Dedicated Offshore CO_2 Storage in a Decarbonization Context

Best Practices to Maximize Environmental and Social Outcomes and Minimize Negative Impacts

[CONFIDENTIAL]

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1. Executive Summary

Public or private actors are likely to encounter carbon reduction and removal opportunities that leverage offshore storage pathways. This report assesses the potential environmental and social impacts of dedicated offshore carbon dioxide (CO_2) storage projects and explores actionable best practices to engage with these projects in a decarbonization context.

CO_2 Storage Scope: Dedicated offshore CO_2 storage represents a scalable commercial storage pathway aligned with decarbonization and net zero goals. The term "dedicated" is indicative of utilization solely for storage purposes rather than in combination with enhanced oil recovery (EOR). EOR is aimed at increasing the production of petroleum fluids and is not aligned with decarbonization goals. This report solely addresses dedicated offshore CO_2 storage, which is hereby referred to as offshore storage.

Role: This report aims to distill consensus from international regulatory bodies, standard organizations, and the scientific community in a condensed and accessible review of offshore storage impacts. The report then presents actionable best practices to maximize positive outcomes and minimize negative impacts. Importantly, this report aligns with global requirements of existing offshore storage regulatory frameworks and standards. Regarding scientific perspectives, there is a significant body of scientific literature evaluating potential impacts, mitigation strategies, and best available monitoring technologies related to offshore storage. The report provides a literature review and highlights the recurrent theme of supporting further site-specific, species-specific field research.

Content: The report addresses the following subjects:

- Explores the applicability of offshore storage to carbon reduction and removal pathways
- Provides context on offshore storage capacity and project development
- Demonstrates alignment with regulations and carbon market standards
- Builds awareness of environmental and social impacts and the strategies to maximize positive outcomes and minimize negative impacts
- Recommends a Best Practices Checklist to guide responsible investment in and scaling of offshore storage projects

Findings: Overall, this report identifies environmental and social best practices that are designed to be implemented in an offshore storage project context and improved with the learnings from field trials and early offshore storage projects. Key findings and associated opportunities presented in this report are:

- **Offshore storage projects are highly site-specific:** The development of project plans, understanding of potential impacts on the ecosystem and communities, and design of safeguards must be highly site-specific. There is an opportunity to foster increased sharing of project learnings through cross-sector collaboration.
- **Developing regulations provide an enforceable baseline for minimizing negative impacts:** Existing and developing offshore storage regulatory frameworks generally require

environmental and social impact assessments. Currently, there is an evolving myriad of national offshore storage regulations.

- **Field trials are needed to benchmark and advance risk-optimized technologies and understanding of impacts:** There is a need to field test risk-optimized, emerging CO_2 monitoring techniques that have the potential to reduce negative environmental and social impacts. Examples of emerging monitoring technologies are provided in **Table 7**.

Best Practices Checklist: A condensed version of the Best Practices Checklist is provided below. Please reference **Table 8** for a detailed version with examples and references.

(This will be an infographic not a table in the final version.)

Categorization	Best Practice
Baseline Assessment	☐ Did the project assess the reservoir seal integrity? ★ General regulatory requirement ☐ Did the project conduct a site-specific baseline assessment? ★ General regulatory requirement ☐ Did the project identify and mitigate potential negative impacts to endangered species? ★ General regulatory requirement
Environmental and Social Impacts	☐ Does the project integrate stakeholder engagement with all impacted communities? ☐ Did the project assess environmental and social impacts? ★ General regulatory requirement ☐ Did the assessment of environmental and social impacts include the impacts of anthropogenic sounds, particularly those associated with seafloor and CO_2 monitoring technologies?
Earthquake Monitoring Plan	☐ Does the project integrate a pressure and microseismic monitoring and management plan? ★ General regulatory requirement
CO_2 Leakage Monitoring Plan	☐ Is the project operating within a jurisdiction characterized by robust and enforceable safety regulations for offshore storage? ☐ Does the project integrate marine life protections beyond the utilization of Protected Species Observers (PSOs) and the soft-start method for active seismic geophysical surveys? ☐ Does the project integrate a CO_2 monitoring plan? ★ General regulatory requirement ☐ Does the project's CO_2 monitoring plan integrate field trials of emerging monitoring technologies? ☐ Does the project integrate maintenance and leakage-response plans? ★ General regulatory requirement
Continuous Improvement	☐ Does the project integrate continuous improvement mechanisms with regards to environmental and social impacts? ☐ Does the project regularly assess the effectiveness of its risk-optimized CO_2 monitoring approach?

Actionable Opportunities: An overarching opportunity that serves as a basis for translating findings into actions is increased cross-sector collaboration amongst regulatory bodies, standard organizations, project operators, scientists, carbon removal buyers and investors, and impacted communities (e.g., coastal communities, fishing communities, and indigenous groups). Additional actionable opportunities are summarized below and further detailed in **Table 9**.

(This will be an infographic not a table in the final version.)

Actor	Opportunities	Report References
All Actors	Foster and participate in cross-sector collaboration	Figure 1: Mapping of offshore storage ecosystem participants
Regulatory Bodies	Ensure environmental and social safeguards are integrated in regulatory requirements	Table 3: Examples of regulatory standards and integrated safeguards Table 5: Potential environmental and social impacts and associated safeguards
	Support field trials of risk-optimized, CO_2 monitoring approaches and technologies that have the potential to reduce negative environmental and social impacts	Table 7: Emerging CO_2 monitoring technologies
Standard Organizations	Integrate / strengthen offshore storage-specific environmental and social safeguards	Table 5: Potential environmental and social impacts and associated safeguards
Project Operators	Provide feedback on the strengths and gaps of the Best Practices Checklist from an operational perspective	Best Practices Checklist: Best practices for ensuring the containment integrity and environmental and social safety of an offshore storage project
	Integrate field trials of risk-optimized, CO_2 monitoring approaches and technologies that have the potential to reduce negative environmental and social impacts	Table 7: Emerging CO_2 monitoring technologies
Scientific Community	Advance research to field trials to assess CO_2 monitoring technologies and offshore storage environmental and social impacts in a project context	Table 5: Potential environmental and social impacts and associated safeguards Table 7: Emerging CO_2 monitoring technologies
	Engage with broader communities to ensure that scientific findings serve as the basis for decision-making in the broader offshore storage ecosystem	Figure 1: Mapping of offshore storage ecosystem participants
Carbon Removal Buyers and Broader Decarbonization Investors	Prioritize investment in projects that align with the Best Practices Checklist to drive adoption of best practices that maximize positive outcomes and minimize negative impacts	Best Practices Checklist: Best practices for ensuring the containment integrity and environmental and social safety of an offshore storage project
Impacted Communities	Engage with offshore storage projects to develop and shaping stakeholder engagement mechanisms, social / environmental impact assessments, and resulting project operations and monitoring plans	Figure 1: Mapping of offshore storage ecosystem participants Table 5: Potential environmental and social impacts and associated safeguards Best Practices Checklist: Best practices for ensuring the containment integrity and environmental and social safety of an offshore storage project

2. Acknowledgement

Placeholder logos

3. 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 $GtCO_2$ [gigatonnes of CO_2] over the 21st century." 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. **Dedicated storage hubs are under active, initial development:** There is active development of dedicated onshore and offshore storage hubs. These hubs operationalize economies of scale by aggregating CO_2 from multiple suppliers and aiming for the injection of larger, consistent volumes. For example, Northern Lights in the North Sea 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 social-acceptance and 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 best practices prior to scaling of offshore storage:** Now is the pivotal moment to shape offshore storage best practices as global hubs are coming online and regulatory / voluntary schemes are developing.

