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U.S. Japan CO_2 Shipping Feasibility Study: Screening Assessment

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Derek Vikara[1,2]: *Conceptualization, Methodology, Formal Analysis, Writing – Original Draft, Writing – Review & Editing, Visualization, Supervision;* ***Christopher Munson[1,2]:*** *Conceptualization, Methodology, Formal Analysis, Writing – Original Draft, Writing – Review & Editing;* ***Connie Zaremsky[1,2]:*** *Conceptualization, Methodology, Formal Analysis, Writing – Original Draft, Writing – Review & Editing;* ***Alana Sheriff[1,2]:*** *Methodology, Formal Analysis, Writing – Original Draft, Writing – Review & Editing, Visualization;* ***Kevin Dooley[3]:*** *Conceptualization, Methodology, Writing – Review & Editing, Funding Acquisition, Supervision;* ***Robert Smith[3]:*** *Conceptualization, Methodology, Writing – Review & Editing, Funding Acquisition, Supervision;* ***Christopher Conwell[1,2]:*** *Conceptualization, Formal Analysis, Writing – Original Draft, Writing – Review & Editing;* ***Patrick Okita[1,2]:*** *Formal Analysis, Writing – Original Draft, Writing – Review & Editing;* ***Jeff Lee[1,2]:*** *Writing – Original Draft, Writing – Review & Editing;* ***Tomas Mora[1,2]:*** *Project Administration, Writing – Review & Editing, Supervision;* ***Delal Gunaydin Tulu[1,2]:*** *Writing – Review & Editing, Supervision;* ***Hannah Hoffman[1,2]:*** *Writing – Review & Editing;* ***Sue Carr[1 2]****: Writing – Review & Editing*

[1]National Energy Technology Laboratory (NETL) support contractor
[2]NETL
[3]U.S. Department of Energy (DOE)

Corresponding contacts:

- Kevin Dooley – kevin.dooley@hq.doe.gov
- Robert Smith – robert.smith8@hq.doe.gov

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Acronyms and Abbreviations

°C	Degrees Celsius
°F	Degrees Fahrenheit
ABS	American Bureau of Shipping
AETI	Asia Energy Transition Initiative
AOGCC	Alaska Oil and Gas Conservation Commission
APAC	Asia Pacific
APPS	Act to Prevent Pollution from Ships
ARCCS	Alaska Railbelt Carbon Capture and Storage Project
ARPA	Archaeological Resources Protection Act
BBNJ Agreement	Agreement on Marine Biodiversity of Areas beyond National Jurisdiction
BIL	Bipartisan Infrastructure Law
BLM	Bureau of Land Management
BOEM	Bureau of Ocean Energy Management
BOG	Boil-off gas
BSEE	Bureau of Safety and Environmental Enforcement
CAA	Clean Air Act
CAPEX	Capital expenses
CarbonSAFE	Carbon Storage Assurance Facility Enterprise
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
CELCP	Coastal and Estuarine Land Conservation Program
CETO	CO_2 Efficient Transport via Ocean
CFR	Code of Federal Regulations
CH_4	Methane
ClassNK	Nippon Kaiji Kyokai
CO	Carbon monoxide
CO_2	Carbon dioxide
CWA	Clean Water Act
CZMA	Coastal Zones Management Act
DNR	Alaska Department of Natural Resources
DNV	Det Norske Veritas
DOC	U.S. Department of Commerce
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOT	U.S. Department of Transportation
EA	Environmental Assessment
EIS	Environmental Impact Statement
EOR	Enhanced oil recovery
EPA	U.S. Environmental Protection Agency
FAST	Fixing America’s Surface Transportation
FAST-41	Title 41 of the Fixing America’s Surface Transportation Act
FEED	Front-end engineering design
FERC	Federal Energy Regulatory Commission
FMC	Federal Maritime Commission
FOA	Funding Opportunity Announcement
FONSI	Finding of No Significant Impact
ft	Foot
ft^2	Square foot

ft^3	Cubic foot
FWCA	Fish and Wildlife Coordination Act
FWS	U.S. Fish and Wildlife Service
GCCSI	Global CCS Institute
GHG	Greenhouse gas
GX	Green Transformation
hr	Hour
H_2	Hydrogen
HMTA	Hazardous Materials Transportation Act
HNS Convention	International Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea
HPGSA	High Pressure Gas Safety Act
hr	Hour
HSPA	Hydrogen Society Promotion Act
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas R&D Programme
IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
ISHA	Industrial Safety and Health Act
ISO	International Organization for Standardization
JOGMEC	Japan Organization for Metals and Energy Security
Jones Act	Merchant Marine Act of 1920
kg	Kilogram
km	Kilometer
KNCC	Knutsen NYC Carbon Carriers AS
kWh	Kilowatt-hour
LCO_2	Liquefied carbon dioxide
LCO_2-EP	LCO_2-Elevated Press
LLMC Convention	Convention on Limitation of Liability for Maritime Claims
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LPMP	Law Relating to the Prevention of Marine Pollution and Maritime Disaster
m	Meter
M	Million
m^2	Square meter
m^3	Cubic meter
MARPOL	International Convention for the Prevention of Pollution from Ships
MDO	Marine diesel oil
METI	Ministry of Economy, Trade, and Industry
mi	Mile
min	Minute
MMPA	Marine Mammal Protection Act
mol	Mole
mol%	Mole percent
Mpa	Megapascal
Mt	Million tonnes
Mtpa	Million tonnes per annum

MTSA	Maritime Transportation Security Act of 2002
MW	Megawatt
MWh	Megawatt-hour
N/A	Not applicable/available
N_2	Nitrogen
NAGPRA	Native American Graves Protection and Repatriation
NATCARB	National Carbon Sequestration Database and Geographic Information System
NETL	National Energy Technology Laboratory
NEPA	National Environmental Policy Act
NOAA	National Oceanic and Atmospheric Administration
NOx	Nitrogen oxides
NPDES	National Pollutant Discharge Elimination System
O&G	Oil and gas
OCS	Outer Continental Shelf
OCSLA	Outer Continental Shelf Lands Act
OECD	Organization for Economic Co-operation and Development
OPEX	Operating expenses
P/T	Pressure and temperature
PHMSA	Pipeline and Hazardous Materials Safety Administration
ppm	Parts per million
psi	Pounds per square inch
PWSA	Ports and Waterways Safety Act
R&D	Research and development
RCRA	Resource Conservation and Recovery Act
RETA	New Mexico Renewable Energy Transmission Authority
RHA	Rivers and Harbors Act
SDWA	Safe Drinking Water Act
SIGTTO	Society of International Gas Tanker and Terminal Operators
SOLAS Convention	Convention for the Safety of Life at Sea
TEA	Techno-economic analysis
tonne	Metric ton (1,000 kg)
TRL	Technology readiness level
U.S.	United States
UIC	Underground Injection Control
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
UNFCCC	United Nations Framework Convention on Climate Change
USACE	U.S. Army Corps of Engineers
USC	U.S. Code
USCG	U.S. Coast Guard
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGS	United States Geologic Survey
yr	Year

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EXECUTIVE SUMMARY

In May of 2024, the Department of Energy Office of Fossil Energy and Carbon Management in partnership with the National Energy Technology Laboratory (NETL) announced the initiation of a study that examines the potential for shipping liquified carbon dioxide (LCO_2) captured from point sources in Japan to Alaska for injection and secure geologic storage. The following Phase I report examines technical, economic, and regulatory aspects of maritime LCO_2 transport to identify potentially feasible large-scale shipping configurations based on identified carbon dioxide transportation infrastructure, Alaskan offshore, coastal, and industrial and port infrastructure characteristics, and existing laws, regulations, and international agreements. Information presented is compiled from various sources of literature, analog projects, and publicly available datasets.

TECHNICAL FEASIBILITY FINDINGS

The technical feasibility analysis in this study is an initial screening level assessment of transpacific LCO_2 shipping from Japan to Alaska for geologic storage. The assessment focuses on four key technical areas:

- Review of the applicable shipping configurations, loading and offloading terminal components, and vessel designs (Section 2.1)
- Assessment of the technical readiness of terminal and shipping configurations (Section 2.2)
- Description and comparison of Alaskan regions potentially suitable for LCO_2 shipping (Section 2.3.1)
- Comparison of generalized shipping corridors and associated LCO_2 offloading configurations between Japan and Alaska (Section 2.3.2)

The LCO_2 shipping value chain involves interdependent components, including loading terminals, vessels, and offloading infrastructure, categorized by low-, medium-, and high-pressure/temperature (P/T) systems. Low-P/T designs currently show the greatest potential for large-scale carbon capture, utilization, and storage (CCUS) applications due to their potential to store on board and transport high volumes of CO_2, but the technology is not yet deployed commercially. Smaller-scale, medium-P/T vessels are in commercial use but may not be cost effective for large scale, long-distance transport. High-P/T vessels may also provide the ability to ship large volumes of CO_2. However, these designs are still in early-stage development, which limits their immediate feasibility. Shipping configurations considered for this study include vessel offloading to an onshore terminal (i.e., ship-to-shore), a vessel offloading to an offshore structure (i.e., ship-to-platform), and direct injection from vessels to sub-seabed geologic storage (i.e., direct injection). The ship-to-shore option requires terminals with sufficient water depth for vessels to navigate and dock. Ship-to-platform offloading can leverage designs similar to past oil and gas platform designs and possibly benefit from using existing structures. Direct injection likely requires conditioning and connection equipment so that the CO_2 can be safely injected into the wellbore and is compatible with the subsurface storage reservoir.

Regional segmentation of Alaska's coastal regions provided a basis to identify and compare unique regional attributes that can contribute to the suitability of different types of LCO_2 offloading configurations and LCO_2 shipping routes. The five opportunity areas include the North Slope, the West Coast, the Aleutian Islands, the Southcentral and Southeastern regions. Among Alaska's five regions, the Southcentral region stands out for its infrastructure, storage potential, and year-round port accessibility. The Southeastern region offers similar benefits but with higher uncertainty in geologic storage and longer shipping distance. Challenges in the North Slope include sea ice and shallow waters, while the Aleutian Islands and West Coast require significant data collection to assess feasibility due to uncertain prospective storage resources and limited infrastructure.

ECONOMIC FEASIBILITY FINDINGS

This screening level economic assessment presents order-of-magnitude cost ranges for applicable LCO_2 vessels and terminal infrastructure derived from cost data and cost models found in literature. The assessment focuses on two key areas:

- Cost discussion for critical components of the shipping value chain (Section 3.1)
- Shipping cost ranges for a hypothetical CCUS shipping scenario under various offloading configurations and P/T regimes (Section 3.2)

The economic feasibility of long-distance LCO_2 transportation depends on optimizing pressure design regime, vessel design, and ship-to-offloading configurations. Current medium P/T vessels used in the food and beverage industry, are small and less cost effective for large-scale LCO_2 transportation. Meanwhile, low P/T designs, drawing from liquefied natural gas (LNG) and liquefied petroleum gas (LPG) shipping practices, show long-term promise for scalability. Transitioning to larger capacity vessels from current commercial sizes, albeit at higher upfront capital investment, provides reduced levelized lifetime costs of shipping.

The shipping scenario investigated for this initial screening assessment includes capital and operating costs of a hypothetical 1 million tonne per year LCO_2 delivery project for 20 years from yet-to-be-identified sources in Japan to the southern coast region of Alaska. The analysis considers the approximate shipping corridor distance, cargo capacity, number of vessels, different offloading approaches, and applicable costs for liquefaction, loading, offloading, conditioning, and intermediate storage components.

Based on the screening-level assessment, resulting order of magnitude cost ranges provide the ability to identify the most cost-effective shipping configuration. Assessment findings indicate that for a standard 10,000 tonne vessel capacity, the ship-to-shore configuration offers the lowest cost in the low-P/T regime at $74/tonne, while the direct injection configuration is the most expensive configuration in the high P/T regime at $251/tonne. Additionally, when de-constraining vessel capacity size for the Low-P/T shipping and ship-to-shore configuration, levelized lifetime costs are additionally reduced by increasing vessel capacity to 30,000 tonne for low-P/T regime vessels, resulting in a revised levelized cost of $52/tonne. All estimated costs presented are at a screening level basis and include an accuracy range that ranges as wide as -50% to 100% corresponding to an AACE Class 5 cost estimate. Ultimately, the lowest cost shipping configuration identified was for two low P/T ships each with 30,000 tonnes of CO_2 cargo capacity connected with ship-to-shore offloading configuration. Liquefaction, vessel, and intermediate storage capital expenses were found to be the biggest cost components.

REGULATORY ASSESSMENT FINDINGS

An initial screening-level landscape review was conducted to assess the regulatory feasibility of transpacific LCO_2 shipping from Japan to Alaska for geologic storage or utilization in Alaska, focusing on two areas:

- Review of potential applicable laws and regulations covering the transportation chain including environmental protection, waste management, shipping safety, security, and construction discussed by parties that are members of international marine pollution authorities, including the International Maritime Organization as well as the Government of Japan, the U.S. federal government and the state of Alaska (Section 4.1 through Section 4.6)
- Review of the regulatory process for the Alaska LNG project was used as analog for what regulations and permitting requirements might need to be met to ship LCO_2 from Japan to Alaska for geologic storage or utilization (Section 4.7)

Various international laws, agreements, and treaties, including an amendment to the London Protocol, should it enter into force or should Japan deposit a declaration of provisional application, may enable the potential export of LCO_2 from Japan to the United States for offshore geologic storage in the sub-seabed of the United States, provided that a bilateral agreement or arrangement is established to confirm and allocate permitting responsibilities consistent with the provisions of the London Protocol.

For potential LCO_2 shipping projects, permitting an LCO_2 vessel and associated import terminal would be a first-of-a-kind activity for LCO_2 transportation to the United States. Federal laws and regulations to support such reviews span federal agencies including but not limited to the U.S. Coast Guard, U.S. Environmental Protection Agency, and U.S. Army Corps of Engineers, among others based on individual project scope and location details.

LCO_2 shipping projects may prompt an assessment under the National Environmental Policy Act. Agencies have conducted similar analyses under that statute for similar types of industrial and energy-related projects that may provide a model to support early project development and regulatory planning purposes for a first-of-a-kind LCO_2 shipping project review.

As of end of calendar year 2024, two relevant Federal rulemaking processes are progressing regarding CO_2 pipeline safety and offshore CCUS development in the U.S. Offshore Continental Shelf (OCS). The Department of Transportation Pipeline and Hazardous Materials Safety Administration is developing a proposed rule to update safety standards for CO_2 pipelines, including requirements related to emergency preparedness, and response. The Department of Interior's Bureau of Ocean Energy Management and Bureau of Safety and Environmental Enforcement are also progressing joint rulemaking processes that will establish new regulations to implement processes in support of safe and environmentally responsible carbon sequestration activities on the OCS.

STUDY OBJECTIVES

The overall goal of this study is to provide an initial assessment of the feasibility of international marine transport of captured CO_2 to the United States for geologic storage or utilization. Specifically, this project aims its focus towards evaluating the feasibility of shipping CO_2 between the country of Japan and the state of Alaska as well as to determine any potential opportunities and other considerations for large-scale development (e.g., technical, regulatory, economic). The study objectives are:

- Establish feasibility of shipping CO_2 from Japan to Alaska by evaluating analog projects in development that intend to utilize LCO_2 carriers for the purpose of CCUS.
- Summarize the technical readiness level of CO_2 shipping, export and import terminal concepts, and any outstanding technical barriers to deployment.
- Determine an order of magnitude range on the cost of shipping, terminal infrastructure, and associated CO_2 pricing needed to justify shipping.
- Identify and summarize Japanese, international, United States federal, and Alaskan state laws that may be applicable to shipping CO_2 from Japan to Alaska.

Information for this study is largely compiled from various sources of literature, analog projects, and available data to assess initial feasibility. Additionally, expert insight, guidance, and supporting materials were provided through various government entities such as members from U.S. federal agencies including the U.S. Department of Energy, Coast Guard, U.S. Army Corps of Engineers, Maritime Administration, U.S. Environmental Protection Agency, Pipeline and Hazardous Materials Safety Administration, and Alaska Department of Natural Resources, as well as federal Japanese agencies including the Ministry of Economy, Trade and Industry; Japan Organization for Metals and Energy Security; and the New Energy and Industrial Technology Development Organization. This study, which outlines opportunities for viable CO_2 shipping strategies between the United States and Japan, will enhance the knowledge base and general understanding of how the U.S. CCUS market can leverage potential opportunities in the future and overcome specific challenges related to international CO_2 shipping.

1 INTRODUCTION

Global interest in mitigating the impacts of climate change has driven the development of technologies that enable progress toward achieving net-zero and even net-negative carbon dioxide (CO_2) emissions [1, 2]. To support the transition to a global low-carbon economy, governments and industries are investing in carbon capture utilization and storage (CCUS) because it is among the critical technologies for reducing CO_2 emissions, particularly for sectors that are hard to decarbonize [3, 4]. Investments in CCUS span through its core components, and transportation of CO_2 from capture sites to storage facilities is emerging as a pivotal area requiring innovative solutions.

Transportation serves as the bridge between capture and storage, typically implemented through pipelines, shipping, rail, and trucks. Pipelines are typically the most cost-effective mode of transporting CO_2 over land for large-scale CCUS projects. But maritime transportation of CO_2 may be a viable solution for countries interested in exporting captured CO_2 to regions with established storage capacity. This approach leverages specialized bulk liquid carrier vessels and port infrastructure to connect emitters in these countries with onshore and offshore storage sites. For industrialized nations with limited geologic storage potential, maritime transport facilitates the development of decarbonization strategies that provide flexibility and scalability, allowing emitters to adapt their CO_2 capture goals to incorporate emerging storage opportunities globally.

The United States and Japan are building on bilateral agreements to strengthen cooperation and innovation on decarbonization and clean energy, with CCUS identified as a key area of focus [5, 6]. Through bilateral cooperation, both nations are exploring the feasibility of an integrated CCUS network to capture CO_2 from point sources in Japan and transport it to Alaska for secure geologic storage. Alaska has a long history of exporting liquefied natural gas (LNG) to Japan via maritime carriers since 1969, which serves as a viable analog for transporting captured CO_2 across national boundaries. For Japan, opportunities to transport captured CO_2 for storage in the United States and other countries serve as a potential solution for meeting their decarbonization targets. For Alaska, the opportunity to utilize its CO_2 storage resources in conjunction with its coastal and land-based infrastructure could offer new revenue streams for Alaskan businesses and the creation of clean energy jobs [7, 8].

The sections that follow discuss the various configurations of maritime CO_2 transport that can be integrated into a full CCUS value chain. This is followed by a more detailed discussion of the state of CCUS development in Japan and the United States. This background information serves to set the stage for analyses presented in this report.

1.1 CCUS AND MARITIME CO_2 TRANSPORT

There are multiple configurations of the CCUS value chain as depicted in Figure 1-1.

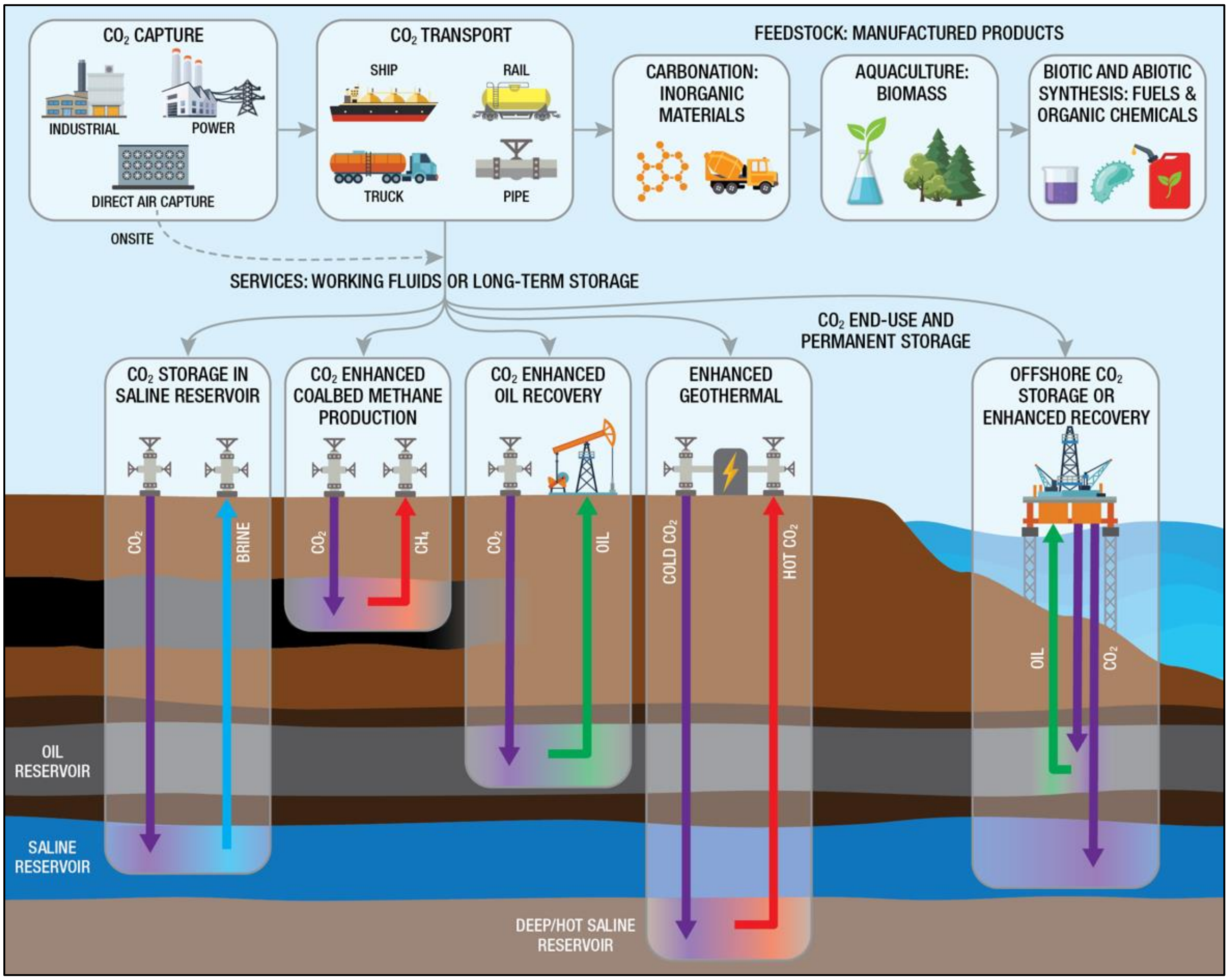


Figure 1-1. Technology options for the different components of the CCUS value chain

The configuration of a CCUS project consists of three components: CO_2 capture, mode of transport, and final CO_2 disposition (i.e., secure geologic storage or utilization) [9, 10, 11]. The mode and cost of transporting CO_2 depends on the proximity of CO_2 capture and final disposition. CO_2 transport becomes particularly important for point-source CO_2 emitters located in regions with no or limited local geologic storage resources or opportunities for utilization.

Modes of CO_2 transport include pipeline, truck, rail, and maritime shipping (i.e., bulk liquid carrier vessels and barges), that typically transport CO_2 in a pressurized liquid state (LCO_2). While pipelines are the most common mode of transport, transporting CO_2 via bulk liquid carrier vessel as a component of an end-to-end multimodal transport system has the potential to expand the range of viable CCUS value chain possibilities [12, 13, 14, 15, 16].

Transporting LCO_2 by ship is not new within the bulk liquid transport industry. Since the late 1980s, marine shipping of LCO_2 has routinely serviced markets with food-grade CO_2 for beverage production and food processing as well as chemical, medical, and industrial customers that require high-purity CO_2 [17, 18]. As of April 2024, there are four vessels in operation with capacities ranging from 1,000 to 2,000 cubic meters (m^3) (35,315 to 70,630 cubic feet [ft^3])[a] in non-CCUS service. Only one of these vessels was purpose-built; the other three were converted general cargo carriers [19, 20, 16]. All four are operated by Larvik Shipping AS (Larvik, Norway). These ships operate at pressures of 15–18 bar (217–261 pounds per square inch [psi]) and temperatures of approximately -28 °C to -22 °C (-18.4 °F to -7.6 °F) [21], commonly classified as medium-pressure, which has cargo size limitations [22].

To meet the demand of the global expansion of CCUS projects, the scale up of LCO_2 carrier fleet is necessary. Operational and planned CCUS projects in Europe tend toward targeting transport and offshore geologic storage in the North Sea. For example, the Northern Lights, Acorn CCS, and Fluxys Carbon Hubs all integrate carrier vessel shipping into a multimodal transport network with pipeline gathering systems that enable multinational transport of LCO_2 from industrial clusters to offshore storage sites [23, 24, 25]. The Zero Emissions Platform recently estimated that 10–20 vessels, on an approximate scale of 20,000 tonnes of cargo, would be needed by 2030 to support European CCUS transportation demands [26]. At present, the first of two LNG-powered, wind-assisted 8,000-tonne LCO_2 vessels to service the Northern Lights project in Norway has completed its sea trials in September 2024 [27]. Vessel designers targeting long-haul, trans-ocean transport of LCO_2 are exploring designs with higher vessel cargo capacity at a reasonable cost. These newer designs incorporate low-pressure (6–8 bar [87–116 psi] and -50 °C [-58°F]) and high-pressure (35–45 bar [507–652 psi] and roughly 0 °C [32 °F]) conditions [28, 29, 30]. The pending delivery of purpose-built LCO_2 carriers, along with others in construction or in contract, is clear evidence that this scale-up is in progress [31, 32, 33, 34, 35, 36, 30].

Particularly relevant to Japan is a joint 2024 study by the Global Centre for Maritime Decarbonization and Boston Consulting Group that highlights the critical role of shipping to enable cross-border CCUS initiatives, particularly in the Asia Pacific (APAC) region [37, 38]. The report underscores that shipping CO_2 is economically advantageous for regions where emitters and storage hubs are separated by vast bodies of water. The report states that the APAC region is projected to transport approximately 100 Mt of CO_2 annually by 2050, which will require up to $25 billion in CO_2 carriers and handling infrastructure. The report also emphasizes the need for government support, long-term contracts, and simultaneous development of the entire CCUS value chain to unlock its decarbonization potential. The study positions APAC as a leader in CO_2 shipping, citing unique geographical and industrial factors, and highlights the importance of collaboration between public and private sectors to overcome barriers and build a sustainable CCUS ecosystem.

1.2 State of CCUS Development in Japan

Japan's Green Transformation (GX) initiative serves as their roadmap for achieving a decarbonized society while ensuring economic growth and energy security. It outlines policies

[a] CO_2 density for this case is about 1.1 tonnes/m^3 depending on the temperature. Thus, this volumetric capacity is approximately 1,100–2,200 tonnes.

and measures to be implemented over the next decade, targeting a reduction of greenhouse gas emissions by 46% from 2013 levels by 2030 and achieving net-zero emissions by 2050 [39, 40]. As part of the implementation of the GX Promotion Strategy, Japan enacted the CCS Business Act in May 2024, which provides the legal framework for permitting and regulating CCS projects and establishes a licensing system for CCS businesses [41, 42].

Additionally, Japan's Ministry of Economy, Trade, and Industry (METI) released their CCS Long-Term Roadmap with plans to develop sufficient capacity to store 6–12 million tonnes of CO_2 per year by 2030 and 120–240 million tonnes of CO_2 per year by 2050 [43, 44, 45]. The roadmap identifies potential CCUS business cases consisting of different combinations of CO_2 source types, transportation approaches, and geologic storage options [46].

Most recently, the Japan Organization for Metals and Energy Security (JOGMEC) selected nine "Advanced CCS Projects" in June 2024 to complete feasibility studies on a fully integrated CCUS value chain comprised of CO_2 separation, capture, transport, and storage with the requirement that CO_2 storage begin by 2030 [47]. Six of these projects are considering marine transport of CO_2, with two evaluating offshore geologic storage around Japan, and the other four evaluating transport CO_2 via carrier vessel to Malaysia and Oceania[b] for geologic storage. Figure 1-2 and Table 1-1 provide summary information on the JOGMEC Advanced CCS Project selections.

[b] Oceania is a geographical region including Australasia, Melanesia, Micronesia, and Polynesia

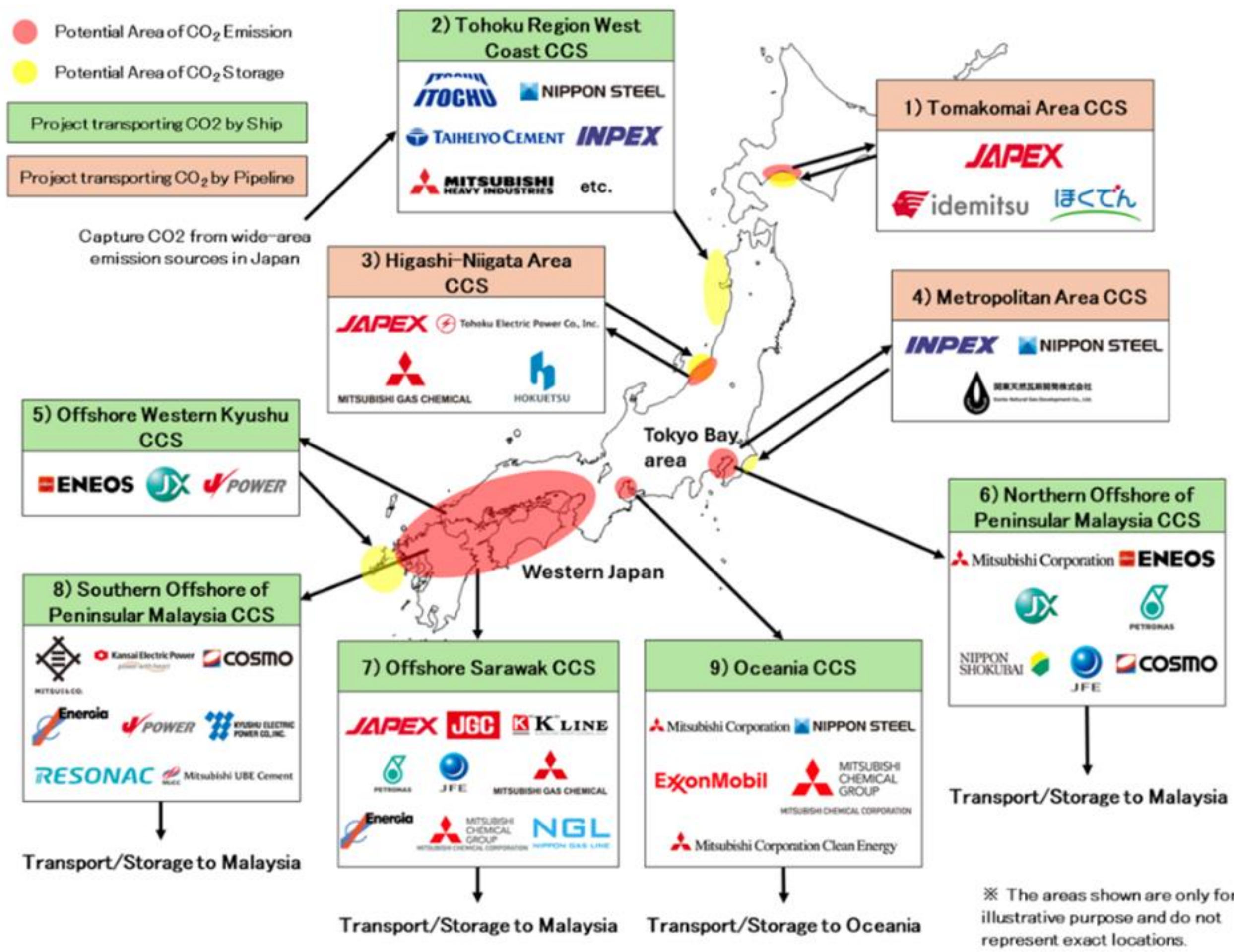


Figure 1-2. Japan's Advanced CCS Projects map

Used with permission from JOGMEC [47]

Table 1-1. Summary of JOGMEC Advanced CCS Projects highlighted in Figure 1-2

Project	Project Name	CO_2 Source Targets	Approximate CO_2 Storage Rate/yr (tonnes)	Transport Method(s) Proposed	Storage Options
1	Tomakomai Region CCS project	Refineries, power plants	1.5–2 million	Pipeline	Saline reservoir, offshore of Tomakomai
2	Tohoku Region CCS project (along the Sea of Japan coast)	Steel, cement, local waste generators	1.5–1.9 million	Carrier and pipelines	Saline reservoir offshore of Tohoku
3	Higashi-Niigata Region CCS project	Chemical plants, paper mills, power plants	1.4 million	Pipeline	Existing oil and gas (O&G) fields, Niigata Prefecture
4	Metropolitan CCS project	Steel, other industries	1.4 million	Pipeline	Saline aquifer, offshore Boso, Chiba Prefecture

Project	Project Name	CO_2 Source Targets	Approximate CO_2 Storage Rate/yr (tonnes)	Transport Method(s) Proposed	Storage Options
5	Western Kyushu offshore CCS project	Oil refineries, power plants	1.7 million	Carrier and pipelines	Saline aquifer, offshore Western Kyushu
6	Malaysia Northern Peninsula CCS project	Steel, chemicals, oil refineries	3 million	Carrier and pipelines	Depleted O&G fields, offshore Malaysia, northeast Malay Peninsula
7	Malaysia Sarawak offshore CCS project	Steel plants, power plants, chemical plants	1.9–2.9 million	Carrier and pipelines	Depleted gas field, offshore Sarawak, Malaysia
8	Malaysia Southern Malay Peninsula CCS project	Power plants, chemicals, cement, oil refineries	5 million	Carrier and pipelines	Depleted O&G fields, saline aquifers, offshore east coast of the Malay Peninsula, Malaysia
9	Oceania CCS project	Steel plants, other industries	2 million	Carrier and pipelines	Depleted O&G fields, saline aquifers, offshore Oceania

Note: Data compiled from JOGMEC [48] and Carbon Herald [49]

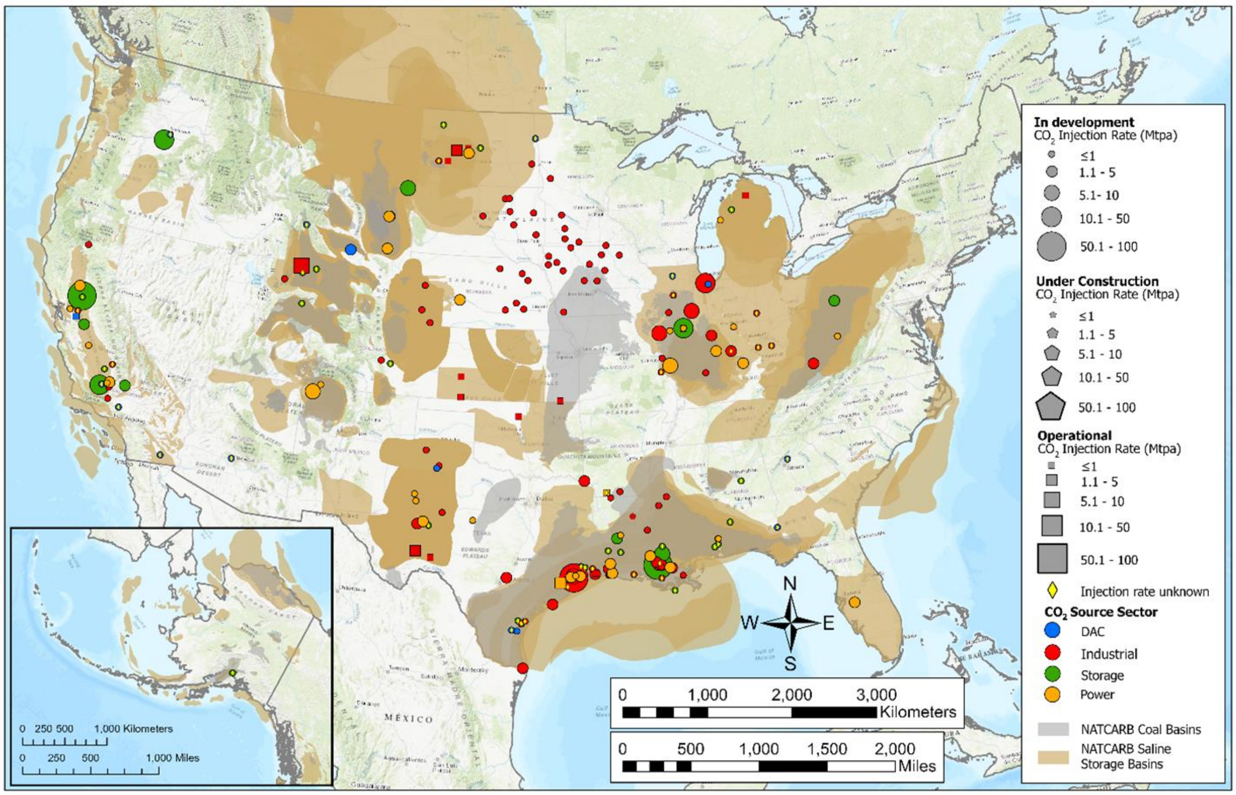
The total annual CO_2 storage of these projects is approximately 19.4 to 21.3 million tonnes (Mt). The storage capacity of the six projects that include bulk carrier vessel transport range from 15.1 to 16.5 Mt CO_2.

Japan is also advancing maritime CO_2 transport through a large-scale demonstration program on long-haul CO_2 shipping, coupled with CO_2 liquefaction and storage. This test will include hauling 10,000 tonnes of CO_2/yr captured at Kansai Electric's 1.8-gigawatt Maizuru coal-fired power plant in Kyoto prefecture and transportation to the Tomakomai storage terminal in Hokkaido [50], traversing an approximately 1,000-kilometer (km) (620-mile [mi]) route using the recently completed Mitsubishi's EXCOOL LCO_2 carrier vessel. EXCOOL is a low-temperature and low-pressure vessel with cargo capacity of 1,450 m^3 (51,206 ft^3). A key objective of this project that began in August 2024 [51] is to improve understanding of specification for ground facilities and operational procedures and to verify possible improved economics [52]. Demonstration was conducted at -35 °C (-31 °F), but full-scale demonstration will be conducted at -50 °C (-58 °F) and 6 bars (87 psi) after completion of the onshore terminals at both Maizuru and Tomakomai [52].

Japan is also implementing its GX international development strategy through partnerships with other nations [53]. Strategies include the Development of Green Markets, Collaboration for Innovation, Asia Zero Emissions Community, the Joint Crediting Mechanism, and the Asia Energy Transition Initiative (AETI). The AETI Strategy will provide financial support for technology development of CCUS and will drive the Asia CCUS network [43]. The Asia CCUS network members include industry representatives, policymakers, government officials, financial institution representatives, and academia, who will convene to share knowledge and ideas on the practical implementation of CCUS in the Asia region. Members include many East Asian and Southeast Asian nations, Australia, and the United States [54].

1.3 State of CCUS in Alaska

According to the Global CCS Institute, the United States is leading the global implementation of CCUS projects, having the largest number of CCUS facilities (>200 [55]) either in operation, in construction, or in development [56]. As shown in Figure 1-3, announced CCUS projects across the United States include a mix of CO_2 capture projects, pipeline transport networks, geologic storage hubs, and fully integrated capture, transport, and storage projects.



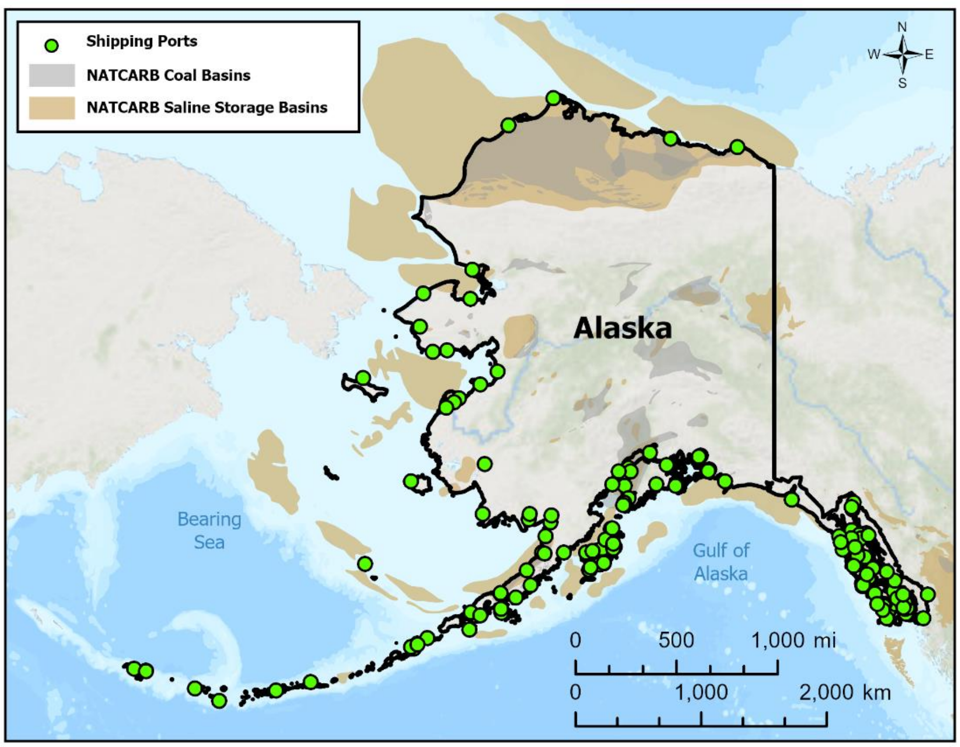
Note: Mtpa = million tonnes per annum; map data are compiled from the Clean Air Task Force and the National Energy Technology Laboratory's (NETL) National Carbon Sequestration Database and Geographic Information System (NATCARB) [55, 57]

Figure 1-3. Map of the announced and active CCUS projects across the United States

The recent surge in planned CCUS projects in the United States is largely due to enacted legislative and financial incentives at the state and federal levels that encourage adoption of CCUS as an essential component for achieving a national low carbon economy. Key drivers include the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA). The BIL, enacted in 2021, allocated more than $10 billion to advance CCUS technologies [58]. These funds are being invested in projects to scale annual CO_2 injection rates to 250 Mt/yr for secure geologic storage by 2035 [59]. The IRA, passed in 2022, enhanced section 45Q tax credits, offering $85/tonne for dedicated secure geologic storage of CO_2 in saline or other geologic formations, $60/tonne for secure geologic storage of CO_2 in association with enhanced oil or gas recovery, \$60/tonne for other beneficial uses of CO_2, and \$180/tonne for direct air capture [60, 61]. Together, these measures provide unprecedented financial and policy support for the development and deployment of CCUS in the United States [62].

