,* 103265. https://doi.org/10.1016/j.ijggc.2021.103265 ;
5 Fletcher, A., et al. (2025). Monitoring CO_2 injection in the Viking CCS project using offshore time-lapse gravity. *86th EAGE Annual Conference and Exhibition,* 1–5. https://doi.org/10.3997/2214-4609.2025101011 ;
6 Flohr, A., et al. (2021). Towards improved monitoring of offshore carbon storage: A real-world field experiment detecting a controlled sub-seafloor CO_2 release. *International Journal of Greenhouse Gas Control, 106,* 103237. https://doi.org/10.1016/j.ijggc.2020.103237 ;
7 Jenkins, C., et al. (2024). Field tests of geological storage of CO_2 at the Otway International Test Centre, Australia: trapping and monitoring the migrating plumes. *Geoenergy, 2.* https://doi.org/10.1144/geoenergy2023-035 ;
8 Khatib, H. A., et al. (2021). Breaking the seismic 4D 'image' paradigm of seismic monitoring. *First Break, 39*(9), 85–91. https://doi.org/10.3997/1365-2397.fb2021072 ;
9 Li, J., et al. (2020). Passive acoustic monitoring of a natural CO2 seep site – Implications for carbon capture and storage. *International Journal of Greenhouse Gas Control, 93,* 102899. https://doi.org/10.1016/j.ijggc.2019.102899 ;
10 Ma et al. (2024). Advances in Geochemical Monitoring Technologies for CO_2 Geological Storage. *Sustainability, 16*(16), 6784. https://doi.org/10.3390/su16166784 ;
11 Meneghini, F., et al. (2025). Detection of CO_2 emissions from Panarea seabed with Distributed Acoustic Sensing (DAS): a preliminary investigation. *Relazione interna Ogs, 106.* https://ricerca.ogs.it/handle/20.500.14083/45625 ;
12 Rørstadbotnen, R. A., & Landrø, M. (2026). Detecting silent whales using seabed fiber-optic cables. *Proceedings of the National Academy of Sciences of the United States of America. 123*(26). https://doi.org/10.1073/pnas.2603077123 ;
13 Sinha, M., et al. (2024). Seismic monitoring of CCS with active and passive data: A synthetic feasibility study based on Pelican site, Australia. *International Journal of Greenhouse Gas Control, 139,* 104277. https://doi.org/10.1016/j.ijggc.2024.104277 ;
14 Utting, N., et al. (2023). Well Integrity Monitoring at CCS Projects: A Case Study. *Geoconvention 2023.* https://geoconvention.com/abstract-archives/

TABLE 8: OFFSHORE STORAGE RECOMMENDATIONS CHECKLIST

1 (2020). What is a "Good Practice?" A Framework to Analyse the Quality of Stakeholder Engagement in Implementation and Follow-up of the 2030 Agenda. *United Nations: Department of Economic and Social Affairs.* https://sdgs.un.org/publications ;

2 (2025). Environment and Social Safeguard Standard. *Global Carbon Council, 4*(1). https://globalcarboncouncil.com/how-gcc-works/regulatory-framework/ ;

3 (2026). *Seascapes: Protecting the places that matter most.* World Wildlife Fund. https://www.worldwildlife.org/our-work/oceans/seascapes/ ;

4 (2026). Survey guidelines for Australia's threatened mammals: Guidelines for detecting mammals listed as threatened under the EPBC Act. *Australian Government: Department of Sustainability, Environment, Water, Population and Communities.* https://www.dcceew.gov.au/environment/epbc/publications/survey-guidelines-australias-threatened-mammals ;

5 Blackford, J., et al. (2015). Marine baseline and monitoring strategies for carbon dioxide capture and storage (CCS). *International Journal of Greenhouse Gas Control, 38*, 221-229. https://doi.org/10.1016/j.ijggc.2014.10.004 ;

6 Crocker, S. E., et al. (2019). Measurement of Sounds Emitted by Certain High-Resolution Geophysical Survey Systems. *IEEE Journal of Oceanic Engineering, 44*(3), 796-813. https://doi.org/10.1109/JOE.2018.2829958 ;

7 Ellison, W. T., et al. (2011). A new context-based approach to assess marine mammal behavioral responses to anthropogenic sounds. *Conservation Biology, 26*(1), 21-28. https://doi.org/10.1111/j.1523-1739.2011.01803.x ;

8 Fewtrell, J. L., & McCauley, R. D. (2012). Impact of air gun noise on the behaviour of marine fish and squid. *Elsevier: Marine Pollution Bulletin, 64*(5), 984-993. https://doi.org/10.1016/j.marpolbul.2012.02.009 ;

9 Furre, A., et al. (2017). 20 years of monitoring CO_2-injection at Sleipner. *Energy Procedia, 114*, 3916-3926. https://doi.org/10.1016/jegypro.2017.03.1523 ;

10 Hovem, J. M., et. al. (2012). Modeling Propagation of Seismic Airgun Sounds and the Effects on Fish Behavior. *IEEE Journal of Oceanic Engineering, 37*(4), 576-588. https://doi.org/10.1109/JOE.2012.2206189 ;

11 Johnson, C. M., et al. (2022). Protecting Blue Corridors - Challenges and solutions for migratory whales navigating national and international seas. World *Wildlife Fund, 1.* https://wwfwhales.org/resources/protecting-blue-corridors-report ;

12 Methratta, E. T. (2020). Monitoring fisheries resources at offshore wind farms: BACI vs. BAG designs. *ICES Journal of Marine Science, 77*(3), 890-900. https://doi.org/10.1093/icesjms/fsaa026 ;

13 Sinha, M., et al. (2024). Seismic monitoring of CCS with active and passive data: A synthetic feasibility study based on Pelican site, Australia. *International Journal of Greenhouse Gas Control, 139*. https://doi.org/10.1016/j.ijggc.2024.104277 ;

14 Southall, B. L., et al. (2021). Marine Mammal Noise Exposure Criteria: Assessing the Severity of Marine Mammal Behavioral Responses to Human Noise. *Aquatic Mammals, 47*(5), 421-464. https://doi.org/10.1578/AM.47.5.2021.421