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[1] (2025). Australian Carbon Dioxide Removal Roadmap. *Commonwealth Scientific and Industrial Research Organization.*
[2] (2019). Global Warming of 1.5°C. *Intergovernmental Panel on Climate Change.*
[3] (2021). IEA Net Zero by 2050: A Roadmap for the Global Energy Sector. *International Energy Agency.*
[4] Accelerating Decarbonization. Northern Lights.
[5] (2025). Northern Lights/Longship. The CCUS Hub.

Applicability to CO_2 Reduction Pathways

CO_2 capture from natural gas plants or hard-to-abate industrial processes (e.g., cement or steel) involves subsequent CO_2 utilization and/or storage. The Sleipner and Snøhvit projects in the North Sea were the first dedicated offshore projects storing CO_2 separated from the production of natural gas / liquefied natural gas in saline aquifers, beginning in 1996 and 2008, respectively.[6, 7]

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 (CO_2) from the atmosphere". 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 Storage Options to CDR Pathways

CDR Pathway	Description	Durability Estimate	Storage Options
Afforestation, Reforestation, Improved Forest Management (AR/IFM)	Store carbon in forest contexts and/or in related bio-based products (e.g., mass timber)[6]	Decades to centuries[6]	Vegetation and soils Human products[6]
Soil carbon sequestration	Store carbon in soil contexts[6]	Decades to centuries[6]	Vegetation and soils[6]
Biochar	Pyrolyze biomass residues to store carbon as a soil amendment[5, 6]	Centuries to millennia[6]	Vegetation and soils[6]
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[3]	10,000+ years[6]	**Geological structures (onshore / offshore)**[6]
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, 6]	10,000+ years[6]	**Geological structures (onshore / offshore)**[6]
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 a carbonate[4, 6]	10,000+ years[6]	Vegetation and soils Ocean minerals and sediment[6]
Peatland and wetland restoration	Restore degraded peatlands, which naturally capture and store CO_2, through rewetting and revegetation[2, 6]	Decades to centuries[6]	Vegetation and soils[6]
Blue carbon	Store CO_2 in mangroves and other intertidal / marine flora[6]	Decades to centuries[6]	Vegetation and soils[6]
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, 6]	10,000+ years[6]	Ocean minerals and sediment[6]
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	Centuries to millenia[6]	Ocean minerals and sediment[6]

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[6] (2024). Carbon capture and storage: What can we learn from the project track record?. *Clean Air Task Force.*
[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.* Cambridge, UK, Woodhead Publishing, 227-253.
[8] IPCC AR6 WGIII: CDR Factsheet. *Intergovernmental Panel on Climate Change.*

	and the consequential uptake of CO_2, which will eventually be stored as carbonate[1, 6]		

Table 1: Mapping of Storage Options to CDR Pathways

Sources: [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 & 7.*; [2] (2024). Carbon Dioxide Removal (CDR). Grantham Institute: Climate Change and the Environment.; [3] (2025). Carbon Capture Utilization and Storage. *International Energy Agency.*; [4] (2025). Enhanced Weathering. Yale Center for Natural Carbon Capture.; [5] (2025). Soil and Water Research; St. Paul, MN: Biochar. *U.S. Department of Agriculture.*; [6] IPCC AR6 WGIII: CDR Factsheet. *Intergovernmental Panel on Climate Change.*

Offshore Storage Ecosystem

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

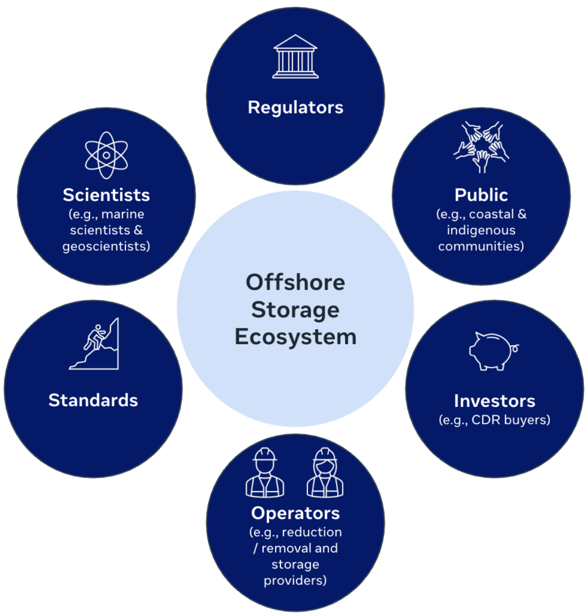

Figure 1: Offshore Storage Ecosystem

4. Context on Offshore Storage

Geological Storage Estimated Capacity

Overall, the IEA conservative geological estimated total storage complex volume of 8,000 Gt far outweighs the 220 Gt of CO_2 predicted to be stored between 2020 to 2070 in the IEA Sustainable Development Scenario. Globally, onshore storage capacity dwarfs that of offshore storage. 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.

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 termed as capacity and contingent storage resources, respectively. There is greater uncertainty on the prospective storage resources where: site-specific geological parameters (e.g., porosity, permeability, structural faults, geochemistry) and commercial feasibility have not been determined. For contingent storage resources, cost reduction is expected to occur with the development of hubs that facilitate scaled collection, transportation, and storage of CO_2, 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 is used by storage proponents to evaluate their CO_2 storage resources.

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. The most advanced CO_2 storage hubs, including Ravenna in the Mediterranean and Northern Lights and Porthos 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.

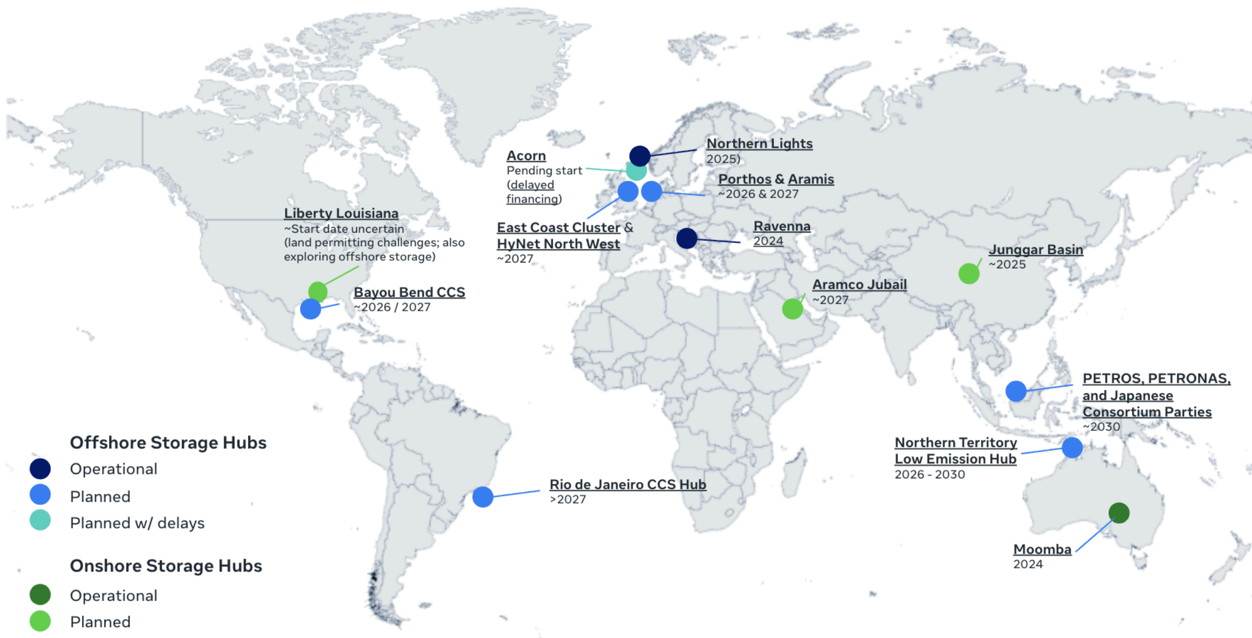

Figure 2: Examples of CO_2 Storage Hubs Leveraging Saline Aquifers or Depleted Reservoirs with Corresponding Commercial Operation Date