The United States possesses extensive geologic basins with gigatonne[c]-scale carbon storage resource potential. According to the National Energy Technology Laboratory (NETL), onshore saline-bearing formations across the U.S. have an estimated storage resource of 2,300–21,150 billion tonnes of CO_2 [63]. This potential is sufficient to store the annual energy-related CO_2 emissions from the electric power, industrial and commercial sectors (2.64 billion tonnes per year in 2023 [64]) in the U.S. for approximately 800–8,000 years.

Typical geological storage options include saline storage basins, depleted oil and gas reservoirs, and active oil and gas reservoirs. Additional subsurface storage options include subsurface mineralization, such as in basalt formations and ultramafic rocks, and unmineable coal seams, though these options require further research and development to optimize the processes and improve economic viability. The state of Alaska encompasses several areas with CO_2 storage potential as shown in Figure 1-4.



Note: Map generated using data from NETL's NATCARB Database [57]

Figure 1-4. Prospective CO_2 storage resources in Alaska with saline storage and coal basins

Several assessments of the storage potential of Alaska have been conducted using different methodologies, scales of data, and different assumptions. The Alaska Department of Natural Resources [65] and the United States Geologic Survey [66] completed screening assessments

[c] A gigatonne is one billion tonnes.

across various prospective basins in Alaska in 2010 and 2014, respectively. The Alaska DNR initially estimated Alaska's CO_2 storage potential could be as high as 16,000 gigatonnes, which included offshore prospects. The Alaska DNR, in cooperation with the DOE supported WESTCARB Region Partnership, reported their 2010 estimates are likely an order of magnitude lower when accounting for access constraints and high costs in some regions, particularly offshore [67]. The USGS reported an estimated 290 gigatonnes of potential CO_2 storage resources in the North Slope [66]. As additional data collection, site scoping, and characterization is undertaken, the Storage Resources Management System (SRMS) can be applied as a consistent methodology to quantify, categorize, and classify storage resources on a project level [68].

To put the storage capacity estimates into context, the EPA reported that Alaska's CO_2 emissions from fossil fuel combustion – covering industrial and electric power sources - were 0.65 gigatonnes in total from 1990 to 2018 [69]. This significant difference between the state's CO_2 storage potential and its CO_2 emissions from industrial and electricity generation sources suggests that Alaska has storage resources well in excess of its own CO_2 emissions through 2050. This estimated surplus of storage resources strongly supports the prospect of Alaska hosting a CO_2 storage hub through partnerships with countries like Japan that are exploring CO_2 storage solutions through bilateral cooperation [70].

Overall, much of Alaska sedimentary basins including the Susitna, Nenana, Yukon Flats, Copper River, and the Colville Basin near Barrow represent prospective exploration opportunities that have yet to be confirmed as viable storage resources. But Alaska has been making progress in efforts to accelerate commercial CCUS development within the state. In 2022 The University of Alaska Fairbanks started the Alaska CCUS Workgroup to explore the opportunities for attracting new investments and creating options that ensure continued operation of carbon intensive activities vital to the state's economy including power generation, refineries, and oil and gas production [71]. Central to the Workgroup's objectives is to accelerate commercial CCUS projects within the state. The Workgroup leadership includes academic, state, and corporate industry representation from the University of Alaska Fairbanks Institute of Northern Engineering, DNR, and Arctic Slope Regional Corporation with financial and expertise support from the University of North Dakota Energy and Environmental Research Center. The key functions of the Workgroup are to help establish a state legal and regulatory framework, leverage government funding opportunities, engage in public education and outreach, and develop a roadmap to accelerate commercial CCUS deployment in Alaska [67].

Further progress was made in 2023 when the University of Alaska Fairbanks was selected for a DOE Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Phase II award for the Alaska Railbelt Carbon Capture and Storage Project (ARCCS). The ARCCS project will investigate the viability of developing a commercial-scale CO_2 geologic storage complex for the secure and economic storage of more than 50 Mt CO_2 in south-central Alaska. Plans are to evaluate the aggregation of storing CO_2 captured from new and existing power generation sources in south-central Alaska for injection into the Beluga River Field complex on the northern shore of Cook Inlet Basin. Project plans also include evaluating the prospect of preserving natural gas production from depleting gas fields with simultaneous CO_2 injection, which will help address pending natural gas supply shortages in the Railbelt where 75 percent of Alaska's population resides [72].

In 2024, ASRC Energy Services, LLC was selected for a CarbonSAFE Phase III award to develop the North to the Future Carbon Capture and Sequestration Hub [73]. The project will initiate the development of a commercial, large-scale CO_2 storage hub in the North Slope region of Alaska by characterizing a dedicated storage location for point-source and direct air capture projects. ASRC Energy Services is planning to drill a stratigraphic well, evaluate CO_2 transport options and associated feasibility to the hub from regional CO_2 emitters, and develop a storage field development plan. The initial storage hub design consists of two injection wells and transport pipelines for two localized regions of CO_2 emitters.

Additional to the CarbonSAFE projects is DNR's work toward supporting and accelerating safe and socially equitable deployment of CCUS in Alaska by offering technical and public support services as well as generating information-sharing resources for CCUS stakeholders. Their effort will include the compilation of an Alaska-centric CCUS database that includes data on societal considerations and impacts related to CCUS development, potential storage reservoirs, prospective storage resources, seal/caprocks, and an assessment of seismic hazards and risks [74]. DNR's efforts are supporting CCUS development by providing resources that can help decision-makers better understand and address technical considerations, environmental factors, and stakeholder perspectives.

With regard to policy, Alaska has made progress on two key pieces of legislation. In May 2023, Alaska Senate Bill 48, introduced initially as part of the Carbon Offset, was enacted into law. The bill authorizes the Alaska Oil and Gas Conservation Commission (AOGCC) to pursue primacy for Class VI underground injection wells in Alaska [75]. Following passage of the bill, the AOGCC submitted a Letter of Intent to the EPA seeking Class VI grant funding that was made available to EPA through the BIL for helping states enhance their agency capacity for carrying out primacy functions [76]. In July 2024, House Bill 50 that establishes a framework that the Department of Natural Resources will implement through regulations for companies to capture CO_2 and build geologic storage infrastructure in Alaska, was enacted into law. [77, 78, 79].

The sections that follow provide a screening-level examination of the various technical, economic, and regulatory aspects of CCUS value chain configurations that consider transpacific shipping of captured CO_2 from Japan to the U.S. state of Alaska for onshore and offshore geologic storage. Each section analyzes available data and information to assess the technical and economic feasibility of CCUS value chain configurations with consideration to existing international and domestic laws that regulate maritime bulk carrier shipping. Findings from these analyses highlight the opportunities and favorable conditions for each possible configuration.

2 TECHNICAL FEASIBILITY ASSESSMENT

This section presents a preliminary technical assessment of potential CCUS value chain configurations for transpacific shipping of LCO_2 from Japan for transfer and geologic storage in Alaska. The assessment is a set of screening-level analyses structured in four steps:

- Review of applicable loading and offloading terminal design and LCO_2 vessel designs and considerations (Section 2.1)
- Assessment of the technical readiness of applicable terminal and shipping configurations for the selected shipping corridor and description of any outstanding technical considerations (Section 2.2)
- Description and comparison of Alaskan areas potentially applicable to LCO_2 shipping (Section 2.3.1)
- Comparison of generalized shipping corridor(s) and associated LCO_2 offloading configurations between Japan and Alaska (Sections 2.3.2)

The analyses as a whole highlight finding about opportunities, suitability, and technology readiness of a theoretical Japan-Alaska transpacific LCO_2 shipping development that can help prioritize the scope of a more detailed Phase II feasibility study. The findings also establish the technical input for commercial and regulatory screening assessments discussed in Section 3 and Section 4, respectively. Information for the analyses presented in this section is derived from a literature review, analog marine LCO_2 transport projects, and public datasets.

2.1 CCUS VALUE CHAIN CONFIGURATIONS WITH MARITIME CO_2 TRANSPORT

A CCUS value chain is typically comprised of CO_2 point source or direct air capture, transportation, and injection into suitable subsurface formations for secure geologic storage or offtake for utilization. The infrastructure of these CCUS value chain elements must be at a high state of technical readiness, affordable, and operationally sustainable over the long term. A CCUS value chain that includes maritime transport of LCO_2 generally consists of some or all of the operational components listed below. The type, scale, and specifications of these operational components depend on the full value chain configuration being used. The configurations considered in this study are shown in Figure 2-1.

- Method of CO_2 capture, purification, and intermediate compression
- Mode of intermediate CO_2 transport
- Liquefaction facilities (CO_2 compressed to LCO_2)
- Intermediate (buffer) LCO_2 storage and loading
- LCO_2 transport via ship (e.g., vessel or barge)
- LCO_2 offloading, conditioning, and buffer storage
- Mode of LCO_2 transport to geologic storage site(s) or offtake facility for utilization
- Injection at geologic storage site

Vessels serve as the “midstream” function in the CCUS value chain, as do all modes of LCO_2 transport that connect CO_2 capture (upstream) with geologic storage sites or utilization off-takers (downstream). Figure 2-1 illustrates the various value chain configurations that integrate transpacific transport of LCO_2 as the midstream component.

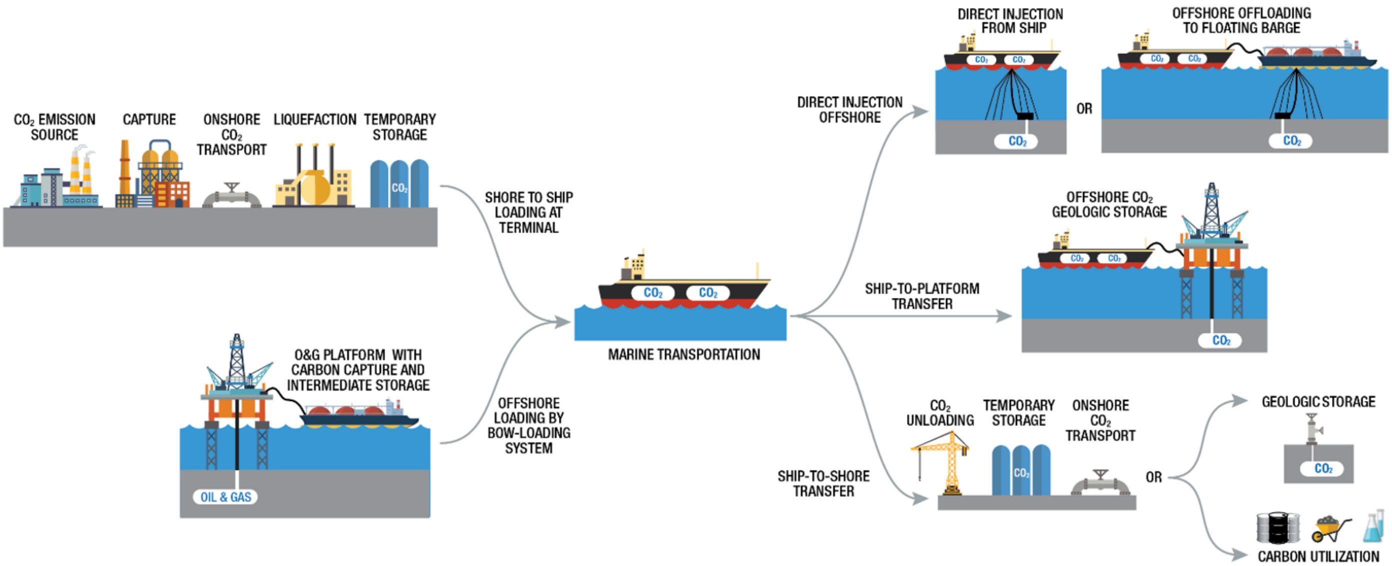


Figure 2-1. Overview of LCO_2 shipping configuration options

As depicted in Figure 2-1, bulk liquid vessels for transpacific transport can be loaded from onshore or offshore LCO_2 loading facilities. Figure 2-1 also shows that vessels can offload the LCO_2 at three different terminal types, consisting of offloading to an onshore terminal (i.e., ship-to-shore), offload to an offshore structure (i.e., ship-to-platform), and direct injection offshore from the vessel to a sub-seabed geological formation (i.e., direct injection). These terminal types, or offloading modes, are described in Table 2-1 and serve as the basis of the analyses in this section.

Table 2-1. Overview of LCO_2 vessel offloading modes

LCO_2 Offloading Mode	Description
Ship-to-shore	• LCO_2 vessel docks at a port terminal for offloaded to temporary storage units prior to injection at onshore geologic storage sites or offtake by utilization end users • Includes offloading of CO_2-filled storage tanks
Direct injection	• LCO_2 vessel equipped with an onboard CO_2 pre-injection conditioning system and connection equipment for ship-to-ship transfer [80] • Multiple mooring systems utilized dependent on the intended CO_2 offloading volume and water depth [16, 81, 82, 83]
Ship to offshore platform	• LCO_2 transfer from the carrier to a fixed or floating offshore receiving platform connected to a seabed wellhead [84] • The offshore platform can be equipped with the CO_2 conditioning, injection systems, and buffer storage to enable continuous injection

Additional ship-to-barge or ship-to-ship transfers potential CO_2 offloading configurations and represent additional approaches for deploying CCUS at large scale in the near term [85, 86]. However, specific economical and practical offloading approaches will depend on site-specific or regional conditions for offloading, including the presence and frequency of sea ice, water depth of navigation channels and port terminals or piers, space for or access to offloading and handling infrastructure, proximity to geologic storage sites, and other factors that are addressed in the analysis [87].

2.1.1 LCO_2 Cargo Considerations

The design of LCO_2 export and import terminals, liquefaction facilities, gas conditioning equipment, and vessels is intricately related. The technical configuration of CO_2 shipping value chains is largely based on the requirement that the CO_2 cargo is kept in a cooled and pressurized liquid state. Transport in the liquid phase maximizes a vessel's CO_2 cargo weight capacity compared to the significantly less efficient transport of low-density CO_2 gas. Therefore, an essential focus of LCO_2 shipping R&D activities is to maximize LCO_2 cargo density through optimal transport P/T conditions for various project scenarios based on CO_2 source volume and purity, transport distance, and final disposition (i.e., geologic storage or utilization).

Studies that have explored the topic of maritime LCO_2 transport conditions outline three P/T combinations for onboard CO_2 storage: low, medium, and high. Figure 2-2 illustrates the relative P/T conditions on a CO_2 phase diagram.

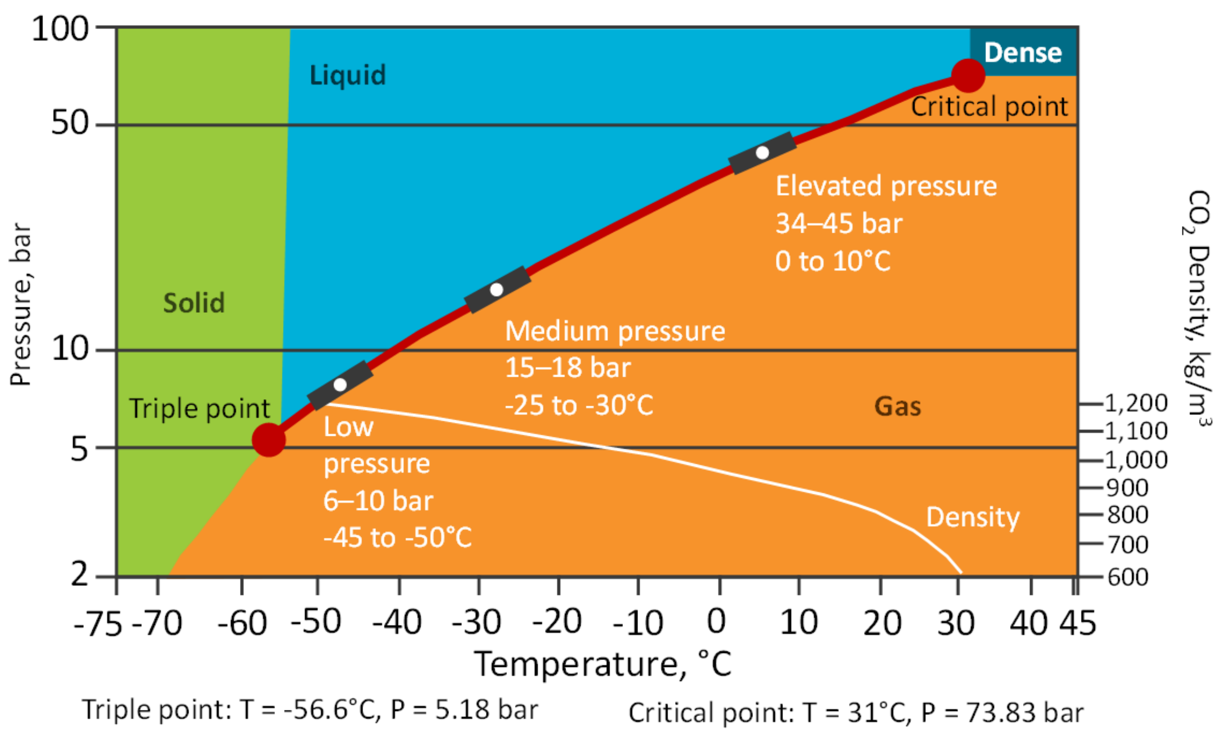


Figure 2-2. CO_2 phase diagram

Each transport condition incurs trade-offs in terms of process economics (e.g., liquefaction cost), technical complexity, technical maturity and risk, and LCO_2 cargo capacity. Table 2-2 summarizes the three common pressure-temperature combinations under consideration for marine transport of CO_2.

Each transport condition incurs trade-offs in terms of process economics (e.g., liquefaction cost), technical complexity, technical maturity and risk, and LCO_2 cargo capacity (Table 2-2). The rapidly growing LCO_2 shipping industry has identified low-pressure transport conditions as an prospective design target because of the potential for larger cargo tanks carrying LCO_2 at maximum density [88, 22, 89]; however, low-P/T transport requires stable P/T conditions near the triple-point of CO_2 phase equilibria at which all three phase envelopes (solid, liquid, and gas) meet (Figure 2-2). In this narrow region of the liquid CO_2 phase envelope, small fluctuations in P/T caused by combined factors of heat ingress to tanks and piping, sloshing of LCO_2 cargo from wave action, and tank pressure buildup from vapor formation can lead to flow obstructions such as solid CO_2 (dry ice) formation or rapid vapor formation, posing major process and safety risks. Additionally, residual impurities remain in the liquefied CO_2 after gas processing that can substantially alter the vapor point of the LCO_2 cargo, requiring adaptability of P/T stabilization systems for CO_2 feed streams with variable impurity compositions [90, 91, 22].

Another technical component necessary for operations is a dynamically integrated simulation to analyze the liquid CO_2 and system behavior during ship loading/unloading. For offshore offloading, this model would have to be integrated with injection wellhead conditions and injection flow rates for monitoring and control [92]. Each shipping P/T regime requires a liquefaction step prior to loading CO_2 onto vessels. LCO_2 liquefaction systems are discussed in Appendix A: Supplementary Information for LCO2 Vessel and Loading and Offloading Terminal Design Considerations.

The following subsections provide a review of the key infrastructure components underpinning the segments of the CO_2 shipping configurations depicted in Figure 2-1. The subsections below are not intended to provide explicit design guidance or operational best practices and direction for the infrastructure components discussed, but more so to provide summary perspectives on 1) the specific role and function of key infrastructure components; 2) their known or planned operating ranges; and 3) implications for designing, optimizing, and harmonizing value chain segment configurations and underlying infrastructure for consideration towards future CCUS enterprises, which may involve shipping CO_2 captured in Japan to Alaska.

Table 2-2. Summary of the three common P/T combinations for CO_2 transport vessels

Shipping Condition	CO_2 Density	Advantages	Disadvantages
Low Pressure **6 to 10 bar at -50°C** **(87 to 145 psi at -58°F)**	1,170 – 1,120 kg/m3	**Design Maturity -** Low pressure technologies available based on LPG shipping and LNG analogs; Large scale demonstration projects in progress **Design Scalability -** Tank wall thickness reductions may support increased vessel sizes **Operability -** Higher CO_2 cargo density may increase cargo size per shipment	**Design Maturity -** No current commercial experience **Energy Demand -** Higher energy intensive configuration **Thermal Design -** Higher insulation requirements anticipated **Design Scalability -** Larger scale vessel designs proposed but not yet commercially deployed **Operability -** Increased risks of phase change and dry ice formation operating cargo near triple point conditions
Medium Pressure **15 to 18 bar at -25°C** **(217 to 261 psi at -13°F)**	1,080 – 1,030 kg/m3	**Design Maturity -** Existing commercial experience with shipping food grade quality CO_2 **Energy Demand -** Moderate energy requirements for conditioning processes **Operability -** CO_2 cargo at P/T conditions distant from triple point reducing risks of phase change and dry ice considerations	**Design Scalability -** Tank and vessel size limitations due to weight and draft considerations
High Pressure **34 to 45 bar at 0° to +10°C** **(493 to 652 psi at -50°F)**	820 - 930 kg/m3	**Design Maturity -** Conceptual designs available in industry **Energy Demand -** Least energy intensive configuration **Thermal Design -** Reduced insulation and cargo handling requirements **Design Scalability -** Small tanks can be stacked vertically in vessel designs **Operability -** P/T conditions relatively closer to pipeline transport conditions and cargo at P/T conditions distant from triple point	**Design Maturity -** No current commercial experience **Design Scalability -** Thick-wall tank systems may inhibit large vessel sizes due to weight and draft considerations **Operability -** Lower CO_2 cargo density may reduce cargo size per shipment; Potential increase in safety considerations for high pressure transportation

2.1.2 LCO_2 Vessel Design Considerations

A functional, fully integrated, and harmonized CCUS value chain is heavily contingent upon the explicit design and associated attributes of the LCO_2 transport ship(s), a component that can have limited flexibility once constructed. Specifically, the design conditions of the ship(s) utilized for marine LCO_2 transport must be directly compatible with the other value chain components described throughout the next several subsections. Given that vessels are considered one of the most capital-intensive components across the CCUS value chain configuration options described in Figure 2-1 [30, 93], planning efforts must consider the broader objectives of the integrated CCUS system (like achieving a yearly CO_2 throughput target, ensuring source-to-sink connectivity and continuity of CO_2 delivery, and overall project economic feasibility) in the context of potential trade-offs based on needed LCO_2 carrier size, design, and number of vessels required.

Vessel design specifications (and associated costs) depend on a multitude of factors and considerations; however, two of the most predominant considerations influencing design are 1) the physical state at which CO_2 will be transported between source(s) and sink(s) and 2) the cargo capacity (i.e., m^3 or tonnes of CO_2 per ship). As discussed and outlined in Table 2-2 of Section 2.1.1, the P/T considerations being explored include high- (or elevated), medium-, and low-pressure regimes [94]; however, only the low- and high- (or elevated) pressure regimes are believed capable of enabling the scaling of CO_2 cargo capacity for CCUS applications.

There exist inherent trade-offs between the overarching objectives of the collective CCUS value chain and choice of P/T regime by which CO_2 would be liquefied and transported—the combination of each is influential on the design of many crucial vessel components. Several of the common LCO_2 carrier design considerations related to cargo capacity and P/T regime are noted from the literature. Table 2-3 presents the design and operational trade-offs between major vessel design components, including cargo capacity, the cargo P/T regime (i.e., cargo conditions), and storage tank design [95, 16, 83, 96, 97, 30, 98, 85, 99, 100]. Other notable carrier design considerations are described in detail in Table A-1 of Appendix A: Supplementary Information for LCO_2 Vessel and Loading and Offloading Terminal Design Considerations.

Table 2-3. Major LCO_2 carrier components and associated design considerations

Component	Description/Purpose	Design and Operational Considerations
CO_2 Cargo Capacity	The total mass (in tonnes) of CO_2 capable of being transported by a ship; vessel payload is often expressed volumetrically (in m^3) based on the total storage size of all onboard tanks	In combination with P/T regime, intended cargo capacity can influence 1) CO_2 tank quantity and size, 2) number of tanks per ship, and 3) overall vessel dimensions (e.g., width, length, draft). Smaller cargo vessels ($\leq$10,000–15,000 m^3 [353,000–530,000 ft^3]) can operate at medium P/T. Larger cargo vessels exceeding 15,000 m^3 (530,000 ft^3) in total tank capacity are more likely to operate under low- or high-P/T conditions. The number of carriers needed to deliver a design flow rate (i.e., 1 Mt/yr) from source(s) to sink(s) is contingent on the cargo capacity per ship and ship service speed.
Pressure and Temperature Regime	Transporting CO_2 in the liquid phase provides for high density and increased ease of handling compared to gas phase; the low-, medium-, and high-P/T conditions outlined in Table 2-2 are widely considered for LCO_2 transport and require pressurization and, in some cases, refrigeration	**Low P/T** – Vessel designs similar to those used for liquefied petroleum gas (LPG) transport and could utilize vertically- or horizontally-oriented tanks. The comparatively highest density enables the most CO_2 onboard storage per given tank size and more compact vessels. **Medium P/T** – Existing fleet of vessels utilizes this P/T regime (Table 2-4). Proposed designs for LCO_2 vessels plan to leverage horizontally aligned cylindrical tanks in single or double (parallel aligned) layouts. Under some cases, an additional tank is proposed for location in the bow of the ship. Difficult to scale beyond 15,000m^3. **High P/T** – May require several small cylindrical tanks aligned in vertical groupings, a concept similar to the piping configuration used for compressed natural gas. Larger capacity tanks are prone to construction hurdles due to tank complexity (increased tank shell plate thickness, weldability issues, etc.). As outlined in Table 2-2, trade-offs in cost and project design exist depending on selection of the transport P/T condition.
Storage Tanks	Major components onboard the vessels that store LCO_2 and consist of these components [101, 102]: • Inner tank made of stainless or carbon steel • Outer carbon steel shell with vacuum insulation • Refrigeration unit to keep the tank cool and sustain CO_2 in a liquid state	According to IGC Code, semi-refrigerated Type C pressurized tanks can be used to maintain CO_2 in a liquid state under low- and medium-P/T conditions. ISO tanks are also applicable under low- and medium-P/T conditions, potentially affording compatibility with onshore rail and truck transport. For a fixed cargo capacity, the vessel size will vary with the tank size and number of tanks. Tanks are separate from the vessel structure and must be fitted within the cargo spaces of the vessel to allow room for inspection. Large-diameter tanks are more space-efficient with a favorable ratio between storage capacity and steel weight. Geometrical constraints of the vessel must be considered to optimize vessel and tank design. Heating equipment may be necessary to manage vapor return during loading or offloading or potential freezing of LCO_2 when transferring into buffer storage tanks.

Many companies are actively developing projects and/or conceptualizing new vessel designs specifically for the transport of large volumes of LCO_2 for CCUS [103]. Several of the key vessel design and operational attributes described in Table 2-3 have been compiled and summarized for several of these developing projects using information from open-source literature. Table 2-4 provides the collective summary of the design and operational attribute information for comparative purposes.[d] By way of comparison, attribute data for typical LNG carriers in operation today is also provided in Table 2-4 as a way to offer perspective to the LCO_2 carrier designs noted.

Multiple shipyards in Japan, Korea, and China are actively working to scale up LCO_2 vessel capacities over vessels currently used for food and beverage maritime CO_2 transport; however, based on the data in Table 2-4, designs vary significantly from one vessel to the next in terms of capacity and cargo technology (including the P/T regime considered) [104]. For instance, the new LCO_2 vessels developed for the Northern Light's project have been built at a significantly higher cargo capacity than those employed for CO_2 transport used in the food and beverage sector (i.e., the Larvik Shipping vessels in Table 2-4) despite using similar medium P/T storage. Larger-sized vessels up to and exceeding 84,000 m^3 (2,966,430 ft^3) capacity are being approved in principle[e] or are being proposed, but not yet deployed. Figure 2-3 depicts two of these LCO_2 vessels summarized in Table 2-4. Both the prevailing and anticipated future designs of LCO_2 carriers provide important context toward broader CCUS value chain development. Specifically, export terminals in Japan, cross-border shipping corridors, and the corresponding LCO_2 receiving terminal in Alaska all must be amenable with designs in regard to terminal spacing needs to accommodate vessels (dictated by length, breadth, and draft), P/T storage regimes, and cargo volume/throughput handling.

[d] The fleet of ships summarized in Table 2-4 is not fully exhaustive of all planned, in development, or operational LCO_2 vessels. The ships summarized in Table 2-4 were featured because sufficient open-source literature exists that indicates the majority of the design and operational specifications featured.

[e] An "approved in principal" design is one that meets current regulations and requirements for specific vessel classification and international conventions [346]. Maritime standards and classification societies relevant to LCO_2 transport are described in detail in Section 4.6.

Table 2-4. Summary of design specifications for several LCO_2 and LNG vessels in operation, under construction, or in concept

Vessel Description (Operational Domain)	Larvik Shipping Helle LCO_2 Vessel (Norway)	Larvik Shipping Fleet - Frøya, Gerda, Embla (Norway)	Mitsubishi Shipbuilding EXCOOL Demonstration Test Ship (Japan)	Dalian Shipbuilding Offshore Co. Northern Light's Project Vessels (Norway)	Hyundai Mipo Mid-size Vessels for Capital Gas (Greece)	Knutsen NYC Carbon Carriers AS (KNCC) LCO_2-EP Carrier for Direct Injection	ECOLOG Large LCO_2 Carrier	Concept Design for a Large, Deep-Water CO_2 Carrier	Small-Scale LNG Carrier Example 1	Small-Scale LNG Carrier Example 2	Large-Scale LNG Carrier Example
Vessel Type	**Food & Beverage LCO_2 Vessel**		**CCUS Purpose-Built LCO_2 Vessel**						**LNG Vessel**		
Volume capacity	1,250 m^3	1,700 m^{3A}	1,450 m^3	7,500 m^3	22,000 m^3	40,000 m^3	84,000 m^3	127,800 m^{3A}	7,500 m^3	30,000 m^3	175,000 m^3
CO_2 cargo capacity	1,250 tonnes	1,770 tonnes	1,450–1,650 tonnes^B	8,000 tonnes	25,800 tonnes	35,000 tonnes^B	100,000 tonnes	150,000 tonnes	3,375 tonnes LNG^C	13,500 tonnes LNG^C	78,750 tonnes LNG^C
P/T regime	Medium	Medium	Low or medium	Medium	Low	High	Low	Low	Low	Low	N/A
Operating conditions	18 bar -40 °C	19 bar -30 °C	6–20 bar -50 to -20 °C	13–15 bar -30 to -26 °C	7–8.5 bar^D -55 °C	34–45 bar 0 to 10 °C	8 bar -55 °C	7–8.5 bar -55 to -46 °C	$\leq$ 1 bar -164 °C	$\leq$ 1 bar -164 °C	N/A
Tanks	1 cylindrical tank (type not specified)	1 tank (type not specified)	2 cylindrical IMO Type C tanks	2 cylindrical IMO Type C tanks	IMO Type C storage tanks (tank number not specified)	>35 tank units – each unit made up of 30-cylinder tanks	N/A	27 vertical bilobe tanks	IMO Type B tanks	IMO Type B tanks	4 IMO Type A aluminum tanks
Length	79.5 m	83 m	72 m	130 m	160 m	255 m	275 m	316.4 m	115 m	170 m	295 m
Breadth	14 m	12.6 m	12.5 m	21.2 m	27.4 m	42.5 m	48 m	49.6 m	18.6 m	29.5 m	45.8 m
Draft	4 m	5.2 m	4.6 m	8 m	N/A	11 m	12.5 m	19 m	5.5–6 m	7.5–8 m	12.5 m
Service speed	14 knots	12.5 knots	12 knots	13.2–14 knots	Not reported	Not reported	15 knots	Not reported	13.5–15.7 knots	16 knots	19.5 knots
Vessel status	Operational	3 operational	In testing	2 in testing; 1 under construction	2 under construction	Approved in principle	Approval in principle	Concept	Concept	Concept	Concept
References	[16, 105, 106, 107]	[16, 21, 108, 109]	[32, 110, 111, 112]	[34, 113, 114, 115]	[116, 117, 118]	[119, 120]	[121]	[122]	[123, 124]	[123, 124, 125]	[126]

Note: Values in the table flagged by superscripted letters were approximated: ^{A} based on reported CO_2 capacity and CO_2 density at P/T conditions; ^{B} based on reported volume capacity and CO_2 density at P/T conditions; ^{C} based on reported volume capacity and typical LNG density at P/T conditions (450 kg/m^3); and ^{D} based on reported volume capacity, CO_2 capacity, and reported pressure

Mitsubishi Shipbuilding EXCOOL

Northern Light's Project Vessel

Figure 2-3. Examples of LCO_2 carriers (from Table 2-4)

Used with permission from Northern Lights [127] and Japan Science and Technology Agency [110].

The variability noted in the number, size, and design of LCO_2 vessels proposed or in operation today is encouraging because it demonstrates optionality and flexibility for maritime LCO_2 transport given the growing interest and the prospects it offers in supporting global decarbonization. This noted optionality also affords the potential for the construction of vessels made fit-for-purpose that require project- or use-case-specific design attributes. For instance, Baggio and Taylor suggested that fit-for-purpose designs are most likely applicable to future ship orders. They noted that the existing diversity in regard to LCO_2 vessel cargo capacities and prevailing designs (Table 2-4), the promising outlook for the possibility of increasingly larger LCO_2 vessels in the future, and the associated costs involved are likely to moderate ordering of notional vessel designs; instead, they anticipate future carriers to be ordered against firm, long-term projects [104].

2.1.3 Loading and Offloading Terminal Components and Design Considerations

In maritime trade, ports are waterfront facilities located at specific convergence locations between the land and maritime purviews of passenger and freight circulation. Ports serve as central stations for commercial operations pertaining to loading and offloading cargo, while a terminal is an explicit part of a port that handles a specific type of cargo [128].

This subsection addresses the necessary terminal infrastructure components needed for handling and processing captured CO_2 arriving onsite, as well as the loading and offloading facilities needed to facilitate maritime LCO_2 transport. Components of port terminals consist mainly of liquefaction facilities (as necessary), bulk liquid storage tanks, loading or offloading mechanisms, vapor return and compression, metering, heat exchangers, and utility systems (like administration buildings and vessel refueling). The applicability of these components varies depending upon terminal use, either as a CO_2 exporting or importing terminal. Additionally, port attributes must be considered to ensure they meet specifications that can accommodate needed infrastructure to enable LCO_2 delivery and handling. For instance, the surface infrastructure types and scales required at either export or import terminals directly influences storage space requirements, electricity demand for continuous terminal operations, and warming and/or cooling water volume demand. Ports must also be able to accommodate incoming or outgoing vessel length, width, and draft as well as provide fuel compatible with vessels calling the port. Moreover, advantages may exist under circumstances where the location of CO_2 storage site(s) or CO_2 utilization end users is in close proximity to import terminals that would aim to minimize the extent of the transport system and complexity of the overall value chain.

LCO_2 terminals serve as the critical connecting linkages between LCO_2 maritime shipment corridors and CO_2 collected from sources and storage or utilization end-use applications. Terminal components and processes of the CCUS value chain that include maritime CO_2 transport are largely well known and understood from the existing, yet small-scale, operations pertaining to food-grade LCO_2 transport; however, there ia a limited number of these types of ports around the world that possess the necessary infrastructure to offload LCO_2 (none of which currently exist in Alaska) [85]. Defining clear pathway options to process, handle, and on- and offload CO_2 is critical to establishing the connection points to broader CCUS value chains that include maritime LCO_2 transport.

Terminals can be categorized as export (i.e., loading) or import (i.e., offloading) for transboundary shipment of LCO_2. Essentially, each terminal type can be further subdivided into either onshore or offshore terminals, depending on shipping configuration [100]. Export terminals receive captured CO_2 from various sources; transport from sources to the export terminal can occur through any form of viable transport, including barges, pipelines, trucks, and/or rail. Import terminals receive LCO_2 transported from vessels and provide a means to transport CO_2 for geologic storage or to CO_2 utilization end users.[f]

The necessary infrastructure at LCO_2 export terminals includes CO_2 liquefaction, intermediate storage, CO_2 piping, and offloading infrastructure. Pumping capability would also be required to support CO_2 transport within the terminal. A brief description of critical infrastructure components follows:

- **CO_2 transportation:** Pipelines can be used to bring CO_2 to the liquefaction facility at the terminal. Other multimodal transport options like truck or rail may also be applicable to deliver CO_2 to the export terminal.
- **CO_2 liquefaction:** Liquefaction is the process of converting gaseous CO_2 into its liquid state, enabling efficient storage and transportation. This infrastructure component is described further in Appendix A: Supplementary Information for LCO_2 Vessel and Loading and Offloading Terminal Design Considerations.
- **Temporary intermediate storage:** Cylindrical or spherical steel tanks are used as buffer storage in order to bridge timing gaps between continuous flow of captured CO_2 and discrete/intermittent transportation by ship. This infrastructure component is described

[f] As discussed in Section 2.1, direct injection and ship-to-offshore CO_2 offloading applications would not involve the vessel interfacing with an onshore terminal. Rather, CO_2 would be offloaded from the vessel via a mooring system or transferred directly to a platform for handling.

further in Appendix A: Supplementary Information for LCO_2 Vessel and Loading and Offloading Terminal Design Considerations.

- **Loading equipment:** CO_2 can be loaded onto vessels using different approaches depending on configuration. One approach may use a conventional articulated loading arm similar to those used by LNG and LPG facilities or transfer using a flexible cryogenic hose [16, 85].
- **Custody transfer:** Ultrasonic or Coriolis cryogenic flow metering equipment is needed for measurement of the amount of CO_2 being transferred from the terminal to the shipping vessel. Product sampling and quality testing may also be required as part of custody transfer at loading and/or unloading terminals based on product quality requirements and contractual agreements between counterparties.

Once the vessel reaches its destination, three main options exist for offloading CO_2 as discussed in Section 2.1. Figure 2-4 revisits only the offloading modes presented earlier in Figure 2-1.

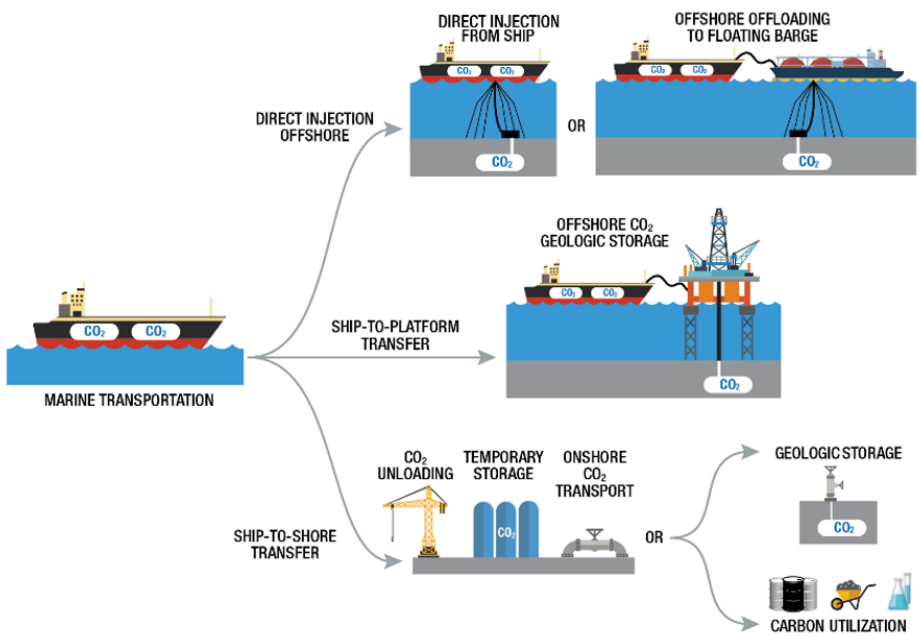


Figure 2-4. CO_2 offloading modes for vessel transport

For import terminals in ship-to-onshore terminal (i.e., ship-to-shore) configurations, the physical infrastructure needed encompasses offloading, temporary intermediate storage, conditioning, and offsite transport. Similar to export terminals, pumping capability would also be required to support LCO_2 transfer within and out of the terminal. A brief description of critical infrastructure components is described in the bullets below:

- **Offloading equipment:** Similar to the loading step, CO_2 can be offloaded from vessels using different approaches depending on configuration. This includes the use of loading arms to remove tanks from vessels or transfer of liquid CO_2 with a flexible cryogenic hose rated appropriately to match the P/T of the CO_2. LCO_2 would transfer from the vessel to onshore temporary intermediate storage. Provisions are also needed for the control and management of the boil-off gas (BOG) generated during offloading.

- **Custody transfer:** Onboard vessel piping systems with metering will interface with onshore temporary intermediate storage via the onshore loading arm/flexible hose described above. Additional metering systems may be placed onshore between the loading arm and storage facility to track the volumes of CO_2 transferred between vessel and terminal. Product sampling and quality testing may also be required as part of custody transfer at unloading terminals based on product quality requirements and contractual agreements between counterparties.
- **Temporary intermediate storage:** Cylindrical or spherical steel tanks are used as buffer storage in order to bridge timing gaps between the discrete/intermittent flow of incoming CO_2 via vessel and the continuous flow to CO_2 storage sites or end users. This infrastructure component is described further in Appendix A: Supplementary Information for LCO_2 Vessel and Loading and Offloading Terminal Design Considerations.
- **Conditioning:** Heating and pumping equipment is needed to bring LCO_2 from liquid-state conditions to P/T conditions amenable to offsite transportation and potentially direct CO_2 injection into the subsurface. This infrastructure component is described further in Appendix A: Supplementary Information for LCO_2 Vessel and Loading and Offloading Terminal Design Considerations.
- **CO_2 transportation:** Pipelines can be used to transfer CO_2 from temporary intermediate storage facilities offsite to geologic storage sites or end uses. Similarly, multimodal transport options like truck or rail may also be applicable to deliver CO_2 offsite to geologic storage locations or CO_2 utilization end users.

Under a ship-to-offshore circumstance where LCO_2 is transported directly to an offshore storage site, custody transfer, conditioning, and offloading equipment remain critical; however, their application can vary depending on configuration. For offshore offloading to a platform, the platform would need to provide conditioning and injection services, and possibly temporary storage. Alternatively, vessels would require their own onboard conditioning capabilities to process CO_2 prior to delivery to the platform. For offshore offloading from the vessel to direct subsurface injection, the vessel would be required to condition the CO_2 prior to transfer. Also, the vessel would need to be affixed with a gas transfer system to connect the vessel to the well to enable CO_2 delivery. For reference, the Element Energy report, “The Status and Challenges of CO_2 Shipping Infrastructures,” provides a detailed review of infrastructure needs and design considerations for several ship-to-offshore offloading configurations [83].

While shipping ports are commonplace in maritime commerce around the world, terminals providing LCO_2 handling capability are limited. Currently, only four to five ports exist that regularly handle food-grade LCO_2 that is transported via vessel worldwide [20], none of which currently exist in Alaska. However, several ports and facilities are currently developing infrastructure projects specifically for CCUS applications, with some in the conceptual design stage and others at the detailed design and execution levels. These projects involve a diverse range of stakeholders from the energy, manufacturing, and maritime industries. For instance, the Antwerp@C CO_2 Export Hub project (Belgium) concept provides an example of a CO_2 processing and export facility layout design with connection to an LCO_2 carrier (Figure 2-5). The export hub is proposed to provide an intra-port pipeline network integrated with shared liquefaction, storage, and export terminal capacity for cross-border shipping. It will be "open access" for industrial participants capturing CO_2 in the Antwerp port area. The project plans to have an initial export capacity of 2.5 Mt/yr, with the aspiration to scale upwards of 10 Mt/yr by 2030 [129].

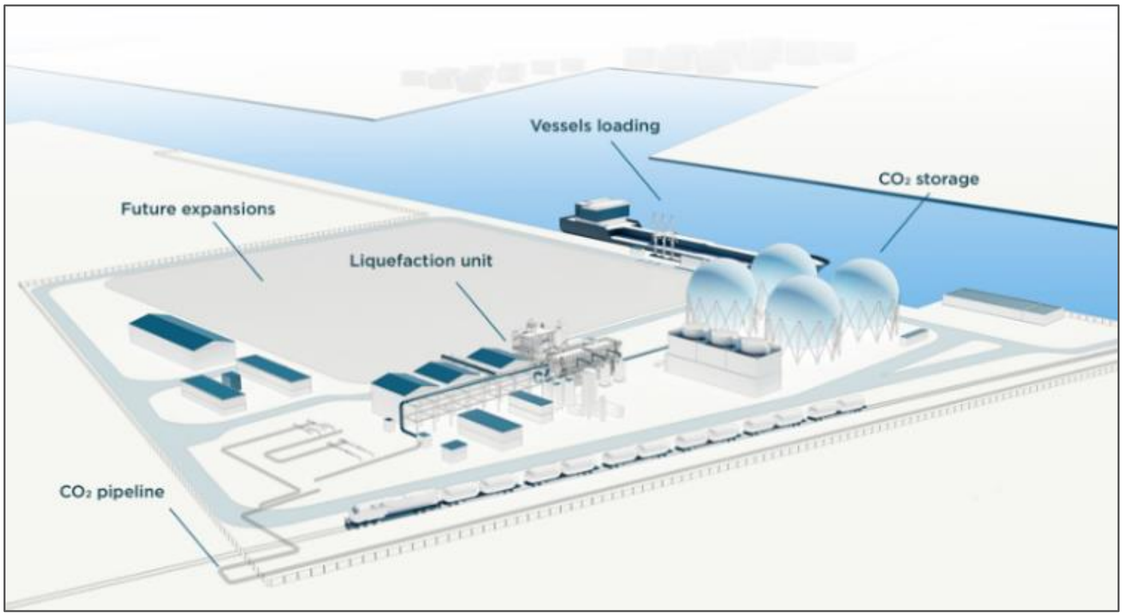


Figure 2-5. Conceptual design of the Antwerp@C CO_2 Export Hub with key components

Used with permission from Fluxys [130]

As an import terminal example, Northern Lights has completed its new large-scale LCO_2 offloading port facility, which is now operational. Figure 2-6 shows the port terminal with labels to key infrastructure components. A key element of the success of the Northern Lights project was the ability to build from an older port and adapt it for vessel offloading, processing and handling, and transport to an offshore geologic storage site for injection.

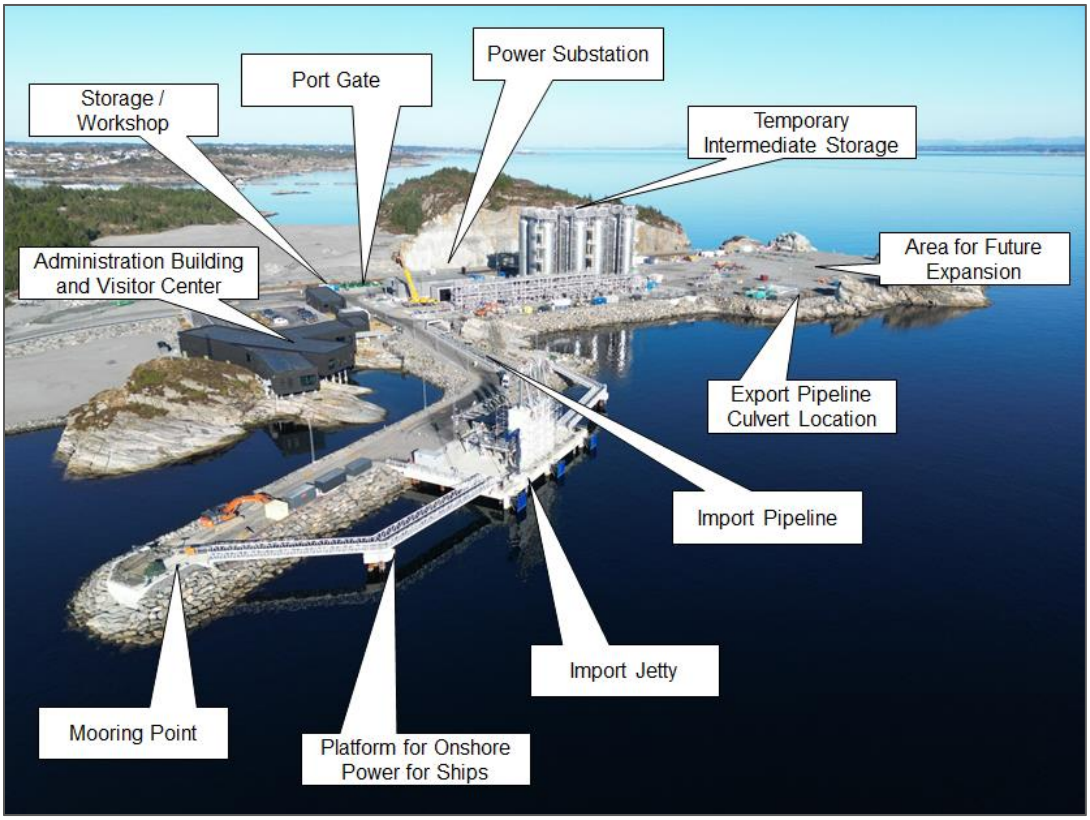


Figure 2-6. Photo of the Northern Lights onshore receiving terminal at Øygarden with key components flagged

Figure modified from the Northern Lights News and Media Archive website [127]

The expected scale of LCO_2 processing and handling components as described previously directly influences many required and enabling port terminal design conditions. The Society of International Gas Tanker and Terminal Operators has prepared guidance material related to infrastructure design associated with jetties and harbors, particularly for ports handling cargoes of liquefied gas. It is written specifically to benefit stakeholders planning marine gas terminal developments [131]. It has significant relevance to the port terminal development related to LCO_2 handling and, therefore, the topics discussed in this section; however, the data provided may also be of help to individual gas companies as they write project specifications.

The factors summarized in Table 2-5 should be considered to ensure effective operational conditions in future efforts aimed at terminal feasibility assessment and development specifically for LCO_2 export or import.

Table 2-5. Design considerations for LCO_2 export or import terminals

Port Terminal Design Consideration	Description
Siting	• Given the operational needs of maritime transportation to serve vessels, access to navigable waterways has been historically the most important and obvious siting consideration. • The presence of sea ice needs to be considered when siting port terminals and developing shipping routes. Sea ice can impact maritime operations in a number of ways. Collisions with sea ice can potentially damage vessel hulls or immobilize vessels entirely. It may force vessels to travel at slower speeds or take alternative (and possibly longer) routes to reach destinations. Also, if sea ice persists in certain areas year-round, it can potentially restrict maritime access to those regions. • Proximity and accessibility to a trained and capable workforce are needed to operate port terminals safely and effectively. Ports in excessively remote locations may impose limits to the human capital available for operation. • Potential logistical advantages exist from 1) close proximity of import terminals to geologic storage site(s) or CO_2 utilization end users and/or 2) close proximity of export terminals to CO_2 emission clusters. • Environmentally sensitive areas and wildlife refuges may have an impact on siting.
Accommodation of vessel length, berth, and draft	• Sufficient water depth and berth dimensions are needed based on the expected length, width, and draft of LCO_2 vessels arriving, docking, and exiting port terminals. • Sites on tidal waterways create a particular consideration for shipping because of the daily rise and fall of water levels at the berths. Low tides can prevent vessels from entering or leaving harbors, while high tides can make it impossible for vessels to pass beneath certain bridges. As a result, there may be periods that will not allow vessels to connect for offloading, and focused scheduling of vessel movements would be needed so the larger vessels do not run aground. Deepwater port development beyond the high-tide boundary may help safeguard against the effects of tidal variation. Transshipment strategies may also be considered but could affect the scheduling frequency of CO_2 delivery. • In the case of terminal requirements, seasonal sea ice around Alaska's shoreline can pose navigational hazards and needs to be thoughtfully considered to ensure year-round loading and offloading of LCO_2. • Certain inland locations may offer suitable port sites that safeguard against tidal effects. • Offshore offloading options can be impacted if excessively large waves are prominent.
Access to supporting utilities	• Availability of supporting utilities like power and water is needed for operations. • Proximity with roads and railroads to enable incoming/outgoing transport of goods is needed to operate the terminal effectively.
Space requirements	• Sufficient maritime interface is needed so that sufficient space is available to support maritime operations, namely the amount of shoreline with suitable maritime accessibility. • The necessary space to accommodate the supporting terminal infrastructure can vary depending on the design attributes of the exporting/importing terminal. • Sufficient land surface access is needed to accommodate landside facilities such as power, water, rail, and truck and to allow for future expansion.

Port Terminal Design Consideration	Description
Expansion of existing ports to accommodate LCO_2 handling	• Initiating LCO_2 offloading into an already complexly operated existing port will likely impact port efficiency and operational performance. Certain ports in Alaska may be able to physically accommodate expansion for LCO_2 handling, but the resulting increase in vessel traffic can present operational impacts. This topic would need to be addressed to convince port authorities of the viability of proposed LCO_2 expansion schemes. • Potential incompatibilities may exist between merchant vessels, LCO_2 receiving vessels, and the existing receiving terminals. Direct compatibility may not exist for aspects like mooring needs, loads/arrangement, berthing and draft requirements, alignment of vessels, types of transfer equipment (loading arm or hoses), location of cargo transfer manifolds, CO_2-specific vapor return and/or purging capabilities, and operational/safety protocols in place. These topics, and others, would need to be vetted for targeted ports considered for potential expansion for LCO_2 handling. • Additional buffer space may be needed to address safety concerns of handling and storing LCO_2, which could add to existing space constraints at existing ports and terminals.

Note: Data are from Rodrigue [128], Global Centre for Maritime Decarbonization [85, 86], and the National Oceanic and Atmospheric Administration (NOAA) [132]

2.1.4 LCO_2 Shipping and Value Chain Optimization

As discussed in Section 2.1 and illustrated in Figure 2-1, transpacific CCUS value chains can assume a number of forms. It is critical that specific products and conditions within those value chain configurations are recognized as interdependent in a CCUS project. Successful design and deployment of a CCUS project requires thorough understanding and optimization of operating parameters to reduce design complexity, infrastructure redundancy, and up-front capital and operating costs. For this report, value chain harmonization is considered the optimization of design parameters (e.g., CO_2 temperature, pressure, and composition) across CO_2 emission sources, transporters, and storage or utilization sites with the intent to improve the efficiency and effectiveness of the overall CCUS operability. For example, Figure 2-7 presents how each value chain parameter in turn can influence the basis for other factors affecting the technical and commercial viability of an integrated CCUS network.

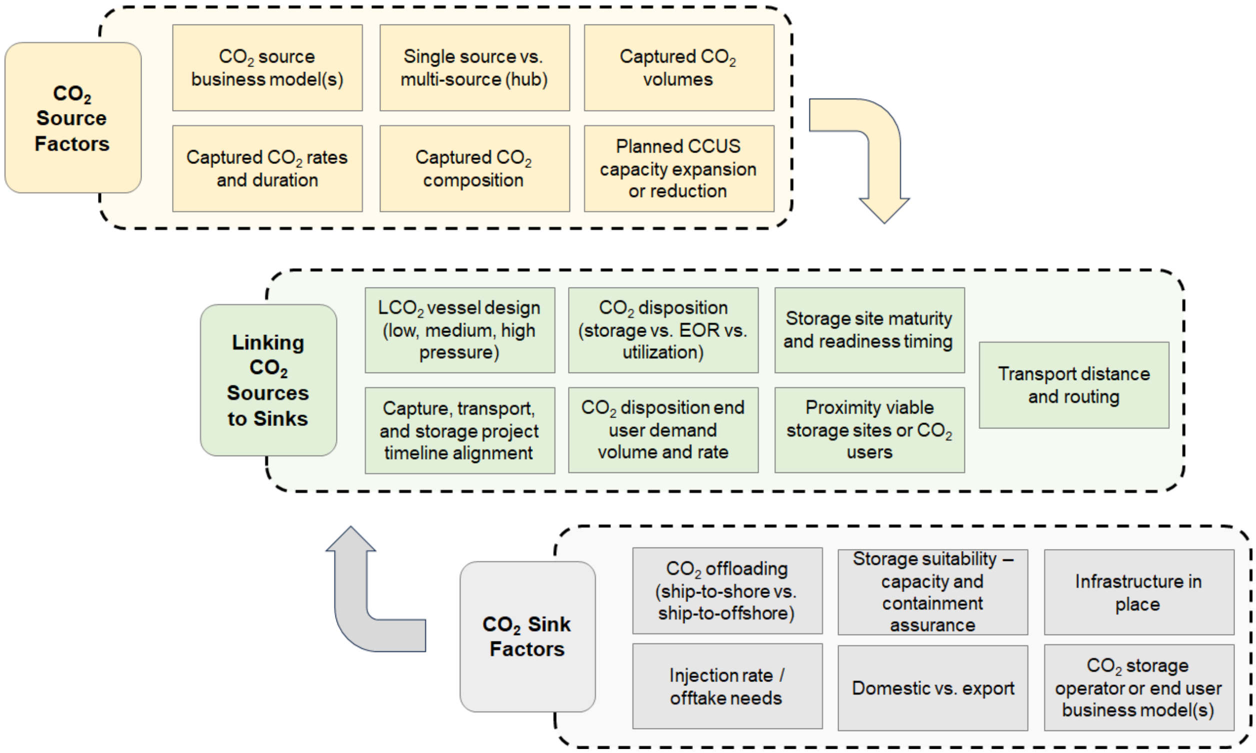


Figure 2-7. Factors affecting CCUS value chain integration and harmonization based on CO_2 source and sink matching considerations

The number and variety of factors that can affect design decisions can be extensive but are not insurmountable to enabling development. Some components may impose rigid design or performance requirements that dictate conditions upstream and/or downstream. For example, choice of CO_2 capture technologies must be matched to the CO_2 source because concentration varies widely by source type (e.g., atmosphere: 0.04 percent; fossil fuel power station: 4–14 percent; cement plant: 22 percent; natural gas, ammonia, ethanol plant: 99–100 percent) [133]. Consequently, multiple capture technologies may be needed when a diverse set of CO_2 source types is included in CCUS networks. Downstream impacts of the capture technology(-ies) include CO_2 volume and purity, which, in turn, impact treatment and storage requirements at the point of export to the use or storage destination.

For any given project, the approach taken towards how the value chain business model is structured can directly impact the scale of CO_2 source integration and harmonization. Business models for CCUS can be divided into two cases: the full-chain model and the partial-chain model [134]. In the full-chain model, a CCUS project is based on a single capture facility transported directly to a single injection location. This situation is typically created when emissions occur from a single activity by one or more emitters (e.g., hydrocarbon production and processing). In that case, the concentration, purity, and supply of the CO_2 is essentially constant, which facilitates design, development, and operation of the downstream components of the value chain. The full-chain model is exemplified by EOR projects in the United States as well as demonstration-stage projects undertaken by "first-of-a-kind" operators [134].

In the partial-chain model, one or more value chain units are separated and assigned to specialist enterprises to execute, with the resulting CO_2 being destined for "CCUS hubs" that provide shared infrastructure [134]. This model is suited to settings where emissions occur from a variety of unrelated sources such as power plants, refineries, steel plants, and cement producers. The partial-chain model can enable small volume and sporadic emitters to participate in a CCUS solution. A large volume emitter might choose this model over the full-chain model depending on business trade-offs. Selected projects in each business model are shown in Table 2-6, which notes that only projects utilizing marine transport of CO_2 are based on the partial-chain model.

Table 2-6. Selected example projects using the two CCUS business models

Full-Chain Model Projects	Partial-Chain Model Projects
Gorgon CCS, Australia	*Project Greensand, Denmark
Illinois Industrial CCS, U.S.	*Northern Lights, Norway
Sleipner, Norway	*Aramis, Netherlands

*Project that includes marine transport of CO_2

Situations where CO_2 emissions occur from disparate emitters, from different generative sources, in small volumes, or in varying amounts may be best served by the partial-chain model. Realistically, in the situation where multiple sources produce emissions in reasonably close proximity, not all capture facilities will come online at the same time nor operate for the total life of the CCUS project. This necessitates flexibility and resiliency most notably in the mode of transport. Marine CO_2 transport by barge and vessels of various capacities could provide the fit-for-need flexibility required. Intermediate storage has inherent flexibility because storage tanks can be taken offline or added relatively easily.

Many of the European and Japanese marine transport projects align with the partial-chain model by de-coupling value chain units and operating a shared-infrastructure and hub configuration. As mentioned, many of those projects plan to undertake cross-border transport as well. Collectively, technical information and performance indicators from those projects and consideration of full- and partial-chain models will guide and inform evaluation of pertinent technical considerations for cross-border shipping of CO_2 from Japan to Alaska.

From a transport perspective, pipelines are an often-cited infrastructure consideration. Their key strength for continuous transport from source to storage comes with counterbalancing consideration of mechanical integrity, flow assurances (i.e., constancy, volume), and high capital cost [135, 136, 137]. These factors also apply in marine settings with an added limitation of higher relative capital cost of offshore construction (versus onshore) and complexity of pumping and compression. As mentioned, marine transport of CO_2 can provide benefits over pipeline transport in source-sink matching; the favorable traits of shipping relative to pipeline transport include transport flexibility (i.e., routing, scheduling), shorter planning and construction time for vessels, lower capital cost, and opportunity for co-utilization of infrastructure [138, 16].

Shipborne transport, however, exerts some unique influences upstream and downstream of its position in the CCUS value chain. Influences include phase and handling needs in transit, landside and sea-side loading and offloading infrastructure, and bespoke vessel design and operation [139, 140]. Considering those effects across the contexts of the factors illustrated in Figure 2-7 helps describe considerations that require a holistic, integrated solution. Table 2-7 lists a set of goals and their required integration of design, operating, source, and end-use considerations throughout the CCUS value chain in the context of maritime transport of LCO_2.

The considerations discussed are already being put to use as evidenced by three recent announcements on commitments by shipping companies to achieve integration through innovation:

- On August 21, 2024, KNCC[g] announced that it is conducting a study to "ensure market preparedness and detail design development" for a new type of LCO_2 carrier [141]. The study vessel will be capable of direct injection offshore. They intend to eliminate the requirement for offloading terminal infrastructure either onshore or using a floating platform offshore. KNCC seeks to leverage their proprietary LCO_2-Elevated Press (LCO_2-EP) technology, which operates at ambient temperature and relatively high pressure, thereby eliminating the need for heating the CO_2 before injection. Their technology received general approval for vessel application in 2023. The vessel design received approval in principle in 2022.
- Also, on August 21, 2024, HGK Shipping announced their completed design of a new vessel class capable of carrying cold liquefied ammonia and LCO_2 and sailing in rivers and seas [142]. The project is named Vanguard and described as a sea-river coaster. They intend to eliminate the need to transfer cargo between different modes of transport. LCO_2 transport will be at a pressure up to 19 bar and a density greater than 1 tonne/m^3 [143].
- On April 17, 2024, HGK Shipping announced that it will construct a first-of-a-kind vessel for inland ship transport of cold liquefied ammonia and LCO_2 [144]. The project is named Pioneer and is dubbed "the floating pipeline." They intend to provide ship transport of LCO_2 from individual industrial emitters not sited at a coastal marine location. LCO_2 transport will be at the same conditions as the Vanguard ship [145].

[g] KNCC is a joint venture company composed of NYK Line, Knutsen Group, and COSCO Shipping Heavy Industries Co. Ltd.—three large shipping enterprises.

Table 2-7. Goals requiring integration of design, operating, source, and end-use considerations throughout the CCUS value chain in the context of shipborne transport of LCO_2

Goal	Objective	Benefit	Integration	Ref.
Ensure stable flow of CO_2 to injection site	Eliminate or minimize intermittent ("batch") injection	Over time, this minimizes physical damage to casing and well barriers (e.g., cement, packers)	Align export supply storage, shipping capacity and schedule, and import storage capacity such that adequate active and storage capacities are resilient to perturbations in capture, transport, and geologic storage/use Evaluate cost/benefit trade-offs of different vessel cargo capacities and fleet sizes per project needed to handle intended CO_2 throughout	[16]
Maintain liquid state of CO_2 during shipping	Establish P/T conditions for transport; harmonize marine transport industry or sectors within	Prevent solidification of CO_2 (i.e., "dry ice") in containment tank	Use Type C pressurized tanks; ensure equipment and detection safeguards to prevent reaching CO_2 triple point	[140]
Define and optimize loading and offloading of LCO_2	Develop safe and effective loading and offloading requirements (e.g., tank pressure control compatibility between vessel and loading/receiving infrastructure)	Avoid the formation of dry ice during offloading Avoid the need for extensive CO_2 conditioning along the value chain	Assess, develop, and deploy technology and procedures for conditioning CO_2 from shipping state to the state required for direct injection or temporary storage	[146, 147]
Standardize specifications for impurities in CO_2 stream along entire CCUS value chain of a project	Achieve understanding of the impacts of impurities in the context of marine transport of LCO_2 (e.g., export handling, shipboard conditions, offshore offloading)	Impurities impact carrier and container design, construction, and operation (e.g., size, shape, material selection, balance of plant) Eliminate conflict of standards along CCUS value chain (e.g., point-to-point specifications differ)	Build upon existing body of knowledge and industry standards; establish most critical determinant for CO_2 purity and apply throughout the value chain	[148, 149]

In cases where vessels are ordered on a project-specific basis (versus standard designs built in bulk), an added value chain harmonization impact exists pertaining to aligning the timing of vessel readiness with other value chain components. For instance, as an analog to LCO_2 carriers, LNG vessels (depending on size) can take upwards of 30 months to construct [150]. In regard to terminal and offloading facilities, the timelines for engineering design, permitting, and construction can be extensive for and vary from one project to another due to varying size and complexity. Major engineering projects have been reported to be on the order of 12–14 months for the pre-front end engineering design (pre-FEED) step, another 12–24 months for the FEED, and 12–36 months for the final design and construction [151]. Evaluating geologic storage options, acquiring the necessary injection permits, and ultimately constructing storage sites also takes time and effort, typically taking longer than 24–36 months in total [152, 153]. Aligning the development timeframes associated with appropriately assessing, designing, and constructing each value chain segment will be critical to facilitating CCUS.

2.1.5 Key Findings Associated with Marine CO_2 Transport as Part of CCUS Value Chains

This technical assessment reveals (a) increasing attention on configuration of terminals and associated gas-handling implications, (b) additional hard commitments to vessel design and cargo conditions, and (c) the criticality of harmonization throughout the value chain that achieves early involvement down to the levels of engineering and operation.

LCO_2 transport delivery concepts – Maritime shipment of LCO_2 is delivered to the final point of offloading by one of three options. Offloading from the vessel follows one of the following paths:

- Ship-to-shore offloading of LCO_2 at a land-based terminal facility occurs via either a direct pipe or hose connection between the terminal's storage facility and the vessel or by ship-to-ship transfer if the primary vessel is not able to dock at the terminal. The transfer ship docks at the terminal and offloads using a direct connection. Thus, a terminal facility must have suitable intermediate storage capacity and may include gas handling and treatment facilities to perform any conditioning of the CO_2 before onward transport to the use point (i.e., geologic storage, CO_2 utilization end user[s]), which may be inland or offshore.
- Ship-to-offshore platform offloading is accomplished via offshore transfer of CO_2 from the vessel to a fixed or floating offshore structure. The structure could be a fixed platform typically used in offshore oil and gas development or a floating barge. This offloading may also occur from the vessel via floating hoses to a buoy system where the CO_2 can then be transferred to a storage facility (which may be onshore or offshore). Intermediate storage capacity and conditioning systems may be installed onshore at a terminal facility or offshore on barges or platforms.
- Direct injection into offshore sub-seabed geologic storage sites is achieved using a floating or fixed injection facility that receives LCO_2 directly from the ship. The injection facility may or may not have storage capacity, may or may not have power, and may or

may not have CO_2 conditional and injection capabilities. The vessel must provide for any capability absent on the injection facility. Importantly, the offloading rate from the vessel will be equal to the injection rate into storage. DNV plans to commence a joint industry project for CO_2 offshore direct injection in Q3 of 2024.

Cargo transport conditions (i.e., pressure, temperature) and vessel design – Current vessel design of CO_2 carriers varies by project and includes barges, river and coastal vessels, and long-haul open ocean vessels with actual and design capacity that is smallest for barges and greatest for ocean-going vessels. Regardless of size, the operating conditions for cargo fall into three small ranges of pressure (P) and temperature (T). Salient aspects include:

- Low pressure and low temperature (6–10 bar at -50 to -45 °C [87–145 psi at -58 to -49 °F]) allow for comparatively lower cost and weight of the vessel but prompt technical considerations related to keeping pressures and temperatures within the relatively narrow range required to maintain liquid conditions. LCO_2 can become gaseous at warmer temperatures or lower pressure. LCO_2 can also solidify at temperatures cooler than about -56 °C (-70 °F). Trace impurities can additionally impact the phase stability of LCO_2 and warrants thoughtful consideration in design and operations. Potential operators of low P-T vessels describe long-distance and floating offloading storage objectives for volumes of 87,000 m^3 and 96,000 m^3 (3,072,380 ft^3 to 3,390,210 ft^3), respectively.
- Medium pressure and medium temperature (15 to 18 bar at -30 to -25 °C [217–261 psi at -22 to -13 °F]) are common conditions currently used to transport food-grade CO_2. The current tank design restricts the vessel scale to less than 10,000 to 15,000 m^3. Potential operators considering medium P-T conditions intend to operate short-distance transport of 14,000 m^3 to 18,145 m^3 (494,400 ft^3 to 640,785 ft^3).
- High pressure and high temperature (34–45 bar at 0° to +10 °C [493–652 psi at 32 to 50 °F]) offers the lowest energy demand to maintain storage conditions, greater flexibility in tank configuration, and possibly higher tolerance for impurities in the LCO_2. The trade-off is lower unit capacity (because the LCO_2 density is lowest of the three options) and large volume requirement for tanks.

Harmonization throughout the value chain is critical – Cross-industry and cross-disciplinary collaboration among operators and designers of key infrastructure is essential to achieve success. This engagement must occur early and align key parameters among emitters, various transporters (i.e., onshore, seaborne), waypoints and terminals (e.g., docks, harbors), and end users (e.g., storage providers). Key parameters include quantity of storage, infrastructure operability ranges, intermediate storage capacity, required composition of CO_2 and any related treatment required, quantity, quality, and cadence of emitted CO_2, and marine transport conditions (i.e., pressure, temperature, quantity).

Sea-side considerations must include terminal siting, the ability to accommodate the size of the ship, and the ability to provide for any sea-side offloading infrastructure or ship-to-ship transfer process. Land-side considerations must include sufficient space for offloading infrastructure, access to utilities, and access to transport infrastructure. Application of "backward-planning" principles should be considered to define the harmonized operating conditions, capacities, and timing required of a project.

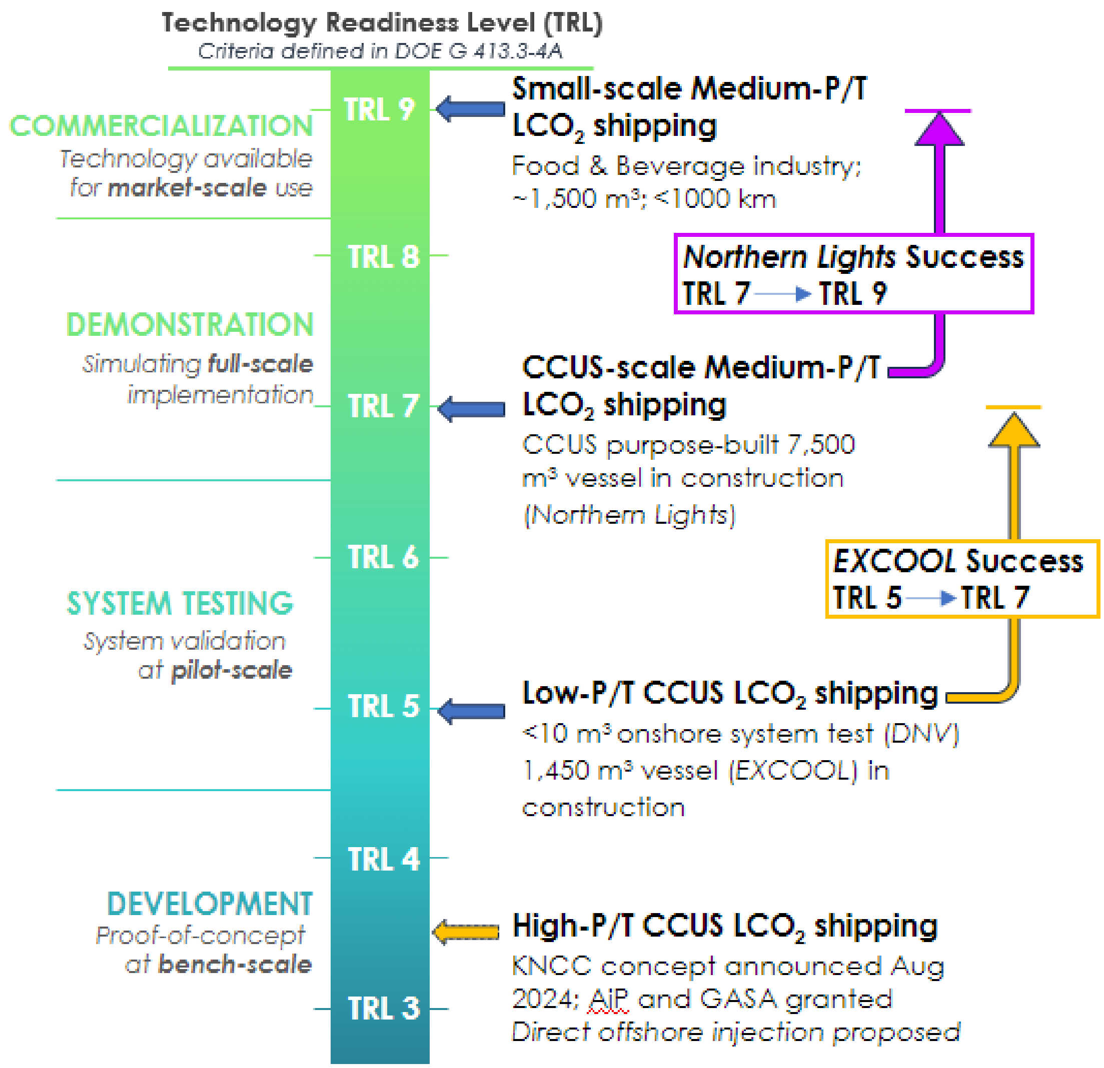
2.2 Technical Readiness of Terminal and Shipping Configurations

This section reviews technology readiness level (TRL) assessments of LCO_2 shipping chains and component technologies from published literature with particular emphasis on low-P/T shipping. A TRL assessment is important because the LCO_2 shipping industry specifically for CCUS is still emerging. This assessment considers that the necessary component technologies needed to support liquefaction, cargo on-/offloading, transport by ship, intermediate storage, and ultimately geologic storage or CO_2 utilization have been successfully implemented in practice at various scales [3]. R&D efforts and emerging technology development related to vessel design, gas handling, vessel and terminal design, and construction for marine transport are currently addressing known and potential questions making the business case more favorable for future widespread adoption [29, 154, 52], as evidenced by the commissioning and ongoing construction of purpose-built CO_2 vessels described previously in Section 2.1.2.

Development and implementation of component technologies are effectively progressing through independent efforts within narrowly defined context (i.e., specific source-sink matches)—recall, for example, the projects noted in Section 1, namely those in the North Sea and the EXCOOL project in Japan. Consequently, the technologies adopted, adapted, and developed in those projects create bespoke solutions that may not directly apply to conceptual projects with significantly different goals and characteristics, such as a desire or need to handle larger capacities or ship longer distances. Nevertheless, those advanced demonstration projects provide valuable information for the conceptualization of other projects. To extract the information value from other projects, it is necessary to consider the maturity and relevance of a component technology in the context of its actual application versus a desired application. Assigning a TRL to the technologies and processes for each context facilitates assessment of the needs and risks facing a component technology and the associated project.

TRL is a 9-point scoring metric that is used to formally assess the R&D status of a technology from the stages of early conception (TRL 1) to full-scale commercial deployment (TRL 9). Although TRL definition standards vary in use by country and/or industry, the rating scheme generally considers the magnitude of successful technology demonstration relative to targets for commercial deployment (e.g., proposed >25,000 m^3 LCO_2 carriers), the applicability of the operational environment (e.g., testing with pure LCO_2 versus impure streams encountered in real-world deployment), and the level of integration of component technologies (e.g., demonstration of one piece of a system versus the whole). The numbering scheme of most TRL scales follows the general form given by DOE [155] where TRL 1 is the observation of basic principles that underpin a technology (e.g., thermodynamics) and TRL 9 is operation of the technology in a commercial environment. For the purpose of this study, the DOE TRL scale [155] is assumed and applied as shown in Figure 2-8 if no other TRL scale is specified in a literature source.

Figure 2-8 provides two examples of LCO_2 shipping projects that upon successful execution and operation will increase the TRL of applied shipping technologies. The Northern Lights Project will broadly move medium-P/T LCO_2 shipping technologies for CCUS applications to a TRL 9 representative of a commercial deployment readiness. Additionally, the successful execution of Japan's EXCOOL project will broadly move the low-P/T LCO_2 shipping technology to a TRL 7 representative of demonstration scale readiness.



Note: The state-of-the-art demonstration for each shipping method is briefly described, and near-term prospects for technology maturation are indicated by the vertical arrows. The orange horizontal arrow indicates the tentative TRL of high-P/T shipping for which limited information is publicly available. AiP = Accepted in Principle; GASA = General Approval for Ship Application

Figure 2-8. TRL of various LCO_2 shipping methods

Note, the nature and implications of differences in approaches to TRL determination between literature sources are further discussed in the following sections. This section uses the terms "large-scale" or "CCUS-scale" ship transport to refer to ship cargo volumes greater than 7,500 m^3 for medium-P/T and 20,000 m^3 for low-P/T shipping [156]. These differences in scale are considered because Medium-P/T vessels have a theoretical 10,000 m^3 cargo limit due to tank material constraints [89]. Finally, this section presents a high-level interpretation of the near-term and long-term feasibility of deployment of different LCO_2 shipping chain technologies.

2.2.1 LCO_2 Shipping TRL from Global CCS Institute Reports

Several global reports provide high-level, whole-chain TRL assessments for ship-based LCO_2 transport. The Global CCS Institute (GCCSI) in 2021 assessed a TRL range of 3–9 (TRL scale standard not specified) for the whole of ship-based LCO_2 transport [157] (Figure 2-9). The report states that "the lowest TRL-3 relates to offshore injection into a geologic storage site from a ship" [157, p. 21], which spans several system concepts such as a floating LCO_2 vessel terminal with attached subsurface injection facility or a ship-based subsurface injection module that directly accesses the ship's cargo (see also Section 2.1.2) [158, 89, 159]. Conversely, the TRL 9 rating refers to "conventional onshore CO_2 injection from onshore facilities (which can be delivered to the injection site by ship)" [157, p. 21]. Although a complete system as described has not been demonstrated at such high TRL, the report considers the maturity of each component technology of the value chain with respect to its commercial application, such as small (<1,800 m^3) medium-pressure LCO_2 carriers supporting the food and beverage industry, or conventional onshore CO_2 pipeline transport and injection demonstrated in some decades-old EOR operations.

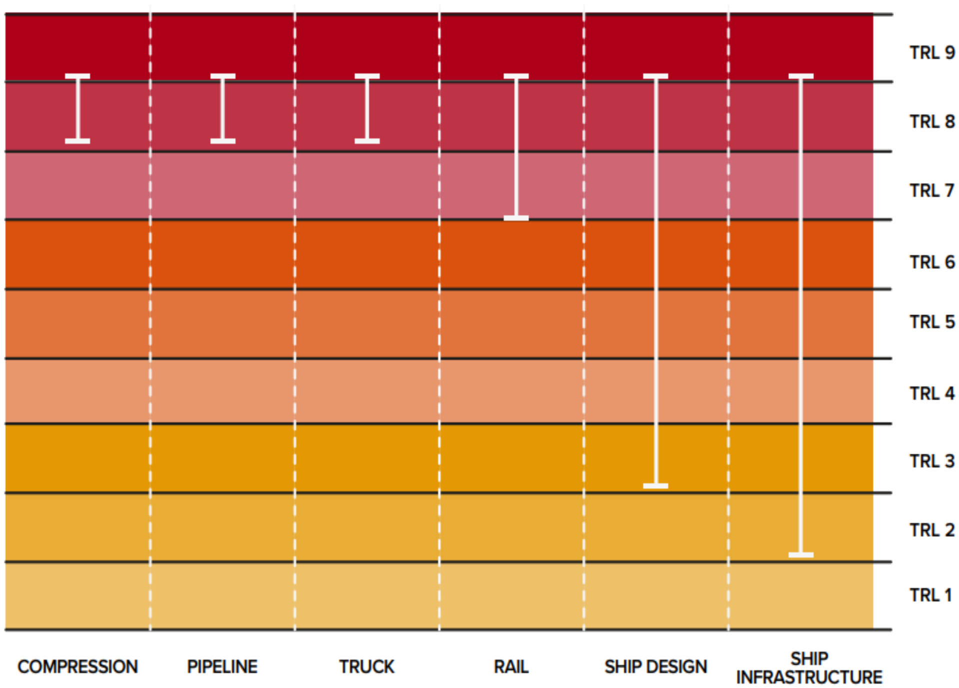


Figure 2-9. TRL ranges for LCO_2 transport systems including purpose-built vessel design and infrastructure

Used with permission from Global Carbon Capture and Storage Institute [157]

A similar 2020 report from the International Energy Agency (IEA) assigns LCO_2 shipping a TRL range of 4–7, or "Small Prototype" to "Pre-Commercial Demonstration," on their 11-point scale [4, p. 103]. Notably, the IEA TRL scale is identical to the DOE TRL scale [155] for TRL 1–8. The IEA report makes the further distinction between port-to-port shipping in the TRL 7–8

"Demonstration" category, and port-to-offshore in the TRL 5–6 "Large Prototype" category, though specific projects that reach these levels of maturity are not discussed, and the report states that "Large-scale transportation of CO_2 by vessel has not yet been demonstrated …" [4, p. 103]. Like the GCCSI report, the IEA TRL assessment concludes that LCO_2 transport has a relatively high TRL based on industry precedents of food and beverage LCO_2 transport as well as pressurized LPG and LNG shipping, noting that "offloading onshore would be relatively straightforward, based on experience with current CO_2 shipping operations and from large-scale shipping of other gases, such as LPG and LNG" [3, p. 107]. Also, like the GCCSI report, the IEA report identifies LCO_2 shipping to offshore/floating injection sites as the low end of the stated TRL range. A related 2020 report from Element Energy commissioned by the IEA Greenhouse Gas R&D Programme (IEAGHG) does not assess LCO_2 shipping TRL but acknowledges that "there are no low-pressure CO_2 vessels in operation today, therefore the technical maturity of the proposed designs is limited…" [89, p. 14].