Sources: [1] (2023). Porthos CO_2 Transport & Storage.; [2] (2024). Moomba Carbon Capture and Storage. *Santos Ltd.*; [3] (2026). Aramis.; [4] (2026). Bayou Bend CCS.; [5] (2026). EAST CO_2AST CLUSTER.; [6] (2026). Hubs in action. *The CCUS Hub.*; [7] (2026). HyNet North West.; [8] (2024). PETROS, PETRONAS, and Japanese Consortium Parties Sign Landmark Storage Site Agreement. *Petroliam Nasional Berhad (PETRONAS).*; [9] (2026). Northern Lights.; [10] (2026). Northern Territory Low Emission Hub (NT LEH) Carbon Capture Storage and Utilisation (CCUS) business case project. *Commonwealth Scientific and Industrial Research Organisation (CSIRO).*; [11] (2026). Ravenna CCS.; [12] (2026). Saudi Arabian Oil Company.; [13] (2026). The Acorn Project.;

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 life cycle into three broadly applicable phases, as outlined in **Table 2**.

[9] Malischek, R., and McCulloch, S. (2021). The world has vast capacity to store CO_2: Net zero means we'll need it. *International Energy Agency.*
[10] (2025). Hubs in action. *The CCUS Hub.*

Table 2: Overview of the Activities Associated with Each Phase of the Offshore Management Life Cycle

PHASE I: Site Assessment	PHASE II: CO_2 Injection	PHASE III: Post-Injection
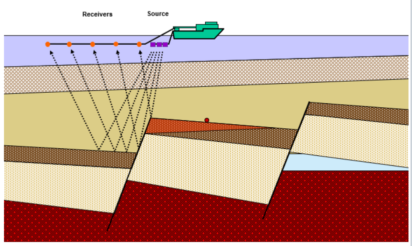	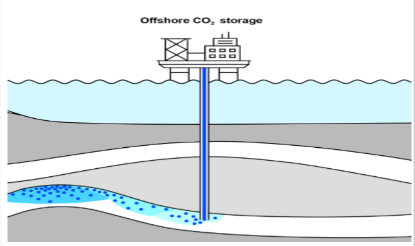	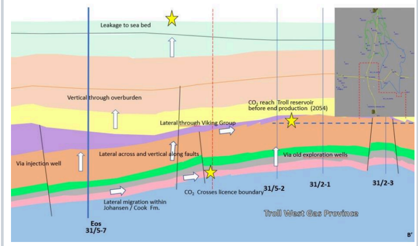
Photo Source: National Science Foundation	*Photo Source: International Energy Agency*	*Photo Source: Northern Lights*
• **Site assessment** - Evaluate potential offshore reservoir; this exploration phase generally employs methodologies established in the oil and gas industry by leveraging active seismic geophysical surveys enduring a couple of months and exploration well(s) • **Site development** - Construct onshore collection / compression and offshore platform facilities; lay pipeline to the injection site	• **Transport to onshore site** - Transport CO_2 to onshore facility via ships / pipeline / trucks • **Transport to offshore site** - Transport CO_2 to offshore injection site via pipeline • **Injection** - Inject CO_2 into 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 and leakage • **Transfer of offshore site from operator to state** - Contractually, after monitoring of 25+ years and demonstration of a stable CO_2 plume, site ownership is generally transferred to the state

Table 2: Overview of the Activities Associated with Each Phase of the Offshore Management Life Cycle
Source: (2021). About CCUS. International Energy Agency.

5. Regulatory and Carbon Markets Alignment

This report aligns with requirements in offshore storage regulatory frameworks and standards. An overview of current regulatory frameworks and standards are provided below.

Alignment with Regulatory Frameworks

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 a national / regional level. Australia, the European Union, Malaysia, and Norway are examples of global leaders in establishing national / regional frameworks for offshore storage. A summary of these regulatory approaches and required environmental and social safeguards are provided in **Table 3**.

Table 3: Summary of Offshore Storage Regulatory Frameworks and 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[3] • **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	• **Establishes global operational baseline:** Provides an international, operational baseline that serves as an environmental / 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[2, 3]

	management[3] • **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[2]	
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 Act 1981, and the Environment Protection and Biodiversity Conservation Act 1999[5]	• **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[5]
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[1] • 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)[1, 3]	• **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[1] • **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[1]
Malaysia	• **CCUS Bill (2025):** Introduced initial federal framework for the entire CCUS value chain, including offshore storage[6, 7]	• **Requires CO_2 plume monitoring but not environmental / social impact assessment 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[6, 7]
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[4]	• **Requires a commercial and environmental impact assessment:** Requires that the project assess the environment that may be significantly impacted and related consequences, monitoring, and preventative / mitigating measures[4] • **Compensation for the fishing community:** Requires projects to compensate the fishing community for financial loss associated with the transport and storage of CO_2[4]

Table 3: Summary of Offshore Storage Regulatory Frameworks and Associated Environmental and Social Safeguards

Sources: [1] (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. *European Union.*; [2] (2012). 2012 Specific Guidelines for the Assessment of Carbon Dioxide for Disposal into Sub-Seabed Geological Formations. *International Maritime Organization, LC34/15, annex 8.*; [3] (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.*; [4] (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.*; [5] (2023). Offshore Carbon Capture and Storage Regulatory Approvals. *Commonwealth of Australia.*; [6] Nair, K. (2025). Cover Story: Who benefits from CCUS in Malaysia?. *Institute of Strategic and International Studies Malaysia.*; [7] 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.*

Alignment with Carbon Market Standards

Storage operations build on the well established methodologies and infrastructure from the oil and gas sector. This includes infrastructure such as offshore platforms and umbilicals as well as monitoring approaches such as active seismic geological 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 aligns with existing carbon market safeguards, with examples provided in **Table 4**, and provides increased specificity on requirements in an offshore context to ensure the sustainable scaling of these project types.

Table 4: Demonstration of Alignment with Applicable Isometric and Verra Modules / Methodologies		
Please Note: This evaluation considered the following internationally-recognized modules / methodologies: Isometric: CO_2 Storage in Depleted Hydrocarbon Reservoirs, CO_2 Storage in Saline Aquifers Verra: VMD0058 CO_2 Storage in Saline Aquifers and Depleted Hydrocarbon Reservoirs, v1.0		
Requirements	**Description**	**Additional Guidance Provided by Report**
Comply with country / 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 leading regulatory frameworks applicable to offshore storage and the associated environmental and social safeguards
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 / social impacts and corresponding safeguards in the context of an offshore storage project
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 and social / environmental impacts) as well as integrate best available technologies and new scientific findings.[2, 3]	Explores developing CO_2 plume monitoring technologies and risk-based strategies that maintain and/or increase integrity of plume monitoring while minimizing negative environmental / social impacts

Table 4: Demonstration of Alignment with Applicable Isometric and Verra Modules / Methodologies
Sources: [1] (2024). VMD0058: CO_2 Storage in Saline Aquifers and Depleted Hydrocarbon Reservoirs. *Verified Carbon Standard, v1.0.*; [2] (2025). CO_2 Storage in Depleted Hydrocarbon Reservoirs. *Isometric, v1.0.*; [3] (2025). CO_2 Storage in Saline Aquifers. *Isometric, v1.1.*; [4] (2025). Isometric Standard. *Isometric, v1.7.6.*

6. Impacts and Associated Safeguards

Summary of Potential Impacts and Corresponding Safeguards

Table 5 summarizes the potential environmental and social impacts of offshore storage. The table also provides optimization strategies to maximize positive impacts and mitigation strategies to 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** *Included in Best Practices 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[12] • Offshore storage projects can enable economies of scale given significant storage volume capacity	**High** likelihood of supporting decarbonization goals	• **[Preferred] 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	• Offshore storage projects can maintain and create local jobs and	**High** likelihood of	• **[Preferred] Community Benefits Plan (CBP):** Prioritize projects that integrate a

	sector workforce	broader contracting opportunities • Offshore storage projects can support the development of storage hubs and the broader decarbonization economy through shared infrastructure	driving local economic opportunities	community or social impacts assessment • **[Preferred] 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 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	• **[Preferred] Energy sector knowledge:** Prioritize projects that build upon local / regional oil and gas sector knowledge, where feasible
Potential Negative Impacts of Offshore Storage Projects				
Site-specific risks influenced by a distinct composition of onshore and offshore geographic, geological, environmental, and societal parameters	✋Coastal communities and indigenous groups 🌊Coastal and marine flora and fauna	• Offshore projects pose site-specific risks that are based on a suite of contextual measurements for social and environmental parameters. Examples of site-specific risks include (i) conflicts with fishing grounds and other coastal / 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	• **[Mandatory] Site-specific baseline assessment:** Require that projects evaluate the baseline community and ecosystem parameters • **[Mandatory] 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 • **[Mandatory] 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 • **[Mandatory] 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[14]	**Low to Medium** likelihood of earthquake events given that the mitigation measures are required by regulatory and standard bodies	• **[Regulatory Requirement] 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
CO_2 leakage *(Further reference provided in "Understanding CO_2 Leakage" section below)*	✋Communities in close proximity to CO_2 infrastructure 🌊Onshore and marine flora and fauna	• Surface leaks (i.e., onshore equipment and pipeline leaks), marine leaks (i.e., subsea pipeline leaks), and subsurface leaks (i.e., leakage via compromised caprock) pose the risks of (i) asphyxiation in onshore / marine contexts and (ii) harm to marine flora and fauna sensitive to increased acidification; these risks are related to elevated, localized CO_2 concentration prior to dispersal[2, 9]	**Low to Medium** likelihood of leakage events given that the mitigation measures are required by regulatory and standard bodies	• **[Preferred] Robust safety regulations:** Prioritize projects operating in robust safety regulatory regimes, such as those provided in Table 3 • **[Regulatory Requirement] Site selection:** Require that projects select storage reservoirs overlain by high-integrity seals (laterally continuous, thick, and low permeability) • **[Regulatory Requirement] CO_2 monitoring plan:** Require that projects integrate a site-specific monitoring plan design with best available technologies that effectively monitor prioritised risks concerning the CO_2 plume while minimizing negative environmental and social impacts; additional monitoring should be triggered if certain risk thresholds are exceeded[8] • **[Regulatory Requirement] Maintenance and leakage-response plans:** Require that projects integrate provisions to maintain pipelines / equipment and

				leakage-response plans
Anthropogenic sounds from active seismic geophysical surveys (i.e., legacy subsurface monitoring tool) *(Further reference provided in "Understanding Anthropogenic Noise of Active Seismic Geological 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 high-resolution geological surveys pose the risks of temporary or permanent physical (e.g., auditory / tissue damage), behavioral (e.g., avoidance of feeding / breeding areas), and physiological (e.g., stress indicators) impacts on marine life, including fish[1, 4]	**High** likelihood of anthropogenic noise generation from active seismic geophysical surveys, given the current reliance on these surveys	• **[Preferred] Risk-optimized monitoring plan:** Prioritize investment in projects that have monitoring and verification plans that appropriately balance the risks with the need for geophysical surveys • **[Preferred] Assessment of anthropogenic sound impacts:** Prioritize projects that integrate an acoustic-biological model with site-specific parameters to assess noise 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[5, 6, 7, 10] • **[Preferred] Recognized limitation of Protected Species Observers (PSOs) personnel or infrared systems on ships and utilize mitigation like the soft-start method:** Prioritize projects that are not solely reliant upon PSOs and 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 • **[Preferred] Emerging monitoring technologies:** Support field trials of emerging CO_2 monitoring approaches that minimize negative environmental and social impacts

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

Sources: [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.*; [2] (2015). Sub-seabed CO_2 Storage: Impact on Marine Ecosystems (ECO$_2$). *European Commission.*; [3] (2024). Ship-mounted camera systems provide real-time detection and increased response time, can reduce the number of whales killed by vessel strikes. *Woods Hole Oceanographic Institution.*; [4] 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).*; [5] Crocker, S. E., et al. (2019). Measurement of Sounds Emitted by Certain High-Resolution Geophysical Survey Systems. *IEEE Journal of Oceanic Engineering, 44(3).*; [6] Ellison, W. T., et al. (2011). A new context-based approach to assess marine mammal behavioral responses to anthropogenic sounds. *Conservation Biology, 26(1)*; [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.*; [8] Furre, A., et al. (2016). 20 years of monitoring CO_2-injection at Sleipner. *Energy Procedia, 114.*; [9] Hall-Spencer, J., et. al. (2008). Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. *Nature, 454 (96-99).*; [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).*; [11] 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).; [12] Malischek, R., and McCulloch, S. (2021). The world has vast capacity to store CO_2: Net zero means we'll need it. *International Energy Agency.*; [13] McCauley, R. D., et al. (2000). Marine Seismic Surveys - A Study of Environmental Implications. *APPEA Journal.*; [14] Nadim, F. and Kvalstad, T. J. (2007). Risk Assessment and Management for Offshore Geohazards. *First International Symposium on Geotechnical Safety & Risk.*; [15] 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).*

Understanding Impacts of CO_2 Leakage

How does CO_2 leakage occur?

CO_2 leakage can occur at each phase of the offshore management life cycle: pre-injection, during injection, and post injection. Regarding surface and marine processes, CO_2 leakage can be a result of pipeline failure, equipment leakage, or equipment venting.[11, 12] Below the seafloor, leakage can occur if CO_2 injection and the resulting increased fluid pressure activates natural channels (e.g., faults) or human-made pathways (e.g., poorly completed wells) that allow fluid and gas transmission between the geological reservoir and seals and enable CO_2 and potentially subsurface formation waters to migrate toward the seafloor.[13, 14] The deep seafloor is hereby referenced as the benthic ecosystem.

What are the potential impacts of CO_2 leakage?

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[11] Steven, M., Smith, K., and Colls, J. (2010). Environmental risk and impacts of carbon dioxide (CO_2) leakage in terrestrial ecosystems. *U.S. Environmental Protection Agency*.
[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.*
[13] (2015). Final Report Summary: ECO2 (Sub-seabed CO_2 Storage: Impact on Marine Ecosystems (ECO2)). European Commission.
[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.*

Regarding potential consequences of failure of infrastructure in an onshore environment, the temporary imbalance of CO_2 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.