The GCCSI and IEA TRL assessments, as well as other CCUS literature that assigns high TRL to LCO_2 shipping [160], do not differentiate between low-, medium-, or high-P/T shipping chains, nor do they consider the scale at which the LCO_2 shipping technology has been demonstrated. These assessments may assume that large-scale purpose-built LCO_2 carriers will be achieved by scaling existing medium-pressure LCO_2 vessel and port terminal technology used in food and beverage and other pressurized gas (LPG, LNG) shipping chains and, therefore, pose an insignificant technological barrier or need for innovation.

A comparatively detailed TRL assessment of CO_2 shipping component technologies is presented in the 2020 CO2LOS Phase II report [100] based on the state of the art in 2019 (Figure 2-10). The report assigns relatively high TRL (6–9) to LCO_2 shipping methods that are in active development on the basis that "technologies not used in commercial trade with CO_2 today may still achieve TRL 9 if it is fully commercialized and its function is not connected to the type of cargo carried" [100, p. 44]. For example, although low-P/T LCO_2 tank containment (here stated <15 bar) had not been demonstrated at the time of the CO2LOS Phase II report publication, the technology is given a relatively high TRL 6 (pilot-scale demonstration in a realistic environment, such as using real captured CO_2 samples). The rationale behind individual TRL scores is not clearly stated, but with respect to low-P/T LCO_2 tank containment, it can be inferred from the quoted statement that the TRL score considered some Type C LNG carriers that use similar cargo conditions (2–10 bar; ≥-160 °C) [161]. Therefore, these TRL scores likely represent a high case for technological maturity and will require further validation such as applied testing of purpose-built LCO_2 systems by EXCOOL.

Concept	Newbuild 9	Conversion 9	Existing LPG/Ethane 7			
Ship tonnage (dwt)	< 2 000 t 9	2 000 t - 5 000 t 9	5 000 t - 10 000 t 7	10 000 t - 40 000 t 6	> 40 000 t 5	
CO_2 Tank pressure	Low (<15 barg) 6	Medium (15-20 barg) 9	High (>20 barg) 3			
CO_2 State	Solid 1	Liquid 9	Gas 5			
Operational Area	Inland 7	Benign 8	World Wide 9	North Atlantic 6		
Alternative fuels	LNG 9	Hydrogen 6	Battery 6	LPG 8	Methanol 7	Ammonia
	Biodiesel 8	Hybrids 8				
Propulsion	Propellers 9	Thruster systems 9	Wind assisted devices 8			
Hull shape	Conventional 9	Slow speed hull 8				
Tank geometry	Horizontal cylinder 9	Vertical cylinder 6	Spherical 6	Bilobe 8	Trilobe 7	
Autonomy	Rules and Regulations 3	Control Systems 4	Hook Up / (Un)Loading 3			

High TRL – Low TRL

Figure 2-10. TRL of LCO_2 shipping value chain components current to 2019

Used with permission from Brevik Engineering AS [100]

2.2.2 Summary of Low-P/T Component Technology Testing

This section briefly summarizes the low-P/T LCO_2 system experiments reported by SINTEF and partners [22], which are treated in greater technical detail in the Appendix Section A.4 Pilot-Scale Testing: Summary of CETO Report Results. This study, referred to as the CETO [CO_2 Efficient Transport via Ocean] Report, performed some of the first lab- to pilot-scale demonstrations (≤10 percent of full commercial scale) of low-P/T LCO_2 shipping component technologies including liquefaction, low-P/T cargo transfer (on-/offloading), as well as onboard cargo tank material testing. The CETO Report assesses a TRL of 4 on an international 7-point scale for all but one of the tested system components (Table 2-8), indicating that these technologies are "qualified for first use" [22, p. 24], [162]. The tests mainly used pure CO_2 but attempted to simulate realistic gas impurities in some tests by adding methane or nitrogen.

The experimental systems tests identified some important process considerations and successes:

- <u>LCO_2 cargo transfer:</u> This test simulated on/offloading of LCO_2 cargo (~1 m^3 scale) held at low-P/T conditions between simulated onshore (vertical) and "shipboard" (horizontal) cargo tanks using a realistic piping configuration. The results identified the problem of inconsistent LCO_2 temperature during transfer due to heat ingress, leading to vapor formation and a resulting drop in flowrate. The report attributes this to the design of the testing rig and suggests that full-scale systems with stronger pumps and heavier pipe insulation would likely avoid such flow issues.
- <u>Closed-loop liquefaction:</u> An experimental low-P/T liquefaction system achieved stable near-triple-point low-P/T conditions for greater than five hours without dry ice formation. The tests were carried out over a range of low-P/T conditions and included tests using nitrogen-contaminated CO_2. Details of the testing and results were published in a corresponding journal article [163].
- <u>Cargo tank material:</u> Performance characteristics of simulated shipboard cargo tank walls made of welded ultra-high-strength carbon manganese steel plates (P690 alloy) did not

meet design criteria. The material failed stress testing because the steel was embrittled near the tank weld, thus increasing the risk of material failure. The report concludes that other steel alloys should be investigated that span a range of strength parameters. Notably, future tests should investigate the trade-offs of higher-strength, but more brittle and lower-TRL, steel alloys that allow for larger tank capacities versus lower-strength, widely used steel tank material (e.g., LNG carriers).

Table 2-8. TRLs of component technologies investigated in the 2024 CETO Report [22]

Item	TRL	Comments
Vessel design	4	The concept design may be further developed and optimized in a project phase addressing design acceleration and integration with the tank design
High-strength carbon-manganese steel for liquid petroleum gas cargo tank	<4	Extra high-strength steel was found not to meet the design requirements; alternative material grades and alloys suitable for low-temperature application and compliant with IGC Code can be employed; the tank needs to be built following a recognized standard
Cargo tanks	4	The design process indicated that fatigue is a key aspect. A possible solution had been identified but should be subject to refinement in the design phase; the design should also be revised to accommodate a suitable material; sloshing load assessment and design of the sloshing bulkhead must be conducted
Cargo handling operation	4	It was demonstrated that cargo handing operations can be conducted without formation of dry ice
Process simulations	4	Benchmarking and application to a design case demonstrated the capability and benefits of the current design tools
Liquefaction and conditioning	4	The conceptual design addressed the technical uncertainties identified at the initial stage of the technology qualification
Thermodynamic prediction	4	This experimental campaign provided data related to the solubility of the non-condensable substance at a low-pressure condition and increased the level of confidence in the thermodynamic prediction

Note: text in this table was taken directly from the CETO report [22]

2.2.3 Knowledge Gaps and Technological Challenges

A main area of uncertainty for the future of LCO_2 shipping chains is the effects of different gas impurities in CO_2 capture streams. Residual gas impurities (e.g., nitrogen [N_2]) from the CO_2 capture source remain in the CO_2 stream even after gas conditioning at the capture facility. Although liquefaction prior to shipping further reduces the concentrations of these contaminants, they have a potentially significant effect on CO_2 bubble pressure and triple-point conditions, leading to unpredictability in tank vapor pressure, risk of dry ice formation, and potential steel corrosion. Water content is a primary concern because, in addition to effects on liquid-vapor equilibria, it forms highly corrosive carbonic acid in the presence of CO_2 and has the potential to form other acids and/or solid hydrates in the presence of certain CO_2 gas impurities [164]. To date, no upper limit on water content in the CO_2 feed stream, nor for LCO_2 cargo, is universally defined[h] [30, 165, 91, 26]. Current LCO_2 purity standards such as those released by Northern Lights [166] and referenced as an informal standard in LCO_2 shipping studies [22, 26] set a relatively stringent requirement of ≤30 ppm-mol water in comparison to the 50 ppm-vol[i] upper limit determined by thermodynamic modeling of CO_2–water mixtures [90]. Both of these limits are well below the 110 ppm-mol threshold for hydrate formation in the presence of oxidizing gas impurities (e.g., SO_2) [22]. The notable effects of water vapor observed in experiments and simulations of binary water-CO_2 mixtures, however, are reduced or even eliminated in the presence of some common non-condensable gas impurities [167]. This highlights a major limitation of studies using binary CO_2-impurity mixtures (e.g., CO_2-N_2) that comprise most of the literature on CO_2 impurity effects in transport conditions [91, 167, 22]. Studies of tertiary blends of CO_2 impurities are needed to reliably predict the effects of a range of impurity profiles representative of expected CO_2 stream compositions in, for example, combined capture streams from industrial emitter hubs. A more detailed understanding of these relationships can help reduce stringent impurity requirements and impact commercial technology deployment [164].

Tank containment material and design, especially for shipboard cargo tanks subject to dynamic forces during transit, comprise another component of LCO_2 shipping chains that faces technological considerations. Improper tank material selection for CO_2 transport has resulted in material failure [168]. For low-P/T transport, extremely low cargo temperatures approach the operational limits of common carbon manganese steel chemistries, and, to date, there is no standard steel alloy nor set of performance parameters that is defined for low-P/T LCO_2 transport [22]. The LCO_2 shipping industry faces the trade-off of using higher-yield strength steels that allow for larger tank capacities but are more prone to fatigue and brittle failure, versus lower-yield strength steels that require smaller tank sizes but are widely used for shipping of low-temperature cargo. Currently, there are several steel alloys with performance characteristics that nominally meet the requirements of low-P/T shipping [100, 22]; however, testing and demonstration is needed to validate tank material performance. Advancement of LCO_2 cargo tank R&D will depend on failure mode analysis of experimental low-P/T tank designs.

2.2.4 Key Findings for LCO_2 Shipping Technical Readiness and Associated Implications for Alaska-Japan CCUS Feasibility

The Technical Readiness Level (TRL) of vessels designed to carry bulk LCO_2 varies depending on the P/T at which the CO_2 is stored and transported. The current literature review of the technology readiness of LCO_2 shipping technologies identifies the following key insights:

Medium-P/T shipping is the most technologically mature shipping technology for CCUS applications (TRL 7), possibly representing a near-term U.S.-Japan LCO_2 shipping solution.

[h] ISO Technical Committee 265 published new guidance on LCO_2 shipping in October 2024 during the review stage of this report [348]. ISO guidance on LCO_2 shipping will be incorporated in future work.

[i] Under the assumption of ideal gas conditions, ppm-mol and ppm-vol are equivalent. Conversion between these units for non-ideal gases, representative of CO_2 in transport conditions, varies by pressure and temperature.

- Two 7,500 m^3 vessels are scheduled to begin commercial operation transporting LCO_2 within the North Sea with respect to the Northern Lights Project, and LCO_2 port terminal facilities for this project have already been completed [169]. This report suggests a current TRL of 7 for Med-P/T LCO_2 shipping for CCUS applications based on the current project status, with the potential to advance to TRL 9 following successful commercial deployment of medium-P/T shipping technologies by the Northern Lights Project (Table 2-4). Additionally, Japan's EXCOOL project team intends to begin operation at medium-P/T shipping conditions before attempting low-P/T transport demonstration [170], representing a second near-term demonstration of an integrated medium-P/T LCO_2 shipping chain. Although the shipping distance of these demonstration projects is less than the long-distance shipping route distance between Alaska and Japan, this presents no known technological barrier for medium-P/T shipping.
- The success of these CCUS-scale medium-P/T LCO_2 shipping projects may promote technology transfer of vessels and port terminals and enable rapid establishment of the LCO_2 shipping infrastructure supply chain that could be leveraged for a shipping chain between Alaska and the United States. However, the higher pressure of medium-P/T shipping requires thicker tank walls than low-P/T shipping and is generally considered unpractical, based on current literature, above a 10,000 m^3 capacity [89]. Therefore, medium-P/T transport may have limited long-term applicability to large-scale, long-distance LCO_2 shipping such as between Japan and Alaska.

Low-P/T shipping systems are relatively less mature than medium-P/T shipping systems (TRL 5), but early results from R&D efforts suggest the technology is feasible, and potential favorable, for commercial scales.

- Advances in Low-P/T shipping technology can be attractive in the long term as the TRL increases with demonstrated LCO_2 cargo capacity significantly greater than medium-P/T systems. The knowledge base for low-P/T LCO_2 shipping, including experimental and computational studies as well as knowledge borrowed from medium-P/T shipping and pipeline transport industries, reveals no major “show-stopping” technological barriers at the current stages of R&D development. This report suggests a current TRL of 5 for low-P/T LCO_2 shipping based on experimental studies and in-progress demonstration projects, with the potential to advance to TRL 7 following successful field deployment of low-P/T shipping technologies by the pilot project EXCOOL (Table 2-4). However, low-P/T LCO_2 shipping literature identifies some impacts to technology maturation toward commercial-scale deployment, which are discussed in Section 2.2.3.
- Longer-term deployment of CCUS shipping chains may favor low-P/T shipping technologies because, despite their relatively low TRL at present, they have significantly enhanced LCO_2 transport efficiency. Low-P/T designs as large as 40,000 m^3 have received approval-in-principle status from international shipping regulators, and efforts to design vessels as large as 74,000 m^3 have been announced [171]. Larger LCO_2 shipping volumes can provide an economic benefit that increases significantly with shipping distance [172], supporting the suitability of low-P/T shipping technology for Japan-Alaska LCO_2 transport.

High-P/T shipping systems appear to be the least mature (TRL 3) due to limited availability of publicly available conceptual designs and pilot-scale and/or demonstration activities. The very early stage of high-P/T shipping technology suggests that the consideration of high-P/T shipping within this U.S.-Japan CCUS value chain assessment would be premature at this time. High-P/T shipping has been proposed as an alternative long-distance shipping method with a lower gas conditioning requirement [173], though it may have the lowest transport efficiency of the three P/T regimes [174]. Further research, testing, and demonstration activities need to be performed first to constrain the operational parameters needed to make a reasonable comparative assessment.

2.3 Regional CO_2 Offloading Conditions in Alaska and Generalized Shipping Corridor(s) from Japan

This section presents analyses that inform about the opportunities and challenges associated with transpacific shipment of CO_2 for offloading to different segments of the Alaskan coastal region. The analyses are presented in two sections:

- Section 2.3.1 presents a regional evaluation of the Alaskan coastline to compare unique coastline attributes and prospective geologic storage options within each region that may support LCO_2 offloading and transport to prospective onshore and offshore locations for geologic storage.
- Section 2.3.2 presents hypothetical shipping routes (i.e., corridors) that align to known commercial maritime traffic patterns. These corridors originate proximal to major CO_2 emissions clusters in Japan and connect to one of several potential CO_2 offloading regions along the coastline of Alaska. Route distances were used to inform the LCO_2 shipping cost analysis summarized in Section 3.2. The bodies of water traversed and associated regulatory jurisdiction of each is important for evaluating the regulatory landscape for the shipping component of a Japan to Alaska CCUS value chain and further examined in Section 4.

The analyses discussed in these sections enable the comparison of opportunity areas and identification of opportunity areas more favorable for future feasibility study investigation and overall LCO_2 shipping technical feasibility. The key findings from these comparisons are discussed in section 2.3.3.

2.3.1 Alaskan Opportunity Area Assessment

This section provides an assessment of Alaska to identify opportunities and potential impacts associated with offloading and handling LCO_2 and the geologic storage resource options potentially available for CCUS development. Alaska is the largest state within the U.S. by land and water area by square mileage. Due to the state's complex distribution of natural features and infrastructure related to LCO_2 shipping, a regional approach is applied to better identify and compare specific areas including the North Slope, the West Coast, the Aleutian Islands, and the Southcentral and the Southeastern coastal regions. The key attributes below were identified in

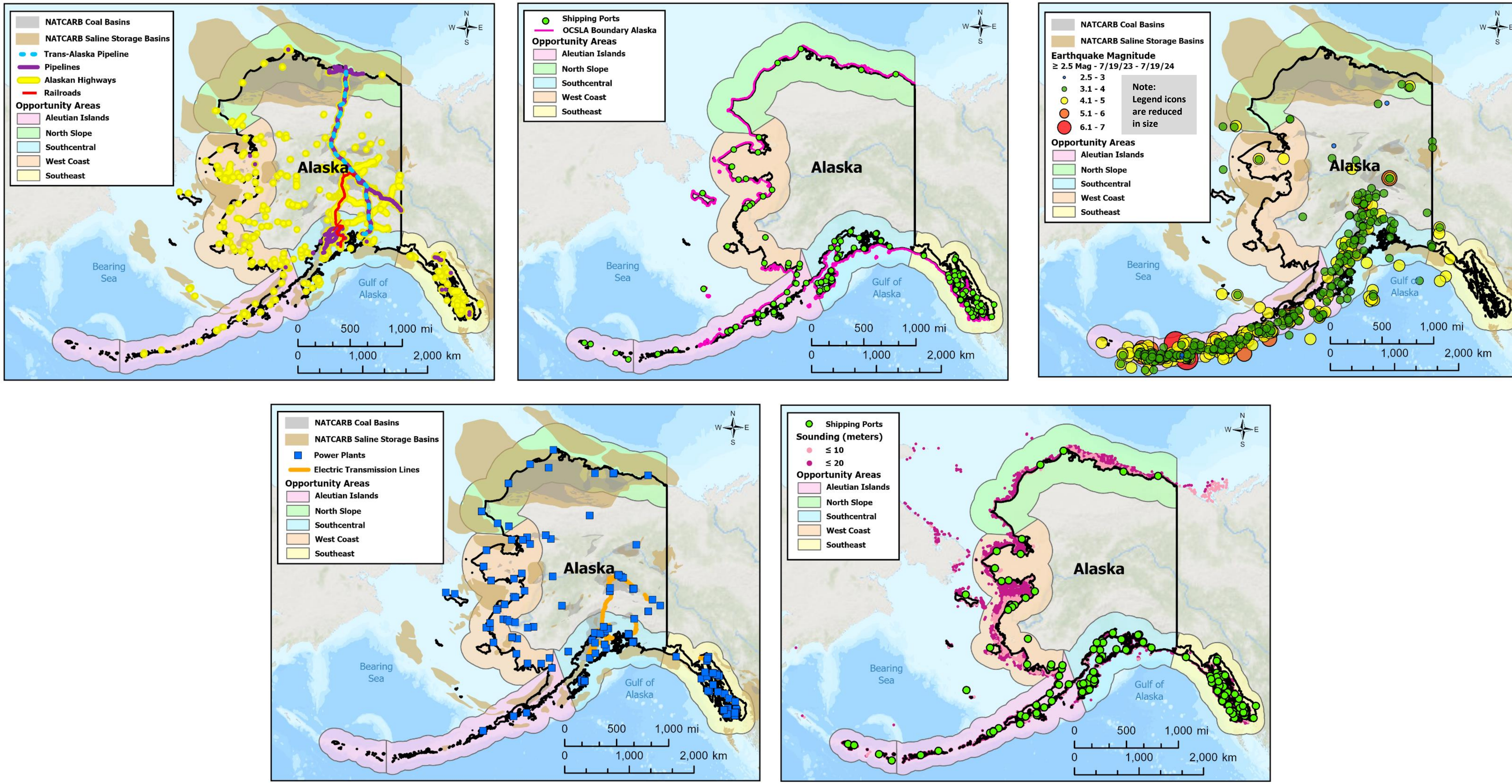
Table 2-5 as essential for assessing the viability of offloading facilities to service maritime LCO_2 transport within each of the opportunity areas.

- Near-coastal bathymetry
- The number, size, and capability of existing shipping ports
- The presence and frequency of sea ice
- Proximity to prospective subsurface CO_2 storage opportunities
- Natural seismicity
- Proximity to transportation infrastructure (e.g., O&G pipelines, highways, and railroads)
- Proximity to electric transmission lines and power plants

Figure 2-11 maps these attributes for each of the five regions and enables a comparative analysis to determine favorable characteristics for the offloading configurations discussed on Sections 2.1 and 2.2. The opportunity assessment considers both quantitative and qualitative analyses of collected data. Examples for quantitative information include port data attributes such O&G terminal count, port and terminal depths, count of ports with cranes, etc. Examples of qualitative information include access proximity to O&G pipelines and their associated rights-of-way and regional CO_2 storage resources. The overall analysis considers both approaches to identify opportunities or impacts that inform the CCUS value chain configurations discussed in Section 2.1.

The opportunity assessment outcomes of the quantitative analysis are presented in Table 2-9 through Table 2-12. These tables use a blue|red color scale to qualify each attribute as more favorable (blue) or less favorable (red) comparatively between the five opportunity areas. Specifically, the color ranking for a given attribute is based on the quantity percentage of the attribute, where red is the highest percentage and blue is the lowest.

Table 2-9 summarizes coastal approach and harbor nautical sounding data (depth) from NOAA electrical navigation charts [175, 176].



Note: Data used are from the World Port Index [177], DNR [178], U.S. Department of the Interior (DOI) [179], Alaska Railroad Corporation [180], NETL [57], Alaska Department of Transportation [181], U.S. Energy Information Administration [182], USGS [183], and NOAA [176]

Figure 2-11. Maps of O&G pipelines, transport, OCS boundary, earthquakes, storage options, power infrastructure and sounding in opportunity areas

Table 2-9. Assessment of nautical sounding depth data by opportunity area

Attribute	South-central	North Slope	Aleutian Islands	West Coast	South-east
10th percentile approach sounding depth (m)	6	2	16	3	7
25th percentile approach sounding depth (m)	16	3	44	7	18
50th percentile approach sounding depth (m)	42	6	86	14	44
75th percentile approach sounding depth (m)	106	14	157	22	99
90th percentile approach sounding depth (m)	187	24	527	42	196
10th percentile harbor sounding depth (m)	3	Data ranges <1–7 m	7	2	4
25th percentile harbor sounding depth (m)	8		16	5	12
50th percentile harbor sounding depth (m)	20		40	15	31
75th percentile harbor sounding depth (m)	46		77	22	71
90th percentile harbor sounding depth (m)	113		108	42	143

Comparatively More Favorable

Comparatively Less Favorable

Note: Data analyzed from NOAA [176]

Data is summarized for each opportunity area, ranging from the 10th (shallower) to the 90th (deeper) percentiles to show ranges of water depth. The data indicate that the Aleutian Islands, Southeast, and Southcentral opportunity areas have relatively deeper soundings. In particular, the Aleutian Islands and Southeast have a mean harbor depth of $\geq$30 meters (98 feet), whereas the West Coast and North Slope area waters are substantially shallower on average. The range in drafts for the vessels listed in Table 2-4 range from 4 to 19 meters, which can serve as an indicator for assessing the minimum required water depth needed for accessibility to each of the regions' harbors and approaches. Given the current uncertainty of the optimal vessel size and configuration at this stage, corridor and routing decisions should consider an analysis of where depth limits are imposed based on a vessel's draft clearance specification.

Table 2-10 summarizes Alaskan port and terminal attributes in terms of total number of ports, coastal ports, and ports with O&G terminals, port channel and cargo pier depths, and ports with cranes for each of the five regions.

The Alaskan coastline is approximately 53,100 km (33,000 mi), more than all other U.S. states combined; however, the state only has a total of about 140 shipping ports, which are primarily concentrated in the south, the Aleutian Islands, and the western margin (Figure 2-11) [184, 185, 177]

Table 2-10. Assessment of shipping ports by opportunity area

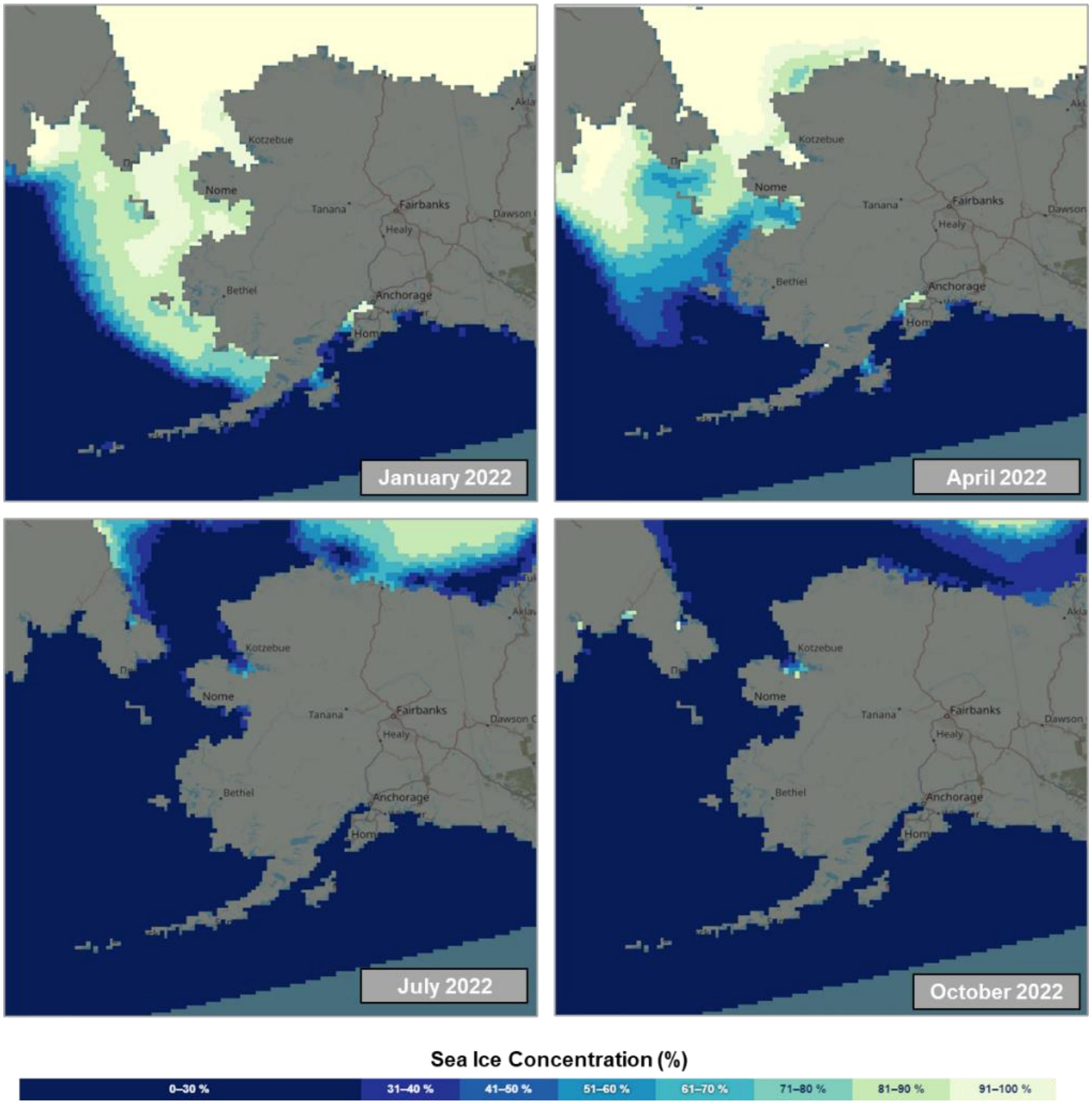
Attribute	South-central	North Slope	Aleutian Islands	West Coast	South-east
Ports – total (count)	41	4	29	17	47
Ports – coastal (count)	36	1	23	4	43
Ports with O&G terminals (count)	10	0	4	0	19
Ports with channel depths $\geq$20 m	3	0	4	0	5
Ports with channel depths $\geq$15 m	3	0	4	0	5
Ports with channel depths $\geq$10 m	3	0	5	0	6
Ports with channel depths $\geq$5 m	8	0	7	0	11
Ports with cargo pier depths $\geq$20 m	0	0	0	0	1
Ports with cargo pier depths $\geq$15 m	0	0	0	0	1
Ports with cargo pier depths $\geq$10 m	2	0	4	0	7
Ports with cargo pier depths $\geq$5 m	23	0	14	0	31
Ports with known cranes onsite (count)	13	0	3	2	3

Comparatively More Favorable (blue) – **Comparatively Less Favorable** (red)

Note: Data analyzed from the World Port Index [177]

This data helps identify regions that may be amenable to future LCO_2 offloading in a ship-to-shore terminal configuration. As noted in Figure 2-10, the Southeast and Southwest regions have the largest share of total number of ports (47 and 41, respectively). Most of these ports serve O&G operations. The North Slope is shown to have the least number of ports (4). About a third of the ports in the southern coastal region also have channel depths greater than 20 meters, which suggests they could accommodate the deepest vessel draft shown in Table 2-4; however, out of all of the ports, only one has a cargo pier depth greater than 20 meters, which suggests there is little accommodation for docking the largest LCO_2 carriers anywhere on the Alaska coast. This limitation is not unmanageable, but it does suggest that dredging may be a necessary consideration for ship-to-shore terminal configurations with larger, deep-draft vessels.

In addition to depth, sea ice concentration (ratio of sea ice to water) is also an indicator of accessibility via vessel [186]. Figure 2-12 and Table 2-11 present sea ice concentration data on a quarterly basis to illustrate changes in sea ice throughout the year.



Note: Data are based on 2022 calendar year data from the University of Alaska Fairbanks Sea Ice Atlas [186]

Figure 2-12. Alaska sea ice concentrations at different times in 2022

Table 2-11. Assessment of sea ice concentration by opportunity area

Attribute	South-central	North Slope	Aleutian Islands	West Coast	South-east	Comparatively More Favorable / Comparatively Less Favorable
Sea ice concentration January 2022 data	0–100%	91–100%	0–70%	81–100%	0–40%	
Sea ice concentration April 2022 data	0–100%	71–100%	0–40%	41–100%	0–40%	
Sea ice concentration July 2022 data	0%	0–70%	0%	0–60%	0%	
Sea ice concentration October 2022 data	0%	0–50%	0%	0–100%	0%	

Note: Data analyzed from the University of Alaska Fairbanks Sea Ice Atlas [186]; the Alaskan coastline is approximately 53,100 km (33,000 mi), more than all other U.S. states combined; however, the state only has a total of about 140 shipping ports, which are primarily concentrated in the south, the Aleutian Islands, and the western margin [184, 185, 177].

The presence of sea ice has been known to restrict offshore oil and gas operations [187], and may similarly impact the prospect of offshore direct CO_2 injection. Extensive sea ice cover in waterways may prohibit a steady flow of vessels in and around an opportunity area or require some form of management (like ice-breaking vessel deployment) to enable ship passage. The Southcentral and Southeast opportunity areas, along with the Aleutian Islands, are typically free from sea ice for most of the year; however, the West Coast and North Slope areas have less favorable accessibility due to the long presence of seasonal sea ice. Consequently, sea ice might be expected to impede the continuity of shipping operations throughout the year in the West Coast and North Slope areas for either onshore or offshore offloading configurations [188].

Table 2-12 summarizes terminal operations and supporting infrastructure for potential onshore CO_2 transportation. The table highlights power generation facilities (and types), associated megawatt (MW) capacity, highway and rail access that could be used to transport CO_2 beyond the port to end users or storage locations within Alaska, and proximity to pipelines and rights-of-way.

Table 2-12. Assessment of supporting infrastructure by opportunity area

Attribute	South-central	North Slope	Aleutian Islands	West Coast	South-east
Railroads – length in opportunity area (km)	599	0	0	0	0
Highways – length in opportunity area (km)	10,328	400	578	1,368	2,513
Trans-Alaska Pipeline in opportunity area (yes/no)	Yes	Yes	No	No	No
Trans-Alaska Pipeline – length in opportunity area (km)	188	126	0	0	0
O&G pipelines – length in opportunity area (km)	965	1,082	1	2	64
Power generation facilities in opportunity area (count)	37	11	7	28	42
Power generation (total MW installed)	1,652	69	62	100	450
Power generation (natural gas MW installed)	1,221	50	0	0	0
Power generation (crude oil MW installed)	90	19	59	93	226
Power generation (bioenergy MW installed)	7	0	0	0	0
Power generation (solar MW installed)	6	0	0	1	0
Power generation (wind MW installed)	27	0	0	5	0
Power generation (hydro MW installed)	249	0	1	0	224
Power generation (battery MW installed)	51	0	0	1	0

Comparatively More Favorable

Comparatively Less Favorable

Note: Data analyzed are from DNR [178], Alaska Railroad Corporation [180], Alaska Department of Transportation [181], and U.S. Energy Information Administration [182]

This data summarizes resources that might be directly leveraged or expanded to support LCO_2 offloading and/or CO_2 transportation within or outside the opportunity area. The majority of potential supporting infrastructure is within the Southcentral opportunity area. For nearly every attribute evaluated, the Southcentral opportunity area has the most favorable attributes. The favorable infrastructure attributes also suggest potential opportunities for future onshore CO_2 transport connectivity between the Southeast region and the North Slope by leveraging existing highway infrastructure, building new CO2 pipelines, following O&G pipeline routes, or expanding the Alaskan rail network (Figure 2-11). Therefore, the Southcentral opportunity area should be considered of high interest for a deeper evaluation in the second phase of this study.

Table 2-13 summarizes potential geologic storage options in and proximal to opportunity areas. The opportunity to co-locate or closely locate CO_2 offloading with viable geologic storage sites can possibly reduce overall costs by minimizing additional CO_2 transportation needs [136, 137].

Table 2-13. Assessment of geologic storage options

Attribute	South-central	North Slope	Aleutian Islands	West Coast	South-east
Potential geologic storage: saline-bearing formations	Majority of known opportunities offshore	Prospective opportunities throughout area	Limited – most known opportunities are far offshore	Mix of onshore and near offshore opportunities exist	Limited – most known opportunities reside offshore
Potential geologic storage: coal seams	Prospective opportunities near Cook Island Inlet and onshore in central Alaska	Prospective opportunities throughout area	None	Limited	None
Potential geologic storage: depleted O&G reservoirs	Prospective near Cook Island Inlet	Prospective opportunities near Prudhoe Bay	Limited	Limited	Limited

Comparatively More Favorable / Comparatively Less Favorable

Note: Data analyzed are from NETL [57]

The geologic storage attributes in Table 2-13 are largely based on theoretical CO_2 storage opportunities derived from the literature versus a more quantitative assessment of a tangible metric like prospective storage resources. In this context, the North Slope and Southcentral opportunities appear to have promising potential prospects for future geologic storage at an initial screening level based on the literature review. For instance, the North Slope and Cook Inlet areas offer potential targets for CO_2-EOR, storage in saline-bearing formations and coal seams [189, 63, 65, 190]. Data presented in Table 2-12 also suggest that potential storage resources are prominent throughout nearly the entirety of the North Slope opportunity area as well, both on- and offshore.

Alaska is prone to natural seismicity due to local tectonic activity. As indicated in Table 2-14, the geographic distribution of seismic events is strongly concentrated along an arcuate zone comprising the Aleutian Island chain, which extends into the west side of Cook Inlet as far north as the west of Anchorage (i.e., Mt. Spurr). By contrast, the North Slope, West Coast, and Southeast opportunity areas experience fewer earthquakes.

Table 2-14. Assessment of natural seismic activity with magnitudes ≥2.5 from July 2023 to July 2024

Attribute	South-central	North Slope	Aleutian Islands	West Coast	South-east	Comparatively More Favorable
Earthquakes since 2023 (count)	70	4	327	6	4	
Mean earthquake size since 2023 (magnitude)	3.8	3.9	4.2	3.9	4.2	
Median earthquake size since 2023 (magnitude)	3.7	3.9	4.1	3.7	4.3	
Max earthquake size since 2023 (magnitude)	4.9	4.5	6.4	4.5	4.6	
Standard deviation earthquake size since 2023 (magnitude)	0.4	0.4	0.5	0.3	0.4	
Mean earthquake depth since 2023 (km)	54.4	10.7	48.6	12.1	9.3	
Median earthquake depth since 2023 (km)	45.2	6.2	38.1	9.8	10.5	
Min earthquake depth since 2023 (km)	0.0	4.0	1.0	5.3	5.2	Comparatively Less Favorable
Standard deviation earthquake depth since 2023 (km)	41.8	9.1	37.7	7.6	2.4	

Note: Data analyzed are from the DNR [178], Alaska Railroad Corporation [180], Alaska Department of Transportation [181], and U.S. Energy Information Administration [182]

Large magnitude earthquakes (and potential associated tsunamis) present an elevated risk of damage to surface infrastructure, which should be accounted for in a risk assessment of any U.S.-Japan LCO_2 shipping and geologic storage partnership project, particularly in the Aleutian Islands region. Large earthquakes have impacted O&G and port operations in Alaska in the recent past [191, 192], but a regionally elevated risk of large-magnitude, tectonics-induced earthquakes does not necessarily correlate to elevated risk to the security of CO_2 stored in saline reservoirs in the same region. Therefore, evaluating the risk of induced seismicity from CO_2 injection operations should constitute a separate risk assessment based on site-specific conditions that may or may not be linked to or affected by natural seismicity. In general, however, the extent of natural seismicity in Alaska suggests that special consideration will be needed when investigating and developing potential geologic storage sites and monitoring activities [193, 194].

2.3.2 Shipping Corridor(s) between Japan and Alaskan Opportunity Areas

Vessel traffic data [195] were compiled for existing commercial shipping routes that traverse the Pacific Ocean, Bering Sea, Chukchi Sea, and Gulf of Alaska to determine potential shipping route corridors between Japan and Alaska. These data have been collated using geographic information systems to demarcate where relatively higher and lower shipping traffic patterns occur. The vessel traffic data were used in combination with nautical sounding [176] and outlined marine highways [196, 197] near the Alaskan coast to create generalized shipping corridors.

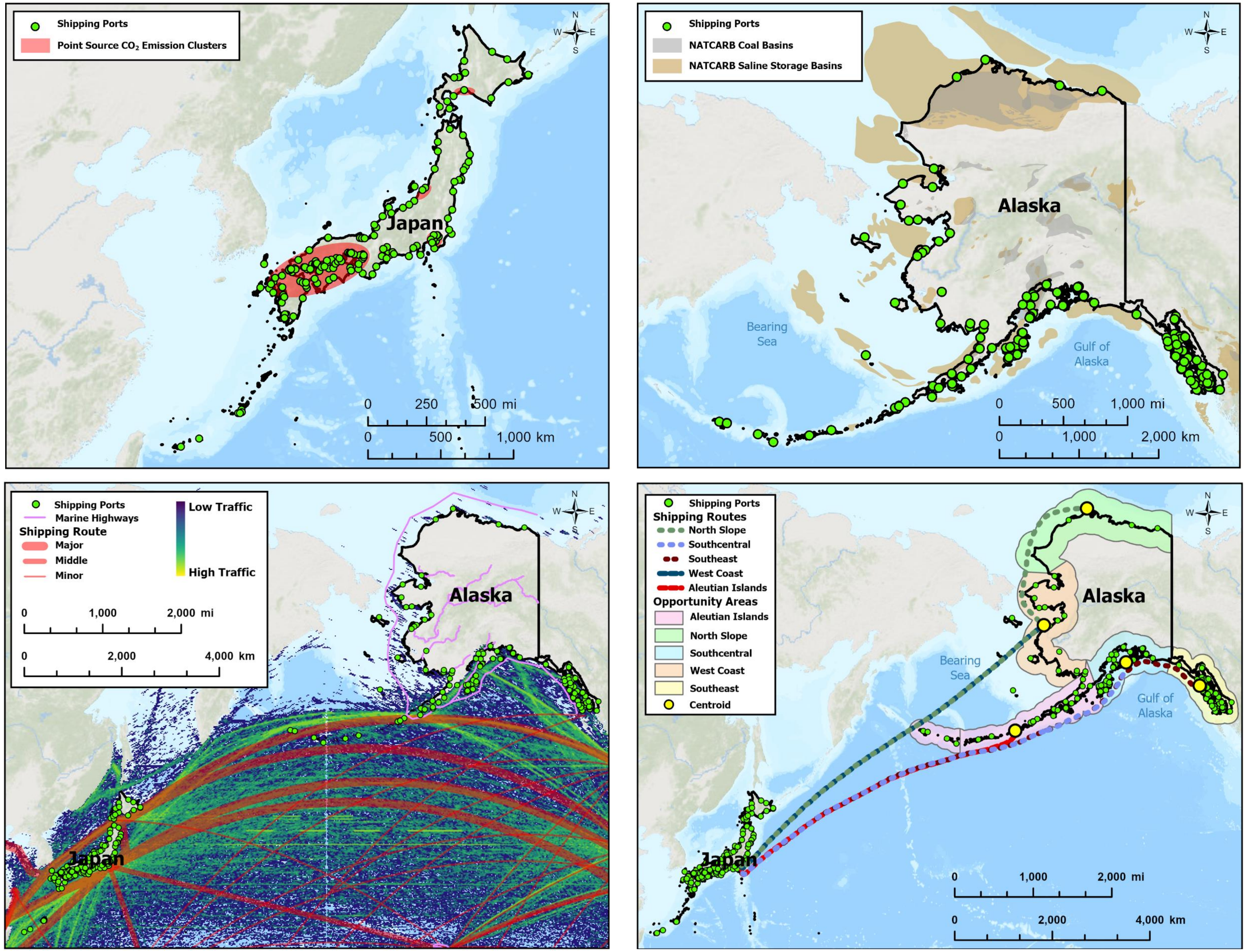
Figure 2-13 maps the potential CO_2 emissions clusters in Japan with shipping port distribution (top left), ports and geologic storage options in the state of Alaska (top right), shipping traffic and marine highways based on public data sources (bottom left) and proposed potential shipping routes to centroids of defined opportunity areas along the Alaskan coastline (bottom right).

For simplicity, the corridors start from a common origin located near the CO_2 emissions cluster around Tokyo Bay in Japan, as outlined in the top left of Figure 2-13. They then extend to the centroid location of each opportunity area in Alaska by following high commercial vessel traffic routes and marine highways around Alaska. The proposed shipping corridor routings to each opportunity area centroid location are displayed in the bottom right graphic in Figure 2-13.

All corridors traverse different segments of Japanese, international, U.S. federal, and Alaskan state bodies of water. As a result, future CO_2 shipment routes will be subject to international, Japanese, U.S., and potentially Alaska state laws and regulations. Corridors range in one-way distance from around 4,743 km (2,947 mi) to the Aleutian Island opportunity area centroid to upwards of 7,160 km (4,450 mi) the Southeast opportunity area. In-service and proposed LCO_2 ship designs (summarized in Table 2-4) traveling in the range of 12–15 knots would complete a one-way journey to Alaska in around 7 to upwards of 12 days, assuming a consistent vessel speed.

Based on data shown in the bottom-left map in Figure 2-13, the proposed corridors from Japan to the Aleutian Islands, Southcentral, and Southeast opportunity areas overlap with relatively higher volumes of commercial maritime traffic. Similarly, waters offshore from these three opportunity areas have the most existing ports. The Southcentral and Southeast opportunity areas have two of the three longest one-way transport distances (the other one being North Slope) but are associated with the most robust collection of existing ports. These two opportunity areas have, in general, ports and terminals with comparatively deeper water depths and ports and terminals specific for handling O&G products. Additionally, large portions of the shoreline for these two opportunity areas (along with the Aleutian Islands) are typically free from sea ice for most of the year per Figure 2-12. The West Coast and North Slope opportunity areas are comparatively limited with regard to existing ports and utilities for potential LCO_2 offloading. Existing port facilities in the West Coast and North Slope opportunity areas do not have sufficient draft to accommodate new, deeper drafting vessel traffic [198]. Additionally, sea ice is prominent in two areas for much of the year.

Vessels may also utilize different routings than the corridors analyzed in this study due to actual location for CO_2 offloading which could reside either offshore or onshore at a port. However, this analysis provides a basis for evaluating the tradeoffs between different opportunity areas in Alaska, shipping logistics, viable vessel designs, associated costs, and any regulatory impacts or gaps that would need to be addressed for vessels to ship CO_2 along similar routes.



Note: Data are from the World Port Index [177], Halpern et al. [195], U.S. Department of Transportation (DOT) Bureau of Transportation Statistics [196], and U.S. Central Intelligence Agency [197]

Figure 2-13. CO_2 emissions clusters in Japan, Alaskan ports and geologic storage options, shipping traffic, and proposed routes

2.3.3 Alaskan Opportunity Area Assessment and Shipping Corridor Key Findings

Analyses presented in Sections 2.3.1 and 2.3.2 provide a tabulated screening-level comparison of key attributes across the five Alaskan opportunity areas. Despite the meta-comparison of opportunity areas along the more to less favorable scale for each attribute analyzed, results do not necessarily exclude any area from consideration. These findings simply outline potential opportunities and varying levels of favorability among the diverse and complex opportunity areas that span the state of Alaska. Actual development of a direct injection site, offshore platform, or terminal offloading LCO_2 shipping facility will require more specific and detailed investigation, analysis, and design.

As shown in Figure 2-13, proposed shipping routes align to known commercial maritime traffic patterns. These corridors originate proximal to major CO_2 emissions clusters in Japan and connect one of several potential CO_2 offloading regions along the coastline of Alaska. One-way shipping route distances range from around 4,743 km (2,947 mi) terminating in the Alaskan Aleutian Islands to over 7,160 km (4,450 mi) terminating in Alaska's southeastern coastline. Shipping corridors from Japan with relatively higher volumes of commercial maritime traffic align with the Aleutian Islands, Southcentral, and Southeast opportunity areas. Corridors to the West Coast and North Slope areas deviate north and away from main commercial corridors. In general, shorter corridor distances can provide cost and efficiency savings for the CO_2 transport component of the value chain. These distances need to be considered as part of future vessel cargo and fuel capacity designs for eventual service between Japan and the Alaskan shoreline.

Table 2-15 provides a summary of the key opportunities and varying levels of relative favorability associated with each area derived from the screening assessment. The right column lists attributes aligned with key CCUS development considerations on receiving, handling, and ultimately storing CO_2. The attributes in Table 2-15 are defined as port and coastal accessibility, intra-area potential geologic storage options, and supporting infrastructure.

Table 2-16 tabulates the key opportunities and varying levels of favorability associated with each opportunity area in the context of navigability of the Alaskan portion of the shipping corridors as well as CO_2 offloading options. The right column lists attributes related to shipping corridor one-way distance, Alaska corridor navigability (i.e., waters near the Alaskan shoreline for each opportunity area), applicability to ship-to-shore CO_2 offloading, and applicability to offshore offloading (either ship-to-offshore structure or direct injection).

Table 2-15. Summary of opportunities and varying levels of favorability for CO_2 offloading across the five Alaskan assessment areas

Area Attributes	North Slope	West Coast	Aleutian Islands	Southcentral	Southeastern
Port and Coastal Accessibility	• No existing large, deep draft ports • Seasonal sea ice • Shallow coastal depths	• Low number of existing large, deep draft ports • Seasonal sea ice • Varying coastal depths	• Low number of existing large, deep draft ports • Limited seasonal sea ice • Varying coastal depths	• Various existing large, deep draft ports • Limited seasonal sea ice (i.e., northernmost cook inlet) • Relatively deep coastal depth availability	• Various existing large, deep draft ports • No seasonal sea ice • Relatively deep coastal depth availability
Intra-Area Potential CO_2 Geologic Storage Options	• Potential onshore and offshore storage options • Historical O&G data and depleted reservoirs • Low relative seismic activity	• Coastal and offshore potential storage options • Large, onshore basins potentially not suitable for geologic storage • Low relative seismic activity	• Potential offshore storage options • Highest relative seismic activity	• Potential onshore and offshore geologic storage options • Active CO_2 storage investigations • Historical O&G data and depleted reservoirs • Moderate relative seismic activity	• Limited potential storage options • Low relative seismic activity
Inland Transport, Distribution, and Power & Utilities	• Existing pipeline infrastructure and rights-of-way • Limited power generation infrastructure	• Limited existing pipeline infrastructure and rights-of-ways and highways • Dispersed number of power generation infrastructure	• No existing pipeline infrastructure and rights-of-ways. • Most limited power generation infrastructure	• Largest relative number of existing pipeline infrastructure and rights-of-ways, highways, and rail • Highest relative clustering of power generation infrastructure	• Limited existing pipeline infrastructure and rights-of-ways, highways, and rail • Moderate power generation infrastructure

Green: more favorable | Orange: moderately favorable | Red: less favorable

Table 2-16. Summary of opportunities and varying levels of favorability for vessel navigation and CO_2 import across the five Alaskan opportunity areas

Corridor & Design Concepts	North Slope	West Coast	Aleutian Islands	Southcentral	Southeastern
Corridor Distance	6,353 km	5,089 km	4,743 km (shortest)	6,372 km	7,166 km (longest)
Alaska Corridor Navigability	• High sea ice impacts	• High sea ice impacts	• Low sea ice impacts	• Low sea ice impacts	• No sea ice impacts
Concept 1: Ship-to-Onshore Offloading Terminal	• No existing large-scale ports • Shallow coastal depth constraints	• Low number of existing large, deep draft ports • Varying coastal depths • Dispersed number of power generation infrastructure	• Low number of existing large, deep draft ports • Varying coastal depths • Limited power generation infrastructure	• Various existing large, deep draft ports • Deepwater coastal depths available • Highest relative clustering of power generation infrastructure	• Various existing large, deep draft ports • Deepwater coastal depth available • Moderate power generation infrastructure
Concept 2: Ship-to-Offshore Offloading Vessel / Platform and Concept 3: Direct Injection to Geologic Storage	• Potential offshore geologic storage options • Low relative seismic activity • Year-round maritime vessel activity not available (sea ice)	• Potential offshore geologic storage options • Low relative seismic activity • Year-round maritime vessel activity not available (sea ice)	• Potential offshore geologic storage options • Highest relative seismic activity • Limited year-round maritime vessel activity	• Potential offshore geologic storage options • Moderate relative seismic activity • Frequent year-round maritime vessel activities	• Limited potential offshore geologic storage options • Low relative seismic activity • Frequent year-round maritime vessel activities

Green: more favorable | Orange: moderately favorable | Red: less favorable

A summary of key findings is listed below based on the varying levels of favorability from Table 2-15 and Table 2-16 to highlight potential focus points within each Alaskan opportunity area.

- **The Alaskan North Slope Region** has a number of positive attributes for onshore and offshore offloading with direct geologic storage, but the viability of this area for transport will require overcoming several key technical impacts. The region has defined geologic storage resources, particularly the coastal and onshore portion of Colville Foreland, and an established hydrocarbon pipeline network that represents leverageable opportunities for LCO_2 onshore transport routing to geologic storage sites. The Alaskan North Slope region has a few existing ports that predominately serve the oil and gas industry. However, the shallow water depths and the frequent presence of sea ice may limit ship-to-shore and ship-to-offshore offloading potential. It is also a relatively longer shipping route from Japan. An alternative solution could be onshore transport from offload terminals in more favorable regions rather than shipping CO_2 directly to the North Slope by sea.
- **The Aleutian Islands** have the positive attribute of being the closest Alaskan region to Japan, but identified impacts may offset the gain of shorter ship passages. The geologic storage resources in the region are largely prospective, and the feasibility of onshore and direct offshore geologic storage would require extensive data collection to better characterize storage resource potential. Opportunities to leverage inland infrastructure and large power sources are limited due to the region being a series of small islands with long distances to the mainland. While the Aleutian Islands are largely free of sea ice all year and the surrounding waters are deep enough for bulk liquid carrier access, existing port reuse is unlikely since most are small and single purpose. Offshore ship-to-ship or ship-to-platform offloading may be the better options if investment in offshore storage resource characterization is justifiable.
- **The West Coast** is characterized by coastal and onshore basins that could present opportunities for geologic CO_2 storage and relatively shorter shipping distance from Japan. However, coastal accessibility may be limited due to the long duration of sea ice and shallow harbor depths. Several sedimentary basins in the open ocean are likely inaccessible, including Norton Basin. While power availability is higher, this area lacks leverageable land-based infrastructure such as existing pipelines and highway networks. Ship-to-shore offloading is unlikely due to shallow depths, lack of deep ports, and long duration of sea ice. The feasibility of channel/pier deepening could be considered in comparison to the potential for ship-to-barge transfer in deeper water. The feasibility of direct offshore storage would likely require extensive data collection to characterize offshore geologic resource potential.
- **The Alaskan Southcentral Region** has a number of favorable attributes that could offer near-term solutions. The Cook Inlet Basin and the Gulf of Alaska are expected to have storage resource potential. Land-based infrastructure such as pipelines, highways, and railways may be leveraged for transport routing to onshore storage sites, and large power source availability is high. The region also has sufficient water depth for bulk carriers to access port terminals, which provide opportunities for port reuse and development. The corridors approaching the region are largely free of sea ice throughout the year, and vessel

traffic is frequent and well established. The drawback of this region is the relatively long shipping distance from Japan.

- **The Alaskan Southeastern Area** shares the southcentral area's positive attributes with the exception that prospective onshore storage resources are more uncertain and longer shipping distance. Consequently, ship-to-ship or ship-to-platform opportunities in this region are likely to be more attractive if offshore storage resource potential in the Gulf of Alaska is confirmed.

It is noted that development of offshore platform and/or direct injection sites or onshore terminal offloading facilities would require more specific and detailed investigation, analysis, and design. Those concepts may directly leverage the best features within each region for design optimization.

Successful design and deployment of a CCUS project will require Japanese and Alaskan stakeholders to consider optimal operating parameters for each value chain component that, in turn, sets the basis for harmonization of all factors affecting technical and commercial viability. Influences include source and intended use of the CO_2, pressure and temperature regime of storage and transport, phase and handling needs in transit, landside and sea-side loading and offloading infrastructure, bespoke vessel design and operation, and conditioning for CO_2 end uses (i.e., additional onshore transport, storage, or utilization).

3 ECONOMIC FEASIBILITY ASSESSMENT

This screening level economic assessment presents order-of-magnitude cost ranges for applicable LCO_2 vessels and terminal infrastructure derived from cost data and cost models found in literature. The assessment focuses on two key areas:

- Cost discussion for critical components of the shipping value chain (Section 3.1)
- Shipping cost ranges for a hypothetical CCUS project under various offloading configurations and P/T regimes (Section 3.2)

The analyses synthesize cost data, models, and assumptions from public literature to capture critical cost components and their dependency on technical design of the shipping value chain. The levelized cost results for hypothetical shipping configurations are estimated using a publicly available cost model results, incorporating realistic project parameters, in order to derive useful insight into important cost drivers and their relations to overall system design such as pressure regimes and offloading configurations. The literature on CO_2 transport vessels has primarily focused on low-P/T designs. Cost data for medium- and high-P/T vessels are limited for sizes below 15,000 tonnes. Larger vessels are generally considered technically unfeasible for medium-P/T designs due to engineering and design constraints, while high-P/T technology is still in the laboratory testing phase [100, 199]. Consequently, the economic assessments for medium- and high-P/T regimes are based on vessels with cargo capacities of 10,000 tonnes or less. The assessment categorizes capital expenses (CAPEX) and operating expenses (OPEX) into four key areas: (1) vessel; (2) liquefaction; (3) loading, offloading, and conditioning; and (4) intermediate storage. These costs are evaluated in 2023 dollars across multiple vessel sizes, transport distances, offloading scenarios, and annual LCO_2 transport capacities. By analyzing these variables, this section offers a range of approximate costs for transpacific LCO_2 transportation, providing stakeholders valuable economic insights for evaluating the feasibility of transoceanic LCO_2 shipping as part of carbon emission reduction efforts. All reported costs can be considered a parameterized Association for the Advancement of Cost Engineering International Class 5 cost estimate that corresponds to a wide accuracy range of -50 to +100% due to the limited development specific data available.

3.1 EVALUATION OF COST RANGES FOR APPLICABLE LCO_2 VESSELS AND TERMINAL INFRASTRUCTURE

This section briefly explains each cost component and connects it to the preceding technical discussion. It also provides an economic overview, highlighting the cost implications and the significance of each component.

3.1.1 Shipping Costs

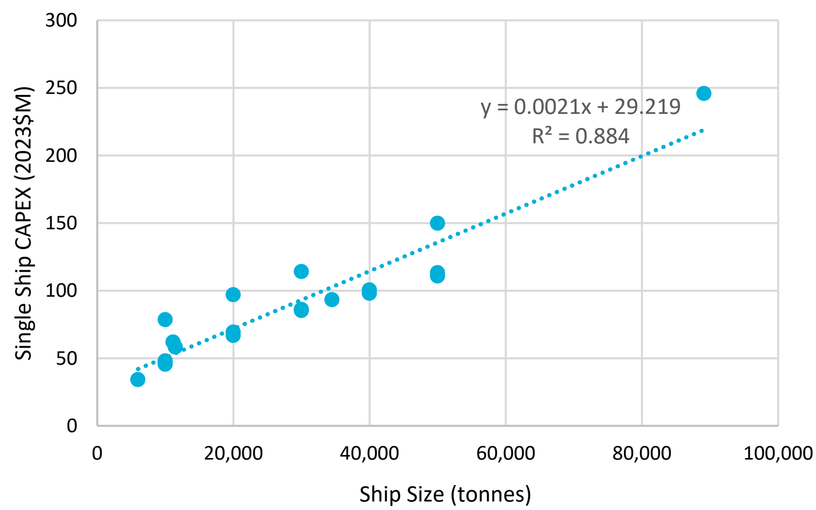
Vessels are the single largest cost component in the entire value chain in terms of CAPEX and OPEX. Although CO_2 shipping has been a commercial operation since the 1980s, the industry remains small-scale compared to future needs for CCUS [96]. Vessel operating conditions generally fall into three P/T regimes suitable for LCO_2 shipping: low, medium, and high. Reliable cost data exists for small-sized, medium-P/T vessels under 2,000 m^3, while cost estimates for low- and high-P/T vessels and larger capacity medium-P/T vessels are based on studies using vendor and shipyard inputs [96, 146]. Most comprehensive cost analyses focus on low-P/T designs due to current industry trends.

Vessel design and size vary by project, influenced by factors such as transport capacity, P/T conditions, port constraints, and operational risks. Vessel size is a key cost driver and is closely tied to annual transport capacity [30, 89, 200, 100]. Projects with larger transport capacities can utilize larger vessels, leading to economies of scale that lower the cost per tonne of CO_2 transported. Longer shipping distances also favor larger vessels, reducing the number of vessels required for the journey and consequently lowering vessel CAPEX and OPEX.

Vessel OPEX includes crew, maintenance, insurance, and fuel. Most studies assume conventional fuels such as marine gas oil, diesel, or LNG, with vessel speeds around 14–15 knots. Fuel consumption rates vary with speed, with 18-knot speeds also reviewed in some studies. Non-fuel fixed OPEX is typically estimated at 4–5 percent of CAPEX [201], [202], [147].

There is ongoing development activity in the LCO_2 shipping industry. Notably, advancements in cargo tank size, shape, and arrangement for low- and high-P/T conditions could lead to reduced construction costs and allow the scale-up of vessel sizes. The drive for zero-emissions shipping design is leading research into alternative fuels and onboard CO_2 capture, with uncertain implications to shipping CAPEX and OPEX. Additions such as onboard conditioning equipment and extra waste heat recovery for offshore direct injection will influence the vessel cost. Also, if the industry moves toward multi-purpose vessels that can carry a different gas in the return cargo or adopt fast-loading, small shuttle vessels between large LCO_2 carriers and the ports, vessel CAPEX and OPEX could be reduced [203].

Increasing vessel size generally raises CAPEX because of increased construction costs (see Figure 3-1); however, the number of vessels required, and the total number of trips decrease, leading to lower harbor fees and fuel costs. Additionally, vessel CAPEX can be reduced due to economies of scale in shipbuilding, with the construction of sister vessels potentially resulting in a 10 percent decrease in construction costs [100].



Note: Data are from the following sources: [14, 174, 147, 89, 96, 204, 100]

Figure 3-1. Scatter plot of vessel CAPEX as a function of vessel capacity

Vessel fuel costs depend on the vessel size, speed, fleet size, and fuel type (LNG, marine diesel oil [MDO]). Literature reviewed provides some metrics for megawatt-hour (MWh)/day for vessels of different LCO_2 carrying capacity and MWh per ton of energy content for LNG and MDO. The long shipping route makes this OPEX component the largest for this analysis. Shipping fuel costs are part of vessel OPEX and scale linearly with the number/size of vessels and the shipping distances.

3.1.2 Liquefaction

CO_2 delivered to the port needs to be in its liquid state for efficient transport onboard vessels. CAPEX for either an open or closed system includes compressors, piping, valves, heat exchangers, process vessels, and refrigeration systems. OPEX consists mainly of electricity for compression and refrigeration. The total liquefaction costs are largely driven by project-specific conditions like the inlet CO_2 P/T, annual CO_2 facility throughput, and intended CO_2 outlet pressure.

For low-P/T LCO_2 transport, liquefaction is one of the most expensive process components due to the high refrigeration requirements [26]; however, costs decrease at higher P/T conditions, as less refrigeration is needed, reducing the power consumption during compression and expansion cycles (see Table 3-1) [174, 159, 96]. Impurity removal of the incoming CO_2 can increase system costs by 34 percent depending on the desired purity in the output stream and pressure [138].

The 2018 CO_2 shipping study, led by Element Energy for the United Kingdom's Department for Business, Energy, and Industrial Strategy (BEIS), provides CAPEX metrics for low-, medium-, and high-P/T scenarios [96]. Liquefaction OPEX is presented as 10 percent of CAPEX plus kilowatt-hour (kWh)/tonne for power consumption. Liquefaction CAPEX and OPEX both scale linearly with the project flow rate.

Table 3-1. Liquefaction cost assumptions used in the Element Energy's BEIS CO_2 shipping cost tool

Transport Pressure	Inlet Pressure	Specific CAPEX (2023$/[tonnes of CO_2/yr])	Fixed OPEX/yr (% of CAPEX)	Energy (kWh/tonne)
Low	Pre-pressurized	16.81	10%	24.6
Low	Non-pressurized	33.45	10%	104.2
Medium	Pre-pressurized	13.04	10%	19.6
Medium	Non-pressurized	25.90	10%	83.1
High	Pre-pressurized	8.41	10%	16.6
High	Non-pressurized	16.64	10%	70.3

Note: Data are from Durusut and Joos [96]

3.1.3 Ports, Intermediate Storage, and Loading/Offloading

This screening assessment focuses on facility costs associated with loading, offloading, and intermediate storage facilities. Retrofitting costs for existing terminals, connecting infrastructure (such as utilities, pipelines, and truck/rail transportation terminals), administrative buildings, and CO_2 injection facilities are not considered.

Intermediate storage tanks are necessary at the export and import terminals for continuous CO_2 loading or injection when there is no vessel in the port. Most literature has recommended a range of 100–200 percent of the intended vessel capacity [30, 96, 100]. Storage CAPEX depends on the P/T regime as it influences insulation, pressure design, tank sizes, and structural design. Intermediate storage facilities can benefit from economies of scale, decreasing the unit cost as the storage capacity increases. A literature review from 2018 to 2022 yields a range of £516–2,998 ($700–4,000)/tonne CO_2 in low-P/T conditions [96, 202, 203]. Both Storage CAPEX and OPEX depend on the system design, particularly in terms of the required buffer capacity to accommodate shipping schedules.

Loading/offloading equipment includes articulated loading arms, cryogenic hoses, emergency shutdown systems, compressors, vapor return lines, and pressure management. The loading rates of this equipment are expected to be sized based on the desired loading and offloading time limits for the anticipated vessel sizes. Therefore, both CAPEX and OPEX vary linearly with the project flow rate. The CAPEX cited in the 2018 Element Energy CO_2 shipping study funded by BEIS is £1/tonne/yr ($2/tonne/yr in 2023 U.S. dollars [2023$]) [96].

OPEX for ports and terminals includes personnel, fuel, power, operations and maintenance, and other indirect field costs. These are generally expressed as a percentage of CAPEX per year. Literature sources sometimes combine this with storage and loading operations. The Element Energy study estimates loading/offloading OPEX at 5 percent of CAPEX and terminal and storage OPEX at 5 percent of CAPEX [96].

Ports and harbors charge a harbor fee for each vessel visit according to the size. This analysis relies on the data compiled by the Element Energy study to approximate this OPEX cost component. The harbor fee depends on the number of vessel visits to ports and the duration of docking.

3.1.4 Conditioning

Gasification and conditioning equipment include apparatus for heating the LCO_2 (to prevent freezing) and pumping it to storage tanks or injection manifolds (for the offshore injection). The P/T conditions at which the CO_2 will be transported on the vessels will directly influence the capital and operational costs of CO_2 conditioning equipment. In general, costs decrease as less pressurization and heating are needed. The medium- and high-pressure vessel designs present fewer conditioning requirements relative to the low-pressure design case and, as a result, offer a cost saving regarding the conditioning step.

The Element Energy study provides conditioning CAPEX in £/tonne/yr and OPEX at £/tonne/yr for onshore scenarios, and CAPEX in £/tonne/yr and OPEX at kWh/tonne plus 5 percent CAPEX for an offshore environment [96]. Both CAPEX and OPEX for an offshore platform or direct injection are significantly higher due to the construction conditions and the lack of shore power. In the case of direct injection, all the conditioning equipment is located onboard the LCO_2 vessels.

3.1.5 Offshore Platform and Direct Injection

Of the three offloading configurations (Table 2-1), ship-to-offshore platforms have the highest cost, followed by direct injection to offshore geologic storage, and then ship-to-onshore terminals. Offshore platforms, subsea installation, and mooring systems are expected to be similar to O&G design. In some cases, an existing platform may be retrofitted from O&G operations to handle LCO_2 injection. Costs for this infrastructure vary greatly depending on water depth, operating environment, material prices, local market conditions, and the platform/subsea connection design. The Element Energy 2018 study cites £91M ($156M 2023$) for a platform with 40,000 tonne of CO_2 storage in the North Sea and £16.5M ($28M 2023$) for an offshore, single-anchor-leg mooring-type subsea connection [96]. Another study published by Neele et al. cites a range of €70–150M ($100–214M 2023$) for an offshore platform with 40,000-tonne storage and offshore infrastructure [147]. The costs for platforms, floating injection barges, and subsea connections do not scale linearly with the project's annual transport capacity; instead, these components are designed based on project-specific factors, which drive their associated costs.

3.1.6 Comparison of Cost Data from the Literature

CAPEX data from CO_2 shipping case studies were collected from various literature sources, focusing on low- and medium-P/T regimes and three offloading options (Table 2-1). The data were categorized into four CAPEX cost categories: vessel; liquefaction; loading, offloading, and conditioning; and intermediate storage (Table 3-2). For comparability, all costs were normalized to 2023$. For studies that did not specify a cost base year, it was assumed to be two years prior to the publication date. Non-U.S. dollar costs were first converted to U.S. dollars using yearly average exchange rates, then escalated to 2023$ using an appropriate escalation rate.

The literature shows that vessel costs, for all vessels in the shipping system, are often the largest CAPEX component, accounting for an average of 51 percent of the total CAPEX costs for onshore offloading (based on values reported in Table 3-2). Depending on the offloading configuration, single-vessel CAPEX ranges $47–246M. Liquefaction is the second largest cost component, averaging 31 percent, followed by intermediate storage and loading, offloading, and conditioning, averaging 13 percent and 8 percent, respectively. Total CAPEX unit costs per tonne range $5–22 for low-P/T transport and $6–11 for medium-P/T transport for offloading to an onshore terminal, $5–17 for low-P/T transport and offloading to an offshore platform, and $5–14 for low-P/T transport and direct injection to offshore geologic storage (Table 3-2).

Most of the existing literature evaluates costs for shorter shipping routes, with the majority being under 2,000 km, making it difficult to estimate OPEX costs for LCO_2 shipping from Japan to Alaska from the literature alone. The increased distance would necessitate a larger fleet of vessels to maintain the same transport capacity, leading to significantly higher fuel costs and other operational expenses that cannot be easily extrapolated from shorter-range data. To obtain more reliable cost estimates for long-distance LCO_2 shipping, this study utilized a cost tool developed by Element Energy for BEIS, which allows a user-defined shipping distance input to arrive at a levelized cost for shipping CO_2 [205].

Table 3-2. Compilation of vessel cost data from the literature

Source	Year	Shipping System (vessel count x tonnes/ship)	P/T Conditions	Transport Capacity (Mt/yr)	Distance (km)	CAPEX (2023$M)							CAPEX Unit Cost (2023$/tonne)
						Single Vessel	All Vessel(s)	Other	Liquefaction	Loading, Offloading, & Conditioning	Intermediate Storage	Total	
Onshore to Onshore (Low P/T)													
Durusut and Joos [96]	2018	1 x 10,000	7 bar/-50°C	1	600	48.03	48.03	-	16.81	4.12	24.02	92.97	4.65
Orchard et al. [83]	2020	3 x 10,000	7 barg/-50°C	1.8	1,000	46.89	140.68	-	99.47	11.37	36.95	289.90	8.05
Seo et al. [174]	2016	1 x 11,167	6 bar/-52.3°C	1	720	61.92	61.92	-	38.70	-	12.90	113.52	5.68
CO2LOS II [100]	2020	3 x 11,500	6 barg/ -50°C	2	1,000	58.26	162.00	-	211.74	5.68	12.79	392.21	9.81
CO2LOS II [100]	2020	4 x 89,125	6 barg/ -50°C	3	9,259	245.84	909.48	-	316.90	7.11	82.42	1315.90	21.93
Fraga et al. [199]	2021	1 x 30,000	7 bar/-50°C	2	-	85.26	85.26	79.58	-	93.79	45.47	304.11	5.07
Onshore to Onshore (Med P/T)													
Orchard et al. [83]	2020	3 x 10,000	15 barg/-28°C	1.76	1,000	72.47	216.00	-	90.95	9.95	79.58	397.90	11.30
Seo et al. [174]	2016	1 x 11,167	15 bar/-27.7°C	1	720	64.50	64.50	-	32.25	-	15.48	112.23	5.61
Fraga et al. [199]	2021	n/a x 6,000	15 bar/-28°C	2	-	72.47	-	387.95	-	78.16	29.84	495.95	8.27
Onshore to Offshore Floating Storage Injection													
Neele et al. [147]	2017	2 x 50,000	7–9 bar/-55°C	4.7	400	149.79	299.57	211.13	-	-	-	510.70	5.43
Neele et al. [147]	2017	3 x 30,000	7–9 bar/-55°C	2.6	1,200	114.12	342.37	219.69	-	-	-	562.06	10.81
Neele et al. [147]	2017	8 x 10,000	7–9 bar/-55°C	4.5	1,200	78.46	627.68	88.02	-	-	-	715.69	7.95
Neele et al. [147]	2017	5 x 20,000	7–9 bar/-55°C	4.5	1,200	97.00	485.02	235.24	-	-	-	720.26	8.00
Neele et al. [147]	2017	4 x 30,000	7–9 bar/-55°C	4.5	1,200	114.12	456.49	227.25	-	-	-	683.74	7.60
Neele et al. [147]	2017	3 x 50,000	7–9 bar/-55°C	4.5	1,200	149.79	449.36	219.26	-	-	-	668.62	7.43
Orchard et al. [83]	2020	3 x 10,000	7 barg/-50°C	1.63	1,000	46.89	140.68	-	89.53	277.11	61.11	567.00	17.39
Onshore to Direct Injection Offshore													
Neele et al. [147]	2017	5 x 10,000	7–9 bar/-55°C	4.2	400	78.46	392.30	55.63	-	-	-	447.93	5.33
Neele et al. [147]	2017	4 x 30,000	7–9 bar/-55°C	2.1	1,200	114.12	456.49	136.95	-	-	-	593.44	14.13
Neele et al. [147]	2017	8 x 10,000	7–9 bar/-55°C	3.8	1,200	78.46	627.68	71.33	-	-	-	699.00	9.20
Neele et al. [147]	2017	5 x 20,000	7–9 bar/-55°C	3.8	1,200	97.00	485.02	163.34	-	-	-	648.36	8.53
Neele et al. [147]	2017	4 x 30,000	7–9 bar/-55°C	3.8	1,200	114.12	456.49	136.95	-	-	-	593.44	7.81
Neele et al. [147]	2017	4 x 50,000	7–9 bar/-55°C	3.8	1,200	149.79	599.15	136.95	-	-	-	736.09	9.69
Orchard et al. [83]	2020	3 x 10,000	7 barg/-50°C	1.37	1,000	46.89	140.68	-	75.32	69.63	28.42	314.05	11.46

3.2 Estimation of Cost Ranges for Transpacific LCO_2 Transportation

This section applies the BEIS CO_2 shipping cost tool, developed by Element Energy, to estimate and compare cost ranges for transpacific LCO_2 shipping configurations from Japan to Alaska by utilizing the tool's comprehensive cost parameters and scenarios. Building on this approach, this study drew specific data from the "Shipping Infrastructure Cost" sheet within the tool for this study. All costs were assumed in 2016£ and converted to 2023$ using the cost conversion methodology detailed in Section 3.1.

Due to the number of parameters influencing the overall system configurations, it is necessary to streamline the assessment. This is achieved by limiting the degree of freedom and reducing the number of configurations to focus on a representative set of scenarios. For example, the transport capacity of a project determines the number of vessels required for the fleet for each vessel size. Different fuel types generate different shipping OPEX and offshore offloading costs; different source CO_2 pressures produce different liquefaction costs for each transport P/T regime. Therefore, to simplify the cost evaluation, the assessment focused on scenarios where CO_2 arrived at the export terminal via a pre-pressurized pipeline, with LNG serving as the fuel source for both shipping and offshore power generation (see Table 3-3 for additional scenario parameters). An annual transport capacity of 1 Mt/yr serves as the base case and is the primary focus of the cost assessment. While this assessment does not discuss costs for other annual transport capacities in detail, Table C-1 in Appendix C: LCO_2 Shipping Cost Data provides cost data for six additional transport capacities.

Table 3-3. Scenario parameters used for the cost screening assessment

Parameter	Value
Discount Rate	8%
Project Transport Capacity (Mt/yr)	1.0
Years of Operation	20
CO_2 Origin	Near Tokyo, Japan
CO_2 Destination	Alaska, border region between Southcentral and Southeast opportunity areas
CO_2 Condition Before Liquefaction	Pre-pressurized
Shipping Distance (one way, km)	6,402

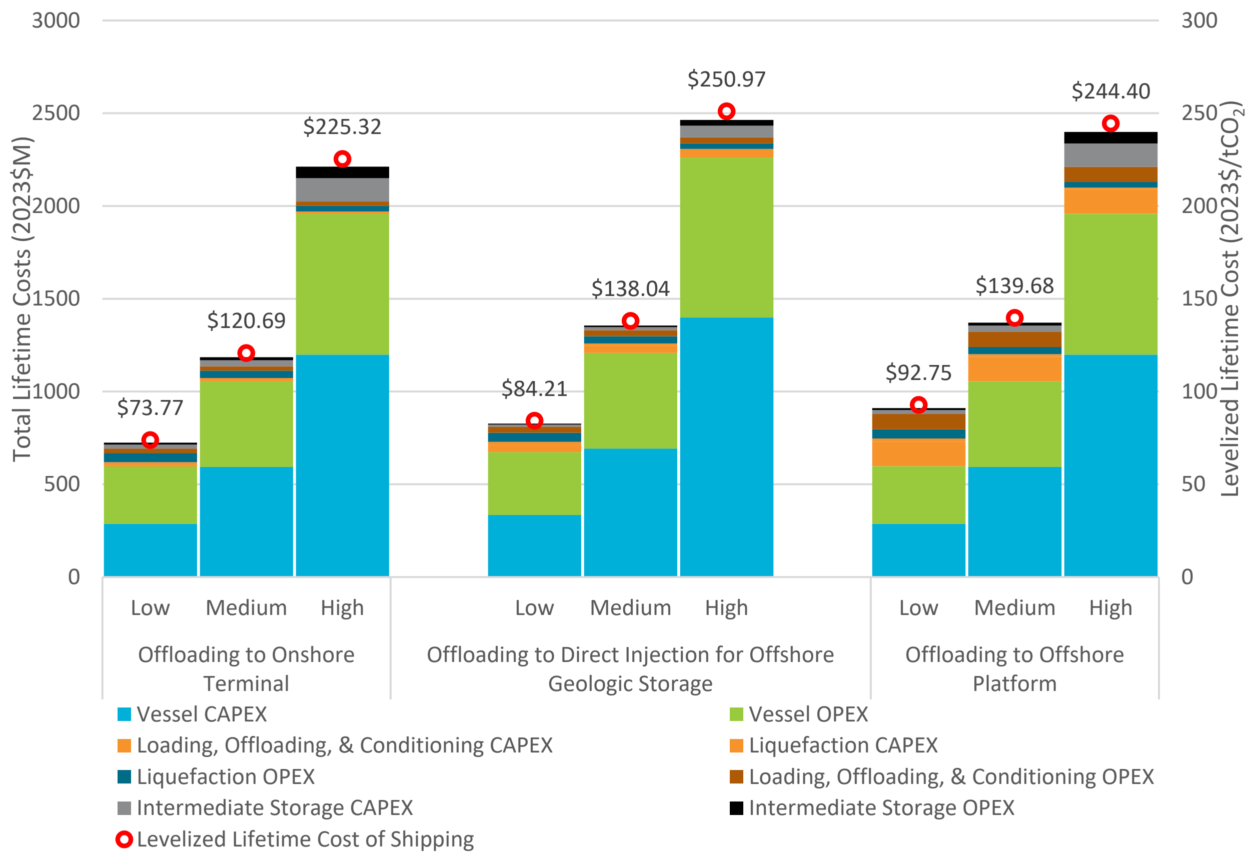
Other noteworthy assumptions in this assessment include the following:

- Parameter default values are used in the cost tool, except for discount rate and shipping distance [205].
- The shipping distance, 6,402 km (one way), is an average from the east coast of Japan to the southern coast of Alaska where many of the suitable geologic storage sites are located.

- The cost of onshore transport facilities in Japan and Alaska, such as pipelines, railroads, trucks, and powerlines, to carry CO_2 to the export terminals and imported CO_2 to its ultimate storage location is not included.
- Geologic storage and injection costs are not included.
- Direct injection to offshore geologic storage assumes that intermediate storage infrastructure and associated costs at the offloading site are not applicable and not included in the configuration.
- The cost of gas pressurization to injection pressure is included for the offshore platform and direct injection setup but excluded from the onshore terminal offloading scenario. This is due to the methodology in the literature, but this can be separated in future phases of study.
- Costs are based on vessels returning to Japan empty (i.e., ballast conditions).
- High-P/T vessels are likely only suited for offshore direct injection as it only makes economic sense to avoid liquefaction costs at the export terminal as well as the import terminal.
- Depending on vessel size and annual transport capacity, the direct injection to offshore geologic storage offloading scenario may require additional vessels compared to other offloading configurations to meet the annual transport capacity. Injection rates for geologic storage may result in longer offloading times than those for offloading to an onshore terminal or an offshore platform.

Results of the economic feasibility assessment are presented in Figure 3-2 and Table 3-4. These visuals provide insights into the cost dynamics of different LCO_2 vessel capacity and offloading configurations while providing comparisons of cost components in terms of lifetime costs and per-tonne costs. By comparing offloading options, transport conditions, and vessel designs, the figures and the table offer a comprehensive perspective on the economic feasibility of shipping LCO_2 from Japan to Alaska.

Figure 3-2 presents a comparative analysis of the estimated costs across three LCO_2 offloading configurations. For each configuration, the figure provides a stacked bar breakdown of cost components for low-, medium-, and high-P/T vessel conditions. The costs for offloading to onshore terminal and offshore platform configurations are based on six vessels, each with a 10,000-tonne capacity, while offloading to direct injection configuration is based on seven vessels of the same capacity. In most direct injection cases, an additional vessel is required to transport the specified capacity due to a slower offloading time compared to the offloading rate of the other two configurations. Also, please note that this figure specifically considers 10,000-tonne vessels across all configurations, as this this vessel size represents the largest and most economically feasible option across all P/T regimes within the available data set provided by the BEIS CO_2 shipping cost tool developed by Element Energy [205]. According to industry development reported in the literature, technology R&D has largely focused on low-P/T vessel design, leveraging well-known practices in the LNG and LPG shipping industries. Medium-P/T vessel design is mature for the food and beverage industry but is widely perceived as potentially not scalable to cargo capacities beyond 12,000–15,000 tonnes [206, 207]. Given these considerations, the 10,000-tonne vessel size offers a practical basis for evaluating costs within the boundaries of current technology and available capacity data.

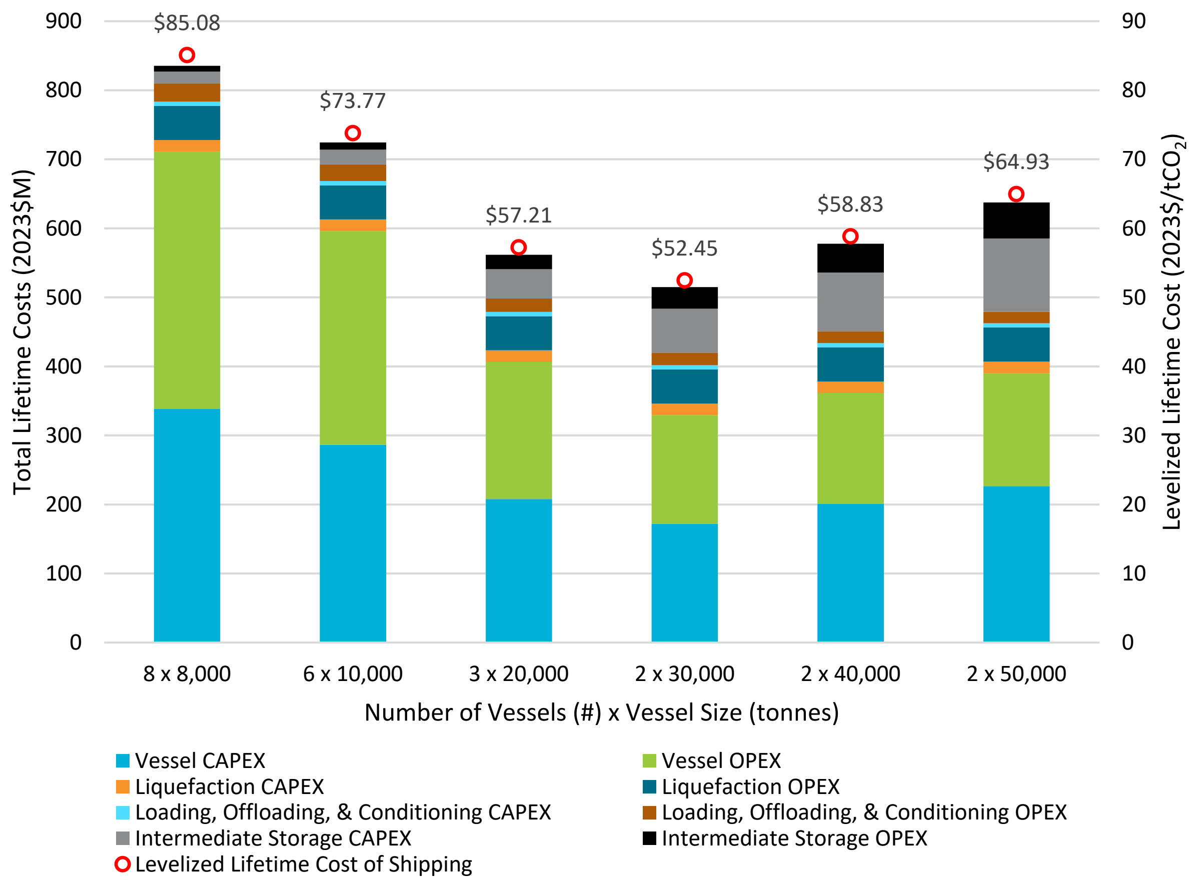


Note: Source data from BEIS CO_2 shipping cost tool [205]

Figure 3-2. Approximation of lifetime and per-tonne CO_2 transport costs for 10,000-tonne vessels under various offloading scenarios and P/T conditions

Examining the cost breakdowns in Figure 3-2 indicates that for offloading to an onshore terminal and direct injection to offshore geologic storage configurations, the low- and medium-P/T regimes offer the lowest costs, with offloading to an offshore platform configuration being the most expensive option. Despite the higher vessel CAPEX and OPEX for direct injection due to the additional vessel required to meet the 1 Mt/yr transport capacity, the increased costs for loading, offloading, conditioning, and intermediate storage make the offshore platform offloading configuration slightly more expensive than the direct injection configuration for low- and medium-P/T regimes. For the high-P/T regime, the onshore offloading configuration remains the most cost-effective option, while the direct injection configuration becomes the most expensive. The increased costs for loading, offloading, conditioning, and intermediate storage in this regime do not outweigh the higher vessel CAPEX and OPEX associated with the additional vessel needed for direct injection.