Offshore CO_2 leakage (be that from infrastructure failure or from subsurface leakage) increases the concentration of CO_2 in the onshore or benthic environment local to the emission site prior to dispersal. Additionally, in a benthic environment, the local salinity could also significantly increase if CO_2 injection triggers the leakage of highly saline formation waters.[13] The time window required for dispersal is dependent on site-specific parameters, including the hydrodynamic conditions (and weather conditions if CO_2 reaches the seasurface) and extent of the receiving environment. Dispersion is likely to occur within the window of hours to weeks.[16]

In benthic environments, CO_2 leakage from the subsurface can increase the local acidity and mobilize metals in the ocean floor sediment.[17, 18, 19] Formation water leak in a benthic environment can cause an imbalance in salinity and could result in osmotic shock for benthic organisms. In a CO_2 and/or formation water leak, the resulting chemical changes can negatively impact benthic organisms and the ecosystem as a whole. Benthic 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.[13]

There have been a number of studies on the potential impacts of CO_2 leakage using natural analogs (e.g., natural CO_2 seeps) or biogeochemical modelling. These studies demonstrate that the CO_2 plume varies with time. They also show that any released CO_2 rapidly dissolves in the water column resulting in a pH change due to the formation of carbonic acid. The area over which a pH change can be observed, as compared to background conditions, is dependent on release rate as well as site specific factors such as hydrodynamic mixing. Biogeochemical models have been, and can be, constructed to develop an understanding of site specific impact length scales over which a pH drop is likely to be observed. Typically these models and field analog observations show that large leakage rates are required, to produce changes in pH that are higher than the natural variance observed in the marine environment (e.g., seasonal changes in pH), beyond just a highly localised area.[20, 21, 22, 23, 24]

These models have typically not included other substances that may be mobilised with CO_2 movement such as heavy metals or hydrocarbons (in the case of depleted fields for CO_2 storage)

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[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*.

[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.*

[17] (2015). Sub-seabed CO_2 Storage: Impact on Marine Ecosystems (ECO_2). *European Commission*.

[18] Hall-Spencer, J., et al. (2008). Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. *Nature, 454 (96-99).*

[19] Lichtschlag, A., et al. (2014). Effect of a controlled sub-seabed release of CO_2 on the biogeochemistry of shallow marine sediments, their pore waters, and the overlying water column. *International Journal of Greenhouse Gas Control, 38.*

[20] Blackford, J., et al. (2008). Regional scale impacts of distinct CO_2 additions in the North Sea. *Marine Pollution Bulletin, 56(8).*

[21] 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*(p.334-373).

[22] 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.*

[23] 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).*

[24] Stalker, L., et al. (2025). Reviewing the implications of unlikely but potential CO_2 migration to the surface or shallow subsurface. *IEAGHG.*

which may represent a higher environmental risk than the CO_2 itself. Another consideration in understanding the impacts of CO_2 leakage in the marine environment is the nature of its release. In the case of a pipeline leak, this would likely be a large instantaneous release, whereas a subsurface leak would likely be of a smaller volume over a longer period of time. CO_2 storage proponents and regulators will have to assess these risks and how they apply to the particular projects.

In assessing project risks proponents will identify subsurface and infrastructure leakage risks and the locations where this may occur, noting that in a well managed project these risks will be very low. These risks will inform site characterisation and monitoring strategies. For example site characterisation may be focussed along pipeline routes and around injection wells, or at the seabed locations where there are uncertainties around subsurface leakage. Environmental characterisation would need to occur for the purposes of the installation of the infrastructure irrespective. Once areas of higher risk or uncertainty are identified environmental characterisation, and the development in understanding of potential impacts can be focussed on these areas. This approach is important in developing monitoring and verification plans that are fit for purpose and appropriately address risk.

Over the lifetime of CO_2 storage projects the marine environment and the receptors within it will change. Careful design of the monitoring programs should seek to identify key data collection requirements and have monitoring contingencies in the case of anomaly detections. If the integrated monitoring and verification plan is designed carefully this will allow the implementation of just-in-time baseline surveys to be able to more accurately determine impacts in the unlikely event of leakage.

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. If a project is operating within a well-regulated jurisdiction, it is estimated that leakage is below 0.0008% per year, corresponding to over 98% of the CO_2 remaining in the subsurface for 10,000 years.[25]

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: Invest in projects that select storage reservoirs with suitable porosity and permeability characteristics that are overlain by impermeable mudstone or sealing formations. Storage reservoirs may either be depleted oil and gas reservoirs or saline aquifers. While depleted oil and gas reservoirs introduce risks and uncertainties regarding previous operations and legacy wells, the data from those wells, and any rocks collected significantly reduce many geological uncertainties including how injection performance and pressure response might behave.[26] Saline aquifers tend to have far less data, as greenfield sites resulting in greater uncertainty thus

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[25] Alcalde, J., et al. (2018). Estimating geological CO_2 storage security to deliver on climate mitigation. *Nature Communications, 9(2201).*
[26] (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.*

potentially requiring new geophysical surveys, which have their own inherent risks as described in the section "Understanding Impacts of Active Seismic Geophysical Surveys." 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 well integrity.

CO_2 monitoring plan: Invest in projects that integrate a site-specific monitoring plan design which 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.[27] Importantly, commercial-scale CO_2 storage projects are actively developing and monitoring technologies which 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.[28]

In the development of monitoring plans the impacts of the monitoring activities themselves across the various monitoring technology options available should be weighed. For example if new monitoring wells need to be drilled what are the impacts of these activities versus the value of the data collected. In the case of passive acoustic sensing can existing fibre optic cables be used (e.g., those within data and power cables) or do cables specific to monitoring be placed in or on the seabed.

Maintenance and leakage-response plans: Invest in projects that integrate operational monitoring, maintenance, and leakage-response plans that are aligned with government regulations. Maintenance plans should include provisions to regularly maintain pipelines and equipment to prevent leaks, overpressure, and corrosion. Potentially impacted communities should be consulted with in the development of these project 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 characterise the subsurface geology prior to CO_2 injection and 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 several months. It is important to note that this process may be less extensive if previous subsurface survey data are 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.

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[27] Furre, A., et al. (2016). 20 years of monitoring CO_2-injection at Sleipner. *Energy Procedia, 114.*
[28] 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.*

These surveys use a diverse array of sound source technologies that span frequencies, durations, applications and sound levels to evaluate and quantify the subsurface geology. These sound sources may include air-gun arrays, boomers, chirp sub-bottom profilers, sidescan sonars, sparkers, and swath bathymetric sonars used to survey the benthos before, during, and after CO_2 injection periods to identify potential leakage.[29]

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, thus 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.[30] These sounds can be detected up to 4,000 km from the source and may be heard without interruption during the survey activity. Thus, this can result in intense (airgun) sounds permeating a potentially large area of the ocean across many months.[31] 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 sound?

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 / tissue damage), behavioral (e.g., avoidance of feeding / breeding areas), and physiological (e.g., stress indicators) impacts.[32, 33] These anthropogenic sounds can also mask communication related to mating, and alter fundamental activities such as feeding, predator evasion, and navigation.[34] Resulting consequences may be short-or long-term at the individual, population, and ecosystem levels, and noise-imacts may also compound as one of multiple stressors animals face.

Animals vary substantially in sound-sensitivity and responses (i.e., squid may respond differently than cod or copepods). Furthermore, within a grouping, (e.g., fish) hearing mechanisms, abilities, and responses can differ substantially.[35] Thus there is a need to address species- and context-specific responses to the greatest extent possible.[Ellison] Nearly every taxa 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 noise on the individuals and populations therein. The research that has been conducted for cetaceans, fish, sea turtles, and invertebrates demonstrates that the noise from active seismic geophysical surveys has demonstrable negative impacts. **Table 6** provides a literature review summary of the potential impacts on marine life.