Figure 3-3 provides an in-depth look at low P/T shipping illustrating the estimated lifetime costs associated with onshore CO_2 offloading and low-P/T transportation vessels, evaluated across different combinations of vessel numbers and capacities. Each bar stack reflects a specific fleet configuration (e.g., 8 vessels x 8000 tonnes), breaking down cost components to show how variations in fleet size and vessel capacity impact total and per-tonne CO_2 costs over the project's lifetime.



Note: Source data from BEIS CO_2 shipping cost tool [205]

Figure 3-3. Approximation of lifetime and per-tonne CO_2 costs for offloading onshore and low-P/T transportation

A closer examination of Figure 3-3 reveals that the lowest cost system at $52/tonne comprises 2 x 30,000-tonne low-P/T vessels. Additionally, vessel costs are the highest cost category at 64 percent, followed by intermediate storage (18 percent), liquefaction (13 percent), and loading, offloading, and conditioning (5 percent).

When comparing the shipping systems, intermediate storage costs increase with vessel size, as larger vessels require more extensive storage facilities to temporarily store the LCO_2 offloaded from a single vessel. Liquefaction costs and loading, offloading, and conditioning costs remain constant, being proportional to the annual transport capacity, which is unchanged. However, loading, offloading, and conditioning OPEX costs decrease as vessel size increases, likely due to operational efficiencies gained from handling more cargo per trip.

Table 3-4 presents cost estimates for transporting LCO_2 from Japan to Alaska based on LCO_2 vessel designs currently in operation or under construction (Figure 2-4). Among the vessels currently in operation, the cargo capacity is less than 2,000 tonnes. Transporting 1 Mt/yr of CO_2 between Japan and Alaska utilizing operational technology would likely require a fleet of 30 x 2,000-tonne vessels with an estimated levelized cost of $182 and $291/tonne for low- and medium-P/T, respectively. The levelized cost could be greatly reduced to around $141 and $52/tonne for a fleet of 8 x 8,000-tonne and 2 x 30,000-tonne vessels, respectively. This results in a comparative cost reduction of up to 71 percent, depending on P/T regime selected and by generally increasing cargo capacity size and reducing the number of vessels.

Table 3-4. Costs for three different transport capacities using operational or under-construction LCO_2 vessel designs for shipping transport from Japan to Alaska

<table>
<tr><th rowspan="2">Vessel Description (operational domain)</th><th rowspan="2">CO_2 Cargo Capacity (tonnes)</th><th rowspan="2">Vessel Size Used for Cost Assessment (tonnes)</th><th rowspan="2">P/T Condition</th><th rowspan="2">Number of Vessels Required per Transport Capacity (1,2,& 5 Mt/yr)</th><th colspan="3">Levelized Cost ($/t$CO_2$) for Offloading Onshore at Varying Transport Capacities (Mt/yr)</th></tr>
<tr><th>1</th><th>2</th><th>5</th></tr>
<tr><td>Larvik Shipping Helle LCO_2 Vessel (Norway)</td><td>1,250</td><td>1,000</td><td>Medium</td><td>60/119/296</td><td>294.83</td><td>292.37</td><td>447.23</td></tr>
<tr><td rowspan="2">Mitsubishi Shipbuilding EXCOOL Demonstration Test Ship (Japan)</td><td rowspan="2">1,450–1,650</td><td rowspan="2">2,000</td><td>Low</td><td>30/60/148</td><td>182.06</td><td>181.74</td><td>179.31</td></tr>
<tr><td>Medium</td><td rowspan="2">30/60/148</td><td rowspan="2">291.44</td><td rowspan="2">290.94</td><td rowspan="2">286.94</td></tr>
<tr><td>Larvik Shipping Fleet – Frøya, Gerda, Embla (Norway)</td><td>1,770</td><td>2,000</td><td>Medium</td></tr>
<tr><td>Dalian Shipbuilding Offshore Co. Northern Light’s Project Vessels (Norway)</td><td>8,000</td><td>8,000</td><td>Medium</td><td>8/15/37</td><td>141.1</td><td>132.31</td><td>129.49</td></tr>
<tr><td>Hyundai Mipo Mid-size Vessels for Capital Gas (Greece)</td><td>25,800</td><td>30,000</td><td>Low</td><td>2/4/10</td><td>52.45</td><td>47.59</td><td>44.68</td></tr>
</table>

It is warranted to note that, entities are developing high-P/T vessels (35–45 bar at 0–10 °C [493–653 psi at 32–50 °F]) that require less energy for cooling and reheating at the offloading point for geologic injection services, most notably KNCC [208]. This design can potentially scale up to 80,000-tonne capacity vessels but is currently less mature and requires further investigation to enable cost estimation on a cost per unit tonne basis for shipping and most importantly a cost estimation on an integrated cost per unit tonne across the CCUS value chain (i.e., capture, transportation, and geologic storage).

3.3 KEY FINDINGS

Following are the key findings from the economic feasibility assessment:

- Vessel construction is typically the largest CAPEX component in the value chain. Among the three P/T design regimes are the following:
  - Costs for smaller-scale, medium-P/T vessels are better understood due to existing fleets and recent data from the Northern Lights project
  - Large-scale, low-P/T vessel CAPEX estimates are considered comparable to current LPG vessels but have some variability since low-P/T vessels are still undergoing testing and demonstration activities
  - Costs for high-P/T vessels are the most uncertain, as this regime is the least mature and proposed at the conceptual level, and may still require further RD&D activity (e.g., testing and demonstration)
- Vessel operations and fuel costs are the largest OPEX component in the value chain. Fleet size and vessel size are mutually dependent on a given project's flow rate, while sailing time and fuel consumption remain relatively fixed for a specific shipping route.
- Using currently available technology commonly deployed on existing vessels would likely require a fleet of 30 x 2,000-tonne capacity carriers, resulting in a levelized cost of $182 and $291 per tonne (see Appendix C: LCO2 Shipping Cost Data) for low- and medium-P/T conditions, respectively. The levelized cost can be significantly reduced, up to 71 percent depending on P/T conditions, when employing vessel design technology for carriers currently under construction based.
- Different offloading configurations offer varying cost efficiencies, driven by vessel size and design choices, with offloading to onshore terminals being the most cost effective overall.
  - Onshore offloading is the most economical configuration for transporting 1 Mt/yr of LCO_2 utilizing two 30,000-tonne low-P/T vessels, with a lifetime levelized shipping cost of $52/tonne (Table 3-2).
  - The lowest cost system for direct injection consists of three 30,000-tonne carriers with a total levelized cost of $66/tonne (see Appendix C: LCO_2 Shipping Cost Data).
  - The lowest cost system for offloading to an offshore platform consists of two 30,000-tonne carriers for at a levelized cost of $72/tonne (see Appendix C: LCO_2 Shipping Cost Data).

4 REGULATORY LANDSCAPE ASSESSMENT

This section examines regulations that may be applicable to shipping CO_2 captured at industrial facilities in Japan to the United States for long-term geologic storage or converted into useful products in Alaska. It is a comprehensive review of the international laws, conventions, and treaties, U.S. federal laws, Alaska state laws, and Japanese laws relevant to CO_2 shipping feasibility. In this preliminary screening study, the regulatory assessment examines potential regulatory aspects concerning transpacific CO_2 transportation services to destinations in the United States where the CO_2 will be offloaded for secure geologic storage.

4.1 OVERVIEW

Applicable laws and regulations covering the transport of LCO_2 from Japan to Alaska span environmental protection including waste management, shipping safety, worker health, security, and design and construction of vessels and receiving facilities. Regulatory and governing authorities range from international bodies, such as the United Nations (UN) and the International Maritime Organization (IMO), to national and state ministries and agencies in Japan and the United States. Japanese laws and regulations apply to the export of CO_2, its infrastructure, storage, handling, and worker health and safety. Similarly, the import and sequestration of CO_2 are subject to the laws and regulations of the U.S. federal and Alaska state governments. International shipping is governed by laws, agreements, and treaties of the UN and IMO, in which both countries participate.

The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), published by the IMO, is an international standard for safely transporting bulk liquefied gases by sea. The IGC Code specifies the design and construction of liquefied gas carrier, including those for the transport of LCO_2 [209]. Classification societies in the shipping industry such as DNV, American Bureau of Shipping (ABS), Nippon Kaiji Kyokai (ClassNK), and Lloyd's Register are involved in various innovation initiatives and guidance development to support the commercial deployment of LCO_2 vessels. Classification societies' rules, guides, and standards are widely accepted and generally required by regulatory authorities and maritime insurance providers. The IGC Code and industry rules often refer to ISO, American Society of Mechanical Engineers, and other professional societies' standards for compliance.

The following section focuses on reviewing regulatory aspects of international and cross-border shipments, offshore receiving terminals and connected injection to the subsea, secure geologic storage, and onshore receiving terminals and temporary onshore storage. Those U.S. elements are depicted in Figure 4-1, along with examples of U.S. federal regulating entities that may be involved along the transportation chain.

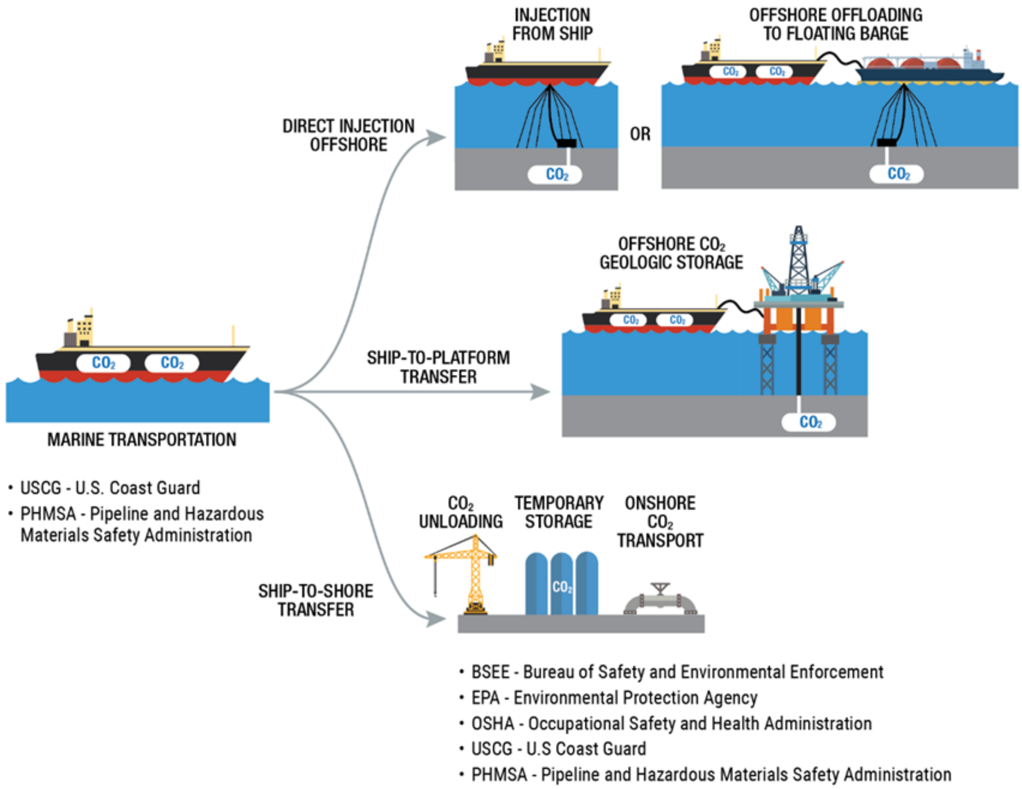


Figure 4-1. Example scenarios for LCO_2 transport

Sections 4.2 through 4.5 discuss examples of potentially applicable regulations and regulatory bodies for different system categories or relevant environments along the CO_2 transportation chain. The sections covering regulations are organized by type, international, national (U. S. or Japan), and state (Alaska). They are not all-inclusive; there may be additional regulations or requirements that apply depending on the specific details of a project and should be assessed on a case-by-case basis.

Section 4.6 examines the standardized sets of regulations and guidelines that define the design specifications that may be required for LCO_2 transport vessels. An LNG project is presented in Section 4.7 as an analog of what might be expected for an LCO_2 project in Alaska. Section 4.7.1 presents the Alaska LNG Project as a potential analog for the permitting process of an LCO_2 import terminal within the state of Alaska. Other potential sources for permitting information can be found in successful applications for recent DOE Funding Opportunity Announcement (FOA) grants as discussed in Section 4.8.

A list of regulatory and statutory authorities in the United States that may be involved in Japan-Alaska CO_2 transport is included in Appendix B: Regulatory and Statutory Authorities.

4.2 International Agreements and other instruments/guidelines

The following subsections discuss in detail some examples of international agreements and other instruments/guidelines that have potential implications for the commercial deployment of transpacific LCO_2 shipping from Japan to Alaska.

4.2.1 UN Framework Convention on Climate Change and the Paris Agreement

The 1992 United Nations Framework Convention on Climate Change (UNFCCC), which entered into force in 1994, has the ultimate objective of stabilizing greenhouse gas (GHG) concentrations in the atmosphere "at a level that would prevent dangerous anthropogenic [i.e., human induced] interference with the climate system," noting further that "[s]uch a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner" [210].

The 2015 Paris Agreement, which was adopted by the Conference of the Parties to the UNFCCC and entered into force in 2016, is a distinct international agreement from, but is related to, the UNFCCC. Although the Paris Agreement is not subsidiary to the UNFCCC, in pursuing its shared ultimate objective, it elaborates provisions in many areas addressed under the Convention, albeit in ways that depart from the Convention. Among other things, the Paris Agreement establishes a global temperature goal of "[h]olding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" [211, 211].

The United States and Japan are both Parties to the UNFCCC and the Paris Agreement. These agreements, and particularly the Paris Agreement, constitute the primary mechanism through which Parties have decided to address climate change.

4.2.2 Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories

The Intergovernmental Panel on Climate Change (IPCC)—the UN's body for assessing the science of climate change—published the "2006 IPCC Guidelines for National Greenhouse Gas Inventories" to provide methodologies for estimating national inventories of anthropogenic greenhouse gas emissions by sources and estimating removals by sinks [212]. The IPCC published an update to its methodology in the "2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories." The 2019 Refinement, in conjunction with the 2006 IPCC Guidelines, provides updates that include supplementary methodologies for sources and sinks that were not covered previously and revised parameters based on the most recent scientific data [213].

At its 60th session, the IPCC requested its Task Force on National Greenhouse Gas Inventories to develop a Methodology Report on Carbon Dioxide Removal Technologies, Carbon Capture Utilization and Storage. This forthcoming Methodology Report could include additional guidance on national reporting of CCS, including shipping emissions. A proposed outline for this methodology report will be considered by the panel in early 2025. The methodology report itself is expected to be finalized by the end of 2027 [214].

4.2.3 International Agreements Potentially Applicable to Regulating Transboundary CO_2 Movement

4.2.3.1 Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (Basel Convention) covers a wide range of wastes defined as "hazardous wastes" (based either on their composition and characteristics or on their designation as such under the relevant party's domestic law), or as "other wastes" subject to the Convention's controls (which include household waste and incinerator ash). The negotiation of the Convention was driven by discovery of exports of hazardous wastes to the developing world where there was less capacity to manage such wastes in an environmentally sound manner [215]. The United States is a signatory to the Convention, but has not ratified it, and therefore it has not entered into force for the United States. The Basel Convention has entered into force for Japan, so it would be up to Japan to consider the extent to which LCO_2 exports to the United States might implicate its obligations under the Convention. The United States does not have obligations under the Convention.

As a threshold matter, Japan may wish to consider whether the LCO_2 in question constitutes a "waste" for purposes of the Basel Convention. The Convention defines "wastes" as "substances or objects which are disposed of or are intended to be disposed of or are required to be disposed of by the provisions of national law." To the extent the LCO_2 in question is considered a "waste" for purposes of the Convention, a further issue for Japan to consider would be whether the LCO_2 would constitute a "hazardous waste" or "other waste" subject to the Convention's controls. The Basel Convention does not specifically list CO_2 in any form (liquid or otherwise) as a "hazardous waste" or "other waste" under Annex II or Annex VIII [216]. As further background, certain hazardous species specifically defined as such in Annexes of the Basel Convention may appear as trace components in captured CO_2 (e.g., mercury). The Intergovernmental Panel on Climate Change does not appear to consider the Basel Convention to be a significant obstacle to cross-border transportation of CO_2 for geologic storage, however, with a generally practical view taken that LCO_2 of acceptable purity for shipping would be permissible and not classify as hazardous waste [217].

Purity requirements for CO_2 shipping are emerging, while national or international standards have not been set in place. Currently, individual emitters, shippers, and storage providers across CCUS value chains must come to agreeable purity specifications on a case-by-case basis. It is noteworthy that current purity standards for LCO_2 shipping can be more stringent than those for pipeline transport.

4.2.3.2 United Nations Convention on the Law of the Sea

The United Nations Convention on the Law of the Sea (UNCLOS) facilitates international communication and promotes the "peaceful uses of the seas and oceans and the equitable and efficient utilization of their resources, conservation of their living resources, and the study, protection and preservation of the marine environment" [218]. The United States recognizes the provisions of UNCLOS relating to traditional uses of the oceans and seas as customary international law but has not ratified it and, therefore, is not party to UNCLOS; Japan is a party to UNCLOS.

UNCLOS does not impose a specific regulatory regime with respect to transporting LCO_2. At a screening level, UNCLOS is not expected to create any regulatory challenges with the expectation that LCO_2 carriers act within standard lawful, informed, and responsive maritime operational practices.

4.2.3.3 The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 and London Protocol

The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Convention) enhanced the protection and preservation of the marine environment and sustainable use and conservation of marine resources by preventing, reducing, and, if practicable, eliminating pollution caused by dumping or incineration at sea of wastes or other materials [219, 220, 221, 222]. The London Protocol was adopted in 1996 to "modernize the Convention and eventually replace it. Under the Protocol, all dumping is prohibited, except for possibly acceptable wastes on the so-called 'reverse list.'" The London Protocol came into force in 2006 [223].

The United States is a party to the London Convention and has signed but not yet ratified the London Protocol. In the United States, London Convention requirements are implemented primarily by EPA for materials other than dredged materials, by the U.S. Army Corps of Engineers (USACE) for dredged materials, and by federal agencies that transport material from any location (for the purpose of dumping) under the Marine Protection, Research and Sanctuaries Act [224]. The United States actively participates in the annual Consultative Meeting of Contracting Parties to the London Convention and London Protocol. The Department of State leads the United States delegation to the annual Consultative Meeting and is supported by the EPA, U.S. Army Corps of Engineers (USACE), National Oceanic and Atmospheric Administration (NOAA), U.S. Navy (Navy), U.S. Coast Guard (USCG), Department of Energy (DOE), and Department of Interior (DOI). The EPA leads the United States delegation to the annual joint meetings of the London Convention Scientific Group and London Protocol Scientific Group and is supported by the State Department, USACE, NOAA, Navy, USCG, DOE and DOI. Japan is a party to both the London Convention and the London Protocol.

LCO_2 is not classified in the London Convention as a prohibited waste or material and, therefore, disposal at sea may be allowed under a permit [219, 220, 221]. The London Protocol was amended to add CO_2 streams from carbon capture processes for storage (CCS) to the list of permittable materials. The London Protocol entered into force in March of 2006, and the CCS amendment entered into force in 2007 [217].

Article 6 of the London Protocol prohibits export of waste or other matter to other countries for the purpose of dumping. In 2009, a London Protocol amendment was adopted which would allow for the export of CO_2 streams, including to non-London Protocol Parties, for the sub-seabed storage of CO_2 The 2009 amendment would enable cross-border transport of CO_2 for CCS provided an agreement or arrangement has been entered into confirming and allocating permitting responsibilities between the exporting country and the receiving country consistent with the requirements of the London Protocol and other applicable international law. This amendment is not yet in force, as it requires two-thirds of the contracting parties to deposit an instrument of acceptance. As of November 2024, 12 out of 55 London Protocol contracting parties have deposited an instrument of acceptance. Japan has not yet adopted the 2009 amendment, but in May 2024, in a preliminary domestic procedure, Japan's Diet approved acceptance of the 2009 Amendment [225].

In 2019, the London Protocol parties adopted a resolution on provisional application of the 2009 amendment to authorize export of CO_2 streams for sequestration in geologic formations. As of November 2024, the nine London Protocol parties that have deposited declarations of provisional application are Norway, The United Kingdom of Great Britain and Northern Ireland, the Netherlands, Sweden, Denmark, Republic of Korea, Belgium, Switzerland, and Australia. For exports of CO_2 streams from a London Protocol contracting party like Japan to a non-contracting party like the United States, the exporting party must assure that the exported matter meets London Protocol requirements for dumping [217].

In 2013, London Protocol parties developed *Guidance on the Implementation of Article 6.2 on the Export of CO_2 Streams for Disposal in Sub-seabed Geological Formations for the Purpose of Sequestration*. The 2013 guidance provides suggestions and recommendations for agreements and arrangements [226] that may be useful to confirm and allocate permitting responsibilities as between Japan (as the exporting party that is an London Protocol party) and the United States (as the receiving party not a party to the London Protocol) for the purpose of CO_2 storage, including:

- Japan and the United States could establish a bilateral agreement or similar arrangements for the LCO_2 shipping corridor for the export of CO_2 from Japan to the United States, consistent with both the Protocol's provisions and other applicable international law.
- Japan and the United States, in advance of CO_2 export, would notify IMO as to the allocation of permitting responsibilities between Japan and the United States under such an agreement or arrangement.
- The United States could issue permits applicable to construction and operation of the injection and sequestration site that are consistent with the London Protocol requirements, including Article 9 requirements for issuance of permits and reporting to IMO and Annex 2 permitting requirements.
- Japan could characterize the CO_2 stream and share data with the United States.
- The United States could characterize storage sites, assess potential effects, verify monitoring and risk management, and share data with Japan.

In order for Japan to meet its London Protocol obligations, it is likely that Japan and the United States would then need to enter into a bilateral agreement or similar arrangements for the export of LCO_2 for disposition in geological formations beneath United States territory. Bilateral agreements and arrangements have recently been made between Norway, Belgium, Denmark, the Netherlands, and Sweden for large-scale CO_2 storage in Norway, notwithstanding the fact that all of these countries are parties to the London Protocol. The agreements can de-risk projects by facilitating sharing of best practices and technologies, promoting international cooperation and knowledge exchange, accelerating storage site readiness, and helping to harmonize regulations and standards [12].

For the United States, authority to enter into any potential bilateral agreement or arrangement would be coordinated through the Department of State while additional federal agencies (e.g., EPA, DOE, etc.) may provide additional support or input.

4.2.3.4 High Seas Treaty or Agreement on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction

Adopted in 2023, the High Seas Treaty or Agreement on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ Agreement) is an “implementing agreement” under UNCLOS, with the objective of the “conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction.” The BBNJ Agreement has four substantive parts:

- Marine genetic resources (i.e. any material of marine plant, animal, microbial or other origin containing functional units of heredity of actual or potential value), including the fair and equitable sharing of benefits [227]
- Measures such as area-based management tools, including marine protected areas
- Environmental impact assessments
- Capacity-building and the transfer of marine technology” [228]

As of the date of this report, the BBNJ agreement has not yet entered into force, which will happen after 60 UN States ratify it [228]. If the treaty comes into force, no issues are immediately identified with CO_2 transport and storage. The BBNJ Agreement requires in Article 7 that Parties be guided by a set of principles and approaches, one of which is “an approach that builds ecosystem resilience, including to adverse effects of climate change and ocean acidification, and also maintains and restores ecosystem integrity, including the carbon cycling services that underpin the role of the ocean in climate.” The United States has signed but not ratified the BBNJ Agreement. At a screening level, the BBNJ Agreement is not expected to create any challenge to LCO_2 shipping feasibility.

4.2.3.5 International Convention for the Prevention of Pollution from Ships

The International Convention for the Prevention of Pollution from Ships (MARPOL) is the main international convention covering prevention of pollution of the marine environment by vessels from operational or accidental causes. MARPOL has been updated by amendment processes since its inception [229]. Both the United States and Japan have ratified MARPOL, and it is in force. In the United States, MARPOL is implemented primarily under the Act to Prevent Pollution from Ships; certain elements of MARPOL Annex 6 (applicable to vessel engines and vessel fuels) are covered by the Clean Air Act.

4.2.3.6 International Convention for the Safety of Life at Sea

The International Convention for the Safety of Life at Sea (SOLAS Convention) specifies minimum standards for the construction, equipment, and operation of vessels, compatible with their safety. SOLAS Chapter VII Part C covers construction and equipment of vessels carrying liquefied gases in bulk, to comply with the requirements of the International Gas Carrier Code [230]. The United States and Japan are parties to SOLAS. The SOLAS Convention does not specifically restrict CO_2 transportation, though LCO_2 carriers would need to act in accordance with all applicable safety standards.

4.2.3.7 International Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea

The International Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea (HNS Convention) establishes a framework for a comprehensive and international liability and compensation regime for incidents involving transportation/release of hazardous and noxious substances. The Convention was adopted in 2010 but is not yet in force pending ratification. Liquefied gases are covered by the Convention [231]. Neither the U.S nor Japan is a signatory to the HNS Convention. At a screening level, the HNS Convention is not expected to be a challenge to LCO_2 shipping assuming LCO_2 carriers are in accord with requirements and obligations that may come into effect if the Convention comes into legal force.

4.2.3.8 Organization for Economic Co-operation and Development—Transboundary Movements of Wastes

The Organization for Economic Co-operation and Development (OECD) Council Decision on the Control of Transboundary Movements of Wastes Destined for Recovery Operations establishes "procedural and substantive controls for the import and export of hazardous waste for recovery operations (activities leading to resource recovery, recycling, reclamation, direct re-use or alternative uses). The agreement is intended to facilitate the trade of such waste and minimize the possibility that such wastes will be abandoned or handled illegally" [232], [233]. The United States and Japan are OECD members and subject to the agreement, which enables the United States to trade certain Basel Convention-covered wastes with other OECD countries for purposes of recovery [234] However, to the extent the LCO_2 in question is destined for final disposal rather than recovery, the OECD agreement would not apply.

4.2.4 International Agreements Focusing on Carriers' Liability

4.2.4.1 Convention on Limitation of Liability for Maritime Claims

The Convention on Limitation of Liability for Maritime Claims (LLMC Convention) allows shipowners to limit their liability to pay compensation for property damage, loss of life, and personal injury [235]. The Convention provides a robust system of limiting carriers' liability for responsibly conducted maritime shipping. The United States has signed the agreement but has not ratified it; Japan ratified it and is subject to the Convention. The Convention limits carrier liability, tending to decrease shipping risk and, therefore, reduce barriers to shipment in general, including LCO_2.

4.2.5 Summary of International Agreements and Other Instruments/Guidelines

Table 4-1 summarizes certain international agreements initially covered in this screening assessment and is considered to be non-exhaustive.

Table 4-1. Summary of international agreements potentially relevant to Japan-Alaska CO_2 transportation and offshore storage

Applicability	International Agreement(s)	International Maritime Organization Treaty	More Information
Climate Change Generally (entire chain)	United Nations Framework Convention on Climate Change (UNFCCC) & Paris Agreements	No	[211]
Transportation and Sequestration in Geologic Formations beneath Submerged Lands under the Ocean (international)	The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Convention) & London Protocol	Yes	[224]
Transportation and Storage (international)	Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (Basel Convention) & Organization for Economic Cooperation and Development (OECD) Council Decision on the Control of Transboundary Movement of Wastes Destined for Recovery Operations	No	[236]
Transportation (international)	United Nations Convention on the Law of the Sea (UNCLOS) & Agreement under UNCLOS on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ Agreement)	No	[228]
Transportation (international by ship)	International Convention for the Prevention of Pollution from Ships (MARPOL)	Yes	[229]
Transportation (international by ship)	International Convention for the Safety of Life at Sea (SOLAS)	Yes	[230], [209]
Transportation (international by ship)	International Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea (HNS Convention)	Yes	[231]
Transportation (international by ship)	Convention on Limitation of Liability for Maritime Claims (LLMC Convention)	Yes	[235]

4.3 Japanese Laws, Regulations, and Initiatives

Japan is an established, industrialized nation with a mature shipping industry and regulatory environment for pressurized gas products. Currently Japan's METI is leading efforts to develop a legal framework for regulating CCUS and associated value chain components. The following sections provide a non-exhaustive list of Japanese laws, including laws potentially related to LCO_2 shipping, and recent CCUS regulatory developments.

4.3.1 Law Relating to the Prevention of Marine Pollution and Maritime Disaster

Japan originally adopted the Law Relating to the Prevention of Marine Pollution and Maritime Disaster (LPMP) in the 1970s to control marine pollution and make provisions for maritime incidents [237]. LPMP aims to control the discharge of oil, noxious liquid substances, and wastes into the ocean from vessels, offshore facilities, and aircraft; regulate the incineration of oil, noxious liquid substances, and wastes on vessels and at offshore facilities; secure appropriate disposal of waste oil and take measures for the removal of the discharged oil, noxious liquid substances, and wastes; prevent the occurrence and spread of fire at sea; and secure appropriate enforcement of international conventions on the prevention of marine pollution and maritime disaster. The law also contains penal provisions [238]. LPMP is in accord with the IMO's MARPOL 73/78 Convention, to which Japan acceded in 1983 [239].

The LCO_2 shipping relevance is the same as for MARPOL as discussed in Section 4.2.4.4. In short, Japan's compliance with LPMP is facilitated by LCO_2 carriers utilizing responsible operational practices, consuming compliant propulsion fuels, and using satisfactory emissions controls on their propulsion systems.

Japan has been implementing the provisions of the London Protocol largely through LPMP. Disposal of wastes at sea is prohibited in principle by Japan, but a permit can be issued by the Minister of the Environment for disposal of CO_2 for CCS, given an established waste exception for gases consisting overwhelmingly of CO_2. Their permitting criteria include the following:

- Suitable geological structure confirmed to prevent a negative impact on the marine environment
- Required monitoring for pollution
- No possibility of negative effects on the environment in the disposal area
- No alternative appropriate disposal options available other than disposal under the seabed
- Technical and financial capability of the applicant to continuously implement disposal and monitoring

Provisions of the CO_2 streams are specified in the current legislation and include the following:

- Concentration of CO_2 is > 99.99 percent

- Only chemical absorption using amines is permitted (to capture the CO_2 in the stream)
- Impurities to be measured include hydrogen (H_2), oxygen, N_2, carbon monoxide (CO) and hydrocarbons
- Expected impurities in the stream need to be listed by the applicant
- Impurities that will not have any impacts on the marine environment do not need to be measured and reported [31]

4.3.2 Industrial Safety and Health Act

Japan's Industrial Safety and Health Act (ISHA) was enacted in 1972, adding more stringent standards than had been in place via the much earlier Labor Standards Act of 1947. ISHA's purpose is to "secure the safety and health of workers in workplaces, as well as to facilitate the establishment of comfortable working environment, by promoting comprehensive and systematic countermeasures concerning the prevention of industrial accidents". There are specialized safety and health system requirements in the Act for construction and shipbuilding industries where prime contractors and subcontractors customarily exist [240].

Potential LCO_2 transportation developments between Japan and Alaska may feature Japanese-built LCO_2 vessels. It is expected that construction of potential Japanese-built LCO_2 vessels would fall under the ISHA. Review of ISHA currently does not indicate special requirements that would significantly prevent ship transportation or handling of LCO_2.

4.3.3 High-Pressure Gas Safety Act

Japan's High-Pressure Gas Safety Act (HPGSA) strictly regulates the production, handling, storage, sale, transportation, and consumption of high-pressure gases, as well as the manufacture and handling of high-pressure gas containers, and encourages "voluntary activities by private businesses and the High Pressure Gas Safety Institute of Japan for the safety of high-pressure gases with the aim of securing public safety by preventing accidents and disasters caused by high-pressure gases" [241]. Compressed gas pressure that is greater than or equal to 1 megapascal (Mpa) (0.2 Mpa for compressed acetylene gas and liquefied gas) is classified as high-pressure gas under HPGSA. LCO_2 must be at a pressure of at least 5.2 bar (0.52 MPa) to be in liquid state[j] and is expected to fall under the Act (even though LCO_2 is not specifically mentioned in the regulation). HPGSA regulations should be taken into consideration in LCO_2 vessel design, LCO_2 cargo handling, and terminal designs in Japan-Alaska LCO_2 shipping corridor development.

Additional Japanese laws related to high-pressure gas include the Fire Service Act and the Act on the Prevention of Disasters in Petroleum Facilities. These acts relate more to petroleum products and natural gas to respond to and mitigate potential fire and high-consequence events [241].

[j] Japan's EXCOOL project plans to eventually transport CO_2 at P/T levels of -50 °C and 0.7 MPa, compared to prior conventional conditions of -20 °C and 2.0 MPa, respectively.

4.3.4 Japanese Legislation on Hydrogen and CCS

On May 17, 2024, the Japanese parliament approved two energy-related bills into law: "The Act on the Promotion of Supply and Utilization of Low-Carbon Hydrogen and its Derivatives for a Smooth Transition to a Decarbonized, Growth-Oriented Economic Structure," and "The Act on Carbon Dioxide Storage Businesses." These are significant as the country's first legislation on H_2 and CCS [242].

4.3.4.1 Hydrogen Society Promotion Act

The Hydrogen Society Promotion Act (HSPA) promotes the supply and use of low-carbon H_2, with the policy jointly formulated by METI and the Ministry of Land, Infrastructure, Transport, and Tourism. Low-carbon H_2 generation methods may involve carbon capture with the need to convert or store the CO_2 to meet the low-carbon H_2 regulatory definition. Therefore, the HSPA policies imply that CCUS will be driven by some of the new facilities, businesses, etc., that are expected to emerge. The HSPA may indirectly support future CCUS development through low-carbon H_2 value chain development, of which one example could be Japan-Alaska LCO_2 transportation for the purpose of long-term geologic storage [242].

4.3.4.2 CCS Business Act

The CCS Business Act promotes the use of CCS in Japan. In general, the CCS Business Act is considered to foster development of an environment where operators can begin CCS businesses by 2030. It establishes a permission system where METI and the Ministry of the Environment will grant permits to CCS operators for designated, specific areas for capture and storage. Key framework elements in this act include the introduction of a new licensing regime for CCS operators and implementation of new regulations/provisions on exploration of reservoirs, prospecting (i.e., exploratory excavation) of reservoirs, and storing CO_2 in reservoirs, and other provisions such as pipeline transportation of CO_2.

The pipeline transportation requirements in the CCS Business Act define "pipeline transportation operations" as transporting CO_2 through a pipeline for the purpose of storing it in a reservoir (including reservoirs in a foreign country). Specifically, the CCS Business Act foresees the situation where CO_2 is exported by vessel for storage in a reservoir in a foreign country, in which case the Minister of METI must be notified of operations for transporting the CO_2 by pipeline to the vessel loading point [243]; however, transport of CO_2 by vessels and vehicles is not regulated by the CCS Business Act at present [244]. Developments or changes in this regulation should be monitored for further developments that may impact the Japan-Alaska transport scenarios.

4.3.5 Japanese Laws, Regulations, and Initiatives Summary

Table 4-2 summarizes Japanese laws and regulations covered in this initial screening assessment and is considered to be non-exhaustive.

Table 4-2. Summary of Japanese regulations potentially applicable to Japan-Alaska CO_2 transportation and offshore storage

Japanese Laws and Regulation Examples			
Applicability	**Regulation/Law**	**Oversight**	**More Information**
Transportation (international by ship)	Law Relating to the Prevention of Marine Pollution and Maritime Disaster (LPMP)	Ministry of Economy, Trade, and Industry (METI)	[237]
Transportation (international by ship)	Industrial Safety and Health Act (ISHA)	Ministry of Health, Labor, and Welfare	[245]
Transportation (international by ship)	High-Pressure Gas Safety Act (HPGSA)	Ministry of Health, Labor, and Welfare	[241]
Hydrogen and CCS	Hydrogen Society Promotion Act (HSPA)	METI and the Ministry of Land, Infrastructure, Transport, and Tourism	[242]
	CCS Business Act	METI and the Ministry of the Environment	[242]

4.4 U.S. Federal Laws and Regulations

The United States has a mature regulatory environment related to industrial development and marine shipping. U.S. federal agencies may directly implement and enforce federal laws or jointly enforce with other agencies. Additionally, federal agencies may grant primacy to individual states to wholly enforce or enforce parts of regulations. The following sections provide a non-exhaustive list of potential U.S. laws related to LCO_2 shipping development.

4.4.1 Hazardous Materials Transportation Act

The Hazardous Materials Transportation Act (HMTA) protects against the risks to life, property, and the environment that are inherent in the transportation of hazardous material in intrastate, interstate, and foreign commerce [246]. The following summarizes a detailed analysis of the applicability of HMTA to the transportation of LCO_2, which addresses both ship-based and pipeline-based transport [217].

The U.S. Coast Guard (USCG) is responsible for enforcing HMTA requirements with respect to the transportation of hazardous materials via ship. Compressed gases must be transported in metal cylinders or containers built in accordance with U.S. Department of Transportation (DOT) regulations. CO_2 is listed as a Class 2.2 (non-flammable gas) hazardous material under DOT regulations; also, CO_2-refrigerated liquid falls into stowage category "B," which allows for both on-deck or under-deck stowage on a cargo vessel.

The Safety Standards for Self-Propelled Vessels Carrying Bulk Liquefied Gases (46 CFR [Code of Federal Regulations] 154) are currently insufficient for the design and construction of LCO_2 vessels in the case of U.S.-flagged vessels; as such, any new U.S. vessel construction would require a design basis agreement (CG-ENG Policy Letter 01-23) for which the USCG provided guidance in 2023 [247].

Historically, the Hazardous Liquid Pipeline Safety Act of 1979 and subsequent reauthorizations have regulated the transportation of hazardous commodities by pipeline. In the Pipeline Safety Reauthorization Act of 1988, Congress amended the Hazardous Liquid Pipeline Safety Act of 1979 to require the Research and Special Programs Administration (RSPA), PHMSA's predecessor agency, to issue regulations for carbon dioxide. [248] .

Currently, federal regulations in 45 CFR Part 195, "Transportation of Hazardous Liquids by Pipeline" provide federal safety regulatory authority to PHMSA over pipelines carrying CO_2, specifically "pipeline facilities and the transportation of hazardous liquids or CO_2 associated with those facilities in or affecting interstate or foreign commerce, including pipeline facilities on the Outer Continental Shelf (OCS)," with the OCS generally extending 3–200 nautical miles from the U.S. coast. Note that PHMSA regulatory scope excludes ship transportation and other non-pipeline transportation modes.

The federal regulations currently define CO_2 as "a fluid greater than 90 percent CO_2 molecules compressed to a supercritical state." As such, CO_2 is classified as a "highly volatile and non-flammable/non-toxic" fluid under the regulations, and not as a "hazardous liquid." However, PHMSA imposes requirements for CO_2 pipelines similar to those imposed on other pipelines carrying hazardous liquids, including crude oil and anhydrous ammonia.

To strengthen CO_2 pipeline safety, PHMSA is undertaking new rulemaking to update standards for CO_2 pipelines, including requirements related to emergency preparedness and response. As of November 2024, the notice of proposed rulemaking has not yet been published in the Federal Register, which would initiate a defined public comment period [249]. When the new rulemaking/official guidance from PHMSA comes into force, it may further guide next steps on planning for Japan-Alaska LCO_2 shipping scenarios that may involve pipeline and terminal connections.

4.4.2 Ocean Shipping Reform Act and Federal Maritime Commission Statutes

The Federal Maritime Commission (FMC) is the federal agency responsible for regulating the United States' international ocean transportation system for the benefit of U.S. exporters, importers, and the U.S. consumer. FMC's mission is to "ensure a competitive and reliable international ocean transportation supply system that supports the U.S. economy and protects the public from unfair and deceptive practices" [250]. FMC administers statutes including the following:

- Ocean Shipping Reform Act of 2022—supports managing international ocean shipping costs, port congestion, and easing supply chain backlogs for U.S. exporters to ship to global markets [251]
- Title 46 U.S. Code (USC) Subtitle IV, Part A – Ocean Shipping

- Title 46 USC Subtitle IV, Part B – Actions to Address Foreign Practices—addresses unfavorable conditions for U.S. carriers in foreign trade, reviews rates, promotes fair competition, and prevents anticompetitive behavior
- Title 46 USC Subtitle IV, Part C Chapter 441 – Evidence of Financial Responsibility for Passenger Transportation
- Title 46 USC Subtitle IV, Part D – Federal Maritime Commission

FMC has the authority to review CO_2 shipping agreements, rates, etc., for foreign LCO_2 carriers importing CO_2 to the United States for CO_2 storage and may take action if it determines that there are any unfavorable conditions or terms.

4.4.3 Ports and Waterways Safety Act

The Ports and Waterways Safety Act (PWSA) authorizes USCG to establish, operate, and maintain vessel traffic services in ports and waterways subject to congestion, specifically via traffic service/separation schemes. Applicability is to commercial vessels weighing 300 gross tons or more [252]; specifically, 33 CFR 160.109 Waterfront Facility Safety establishes this authority.

Although USCG has authority through PWSA to regulate the transfer of bulk LCO_2 at waterfront facilities, LCO_2 is currently not directly accounted for in USCG's existing safety or security regulations. This situation necessitates a case-by-case approval process via the Captain of the Port Authority (33 CFR § 6.01-3 – Captain of the Port) [253]. The Captain of the Port, a USCG officer designated by the USCG Commandant, can assess each project based on safety and security and apply certain measures if he or she can articulate the risk of a transportation security incident. While this process is very seldom used because USCG typically has prescriptive regulations for most situations and cargos, the mechanism does exist. Given the current lack of specific regulatory guidance in waterfront bulk LCO_2 transfer, a first-of-a-kind project would necessitate its potential application in the near term until more specific guidance is available. This situation may increase regulatory processes and timelines only to a moderate degree since the Captain of the Port can review an Oversight and Compliance Program under the authority of PWSA.

4.4.4 Maritime Transportation Security Act

The Maritime Transportation Security Act (MTSA), 33 CFR 101 through 103, places stringent security requirements on port authorities and vessel and facility operators, covering port operations (including identifying the Captain of the Port as the leading authority), vessel operations, facility operations and security, and OCS security [254]. USCG has security jurisdiction through MTSA for operations involving transfer of bulk LCO_2.

4.4.5 Merchant Marine Act of 1920

The Merchant Marine Act of 1920 (i.e., the Jones Act) [255] is the U.S. marine cabotage law, designed to help ensure the United States maintains cargo shipbuilding capacity, vessels, and crews needed for defense purposes. It requires that goods carried between two U.S. ports by water must be carried in U.S. flag vessels that are American built, owned, controlled, and crewed [256]. The scope of "goods" was extended to valueless material such as dredged material, and vessel scope includes tugs, barges, etc. [257]. Detailed guidance regarding the procedures that control the coastwise transportation of merchandise between U.S. coastwise points, along with illustrative examples, is provided by the U.S. Customs and Border Protection 2020 publication, "The Jones Act" [258].

In the simplest shipping scenario where a vessel loads LCO_2 from a Japanese terminal and unloads in an Alaskan terminal, the Jones Act would generally not apply, as the transport is not between two U.S. ports. This can theoretically enable both Japan-based and American-based LCO_2 vessels to potentially participate in the LCO_2 shipping portion of a transboundary value chain. Additional scenarios, that can be envisioned with increasing complexity, would need to be considered on a case-by-case basis. As a supplementary consideration, the Cargo Preference Act of 1954, which requires that 50 percent of civilian agencies' cargo (cargo that is not military cargo and not covered under the Agricultural Food Aid Program) and agricultural cargo be carried on U.S.-flagged vessels [259], could have additional implications. Future feasibility studies must be clear about all aspects of the transportation scenarios to verify potential Jones Act compliance.

4.4.6 Act to Prevent Pollution from Ships

The Act to Prevent Pollution from Ships (APPS) is a U.S. law that specifically enforces the air pollution requirements for ocean-going vessels as established in Annex VI of MARPOL. The international air pollution requirements of Annex VI establish requirements on engines and limits on nitrous oxide (NOx) emissions and require the use of fuel with lower sulfur content. The requirements apply to vessels operating in U.S. waters as well as vessels operating within 200 nautical miles of the coast of North America, also known as the North American Emission Control Area. EPA and USCG have established various protocols to manage enforcement of Annex VI [260]. Compliance with these regulations would be accomplished through proper certifications of vessels and engines, suitable operating practices, use of compliant fuels, and satisfaction of record-keeping requirements [261]. These routine air pollution control requirements are not expected to prevent potential Japan-Alaska LCO_2 shipping. Fugitive emissions of CO_2 from LCO_2 vessels are of concern with respect to GHG emissions. Although these are not addressed in APPS, IMO has issued goals on GHG emissions from vessels, which inform design codes for vessels; see Section 4.6.

4.4.7 Safe Drinking Water Act

Due to the potential impact of underground injection of CO_2 and other fluids on underground sources of drinking water such as aquifers, EPA is authorized by the Safe Drinking Water Act (SDWA) to develop requirements and provisions for Underground Injection Control (UIC) in the United States. There are six classes of injection wells that EPA's UIC Program regulates; Class VI well requirements apply to the geologic storage of CO_2 and are designed to protect public health and underground sources of drinking water from the unique nature of CO_2 injection associated with its high relative buoyancy, subsurface mobility, corrosivity in the presence of water, and large injection volumes involved. Requirements are extensive and cover injection site/geologic characterization, modeling of the injected CO_2 plume, well construction, testing and monitoring, operations, well plugging, financing, emergency and remedial response planning, and reporting [152].

Currently, only Wyoming, North Dakota, and Louisiana have primary enforcement responsibility for Class VI wells, so in the case of Alaska, the UIC Program would be implemented by EPA's Region 10 (Pacific Northwest) office. Alaska is currently seeking primacy for Class VI, but the application is not yet under evaluation as of summer 2024 [262].

Underground storage via injection wells requires a Class VI well permit for each well. The Class VI permitting process involves pre-permitting (notification of permitting authority, community dialogue/stakeholder engagement), pre-construction (review of the permit application, public comment), pre-operation if a permit is issued (construction, testing), injection (operation of well, monitoring), and post-injection (plugging, monitoring, site closure). EPA notes that it aims to review Class VI applications and issue final permit decisions within approximately 24 months of receipt of a complete application. The timeframe is dependent on factors like timely responses from the applicants [152].

Class VI regulations' definition of a CO_2 stream to be geologically stored in the well is CO_2 captured from an emission source (e.g., power plant) that may include incidental substances and/or impurities derived from the source and capture process, plus substances added to the stream to enable or improve the injection process. Although allowable impurities levels are not specified, it is noted that if the CO_2 stream meets the definition of hazardous waste under 40 CFR part 261, then the Resource Conservation and Recovery Act hazardous waste regulations apply [263]. However, EPA has conditionally excluded CO_2 streams to be geologically stored via Class VI wells from the definition of hazardous waste if the streams are transported in compliance with DOT requirements and regulations adopted and administered by a state authority, such as pipeline safety regulations, injected into UIC Class VI wells for purposes of geologic sequestration not mixed with, or otherwise co-injected with, any other hazardous waste [264], and meet certain other conditions such as certification. Although SDWA-driven regulations and Class VI well permitting are extensive in scope and entail considerable efforts/actions to satisfy, they are unlikely to prevent LCO_2 shipping and terminal infrastructure development that is potentially co-located with a storage development that falls within applicable sources of drinking water siting considerations [265].

4.4.8 Resource Conservation and Recovery Act

The Resource Conservation and Recovery Act (RCRA) was originally established in 1976, authorizing EPA to control hazardous waste from cradle to grave, including its generation, transportation, treatment, storage/s, and disposal. RCRA was amended in 2014 to conditionally exclude CO_2 streams that could be interpreted as hazardous from the definition of hazardous waste, provided these CO_2 streams are captured from emission sources, are injected into UIC Class VI wells for purposes of geologic sequestration, and meet certain other conditions including not having been mixed with, or otherwise co-injected with, other hazardous wastes. EPA justified the exclusion based on the belief that the management of CO_2 streams for purposes of geologic sequestration, when meeting certain conditions, does not present a substantial risk to human health or the environment, and, therefore, additional regulation pursuant to RCRA's hazardous waste regulations is not necessary [266]. With RCRA's conditional exclusion for CO_2 streams in geologic sequestration activities, combined with the unlikely addition of injection process agents causing hazardous waste designation, it is not expected that RCRA would prevent potential Japan-Alaska LCO_2 shipping scenarios.

4.4.9 Outer Continental Shelf Lands Act

The Outer Continental Shelf Lands Act (OCSLA) defines the OCS as all submerged lands lying between 200 nautical miles from shore and seaward of state-submerged lands and waters (state-submerged lands usually extend three nautical miles offshore, or nine nautical miles in the case of Texas and the Florida Gulf Coast) as being under U.S. jurisdiction and control. Under OCSLA, DOI's Bureau of Ocean Energy Management (BOEM) and Bureau of Safety and Environmental Enforcement (BSEE) regulate and administer oversight of mineral exploration and the development of oil and gas leases, carbon capture and storage, and alternate energy related uses on the OCS by granting leases for such to bidders and regulating an O&G exploration program, establishment of an oil spill liability fund, etc. More recently, the Energy Policy Act of 2005 amended OCSLA to "give jurisdiction of alternate energy-related uses (including renewable energy projects) on the outer continental shelf" to DOI [267].

The BIL amended OCSLA to issue leases for storage of CO_2 in the OCS for any captured CO_2 streams that meet the same definition of CO_2 streams as established in other federal regulations such as SDWA. The BIL provides that the Secretary of Interior may issue leases, easements, or rights-of-way for energy and related purposes, including those that "provide for, support, or are directly related to the injection of a carbon dioxide stream into sub-seabed geologic formations for the purpose of long-term carbon sequestration" [268].

The requirement to obtain a CO_2 storage lease for locations on the OCS is a result of the fact that the U.S. federal government controls the OCS, so in the case a private entity wants to use the OCS, it needs approval from the federal government [217]. Currently, the joint rulemaking between BOEM and BSEE will establish new regulations to implement processes in support of safe and environmentally responsible carbon sequestration activities on the OCS. The proposed rule will address the transportation and geologic sequestration aspects of a development, including leasing; siting of storage reservoirs; environmental plans and mitigations; facility and infrastructure design and installation; injection operations; monitoring; incident response; financial assurance; and safety [269]. In the long term, OCS regions may be broadly available for carbon sequestration activities after federal rulemaking processes are complete and compliment state-led leasing programs occurring to date. There are numerous regulations, associated federal agencies, and federal, state, and tribal consultations involved in implementing CCS on the OCS [270]. A National Environmental Policy Act review would be required if BOEM or BSEE leases offshore land for the storage of CO_2 in the OCS (see Section 4.4.10).

4.4.10 Rivers and Harbors Act

The 1899 Rivers and Harbors Act (RHA), the oldest U.S. federal environmental law, was enacted to protect navigation by requiring Congressional approval for construction of a bridge, dam, or dike over navigable U.S. waterways [271]. Section 10 of RHA requires permitting for certain activities affecting the navigable waters of the United States, including construction of piers, wharves, bulkheads, ramps, floats, pipeline crossings, and dredging and excavation [272]. USACE controls this permitting. Construction/major modification of a pier to offload CO_2 from a ship and/or temporarily store it would likely require a permit from USACE.

4.4.11 National Environmental Policy Act

The National Environmental Policy Act (NEPA) requires federal agencies to assess the environmental effects of their proposed actions. Using the NEPA process, agencies "evaluate the environmental and related social and economic effects of their proposed actions and provide opportunities for public review and comment on those evaluations" [273].

NEPA applies whenever one or more of the following four conditions is present for the proposed activity or action:

- Is proposed on federal lands;
- Requires passage across federal lands;
- Is to be funded entirely or in part by the federal government, or
- Affects air or water quality that is regulated by federal law. [274]

There are three main levels of analysis for environmental reviews under NEPA: [275]

- Categorical Exclusion (CX)—when the proposed action normally does not have a significant effect on the environment
- Environmental Assessment (EA)/Finding of No Significant Impact (FONSI)—when the CX does not apply, an EA may be prepared that discusses the purpose and need of the proposed action, alternatives, environmental impacts, and agencies and persons consulted. The results of the EA may result in a FONSI in which it is concluded that no significant environmental impacts are projected to occur or, if the environmental impacts are expected to be significant, an Environmental Impact Statement is prepared
- Environmental Impact Statement (EIS)—a more detailed and rigorous analysis than an EA involving publishing a Notice of Intent, draft EIS issuance and public review/comment, and a final EIS including comment response

NEPA may apply to Japan-Alaska CO_2 transportation and storage scenarios if elements of the transport and storage chain occur on federal lands or require a federal permit, in which case the lead federal agency would determine whether the project significantly affects the environment and involves substantial control and responsibility. Those determinations would require either a categorical exclusion or require the preparation of an EA or EIS [217].

Table 4-3 provides examples of regulations and related agencies. [217]. Note that pier modification/construction would likely need USACE permitting and NEPA review.

Table 4-3. Examples of regulations and related agencies

Value Chain Component	Regulation/Statute	Agency
Transportation	HMTA	DOT (vessels); PHMSA (pipelines)
Transportation	APPS	EPA
Pier Modification or Construction	CWA RHA	USACE

Depending on the specific scenario, Japan-to-Alaska transport and storage of CO_2 will involve movement of large vessels in and out of Alaska waters, the possibility of new construction of piers or terminals, and other actions with potential environmental impacts towards air or water quality. Regardless of the scope of NEPA review for any or all the actions and regulation-mandated public comment, it will be essential to engage stakeholder communities at the earliest possible opportunity to seek input regarding project planning.

Additionally, the White House's Council on Environmental Quality requirements for NEPA reviews direct agencies to include direct, cumulative, and indirect effects, including those on GHG emissions. In a pier construction scenario, USACE review may potentially include emissions for construction, operation, and impacts. The Fiscal Responsibility Act of 2023 contains amendments narrowing NEPA's scope of consideration, for instance, no environmental review is required for actions with impacts entirely outside the United States [276], so in the Japan-Alaska transportation scenario, a NEPA review may not be required for capture in Japan and subsequent vessel transport up to the U.S. maritime boundary [217]. It should be noted that when NEPA requires the preparation of an EIS, the appropriate time necessary to complete the process and potentially obtain a permit should be thoughtfully planned and considered in early phases of project development.

4.4.12 Fixing America's Surface Transportation Act

Title 41 of the Fixing America's Surface Transportation (FAST) Act (FAST-41) is intended to improve the time for federal environmental review and authorization, without altering any regulatory requirement or environmental law. One of the FAST-41 improvements is the Permitting Dashboard, a public online tool that can be used to follow project timelines and actions to be made or already made by U.S. federal agencies [277].

Additionally, the Federal Permitting Improvement Steering Council (now known as the Federal Permitting Council) was established by FAST-41 to coordinate all federal environmental reviews for covered infrastructure projects, including CCS projects, and is comprised of 13 federal agency council members [278]. As an example, a recent announcement of a memorandum of understanding between the Federal Permitting Council and the New Mexico Renewable Energy Transmission Authority (RETA) provides federal permitting support for RETA's projects that qualify for the Federal Permitting Council's FAST-41 program, potentially providing a template for an expedited process relevant to this study. See Figure 4-4 in Section 4.7.2 as an example regarding the Alaska LNG permitting dashboard provided by the Federal Permitting Council.

4.4.13 Clean Air Act

The Clean Air Act (CAA) supports control of ambient/outdoor air pollution to safeguard public health and the environment. CAA requires EPA to establish minimum national standards for air quality, i.e., the National Ambient Air Quality Standards for six principal "criteria pollutants," namely:

- Carbon monoxide
- Particulate matter
- Nitrogen dioxide
- Sulfur dioxide
- Lead
- Ozone

CAA assigns the primary responsibility to states to comply with the standards. The CAA Amendments of 1990 added Title V to the Act requiring states to administer a comprehensive permit program for the operation of sources emitting air pollutants; those sources subject to the permit requirements include major sources quantified as having actual/potential emissions of 0.1 Mtpa of any regulated pollutant.

Geographic areas not meeting the standards are referred to as “nonattainment areas” and are required to implement more stringent air pollution controls [279], [280].

Considering the transport chain for ship-based CO_2 transport and offloading in Alaska, a notable source of air emissions involving the criteria pollutants would be a CO_2 storage terminal that might be consuming fossil fuels such as natural gas or liquid fuels for CO_2 handling purposes. More generally, any industrial installation for the transport and storage chain (e.g., compression, purification/liquefaction, loading/offloading) will need the initial reviews and permits for facility pollutant emissions. Whether routine operations of these would rise to the level of a “major source” that would need to be permitted under CAA depends on case-by-case project specifics. In future feasibility study phases when a theoretical transport and storage value chain is more firmly defined, the applicability of CAA permitting may be considered in greater detail.

4.4.14 Clean Water Act

The Clean Water Act (CWA) of 1972 regulates discharges of pollutants into the waters of the United States and regulates quality standards for surface waters. EPA has set wastewater standards for industry and developed national water quality criteria recommendations for pollutants in surface waters under CWA. Permits are required for discharge of pollutants from industrial, municipal, or other facilities from point sources (i.e. pipes, ditches) into navigable or surface waters; the permit program is called the National Pollutant Discharge Elimination System (NPDES) [281].

In consideration of the possible effects of CWA regulations on potential carbon capture and storage developments, a permit may be required under CWA if a project or pipeline crosses water or wetlands. Additionally, if a development requires the discharge of dredge or fill materials into U.S. waters, Section 404 of CWA requires a permit from USACE [282].

In the transport chain for ship-based CO_2 transport and offloading in Alaska, it is possible that a modified or newly constructed pier will be required. This may involve associated discharge of dredge or fill materials in Alaska waters. Also, any pipeline construction may involve pipeline crossings as discussed. Either of these could require a permit through the NPDES program and should be considered in early phases of project development.

4.4.15 Coastal Zones Management Act

The Coastal Zones Management Act (CZMA) (16 U.S.C. §1451 et seq.) is administered by NOAA and provides for the management of the nation's coastal resources, with a goal to "preserve, protect, develop, and where possible, to restore or enhance the resources of the nation's coastal zone" [283].

Three national programs are established through CZMA:

- National Coastal Zone Management Program—Alaska withdrew in 2011 from the federally approved Alaska Coastal Management Program.
- National Estuarine Research Reserve System—Consists of a network of 30 coastal sites designated to protect and study estuarine systems. The system lists the Kachemak National Estuarine Research Reserve in Alaska as part of the system. This is located on the west coast of the Kenai peninsula, which borders the Cook Inlet.
- Coastal and Estuarine Land Conservation Program (CELCP)—This program protects coastal lands that are ecologically important or possess other coastal conservation values, such as historic features, scenic views, or recreational opportunities. There is one CELCP project in Alaska in the Bristol Bay Borough [283], [284].

Notwithstanding Alaska's withdrawal from the National Coastal Zone Management Program, CZMA still requires avoiding impacts to the Kachemak National Estuarine Research Reserve, located on the Cook Inlet. Potential developers of transportation and/or storage terminal locations in Alaska should be aware of and consider coastal sites covered under CZMA in early phases for potential impacts based on the site-specific attributes of project development, as applicable.

4.4.16 Fish and Wildlife Conservation Act/Fish and Wildlife Coordination Act

The Fish and Wildlife Conservation Act/Fish and Wildlife Coordination Act (FWCA) "authorizes financial and technical assistance to the States for the development, revision, and implementation of conservation plans and programs for nongame fish and wildlife" [285]. The FWCA also directs the U.S. Fish and Wildlife Service (FWS) to "investigate and report on proposed federal actions that affect any stream or other body of water and to provide recommendations to minimize impacts on fish and wildlife resources" [286]. It is possible that actions taken in a CCUS value chain may impact non-game fish and wildlife species and their habitats. Accordingly, potential transportation and storage projects should consider consultation with FWS and state agencies regarding any such potential impacts in early phases of project development.

4.4.17 Regulations Protecting Endangered/Threatened Species and Migratory Birds

Multiple federal regulations protect endangered or threatened species and their habitats, including:

- Endangered Species Act—Conservation of threatened and endangered plants and animals and their habitats, including birds, insects, fish, reptiles, mammals, crustaceans, flowers, grasses, and trees [287]
- Marine Mammal Protection Act (MMPA)—Conservation/protection specifically of marine mammals including whales, dolphins, porpoises, seals, sea lions, walruses, polar bears, sea otters, manatees, etc. [288]
- Migratory Bird Treaty Act of 1918 and Bald and Golden Eagle Protection Act of 1940—Conservation/protection specifically of native migratory birds and threatened/endangered eagle species [289]

Generally, the regulations are to ensure actions do not “jeopardize the continued existence of any listed species or result in the destruction or adverse modification of designated critical habitats” [287]. They prohibit “taking” of species without permit, the definition of which broadly includes any harmful action to the species or their habitats.

It is possible that potential transportation and storage development may impact threatened, listed, or protected species located in Alaska depending on site-specific attributes of a development. Consultations with the relevant agencies (FWS, NOAA fisheries, Alaska State wildlife agencies) should be considered early in phases of development to identify and potentially incorporate siting, design, and operational considerations regarding endangered/threatened species and migratory birds and associated permits. Incorporating potential protected animals and habitats within site selection, routing, and development activities can mitigate potential impacts and regulatory review considerations [290].

4.4.18 Executive Orders

Executive orders are written directives from the President of the United States and have the force of law. They are used by the President to manage the federal government [291].

Executive Order 12898, “Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations,” (59 FR 7629, 1994) addresses “environmental and human health effects of federal actions on minority and low-income populations with the goal of achieving environmental protection for all communities” [292].

Executive Order 14096, “Revitalizing Our Nation’s Commitment to Environmental Justice for All” (88 FR 25251, 2023), broadens the scope of Executive Order 12898, offering agencies specific guidance on how to take environmental justice-related concerns into consideration while fulfilling their statutory mandates, including under NEPA [293].

Executive Order 13175 (2000), "Consultation and Coordination with Indian Tribal Governments" requires regular and meaningful consultation and collaboration with tribes in conjunction with any federal agency actions with tribal implications [292]. Any CO_2 transportation or storage action in the vicinity of Alaska Native peoples' lands, impacting their resources, etc., may require consultation and coordination with tribal governments based on the unique attributes of a proposed site.

Executive Orders 11988 and 11990 (1977) require that federal agencies consider the impact of their actions on floodplains and wetlands, conducting a formal assessment if necessary. For example, the Cook Inlet Basin contains a mosaic of uplands and wetlands including a salmon spawning habitat, while peatlands distinctive to the Cook Inlet Basin lowlands contribute to stream flows and help to maintain fluvial habitats for the salmon [294]. Therefore, any CO_2 transportation or storage development, as well as terminal location development, in the Cook Inlet has the potential for impact and should be considered in early phases of a project as requiring future consideration for supporting assessments.

4.4.19 Miscellaneous Regulations

Certain regulations/statutes listed below may come into play if any CO_2 transportation or storage action impacts parks, recreation areas, refuges, historic sites, wild/scenic rivers, Native American ruins/artifacts/gravesites, Native American lifestyles, etc.:

- Department of Transportation Act of 1966 [295]
- Wild and Scenic Rivers Act of 1968 [296]
- Antiquities Act of 1906/Archaeological Resources Protection Act (ARPA)/Native American Graves Protection and Repatriation Act (NAGPRA) [297]
- Indian Religious Freedom Act of 1978 [298]

It is likely that Japan-Alaska transport and storage will not involve actions that will impact these protected and sensitive areas and sites, and consideration should be given during project development to inform siting. A Cultural Resources Management Plan could be prepared and published to reduce concerns from the public.

4.4.20 U.S. Federal Laws Summary

Table 4-4 summarizes U.S. federal laws, regulations, and Executive Orders specifically related to LCO_2 shipping development that are covered in this initial screening assessment and is considered to be non-exhaustive. Table B-1 and Table B-2 of Appendix A: Supplementary Information for LCO_2 Vessel and Loading and Offloading Terminal Design Considerations present additional information, produced by the U.S. EPA, related to regulatory and statutory authorities (along with action(s) required, affected medium, and authorizing/implementing agency) generally related to CO_2 transportation, site selection, and CO_2 storage for additional review and consideration.

Table 4-4. Summary of U.S federal regulations potentially applicable to Japan-Alaska CO_2 transportation and offshore storage

Applicability	Regulation/Law	Oversight	More Information
Transportation (intrastate Alaska) by vessel or pipeline	Hazardous Materials and Transportation Act (HMTA)	U.S. Department of Transportation	[266]
Transportation	Ocean Shipping Reform Act and FMC Statutes	Federal Maritime Commission (FMC)	[250]
Transportation (cargo handling and terminal operations)	Ports and Waterways Safety Act of 1972 (PWSA) and Marine Transportation Security Act of 2002 (MTSA)	U.S. Coast Guard (USCG)	[252], [253]
Transportation	Merchant Marine Act of 1920 (Jones Act)	Customs and Border Protection (CBP)	[258]
Transportation	Act to Prevent Pollution from Ships (APPS)	U.S. Environmental Protection Agency (EPA), USCG	[260]
Transportation and storage	Safe Drinking Water Act (SDWA)	EPA	[152]
Transportation and storage	Resource Conservation and Recovery Act (RCRA)	EPA	[275]
Transportation and storage	Outer Continental Shelf Lands Act (OCSLA)	U.S. Department of the Interior, Bureau of Ocean Energy Management (BOEM), and Bureau of Safety and Environmental Enforcement (BSEE)	[267]
Transportation and storage	Rivers and Harbors Act (RHA)	USACE	[271]
Transportation and storage	National Environmental Policy Act (NEPA)	Multiple	[273]
Transportation and storage	Fixing America's Surface Transportation (FAST) Act	Federal Permitting Council; various	[299]
Transportation and storage	Clean Air Act (CAA)	EPA	[280]
Transportation and storage	Clean Water Act (CWA)	EPA	[281]
Transportation and storage	Coastal Zone Management Act (CZMA)	U.S. Department of Commerce (DOC), NOAA, Office for Coastal Management, Alaska state agencies	[283]
Surface water bodies and forested areas	Fish and Wildlife Conservation Act (FWCA)	DOI, FWS; Alaska state wildlife agencies	[286]
Surface water bodies and forested areas	Endangered Species Act	DOI, FWS; DOC, NOAA Fisheries	[287]
Oceans in U.S. jurisdiction	Marine Mammals Protection Act (MMPA)	DOC, NOAA Fisheries	[300]
Site characterization	Migratory Bird Treaty Act of 1918; Bald and Golden Eagle Protection Act of 1940	DOI, FWS	[289]
Native American	Antiquities Act of 1906/ARPA/NAGPRA/ Indian Religious Freedom Act	Various	[297]

4.5 ALASKAN STATE LAWS

4.5.1 Alaska House Bill 50

House Bill 50 was signed into law on July 31, 2024, by Governor Mike Dunleavy [301]. It combines new regulations/incentives for "carbon storage, new regulation of natural gas storage, state financing for new Cook Inlet natural gas development and an expansion of the state's geothermal energy program" [301]. The carbon storage portion of the bill empowers AOGCC to regulate storage of CO_2 on all lands in the state and enables DNR to lease state lands for geologic storage and issue right-of-way leases for CO_2 transportation pipeline. The bill allows for setting fiscal terms and addresses long-term monitoring. A major impetus of the bill was to set up a regulatory and commercial framework for Alaska to perform carbon storage, with potential for significant revenue-earning opportunities.

House Bill 50 requires that the CO_2 to be stored be of a quality that will not compromise geologic storage and will not compromise the properties of a storage reservoir that allow the reservoir to effectively enclose and contain a stored gas or stored supercritical fluid. Also, it is noted that the injection of CO_2 and substances commonly associated with CO_2 injection is not considered waste, as waste disposal in reservoirs is historically prohibited in Alaska. This functional requirement does not provide specific purity requirements for CO_2, but it is expected that additional clarifications will emerge as a function of intended storage reservoir and operating conditions or that the evaluation of CO_2 purity will be reviewed on a case-by-case basis. Generally, this requirement is not expected to prevent LCO_2 shipping for the purpose of long-term geologic storage in the context of this study. In fact, House Bill 50 supports storage of CO_2 in Alaska because it sets forth regulatory requirements and fiscal terms for storage, decreasing uncertainty in project planning, economic analysis, and funding. Additional noteworthy aspects of House Bill 50 include barring companies from offsetting state O&G production taxes with carbon storage costs and requiring 50 percent of revenue of carbon storage leasing to go to the Alaska Permanent Fund.

4.5.2 Alaska State Laws Summary

Table 4-5 summarizes Alaska state laws and regulations covered in this initial screening assessment and is considered to be non-exhaustive.

Table 4-5. Summary of Alaska state regulations potentially applicable to Japan-Alaska CO_2 transportation and offshore storage

Applicability	Regulation/Law	Oversight	More Information
Construction/ operational activities	Certification and Antidegradation Analysis	Alaska Department of Environmental Conservation Water	[302]
Construction/ operational activities	Prevention of Significant Deterioration Permit Minor or Major Source	Alaska Department of Natural Resources, Division of Air Quality	[303]

Applicability	Regulation/Law	Oversight	More Information
Construction/ operational activities	Title 16 Fish Habitat Permit	Alaska Department of Fish and Game	[304]

4.6 International Design Codes

4.6.1 International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk

IMO's International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) [151] has been in effect since 1986. The IGC Code applies to vessels engaged in carriage of liquefied gases having a vapor pressure exceeding 2.8 bar absolute at a temperature of 37.8 °C (applies to CO_2). The aim of the IGC Code is to "provide an international standard for the safe carriage by sea in bulk of liquefied gases by prescribing the design and construction standards of ships involved in such carriage and the equipment they should carry so as to minimize the risk to the ship and to its crew and to the environment" [209]. The American Bureau of Shipping (ABS) has issued design requirements for LCO_2 carriers that are informed by IMO's international standards [305], [95], published as "Requirements for Liquefied Carbon Dioxide Carriers." According to ABS, this is the "first publication available in the maritime industry dedicated to the design, construction, and classification of LCO_2 carriers where liquefied CO_2 is carried as cargo" [306].

Within these standards, there is possible reference to CO_2 reliquefaction to address the issue of fugitive emissions from the LCO_2 cargo storage tanks. Although it is not apparent that any regulations require this, there is interest in CO_2 cargo handling and reliquefaction, as it's generally good practice to minimize GHG emissions.

4.6.2 Maritime Standards/Design Guidance and Standards Due Diligence

LCO_2 carrier transport is subject to international technical and safety regulations stipulated by classification societies. Examples of some of the largest classification societies include DNV, ABS, ClassNK, and Lloyd's Register. To illustrate the role of classification societies, DNV supports innovations in LCO_2 carrier design; while low and medium pressure is handled within the current regulatory regime, the parameters for transporting CO_2 under high pressure go somewhat outside the current IGC Code. DNV has studied and made recommendations accordingly [208].

ABS and Japan's ClassNK are active in classifying vessels that are being developed for long-distance ocean voyages and may travel in a potential Japan-Alaska LCO_2 shipping corridor. They have jointly provided Approval-in-Principle certification for two LCO_2 carrier low-pressure vessel types, a 50,000 m^3-class and a 23,000 m^3-class [307].

The purpose of the Society of International Gas Tanker and Terminal Operators (SIGTTO) is to "promote shipping and terminal operations for liquefied gases which are safe, environmentally responsible and reliable"; historical focus was on LNG/LPG, but in 2024, SIGTTO published guidance for carriage of LCO_2 in the publication, “Carbon Dioxide Cargo on Gas Carriers” [308]. This document provides detailed guidance for vessel systems and practices for carriers.

Additionally, seven major shipbuilders in Japan have started a joint study to establish standard specifications and designs for LCO_2 carriers and to establish a construction supply chain [309]. This study assumes that the first large Japanese LCO_2 vessels are under construction by 2027, with large-scale international marine transport of LCO_2 by 2028 [310]. When they become available, the study results should be reviewed and compared to other standards for possible relevance and potential application to a Japan-Alaska LCO_2 shipping corridor.

4.7 PERMITTING SCENARIO – LCO_2 RECEIVING TERMINAL

As discussed in Section 2.1, there are a multitude of design configurations in the value chain of a CO_2 shipping operation. As a way to understand which regulations and permitting requirements might need to be met, the regulatory process for the LNG facility portion of the Alaska LNG project can be used as an analog [311]. Depending upon which of the design configurations is selected, the LCO_2 project may require an onshore terminal and facility similar to that of the Alaska LNG project. The LCO_2 terminal is built at an Alaskan port with intermediate storage tanks to receive the CO_2 from Japan that is sent via pipeline to the geologic storage facility. A similar CCS project, Northern Lights near Øygarden in western Norway, was completed in September 2024, with operations soon to be underway. The LCO_2 storage tanks can be seen on the left in Figure 4-2, and the port jetty is center right.

Figure 4-2. Northern Lights facilities

Used with permission from Northern Lights [312]

4.7.1 Alaska LNG Project

The Alaska LNG project, being developed by the Alaska Gasline Development Corporation, is to deliver on average about 3.5 billion cubic feet of gas per day, with approximately 75 percent from Prudhoe Bay and 25 percent from the Point Thomson, North Slope gas fields. The gas is planned to be cleaned, dehydrated, and compressed in a facility to be built near Prudhoe Bay and transported via a new 42-inch diameter, 800-mile pipeline to an LNG liquefaction facility to be built in Nikiski in the Southcentral region that will process, store, and transport up to 20 Mt of LNG/yr.

The Alaska LNG Terminal facility at Nikiski, as planned, includes three liquefaction trains, two 240,000 m^3 storage tanks, terminal auxiliary and supporting facilities and marine services, and two loading berths to accommodate LNG export carriers [311]. Additionally, the Terminal would incorporate gas treatment facilities to remove mercury, water, and heavy hydrocarbons that the North Slope Gas Treatment Plant cannot remove. The Alaska LNG Terminal would also have its own on-site power generation facility.

4.7.2 Alaska LNG Project Regulatory Process

An EIS was prepared for the Alaska LNG project because, under the Natural Gas Act, the Federal Energy Regulatory Commission (FERC) is responsible for issuing licensing for new natural gas infrastructure and is also required to conduct an environmental review. While FERC has no responsibility for licensing new LCO_2 infrastructure or conducting an environmental review, the Alaska LNG Project EIS provides insight into the potential permitting characteristics that may be applicable to a new LCO_2 terminal in Alaska.

The scope of the Alaska LCO_2 project is smaller than that of the proposed LNG project. The major aspects of the Alaska LNG project are illustrated in Figure 4-3. The similarity is that the Alaska LCO_2 project plans to build and operate an LCO_2 import facility and a marine terminal, similar to what is depicted in the left portion of the figure as “Alaska LNG Facility.”

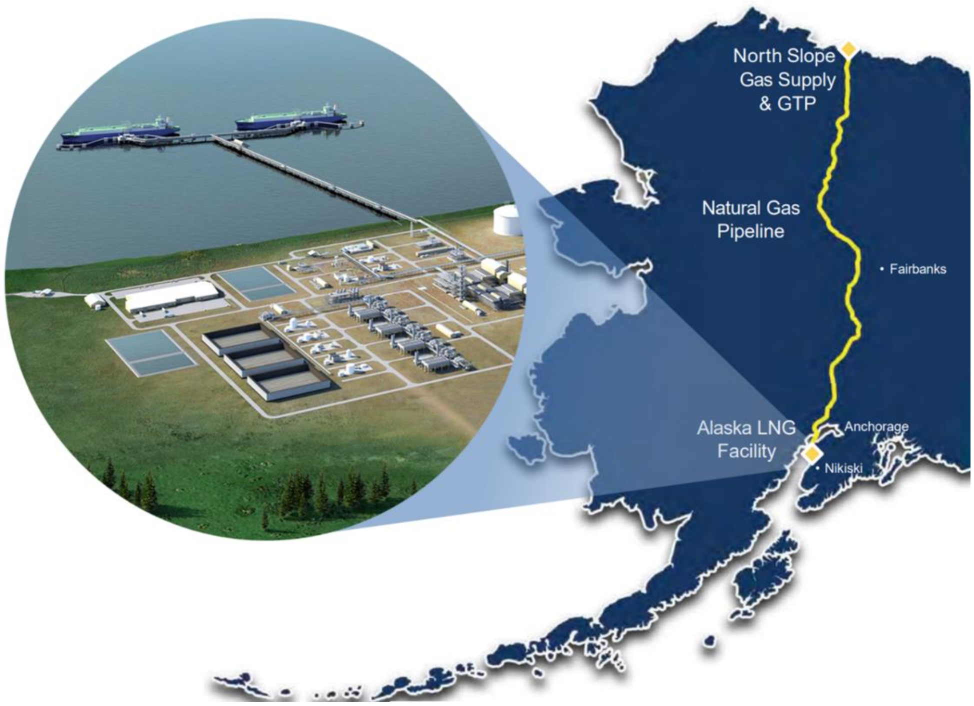


Figure 4-3. Alaska LNG project

Used with permission from AGDC [313]

The timetable for the environmental review and permitting processes for the Alaska LNG Project, which was completed on September 16, 2020, is illustrated in Figure 4-4.

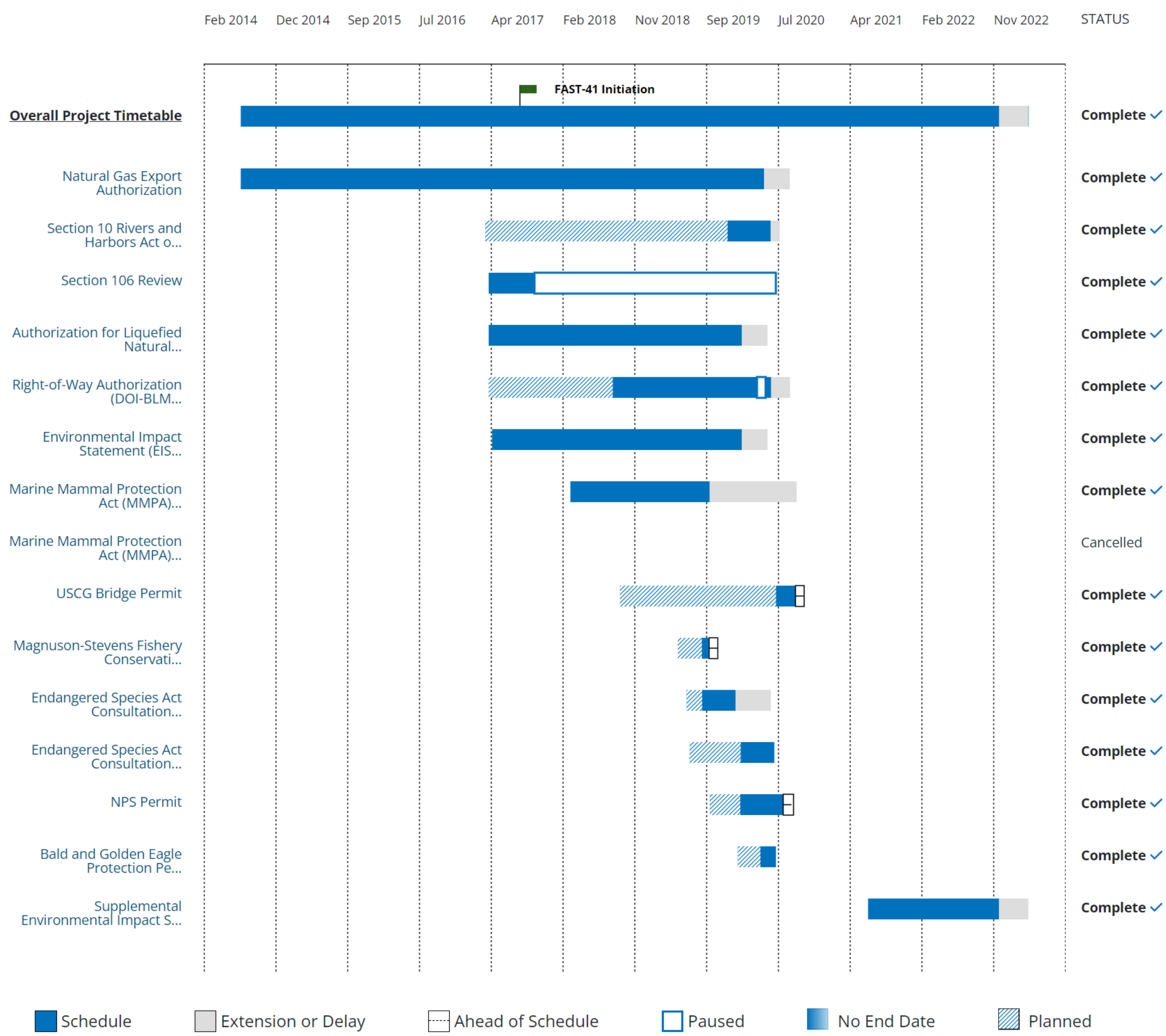


Figure 4-4. Alaska LNG project permitting timetable [314]

Source: Federal Infrastructure Permitting Dashboard [315]

The applicable permits for the LCO_2 terminal and jetty scenario might include those shown in Table 4-6.