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[29] Crocker, S. and Fratantonio, F. (2016). Characteristics of Sounds Emitted During High-resolution Marine Geophysical Surveys. *U.S. Department of the Interior: Bureau of Ocean Energy Management, 12 (203)*.
[30] Weilgart, L. (2016). Alternative Quieting Technology to Seismic Airguns for Oil & Gas Exploration and Geophysical Research. *UN Global Sustainable Development Report*.
[31] 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*.
[32] 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).*
[33] (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.*
[34] Ellison, W. T., et al. (2011). A new context-based approach to assess marine mammal behavioral responses to anthropogenic sounds. *Conservation Biology, 26(1).*
[35] Popper, A. N., et al. (2022). Fish hearing "specialization" - a re-evaluation. *Hearing Research, 425.*

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 / 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]

Impacts on Mammals	Impacts on Fish	Impacts on Sea Turtles	Impacts on Invertebrates
Impacts on cetaceans: • Odontocetes - Dolphins can demonstrate shift in auditory thresholds as well as behavioral changes[9, 10] • Porpoises show change in movement patterns[3] • Belugas can demonstrate behavioral disruptions[8] • Pygmy / dwarf sperm whales can experience lower levels of harassment to serious injury[2] • Mysticetes- Bowhead whales decrease calls with increasing exposure levels and become silent after a certain threshold[4] • Whales - Humpbacks 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 on noise impacts for pinnipeds; yet similar risks (hearing loss, disturbance and displacement) have been associated with geophysical sounds[13, 15]	**General impacts on fish:** • For those species studied, there is evidence of a variety of impacts, including: (i) physical (e.g., damaged hearing organs); behavioral (e.g., movement away from air-gun arrays, an increase in swimming activity, a decrease in feeding activity); (ii) physiological (e.g., temporary threshold shifts)[7, 18, 19, 21, 23] • Degree of impact - the incidence of behavioral responses increases with increasing impulsive sound levels[7, 14] • Research gaps - Fish constitute a diverse taxonomic group and noise-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 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 demonstrate increased dispersal[6]	**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 stemming concern • Impacts - Sea turtles respond to high-amplitude, low-frequency anthropogenic sounds; responses include increased swimming speed, change of swimming pattern / direction, and alarm / avoidance[17, 19] • Foraging impacts - Leatherback sea turtles demonstrated 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]	**General impacts on invertebrates:** • Impacts / research gaps - Invertebrates can experience severe negative impacts; they too are highly diverse and sound sensitivity studies are only emerging **Impacts on squid:** • Squid - Squid show alarm response, with increasing response 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 & krill have immediate mortality and overall abundance[3]

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

Sources: [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.;* [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.*; [3] Affatati, A., Camerlenghi, A. (2023). Effects of marine seismic surveys on free-ranging fauna: a systematic literature review. *Frontiers*, 10.; [4] Blackwell, S., et al. (2015). Effects of Airgun Sounds on Bowhead Whales Calling Rates: Evidence for Two behavioral Thresholds. *PLOS.*; [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).*;* [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).*; [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.*; [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).*; [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.*; [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).*; [11] Gordan, J., et al. (2003). A Review of the Effects of Seismic Surveys on Marine Mammals. *Marine Technology Society Journal, 37(4).*; [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.*; [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).*; [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).*; [15] Hermannsen, L., et al. (2015). Characteristics and Propagation of Airgun Pulses in Shallow Water with Implications for Effects on Small Marine Mammals. *PLOS.*; [16] 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).*; [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.*; [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).; [19] McCauley, R. D., et. al. (2000). Marine Seismic Surveys - A Study of Environmental Implications. *APPEA Journal.*; [20] Patel, S. H., et al. (2026). Leatherback sea turtles (Dermochelys coriacea) react to impulsive sounds. *Scientific Reports, 16.*; [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, 116(6).*; [22] Salas, A., et al. (2024). Narrowband noise induces frequency-specific underwater temporary threshold shifts in freshwater turtles. *JASA Express Lett, 4(8).*; [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).

What is the likelihood of occurrence?

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

What are the potential mitigation strategies?

Risk-optimized monitoring plan: Prioritize investment in projects that have monitoring and verification plans that appropriately balance the risks with the need for geophysical surveys, particularly 3D surveys. Globally, offshore storage projects are suggesting a geophysical survey cadence that is not necessarily commensurate to subsurface risks but rather a response to unfounded concern or project funding conditions. There is an opportunity for projects to utilize a hierarchy of controls to partially reduce and limit geophysical surveys through the substitution of emerging methods, further expanded upon below.

Assessment of anthropogenic sound impacts: Prioritize investment in projects that integrate an acoustic-biological model with site-specific parameters to assess noise 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 noise is no longer causing acoustic masking for marine life, represented in **Figure 2**. The site-specific parameters integrated into the assessment model include: behavioral and physiological responses of marine life to the anthropogenic noises expected, relative sound levels and hearing thresholds, and acute and chronic noise 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 noise. Additionally, the model should leverage comprehensive acoustic source data for the specific geophysical survey system that will be utilized.[29, 34, 31, 36]

Recognized limitations of protected species observers (PSOs) and soft-start methods: Prioritize investment in projects that are not solely reliant upon PSOs and soft-start as mitigation strategies. During geophysical 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 and animals surfacing in vision-limited scenarios like 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 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

[36] 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).*

overall harassment.[37] 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, or taxa that are habituated to the sound) and assumes simple sound propagation or the assumption that decreasing sound levels decrease away from the source.

Emerging monitoring technologies: Support field trials of emerging animal and CO_2 monitoring approaches that minimize negative environmental and social impacts. These emerging monitoring approaches, summarized in **Table 7**, 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 monitoring of the subsurface CO_2 plume and associated impacts in CCS projects, it is likely that a combination of monitoring technologies will be deployed in addition to, or instead of, conventional 3D geophysical technologies. 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., fibre 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 Emerging CO_2 Monitoring Methods

Method	Pros & Cons	Maturity for CCS	Optimal 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	**Pros:** Continuous monitoring; uses existing fiber optics; real-time; low cost; fine spatial sampling; can operate on seabed and downhole using existing fiber infrastructure. **Cons:** Limited resolution; large data volumes due to fine spatial sampling.	**Moderate:** passive acoustic monitoring - mature; (surface DAS emerging; Vertical Seismic Profiling (VSP-DAS) mature; passive seismic mature). Emerging for acoustic CO_2 bubble monitoring [1, 2].	Leakage monitoring; induced seismicity; fault reactivation; pipeline/well monitoring [3].
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	**Pros:** Directly measures microorganisms and marine life that could be impacted by CO_2 leakage. **Cons:** Highly localized impacts may not be easily sampled; impacts could relate to climate change; baseline monitoring and regional understanding important; identify charismatic species to be assessed.	**High** (well-established methods for baseline biological surveys of seabed and marine species).	Baseline ecological characterization; post-leakage impact detection [5].
Geochemical Monitoring Chemical measurements to detect CO_2-related anomalies in water or sediments	**Pros:** Detects leakage; simple; highly cost-effective. **Cons:** Surface-focused; susceptible to false positives; frequent maintenance for moored/seabed systems; seawater baselines shifting due to climate change.	**High** (well established for leakage detection).	Assurance monitoring for marine environmental characterization; localized leakage detection near wells; ad-hoc data collection during escalation [4].

[37] (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.*

Ground Uplift Satellite InSAR, Tiltmeters: Surface deformation measurements indicating subsurface pressure changes	**Pros:** Wide-area coverage (depending on technique); detects surface deformation. **Cons:** Indirect subsurface measurement; weather issues; very limited depth penetration (a few meters); satellite techniques onshore only.	**High–Medium** (widely used for onshore surface deformation)	Detecting surface uplift/subsidence, especially during leakage events [10].
Marine Acoustic Methods - Hydrophone Arrays (Can be leveraged as periodic or continuous monitoring)	**Pros:** Detects CO_2 bubbles. **Cons:** Costly equipment; regular maintenance; sensors need dense spacing or proximity to bubbles (co-located DAS cable can reduce this need).	**Moderate** (trial in Australia and overseas).	In-situ monitoring of CO_2 bubbles during severe leakage [7, 8].
Marine Acoustic Methods - Sonar Acoustic imaging to detect gas escape at or near the seafloor	**Pros:** Highly sensitive to low-level gas leakage. **Cons:** Detects leakage only at or from seabed (too late); susceptible to false positives.	**High** (well established for leakage detection).	Baseline characterization; periodic surveys; ad-hoc surveys during escalation [6].
Marine Sparker/Sub-bottom Profilers	**Pros:** Sensitive to low levels of gas in seabed (e.g., geohazards 50–100 m); lower marine noise than other subsurface imaging methods. **Cons:** Shallow imaging only; dependent on substrate.	**High** (well established for marine geohazard surveys).	Baseline characterization; infrastructure hazard assessment; ad-hoc surveys during escalation [6].
Sparse Geophysical Data Acquisition Survey Single Source–Single Receiver	**Pros:** Lower-impact geophysical surveys; short-duration discrete location sampling; focused on high-risk locations. **Cons:** Requires seismic sources; low spatial resolution.	**Low** (initial testing performed; needs further demonstration).	Monitoring specific high-risk areas; ad-hoc surveys during escalation [9].
In-well monitoring methods (leverage existing infrastructure)			
Electromagnetic (EM) Methods Electromagnetic measurements sensitive to fluid saturation variations	**Pros:** Sensitive to saturation changes. **Cons:** Limited depth; expensive.	**Low–Moderate** (still experimental for CCS).	Tracking CO_2 plume migration [11].
In-well Sampling Direct sampling of reservoir fluids to verify CO_2 movement	**Pros:** Direct measurement of reservoir fluids. **Cons:** Complex well completions can increase leakage risk (e.g., ADM leak at Decatur).	**High–Medium** (used in demonstration projects).	Validation of CO_2 migration behavior [13].
Pressure Tomography Pressure-based imaging to track CO_2 migration between wells	**Pros:** High sensitivity to CO_2 plume presence and migration. **Cons:** Limited spatial coverage due to well geometry; requires dense wells (costly).	**Low** (field-tested in pilot phase at Otway).	Early detection and tracking of migrated CO_2 plume [12].
Time-Lapse Gravity Monitoring Gravity measurements detecting large-scale mass changes from CO_2 injection	**Pros:** Cost-effective; minimal environmental impact. **Cons:** Low spatial resolution; effectiveness reduced in depleted reservoirs with residual gas.	**High** (UK's Morecambe and Norway's Snøhvit fields show **high** repeatability).	Large-scale plume delineation; mass change within the reservoir; long-term injection monitoring [14].

Table 7: Overview of Emerging CO_2 Monitoring Methods

Sources: [1] Caudron, et al. (2024). Monitoring underwater volcano degassing using fiber-optic sensing. Scientific Reports, 14(1), 3128.; [2] Meneghini et al. (2025). Detection of CO_2 emissions from Panarea seabed with Distributed Acoustic Sensing (DAS): a preliminary investigation. Relazione interna Ogs 2025/106.; [3] Sinha et al. (2024). Seismic monitoring of CCS with active and passive data: A synthetic feasibility study based on Pelican site, Australia. Int. J. Greenh. Gas Control, 110 (2021), 103437. https://doi.org/10.1016/j.ijggc.2024.104277; [4] Ma et al. (2024). Advances in Geochemical Monitoring Technologies for CO_2 Geological Storage. Sustainability, 16(16), 6784.; [5] Dale 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; [6] Flohr et al. (2021). Towards improved

monitoring of offshore carbon storage: A real-world field experiment detecting a controlled sub-seafloor CO2 release. International Journal of Greenhouse Gas Control, 106, 103237.; [7] Li et al. (2020). Passive acoustic monitoring of a natural CO_2 seep site – Implications for carbon capture and storage. International Journal of Greenhouse Gas Control, 93, 102899.; [8] Hughes et al. (2021). Methodology to deploy shallow-focused subsea CCS technologies: M6a DRAFT Final Report on fixed sensor network designs for CCS site Marine Monitoring and Verification EP211139. CSIRO, Australia.; [9] Khatib et al. (2021). Breaking the seismic 4D 'image' paradigm of seismic monitoring. First Break, 39, 85–91. 10.3997/1365-2397.fb2021072.; [10] Zhang et al. (2022). Analysis of Available Conditions for InSAR Surface Deformation Monitoring in CCS Projects. Energies, 15. 10.3390/en15020672.; [11] Barajas-Olalde et al. (2023). Application of Electromagnetic Methods for Reservoir Monitoring with Emphasis on CCUS. Minerals, 13, 1308. https://doi.org/10.3390/min13101308; [12] Jenkins 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, Vol. 2, 2024, geoenergy2023-035.; [13] Utting et al. (2023). Well Integrity Monitoring at CCS Projects: A Case Study. Geoconvention 2023.; [14] Fletcher et al. (2025). Monitoring CO_2 injection in the Viking CCS project using offshore time-lapse gravity. 86th EAGE Annual Conference & Exhibition, Jun 2025, p.1–5.

7. Best Practices Checklist

A summary of the best practices for ensuring the containment integrity and environmental and social safety of an offshore storage project are provided in **Table 8**. Ensuring that an offshore storage project meets these best practices supports: (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 Best Practices Checklist		
Categorization	**Best Practice**	**Examples frameworks / references**
Phase I: Site Assessment		
Conduct a baseline assessment	**Did the project assess the reservoir seal integrity?** ➢ Require that projects select storage reservoirs with high-integrity seals that are laterally continuous and which have a low permeability. ★ General regulatory requirement **Did the project conduct a site-specific baseline assessment?** ➢ Require that projects evaluate baseline community and ecosystem parameters, with a strong preference for leveraging a minimum of 1 year of data. Broader datasets can be leveraged in combination with locally collected data. These global data sources include GEOTRACES, International Council for the Exploration of the Sea (ICES), Argo Program, national buoy networks, and fisheries and species databases. ★ General regulatory requirement **Did the project identify and mitigate potential negative impacts to endangered species?** ➢ Ensure that projects identify endangered species, fisheries taxa, ecosystem engineers and those playing a key role in the community, and species of concern. The project design should alter operations accordingly and/or demonstrate that impacts to critical species are negligible. ★ General regulatory requirement	• **Guidance on baseline parameters:** Blackford et al. (2015) recommends a baseline survey that integrates temporal and spatial dynamics.[Blackford, 2015] • **Guidance on baseline parameters:** Methratta (2020) recommends a before-and-after gradient design to test parameters at increasing distance from the site of operation before and after development.[Methratta] • **Guidance on detection of threatened mammals:** The Australian Government's Department of Climate Change, Energy, the Environment and Water provides guidance on methods for determining the presence / absence of threatened mammals.[Australian Government] • **Examples of critical ecosystems for biodiversity:** Examples of critical ecosystems include the Arctic Wildlife Refuge and Eastern Pacific Blue Corridors.[WWF]
Evaluate environmental and social impacts	**Does the project integrate stakeholder engagement with all impacted communities?** ➢ 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. **Did the project assess environmental and social impacts?** ➢ 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. ★ General regulatory requirement **Did the assessment of environmental and social impacts include the impacts of anthropogenic sounds, particularly those associated with CO_2 monitoring technologies?** ➢ Prioritize projects that (i) integrate an acoustic-biological model with site-specific parameters to assess noise propagation and biological	• **Guidance on applying an analytical framework to assess the quality of stakeholder engagement:** 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. • **Guidance on 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. • **Guidance on evaluating behavioral impacts:** Southall et al. (2021) provides guidance on how to evaluate

	impacts on the species in the affected area and (ii) minimize negative impacts on marine life and fishing communities. The model should leverage comprehensive acoustic source data for the specific geophysical survey system.[Crocker, Ellison, Fewtrell, Hovem]	for behavioral impacts on marine mammals from sound exposure. The evaluation integrates variability across species, individuals, situational contexts, and temporal / spatial scales.[Southall]
Develop an earthquake monitoring plan	**Does the project integrate a pressure and microseismic monitoring and management plan?** ➢ Require that projects integrate pressure and microseismic management programs ★ General regulatory requirement	
Develop CO_2 leakage monitoring plan	**Is the project operating within a jurisdiction characterized by robust and enforceable safety regulations for offshore storage?** ➢ Prioritize projects operating in robust safety regulatory regimes. **Does the project integrate marine life protections beyond the utilization of Protected Species Observers (PSOs) and the soft-start method for active seismic geophysical surveys?** ➢ Prioritize projects that are not solely reliant upon PSOs and soft-start as mitigation strategies for the negative impacts of active seismic geophysical surveys on marine life. These strategies are not effective at preventing negative impacts to marine life and human communities dependent on marine life. **Does the project integrate a CO_2 monitoring plan?** ➢ Require that projects integrate a site-specific monitoring plan design with best available technologies that effectively monitor prioritised risks concerning the CO_2 plume while minimizing negative environmental and social impacts. Additional monitoring should be triggered if certain risk thresholds are exceeded.[Furre] ➢ Prioritize projects that have monitoring and verification plans that appropriately balance the risks with the need for geophysical surveys. ★ General regulatory requirement **Does the project's CO_2 monitoring plan integrate field trials of emerging monitoring technologies?** ➢ Prioritize projects that integrate field trials of emerging CO_2 monitoring approaches that minimize negative environmental and social impacts. **Does the project integrate maintenance and leakage-response plans?** ➢ Require that projects integrate provisions to maintain pipelines / equipment and leakage-response plans. ★ General regulatory requirement	• **Examples of robust and enforceable safety regulations for offshore storage:** Table 3 provides a summary of offshore storage regulatory frameworks and associated environmental and social safeguards. • **Guidance on a risk-optimized monitoring approach:** Sinha et al. (2024) provides guidance 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.[Sinha] • **Guidance on a risk-optimized monitoring approach:** Furre et al. (2017) provides guidance on optimizing monitoring approaches (i.e., technology, timing, extent) to the project-specific risks.[Furre] • **Examples of low-impact monitoring technologies:** Table 7 provides examples of technologies with lower-impact potential compared to the potential negative impacts of active seismic geophysical surveys.

Phase II: CO_2 Injection & Phase III: Post-Injection CO_2 Monitoring

Contextual information regarding leakage risks post injection:

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 and in some cases these residual 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 however 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). If ongoing monitoring requires this infrastructure, this could actually increase risk over time.

Implement continuous improvement	**Does the project integrate continuous improvement mechanisms with regards to environmental and social impacts?** ➢ Require that projects regularly assess for site-specific impacts during the lifetime of the project and update operations accordingly. Projects should work with experts and regulators to proactively implement operational and monitoring tactics that manage the various environmental impacts (and related impacts on human communities such as fishing communities).	• **Guidance on continuous stakeholder engagement:** 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.

	Does the project regularly assess the effectiveness of its risk-optimized CO_2 monitoring approach? ➢ Use dynamic risk assessments to update the risk-optimized CO_2 monitoring approach. Integrate monitoring technologies that reduce negative impacts on marine ecosystems wherever feasible.	

Table 8: Offshore Storage Best Practices Checklist

Sources: [1] (2024). 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.*; [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.*; [3] (2025). Environment and Social Safeguard Standard. *Global Carbon Council. 4(1).*; [4] Blackford, J., et al. (2015). Marine baseline and monitoring strategies for carbon dioxide capture and storage (CCS). *International Journal of Greenhouse Gas Control. 38.*; [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).*; [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)*; [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.*; [7] Furre, A., et al. (2016). 20 years of monitoring CO_2-injection at Sleipner. *Energy Procedia, 114.*; [8] 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).*; [5] Methratta, E. T. (2020). Monitoring fisheries resources at offshore wind farms: BACI vs. BAG designs. *ICES Journal of Marine Science, 77(3).*; [9] Marine Mammal Noise Exposure Criteria: Assessing the Severity of Marine Mammal Behavioral Responses to Human Noise. *Aquatic Mammals, 47(5).*; [10] 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.*

8. Conclusion

Findings

This report demonstrates that there are opportunities to integrate offshore storage best practices that maximize positive social impacts and minimize negative environmental and social impacts. These best practices build upon regulatory and carbon market requirements and recommendations.

Through review of perspectives from the scientific community, regulatory bodies, and standard organizations, this report provides the following findings:

- ❖ **Offshore storage projects are highly site-specific:** The development of project plans, understanding of potential impacts on the ecosystem and communities, and design of safeguards is highly site-specific. The best practices shared in this report must be considered and applied in the context and locations in which offshore projects are operated.
- ❖ **Regulations provide an enforceable baseline for minimizing negative impacts:** Existing and developing regulatory offshore storage regulatory frameworks generally require environmental and social impacts assessments.
- ❖ **Field trials are needed to advance low-impact, risk-optimized monitoring technologies and understanding of environmental and social impacts:** There is a need to field test risk-optimized, emerging monitoring technologies in active offshore storage field projects. These emerging technologies, provided in Table 7, have the opportunity to reduce the negative environmental and social impacts associated with traditional active seismic geophysical surveys. Monitoring of active projects also enables the increased understanding of short-term and long-term potential environmental and social impacts.

Evolutions in regulatory policy, monitoring technologies, and evaluations of environmental and social impacts are expected to progress as offshore storage projects become operational in the near-term.

Actionable Opportunities

Key opportunities to translate findings into actions are summarized in **Table 9**. An overarching opportunity is cross-sector collaboration amongst regulatory bodies, standard organizations, project operators, scientific community, carbon removal buyers and investors, and impacted communities (e.g., coastal communities, fishing communities, and indigenous groups).

Table 9: Actionable Opportunities for Participants in the Offshore Storage Ecosystem

Actor	Opportunity
All Actors	• **Foster and participate in cross-sector collaboration:** Cross-sector communication and collaboration amongst regulatory bodies, standard bodies, project operators, carbon removal buyers and broader decarbonization investors, and 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.
Regulatory Bodies	• **Translate safeguards as regulatory requirements:** Integrate site-specific environmental and social impact assessments, pressure and microseismic monitoring and management plans, risk-optimized CO_2 plume monitoring plans, and continuous stakeholder engagement as regulatory requirements for offshore storage projects. • **Support monitoring technologies that have the potential to reduce negative environmental and social impacts:** Support field trials of low-impact, emerging monitoring technologies. Examples of these monitoring technologies are provided in Table 7.
Standard Organizations	• **Integrate / strengthen offshore storage-specific environmental and social safeguards:** Offshore-specific safeguards can serve as an international baseline as regulations develop.
Project Operators	• **Implement the Best Practices 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. • **Integrate field trials of low-impact, emerging monitoring technologies:** The field testing of monitoring technologies that have the potential to reduce environmental impact 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 monitoring technologies, 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, standard 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 Best Practices Checklist:** Integration of the Best Practices Checklist in project assessment processes increases adoption of best practices that maximize positive outcomes and minimize negative impacts
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. There is a crucial opportunity to share these site-specific perspectives in developing and shaping stakeholder engagement mechanisms, social / environmental impact assessments, and resulting project operations and monitoring plans

Table 9: Actionable Opportunities for Participants in the Offshore Storage Ecosystem