Table 4-6. Applicable permits for the LCO_2 terminal and jetty scenario

Permit	Responsible Agency	Bureau
Section 10 RHA and Section 404 CWA	Department of the Army	USACE – Regulatory
EIA	FERC	FERC
MMPA Incidental Take Authorization	DOC – NOAA/National Marine Fisheries Service	NOAA
USCG Permit	Department of Homeland Security	USCG
Magnuson-Stevens Fishery Conservation and Management Act, Section 305 Essential Fish Habitat Consultation	DOC	NOAA
Endangered Species Act Consultation (National Marine Fisheries Service)	DOC	NOAA

4.8 Other Potential Sources of Relevant Permitting Information

DOE provides funding opportunities to support research and development of CO_2 transportation projects. The announcement of projects selected under DE-FOA-0002730 "BIL: Carbon Capture Technology Program, Front-end Engineering and Design for Carbon Dioxide (CO_2) Transport" are funded to support and accelerate the planning for CO_2 transport by various modes, including marine transportation by vessel or barge. Although these projects are currently in process and results have not yet been presented, the results of the FEED studies may include regulatory processes and procedures for LCO_2 terminal and vessel permitting in the United States which could further inform the study of CO_2 shipping between Japan and Alaska [316].

4.8.1 Key Findings

Key findings from the regulatory landscape review are as follows:

- Among various international laws, agreements, and treaties, the London Protocol creates a consideration applicable to the potential export of LCO_2 from Japan to the United States for sequestration in geologic formations in submerged lands beneath U.S. waters. The London Protocol includes an export prohibition applicable to LCO_2 but, provided that Japan deposits a declaration of provisional application of a 2009 London Protocol amendment with the International Maritime Organization, Japan and the United States can enter into an agreement or arrangement to confirm and allocate permitting responsibilities enabling potential export.
- In the near term, offshore CCS development may be permitted in state waters while regulations for the OCS are in development. In the long term, it is anticipated that the expansion of carbon sequestration activities on OCS regions is feasible once rulemaking processes are complete.

- Carbon sequestration of Japan's exported LCO_2 streams at terrestrial locations in Alaska would be subject to federal Safe Drinking Water Act requirements for deep well injection.
- For potential LCO_2 shipping projects, permitting an LCO_2 vessel and associated import terminal would be a first-of-a-kind activity for LCO_2 transportation in the United States. Federal laws and regulations are in place to support such reviews spanning federal agencies including, but not limited to, USCG, EPA, and USACE, among others based on individual project scope and location details.
- NEPA reviews may be required if (1) CO_2 transport or storage activities/actions are on or require passage across federal lands, (2) construction of any structure or alterations is in or over any navigable U.S. waters; (2) major modifications of or a new pier for CO_2 offloading is needed; or (4) NEPA requires that federal agencies prepare an EIS for "every recommendation or report on proposals for legislation and other major Federal actions significantly affecting the quality of the human environment" [317]. Similar types of industrial and energy-related projects can be used as starting analogs to support early project development and regulatory planning purposes [54].
- Engaging local communities early in the regulatory process is essential to facilitate applicable regulatory reviews at the federal and state level.

The shipment, delivery, and offloading of LCO_2 from a Japanese export terminal to an Alaskan import terminal for the purposes of geologic storage with a Japanese LCO_2 carrier does not violate the Jones Act provided the vessel returns to the Japan export terminal empty (i.e., in ballast conditions). More complex shipping routing and cargo configurations should be further evaluated on a case-by-case basis.

5 CONCLUSIONS

This assessment provides a screening-level examination of the various technical, economic, and regulatory aspects of CCUS value chain configurations that consider transpacific shipping of LCO_2 from Japan to the state of Alaska via bulk liquid carriers. The findings described throughout the report provide insights into vessel technology and maturation levels, conditions for shipping corridors and offloading and disposition options in Alaska, economic considerations, and navigation of the regulatory landscape.

Key findings from on technical and economic assessment indicate that the LCO_2 shipping value chain involves interdependent components, including loading terminals, vessels, and offloading infrastructure, categorized by low, medium, and high pressure/temperature (P/T) systems. Shipping configurations include ship-to-shore, ship-to-platform, and direct injection to subsea geologic storage from vessels. Each configuration presents its own unique advantages and challenges. Ship-to-shore option requires terminals with sufficient water depth for vessels to navigate and dock. Ship-to-platform can borrow designs similar to oil and gas operations. Direct injection likely requires CO_2 conditioning equipment and incurs longer offloading time. Among Alaska's five regions, the Southcentral region stands out for its infrastructure, storage potential, and year-round port accessibility. The Southeastern region offers similar benefits but with higher relative uncertainty in geologic storage and longer shipping distance. Challenges in the North Slope region include sea ice and shallow waters, while the Aleutian Islands and Western Coast regions have limited infrastructure and will require significant data collection to assess feasibility due to increased relative uncertainty in prospective storage resources and limited infrastructure.

Technologies like bulk liquid handling, storage, and some parts of liquefaction are mature across all pressure conditions, but offshore offloading and vessel designs remain in development. Commercial, small-scale, medium-PT vessels are currently in use but may not be economical for long-distance transport, while low-pressure vessels show long-term promise for scalability based on LPG and LNG shipping experience. High-pressure vessels (TRL 3) are still in early-stage development, which limits their immediate feasibility. Based on this screening-level assessment, the most economical scenario for transporting 1 Mt/yr is an onshore offloading configuration utilizing two 30,000-ton low-P/T vessels, with an estimated lifetime levelized shipping cost of $52/ton. Given the Class 5 cost estimate classification, which corresponds to an uncertainty range of -50% to +100%, a detailed comparison of costs across onshore terminal, direct injection, and offshore platform configurations under low-, medium-, and high-P/T regimes indicate the following:

- Offloading to Onshore Terminal:
    - Low P/T: $74tonne (range: $37–$148/tonne)
    - Medium P/T: $121/tonne (range: $60–$241/tonne)
    - High P/T: $225/tonne (range: $113–$451/tonne)
- Offloading to Direct Injection:
    - Low P/T: $84/tonne (range: $42–$168/tonne)

  - Medium P/T: $138/tonne (range: $69–$276/tonne)
  - High P/T: $251/tonne (range: $125–$502/tonne)
- Offloading to Offshore Platform:
  - Low P/T: $93/tonne (range: $46–$186/tonne)
  - Medium P/T: $140/tonne (range: $70–$279/tonne)
  - High P/T: $244/tonne (range: $122–$489/tonne)

The analysis, based on publicly available information provided through the 2018 U.K. BEIS CO_2 Shipping Cost Tool developed by Element Energy, demonstrates that low P/T systems consistently offer the lowest costs across all configurations. Costs increase significantly in medium- and high P/T regimes, particularly for offloading to direct injection and offshore platform configurations.

Review of the regulatory landscape suggests that transpacific shipping of CO_2 from Japan to Alaska can be made operational within the established international regulatory framework for the maritime bulk liquid shipping industry and geologic carbon storage. In particular, an amendment to the London Protocol, should it enter into force in the future or should a declaration of provisional application be deposited by Japan, may enable the potential export of LCO_2 from Japan to the United States for sequestration in geologic formations in submerged lands beneath U.S. territory, provided that Japan and the United States establish a necessary bilateral agreement confirming and allocating permitting responsibilities and adhere to applicable regulatory requirements. New rulemaking by U.S. regulators to establish regulations for CO_2 sequestration in geologic formations below the OCS are under development, and such locations (as well as terrestrial injection locations) should be additionally considered and incorporated once available.

Overall, the findings from this screening-level assessment suggest a number of activities for consideration in a future study. These considerations include the following:

- **Conduct a Techno-Economic Analysis (TEA)** – The key findings summarized above could be used as criteria for a detailed, project-specific TEA to identify and compare the most promising CCUS value chain configurations for near-term implementation. This could be mutually beneficial to the U.S. and Japan in their pursuit of collaborative solutions for achieving a global low-carbon economy.
- **Conduct a Lifecycle Analysis (LCA)** – The project-specific TEA could be complemented with an LCA to estimate the total emissions of transportation and handling processes from the capture point in Japan to the geologic storage site in Alaska. The LCA could demonstrate the actual benefit of CO_2 stored after accounting for all other CO_2 emissions sources within the project-specific CCUS value chain.
- **Perform Advanced Studies of Legal and Commercial Criteria** – Detailed studies on legal frameworks and potential commercial arrangements could be performed to aid in developing mutually beneficial CCUS business models and addressing regulatory challenges. This could include expanding the regulatory assessment to consider CO_2 utilization and conversion pathways.

REFERENCES

[1] IPCC, "Global Warming of 1.5°C," 12 March 2020. [Online]. Available: www.ipcc.ch/sr15/download. [Accessed 20 March 2022].

[2] IEAGHG, "CCS in Energy and Climate Scenarios," Cheltenham, United Kingdom, July 2019.

[3] IEA, "Energy Technology Perspectives 2020," OECD Publishing, Paris, France, 2020.

[4] IEA, "CCUS in Clean Energy Transitions: Report extract - CCUS in the transition to net-zero emissions," IEA, 2020. [Online]. Available: https://www.iea.org/reports/ccus-in-clean-energy-transitions/ccus-in-the-transition-to-net-zero-emissions. [Accessed 8 November 2023].

[5] Ministry of Foreign Affairs of Japan, "Japan-U.S. Climate Partnership on Ambition, Decarbonization, and Clean Energy," Undated. [Online]. Available: https://www.mofa.go.jp/files/100178075.pdf. [Accessed 16 July 2024].

[6] The White House, "FACT SHEET: U.S.- Japan Climate Partnership," 23 May 2022. [Online]. Available: https://www.whitehouse.gov/briefing-room/statements-releases/2022/05/23/u-s-japan-climate-partnership-fact-sheet/. [Accessed 16 July 2024].

[7] Alaska Division of Oil and Gas, "Carbon Capture, Utilization & Storage Act (CCUS)," Undated. [Online]. Available: https://www.akleg.gov/basis/get_documents.asp?session=33&docid=567. [Accessed 26 July 2024].

[8] S. Milkowski, "Alaska legislators give closer look at bill aimed at storing carbon emissions underground," Alaska Beacon, 19 February 2024. [Online]. Available: https://alaskabeacon.com/2024/02/19/alaska-legislators-give-closer-look-at-bill-aimed-at-storing-carbon-emissions-underground/. [Accessed 26 July 2024].

[9] NPC, "Chapter Two: CCUS Supply Chains and Economics," in Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage, National Petroleum Council, 2021.

[10] D. Vikara, C. Shih, A. Guinan, S. Lin, A. Wendt, T. Grant and P. Balash, "Assessing Key Drivers Impacting the Cost to Deploy Integrated CO2 Capture, Utilization, Transportation, and Storage (CCUS)," in *36th USAEE/IAEE North American Conference*, Washington, D.C., September 23–26, 2018.

[11] J. Pires, F. Martins, M. Alvium-Ferraz and M. Simões, "Recent developments on carbon capture and storage: An overview," *Chemical Engineering Research and Design,* vol. 89, p. 1446–1460, 2011.

[12] C. Shih, S. Lin, M. Milligan, A. Wendt, M. Marquis, J. Eppink and T. Grant, "Benefit Analysis of CO2 Delivery Options for Offshore Storage or Enhanced Oil Recovery," NETL, Pittsburgh, Pennsylvania, DOE/NETL-2022/3792, 2022.

[13] Chiyoda Corporation, "Preliminary Feasibility Study on CO2 Carriers for Ship-based CCS," Global CCS Institute, 2011.

[14] S. Roussanaly, G. Bureau-Cauchois and J. Husebye, "Costs benchmark of CO2 transport technologies for a group of various size industries," *International Journal of Greenhouse Gas Control,* vol. 12, p. 341–350, 2013.

[15] A. Reyes-Lúa, Y. Arellano, I. Røe, T. Wildenborg and K. Jordal, "CO_2 ship transport: Benefits for early movers and aspects to consider," European Union, EU CCUS PROJECTS NETWORK (No ENER/C2/2017-65/SI2.793333), 2021.

[16] K. Orchard, "CO2 transport: The role of CO2 shipping," in *UK CCS Research Centre Workshop*, Octobrer 12, 2019.

[17] S. Topham, A. Bazzanella, S. Luhr, L. Zhao, A. Otto and D. Stolten, "Carbon Dioxide," in *Ullmann's Encyclopedia of Industrial Chemistry*, Weinheim, Wiley-VCH Verlag GmbH & Co. KGaA, 2014, p. 43.

[18] Clarkson PLC, "Liquid CO2 carriage by sea: an introduction," Clarkson PLC, 29 June 2022. [Online]. Available: https://www.clarksons.com/home/news-and-insights/2022/liquid-co2-carriage-by-sea-an-introduction/. [Accessed 02 July 2024].

[19] Splash 247.com, "Shipping of carbon dioxide readies to go mainstream," Splash Extra, 27 September 2023. [Online]. Available: https://splash247.com/shipping-of-carbon-dioxide-readies-to-go-mainstream/. [Accessed 25 June 2024].

[20] S. Parker, "New wave of LCO2 ships emerges, but ports remain a bottleneck," Riviera, 14 April 2024. [Online]. Available: https://www.rivieramm.com/news-content-hub/news-content-hub/new-wave-of-lco2-ships-emerges-but-ports-remain-a-bottleneck-80312. [Accessed 25 June 2024].

[21] H. A. Haugen, N. H. Eldrup, A. M. Fatnes and E. Leren, "Commercial capture and transport of CO2 from production of ammonia," *Energy Procedia,* vol. 114, p. 6133–6140, 2017.

[22] G. Notaro, J. Belgaroui, K. Marak, R. Tverra, S. Burthom and E. M. Sorhaug, "CETO: Technology qualification of low-pressure CO2 ship transport," in *16th International Conference on Greenhouse Gas Control Technologies, GHGT-16*, Lyon, France, October 23–27, 2022.

[23] Northern Lights, "About the Longship project," Undated. [Online]. Available: https://norlights.com/about-the-longship-project/. [Accessed 11 June 2024].

[24] Acorn, "Acorn project signs MoU with Uniper to ship and store captured CO_2," 14 December 2023. [Online]. Available: https://www.theacornproject.uk/news-and-events/acorn-project-signs-mou-with-uniper-to-ship-and-store-captured-co2. [Accessed 11 June 2024].

[25] Fluxys, "CO_2, much more than a greenhouse gas," 2024. [Online]. Available: https://www.fluxys.com/en/co2#/. [Accessed 11 June 2024].

[26] Carbon Capture & Storage Association and Zero Emissions Platform, "Achieving a European market for CO2 transport by ship," 2024.

[27] Offshore Energy, "Northern Lights' first LNG-fueled LCO2 carrier wraps up sea trials," 6 September 2024. [Online]. Available: https://www.offshore-energy.biz/northern-lights-first-lng-fueled-lco2-carrier-wraps-up-sea-trials/. [Accessed 26 November 2024].

[28] Mizuho Financial Group, "The Path for the Development of CCS in Japan," Mizuho Bank Industry Research Department, Tokyo, Japan, 2023.

[29] Det Norske Veritas, "CO2 Efficient Transport via Ocean - CETO," Undated. [Online]. Available: https://www.dnv.com/maritime/jip/ceto/background/. [Accessed 25 July 2024].

[30] H. Al Baroudi, A. Awoyomi, K. Patchigolla, K. Jonnalagadda and E. Anthony, "A review of large-scale CO2 shipping and marine emissions management for carbon capture, utilisation and storage," *Applied Energy,* vol. 287, p. 42, 2021.

[31] M. Schuler, "New Details on the World's Largest Liquid CO2 Carriers," gCaptain, 21 July 2023. [Online]. Available: https://gcaptain.com/new-details-on-the-worlds-largest-liquid-co2-carriers/. [Accessed 25 July 2024].

[32] Baird Maritime, "VESSEL REVIEW | Excool – Japanese partnership delivers liquefied CO2 carrier demonstrator," 6 March 2024. [Online]. Available: https://www.bairdmaritime.com/shipping/gas/vessel-review-excool-japanese-partnership-delivers-liquefied-co2-carrier-demonstrator. [Accessed 25 July 2024].

[33] G. Dixon, "Evangelos Marinakis' Capital Maritime splashes $145m on world's biggest CO2 carriers at Hyundai Mipo," TradeWinds, 19 July 2023. [Online]. Available: https://www.tradewindsnews.com/gas/evangelos-marinakis-capital-maritime-splashes-145m-on-world-s-biggest-co2-carriers-at-hyundai-mipo/2-1-1488763. [Accessed 25 July 2024].

[34] C. Lambton, "Northern Lights - Presentation and status update," Northern Lights, 27 June 2022. [Online]. Available: https://fossil.energy.gov/archives/cslf/sites/default/files/documents/Bergen2022/Northern-Lights_CSLF-Bergen-2022.pdf. [Accessed 25 July 2024].

[35] The Maritime Executive, "Hanwha Ocean Launches Partnership Competing in Design Race for LCO2 Carrier," 22 September 2023. [Online]. Available: https://maritime-executive.com/article/hanwha-ocean-launches-partnership-competing-in-design-race-for-lco2-carrier. [Accessed 25 July 2024].

[36] M. Buitendijk, "HGK develops inland tanker for shipping ammonia and LCO2," SWZ Maritime, 18 April 2024. [Online]. Available: https://swzmaritime.nl/news/2024/04/18/hgk-develops-inland-tanker-for-shipping-ammonia-and-lco2/. [Accessed 25 July 2024].

[37] Tanker Operator, "GCMD/BCD report on maritime CO2 transportation market," Tanker Operator, 2024.

[38] S. C. Kuttan, E. K. Koh, C. Clayton, D. Sivaprasad, A. Veeraraghavan, S. Mohottala and C. Khaing, "Opportunities for Shipping to Enable Cross-Border CCUS Initiatives," Global Centre for Maritime Decarbonisation, Singapore, 2024.

[39] K. Hirata, C. Watanabe and H. Mizota, "What's GX?," Climate Integrate, January 2024. [Online]. Available: https://climateintegrate.org/wp-content/uploads/2024/01/Whats-GX_EN.pdf.

[40] Prime Minister's Office of Japan, "GX Implementation Council (The Prime Minister in Action)," 27 July 2022. [Online]. Available: https://japan.kantei.go.jp/101_kishida/actions/202207/_00021.html. [Accessed 15 July 2024].

[41] M. Fukishima and H. Konno, "Japan’s CCS Bill in Brief," Lexology, 6 March 2024. [Online]. Available: https://www.lexology.com/library/detail.aspx?g=cc91231d-f000-41d0-9552-9bb8492451b8. [Accessed 25 July 2024].

[42] A. Clarke and A. Takamatsu, "Japan takes a step forward passing key hydrogen and CCS Acts," Norton Rose Fulbright, 28 May 2024. [Online]. Available: https://connections.nortonrosefulbright.com/post/102j8m6/japan-takes-a-step-forward-passing-key-hydrogen-and-ccs-acts. [Accessed 21 August 2024].

[43] GR Japan, "Overview of Japan's Green Transformation," January 2023. [Online]. Available: https://grjapan.com/sites/default/files/content/articles/files/gr_japan_overview_of_gx_plans_january_2023.pdf. [Accessed 15 July 2024].

[44] IEA, "CCS Long-Term Roadmap," 8 June 2023. [Online]. Available: https://www.iea.org/policies/17537-ccs-long-term-roadmap. [Accessed 25 July 2024].

[45] K. Senoo and M. Uga, "Policies for Carbon Capture and Storage (CCS) in Japan and overview of CCS under the Joint Crediting Mechanism (JCM)," 28 June 2023. [Online]. Available: https://www.nies.go.jp/gio/wgia/turhqd000002mtza-att/IV-5_MoEJ.pdf. [Accessed 15 July 2024].

[46] N. Saeki, "Japan's Long-Term Roadmap," Ministry of Economy, Trade and Industry, Undated. [Online]. Available: https://www.asiaccusnetwork-eria.org/s/S3-3_Saeki_230924_%E3%80%90ACNF3%E3%80%91%20Japan's%20Long-Term%20Roadmap.pdf. [Accessed 25 July 2024].

[47] Japan Organization for Metals and Energy Security, "Advanced Efforts for Commercialization of CCS - JOGMEC selects nine projects as Japanese Advanced CCS Projects," JOGEC, 24 July 2024. [Online]. Available: https://www.jogmec.go.jp/english/news/release/news_10_00072.html. [Accessed 26 July 2024].

[48] Japan Organization for Metals and Energy Security, "Outline of projects selected for "Design work related to advanced CCS projects" in FY6 of Reiwa (hereinafter described from north to south)," 28 June 2024. [Online]. Available: https://www.jogmec.go.jp/content/300390317.pdf. [Accessed 22 July 2024].

[49] V. Velev, "Japan Selects Nine Carbon Capture Projects for Development," Carbon Herald, 5 July 2024. [Online]. Available: https://carbonherald.com/japan-selects-nine-carbon-capture-projects-for-development/. [Accessed 24 July 2024].

[50] T. Kumagai, "Japan set for world's first transport of liquefied CO2," S&P Global, 26 April 2024. [Online]. Available: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/042624-japan-set-for-worlds-first-transport-of-liquefied-co2. [Accessed 29 July 2024].

[51] Japan CCS Co., Ltd., "Startup of the liquified CO2 ship transportation demonstration project," 19 August 2024. [Online]. Available: https://www.japanccs.com/wp/wp-content/uploads/2024/08/20240819-oshirase_JCCS-NGL_EN.pdf. [Accessed 5 September 2024].

[52] The Maritime Executive, "Japan Completes Construction of First Demonstration LCO2 Transport Vessel," 28 November 2023. [Online]. Available: https://maritime-executive.com/article/japan-completes-construction-of-first-demonstration-lco2-transport-vessel. [Accessed 29 July 2024].

[53] Ministry of Economy, Trade and Industry, "The Basic Policy for the Realization of GX - A roadmap for the next 10 years - Provisional Translation," February 2023. [Online]. Available: https://www.meti.go.jp/english/press/2023/pdf/0210_003a-2.pdf. [Accessed 09 July 2024].

[54] Asia CCUS Network, "Asia CCUS Network Homepage," 2021. [Online]. Available: https://www.asiaccusnetwork-eria.org/. [Accessed 31 July 2024].

[55] Clean Air Task Force, "U.S. Carbon Capture Activity and Project Map," 3 August 2023. [Online]. Available: https://www.catf.us/ccsmapus/. [Accessed 15 July 2024].

[56] Global CCS Institute, "Global Status of CCS 2023 - Scaling up through 2030," Melbourne, Australia, 2023.

[57] NETL, "NATCARB Viewer (2.0)," 2015. [Online]. Available: https://edxspatial.arcgis.netl.doe.gov/maps/edxspatial-natcarb-index.html. [Accessed 8 July 2024].

[58] "DOE Fact Sheet: The Bipartisan Infrastructure Deal Will Deliver For American Workers, Families and Usher in the Clean Energy Future," DOE, 9 November 2021. [Online]. Available: https://www.energy.gov/articles/doe-fact-sheet-bipartisan-infrastructure-deal-will-deliver-american-workers-families-and-0. [Accessed 27 December 2024].

[59] Department of Energy (DOE), "Carbon Transport and Storage Multi-Year Program Plan," DOE, Washington, DC, 2024.

[60] The White House, "Inflation Reduction Act Guidebook - Clean Energy," Undated. [Online]. Available: https://www.whitehouse.gov/cleanenergy/inflation-reduction-act-guidebook/. [Accessed 8 November 2023].

[61] Clean Air Task Force, "Carbon Capture and the Inflation Reduction Act," 16 February 2023. [Online]. Available: https://www.catf.us/resource/carbon-capture-inflation-reduction-act/. [Accessed 8 November 2023].

[62] K. Lebling, A. Gangotra, K. Hausker and Z. Byrum, "7 Things to Know About Carbon Capture, Utilization and Sequestration," World Resources International, 13 November 2023. [Online]. Available: https://www.wri.org/insights/carbon-capture-technology. [Accessed 17 June 2024].

[63] NETL, "Carbon Storage Atlas - Fifth Edition (Atlas V)," DOE, Pittsburgh, Pennsylvania, 2015.

[64] EPA, "U.S. Energy-Related Carbon Dioxide Emissions, 2023," 25 April 2024. [Online]. Available: https://www.eia.gov/environment/emissions/carbon/. [Accessed 14 January 2025].

[65] D. Shellenbaum and J. Clough, "Alaska Geologic Carbon Sequestration Potential Estimate: Screening Saline Basins and Refining Coal Estimates," Alaska Department of Natural Resources, Anchorage, Alaska, 2010.

[66] USGS, "Geologic Framework for the National Assessment of Carbon Dioxide Storage Resources–Alaska North Slope and Kandik Basin, Alaska," DOI, Reston, Virginia, 2014.

[67] F. Paskvan, H. Paine, C. Resler, B. Sheets, T. McGuire, K. Connors and E. Tempel, "Alaska CCUS Workgroup and a Roadmap to Commercial Deployment," in *SPE Western Regional Meeting*, Anchorage, Alaska, 2023.

[68] S. o. P. Engineers, "CO2 Storage Resources Management System," July 2017. [Online]. Available: https://www.spe.org/en/industry/co2-storage-resources-management-system/?_gl=1*v7ag8t*_ga*NjI4NzYxNDU1LjE3MTk1MDIzOTY.*_ga_231RWK74JW*MTczNTkzNDUwNi43LjEuMTczNTkzNDc3Mi40Ny4wLjA..

[69] EPA, "State CO2 Emissions from Fossil Fuel Combustion, 1990–2018," U.S. Environmental Protection Agency, Washington, D.C., 2019.

[70] T. Stankova, "DOE Study To Assess Shipping Carbon Emissions From Japan For Storage In Alaska," Carbon Herald, 10 May 2024. [Online]. Available: https://carbonherald.com/doe-study-to-assess-shipping-carbon-emissions-from-japan-for-storage-in-alaska/. [Accessed 6 June 2024].

[71] Institute of Northern Engineering, "Alaska CCUS Workgroup accelerates commercial carbon capture, use, and storage," University of Alaska, Fairbanks, Fairbanks, AK.

[72] National Energy Technology Laboratory (NETL), "Project Landing Page: Bipartisan Infrastructure Law (BIL): Alaska Railbelt Carbon Capture and Storage (ARCCS) Project," National Energy Technology Laboratory (NETL), 2024. [Online]. Available: https://www.netl.doe.gov/projects/project-information.aspx?k=FE0032453. [Accessed 30 December 2024].

[73] DOE, "Project Selections for FOA 2711: Carbon Storage Validation and Testing (Round 3)," Office of Fossil Energy and Carbon Management, Undated. [Online]. Available:

https://www.energy.gov/fecm/project-selections-foa-2711-carbon-storage-validation-and-testing-round-3?utm_medium=email&utm_source=govdelivery. [Accessed 28 October 2024].

[74] NETL, "State of Alaska Initiative to Create a Statewide Carbon Capture, Utilization, and Storage (CCUS) Database," DOE, Undated. [Online]. Available: https://www.netl.doe.gov/project-information?p=FE0032370. [Accessed 16 September 2024].

[75] Alaska State Legislature, "Bill History/Action for Legislature," Alaska State Legislature, 23 May 2023. [Online]. Available: https://www.akleg.gov/basis/Bill/Detail/33?Root=SB%20%2048#tab1_4. [Accessed 30 December 2024].

[76] Alaska Oil and Gas Conversion Commission, "Letter of Intent from Alaska for the Underground Injection Control (UIC) Class VI Grant," Alaska Oil and Gas Conversion Commission, 31 January 2023. [Online]. Available: https://www.akleg.gov/basis/get_documents.asp?docid=1517. [Accessed 30 December 2024].

[77] Y. Rosen, "Alaska Legislature passes carbon-storage bill with additional energy provisions," Alaska Beacon, 16 May 2024. [Online]. Available: https://alaskabeacon.com/2024/05/16/alaska-legislature-passes-carbon-storage-bill-with-additional-energy-provisions/. [Accessed 23 July 2024].

[78] J. Brooks, "Alaska House, seeking to boost oil and gas business, approves carbon storage bill," 18 April 2024. [Online]. Available: https://alaskabeacon.com/2024/04/18/alaska-house-seeking-to-boost-oil-and-gas-business-approves-carbon-storage-bill/. [Accessed 23 July 2024].

[79] S. Grey, E. Shenkman and S. Pickerill, "State Action on CCS Continues in Alaska, Colorado, Illinois, Alabama, and Pennsylvania," Arnold & Porter, 18 July 2024. [Online]. Available: https://www.arnoldporter.com/en/perspectives/blogs/environmental-edge/2024/07/mid-2024-state-ccs-legislative-update. [Accessed 16 September 2024].

[80] FUKY MarinTech, "Permanent Mooring," Undated. [Online]. Available: https://fukymarintech.weebly.com/mooring-types.html. [Accessed 7 October 2024].

[81] EPCM, "SPM Calm Buoy System - The Ultimate Guide," Undated. [Online]. Available: https://epcmholdings.com/spm-calm-buoy-system/. [Accessed 7 October 2024].

[82] G. Rutkowski, "A Comparison Between DP Offshore Loading Operation on Submerged Turret Loading System STL, Submerged Single Anchor Loading System SAL and Offshore Loading System OLS Considering the Hydro-meteorological Condition Limits for the Safe Ship’s Operation Offsh," *International Journal on Marine Navigation and Safety of Sea Transportation,* vol. 13, no. 1, p. 175–185, 2019.

[83] K. Orchard, E. Durusut, R. Skagestad, M. Hay and I. Ombudstvedt, "The Status and Challenges of CO2 Shipping Infrastructures Final Report," IEAGHG, Cheltenham, United Kingdom, 2020.

[84] National Ocean Industries Association, "The Basics of Offshore Oil & Gas," Undated. [Online]. Available: https://www.noia.org/basics-offshore-oil-gas/. [Accessed 7 October 2024].

[85] Global Centre for Maritime Decarbonization, "Landmark study on offloading onboard captured carbon dioxide," 19 March 2024. [Online]. Available: https://www.gcformd.org/landmark-study-on-offloading-onboard-captured-carbon-dioxide/. [Accessed 12 August 2024].

[86] Global Centre for Maritime Decarbonization, "Concept Study to Offload Onboard Captured CO2 - Key Findings and Executive Summary," 2024.

[87] R. Skagestad, A. Mathisen and K. Aas, "CO2 offloading alternatives and guidelines," Everlong CCUS, 2024.

[88] Zero Emissions Platform, CCSA, "Achieving a European market for CO2 transport by ship," 2024.

[89] IEAGHG, "The Status and Challenges of CO2 Shipping Infrastructures," https://ieaghg-publications.s3.eu-north-1.amazonaws.com/Technical+Reports/2020-10+The+Status+and+Challenges+of+CO2+Shipping+Infrastructures.pdf, 2020.

[90] F. Engel and A. Kather, "Improvements on the liquefaction of a pipeline CO2 stream for ship transport," *International Journal of Greenhouse Gas Control,* vol. 72, p. 214–221, 2018.

[91] B. Wetenhall, H. Aghanjani, H. Chalmers, S. D. Benson, M.-C. Ferrari, J. Li, J. M. Race, P. Singh and J. Davison, "Impact of CO2 impurity on CO2 compression, liquefaction, and transportation," *Energy Procedia,* vol. 63, p. 2764–2778, 2017.

[92] N. Kokubun, K. Ko and M. Ozaki, "Cargo Conditions of CO2 in Shuttle Transport by Ship," *Energy Procedia,* vol. 37, p. 3160–3167, 2013.

[93] S. Decarre, J. Berthiaud, N. Butin and J. Guillaume-Combecave, "CO2 maritime transportation," *International Journal of Greenhouse Gas Control,* vol. 4, p. 857–864, 2010.

[94] Det Norske Veritas, "Shipping's future role in carbon capture and storage," DNV, 11 January 2022. [Online]. Available: https://www.dnv.com/expert-story/maritime-impact/Shippings-future-role-in-carbon-capture-and-storage. [Accessed 19 August 2024].

[95] S. Bond, "Ship Design for CO2 Transportation," in *Global Gas Development Science Day*, London, England, 2024.

[96] E. Durusut and M. Joos, "Shipping CO2 - UK Cost Estimation Study Final Report for the UK Department for Business, Energy, & Industrial Strategy (BEIS)," 2018. [Online]. Available:

https://assets.publishing.service.gov.uk/media/5c07a24f40f0b67052a55bf9/BEIS_Shipping_CO2.pdf.

[97] Equinor, "Northern Lights FEED Report RE-PM673-00057," Northern Lights JV DA, 2020.

[98] R. Delpizzo, "CO2 Carriers Safety and Design Aspects," American Bureau of Shipping, October 2022. [Online]. Available: https://usea.org/sites/default/files/event-/ABS%20Presentation%20-%20R%20Delpizzo%2012%20Oct%202022.pdf. [Accessed 29 August 2024].

[99] Zero Emissions Platform and Carbon Capture and Storage Association, "Network Technology Guidance for CO2 transport by ship," ZEP/CCSA Shipping Workgroup, 2022.

[100] CO2 Logistics by Ship Phase II, "CO2LOS II - Final Report with tool box for CCS logistics," Brevik Engineering AS, 2020.

[101] Fire Systems, Inc., "Your Ultimate Guide to Understanding Low Pressure CO2 Systems," 2024. [Online]. Available: https://firesystems.net/2024/06/19/your-ultimate-guide-to-understanding-low-pressure-co2-systems/. [Accessed 3 September 2024].

[102] ASCO, "CO2 Storage - ASCO CO2 Storage Tanks Vacuum Insulated," May 2024. [Online]. Available: https://www.ascoco2.com/fileadmin/PDF_Download/PDF_Produkte/PDF_CO2_und_Trockeneis_Zubehoer/CO2_Lagerung/en/ASCO_Vacuum_Insulated_CO2_Storage_Tanks.pdf. [Accessed 3 September 2024].

[103] IEA, "CO2 Transport and Storage," 25 April 2024. [Online]. Available: https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/co2-transport-and-storage. [Accessed 5 August 2024].

[104] T. Baggio and E. Taylor, "Liquid CO2 carriage by sea: Market movements," Clarksons, 8 October 2022. [Online]. Available: https://www.clarksons.com/home/news-and-insights/2022/liquid-co2-carriage-by-sea-market-movements/. [Accessed 28 August 2024].

[105] Shipspotting, "HELLE - IMO 9201906," Undated. [Online]. Available: https://www.shipspotting.com/photos/3424552?navList=moreOfThisShip&page=1&perPage=8&imo=9201906&lid=3128385. [Accessed 27 August 2024].

[106] Wartsila, "Liquefied CO2 carrier CORAL CARBONIC," 2024. [Online]. Available: https://www.wartsila.com/encyclopedia/term/liquefied-co2-carrier-coral-carbonic. [Accessed 27 August 2024].

[107] LarvikShipping, "M/T Helle," 2023. [Online]. Available: https://www.larvik-shipping.no/helle/. [Accessed 6 September 2024].

[108] LarvikShipping, "M/T Embla," 2023. [Online]. Available: https://www.larvik-shipping.no/embla-3/. [Accessed 28 August 2024].

[109] LarvikShipping, "M/T Gerda," 2023. [Online]. Available: https://www.larvik-shipping.no/gerda-2/. [Accessed 28 August 2024].

[110] Science Japan, "Using low-temperature, low-pressure liquefied CO2 to realize low-cost mass transportation: Demonstration test ship "EXCOOL" completed with expectations for social implementation in the future," Japan Science and Technology Agency, 15 January 2024. [Online]. Available: https://sj.jst.go.jp/news/202401/n0115-02k.html. [Accessed 27 August 2024].

[111] VesselFinder, "EXCOOL CO2 Tanker, IMO 9966336," 2024. [Online]. Available: https://www.vesselfinder.com/vessels/details/9966336. [Accessed 28 August 2024].

[112] MHI, "Liquefied CO2 Carrier "EXCOOL"," Mitsubishi Heavy Industries Technical Review Vol. 61 No. 2, 2024.

[113] Equinor, "EL001 Northern Lights - Receiving and permanent storage of CO2," Stavanger, Norway, 2019.

[114] The Maritime Executive, "Video: First CO2 Carriers Launched in China for Northern Lights Project," 3 April 2024. [Online]. Available: https://maritime-executive.com/article/video-first-co2-carriers-launched-in-china-for-northern-lights-project. [Accessed 25 July 2024].

[115] Equinor, "Northern Lights Project Concept Report," RE-PM673-00001, 2019.

[116] The Maritime Executive, "Capital Gas Advances LCO2 Carrier Operations Adding Onboard Carbon Capture," 5 June 2024. [Online]. Available: https://maritime-executive.com/article/capital-gas-advances-lco2-carrier-operations-adding-onboard-carbon-capture. [Accessed 27 August 2024].

[117] F. Bahtić, "HMD to build world's largest ammonia-ready LCO2 multi-gas carriers," Offshore Energy, 19 July 2023. [Online]. Available: https://www.offshore-energy.biz/hmd-to-build-worlds-largest-ammonia-ready-lco2-multi-gas-carriers/. [Accessed 27 August 2024].

[118] Capital Gas Ship Management, "Capital Gas Ship Management Corp. announces the order of the two first-ever 22,000 cbm liquid CO2 (LCO2) carrier newbuildings.," 20 July 2023. [Online]. Available: https://www.capitalgas.gr/content/media-releases/21-capital-gas-ship-management-corp-announces-the-order-of-the-two-first-ever-22-000cbm-liquid-co2-lco2-carrier-newbuildings. [Accessed 27 August 2024].

[119] Knutsen NYK Carbon Carriers AS, "A LCO2 shipping provider with a wholistic CCS value chain approach," 15 November 2023. [Online]. Available: https://jp.globalccsinstitute.com/wp-content/uploads/sites/3/2023/11/2-8-P9-KNCC-Mr-Anders-Lepsoe.pdf. [Accessed 27 August 2024].

[120] A. Lepsøe, "Introduction of Three Modes of handling LCO2 – A viable option contributing to the realization of a CCS Value Chain," Knutsen NYK Carbon Carriers AS, Global CCS Institute, 4 March 2024. [Online]. Available: https://jp.globalccsinstitute.com/wp-content/uploads/sites/3/2024/03/P1-1.pdf. [Accessed 6 September 2024].

[121] ECOLOG, "Creating the infrastructure where it's needed," 2024. [Online]. Available: https://ecolog.earth/how-we-do-it/. [Accessed 27 August 2024].

[122] A. Larsen, R. Skagestad, K. Knudsen and G. Nysæter, "Ship Design for CO2 Transport - Purpose Made or Multigas Carrier?," in *16th International Conference on Greenhouse Gas Control Technologies, GHGT-16*, Lyon, France, October 23–27, 2022.

[123] Asia-Pacific Economic Cooperation, "Study on Optimal Use of Small-scale Shallow-draft LNG Carriers and FSRUs in the APEC Region," Berkeley Research Group, LLC, Houston, Texas, 2020.

[124] Y. Bai and J. Wei-Liang, "Chapter 4: LNG Carrier," in *Marine Structural Design (Second Edition)*, Oxford, UK, Butterworth-Heinemann, 2016, p. 49–71.

[125] CHIV, "All About LNG," Undated. [Online]. Available: https://ch-iv.com/all-about-lng/. [Accessed 27 August 2024].

[126] LNT Marine, "Large Scale LNG Carrier," LNT, Undated. [Online]. Available: https://lntmarine.com/our-business/lnt-a-box-system/large-scale-lng-carrier/. [Accessed 27 August 2024].

[127] Northern Lights, "News and media archive," Undated. [Online]. Available: https://norlights.com/news-media-and-technical-reports/news-and-media-archive/. [Accessed 14 August 2024].

[128] J. Rodrigue and T. Notteboom, "The Geography of Transport Systems: 6.3 - Port Terminals," Transport Geography, Undated. [Online]. Available: https://transportgeography.org/contents/chapter6/port-terminals/. [Accessed 13 August 2024].

[129] P. Vinet, P. De Buck and J. Vandermeiren, "Air Liquide, Fluxys Belgium and Port of Antwerp-Bruges awarded EU funding for building the Antwerp@C CO2 Export Hub," Chemical Parks in Europe, 12 December 2022. [Online]. Available: https://chemicalparks.eu/news/air-liquide-fluxys-port-of-antwerp-bruges-eu-funding-antwerp-c-co2-export-hub. [Accessed 14 August 2024].

[130] Fluxys, "Antwerp@C CO2 Export Hub," 2024. [Online]. Available: https://www.fluxys.com/en/projects/antwerp-export-hub. [Accessed 14 August 2024].

[131] SIGTTO, "SIGTTO Information Paper No. 15: A Listing of Design Guidelines for Liquefied Gas Terminals (Referencing Ports and Jetties)," Witherby & Co. Ltd., Livingston, UK, 1997.

[132] National Ocean Service, "Tides and Currents," NOAA, Undated. [Online]. Available: https://oceanservice.noaa.gov/navigation/tidesandcurrents/. [Accessed 15 August 2024].

[133] M. Ackiewicz, "Update on CCUS in the United States," in *Maryland Energy Administration on CCUS Workshop*, 2019.

[134] The Oxford Institute for Energy Studies, "Capture Carbon, Capture Value: An Overview of CCUS Business Models," Oxford Institute for Energy Studies, 2024.

[135] M. Ozaki and T. Ohsumi, "CCS from multiple sources to offshore storage site complex via ship transport," *Energy Procedia,* vol. 4, p. 2992–2999, 2011.

[136] T. Grant, A. Guinan, C. Shih, S. Lin, D. Vikara, D. Morgan and D. Remson, "Comparative analysis of transport and storage options from a CO2 source perspective," *International Journal of Greenhouse Gas Control,* vol. 72, p. 175–191, 2018.

[137] D. Morgan, A. Sheriff, M. Mark-Moser, G. Liu, T. Grant, G. Creason, D. Vikara and L. Cunha, "Modeling the Cost of Onshore CO2 Pipeline Transport and Onshore CO2 Saline Storage," in *SPE AAPG SEG CCUS Conference*, Houston, Texas, March 11–13, 2024.

[138] H. Deng, S. Roussanaly and G. Skaugen, "Techno-economic analyses of CO2 liquefaction: Impact of product pressure and impurities," *International Journal of Refrigeration,* vol. 103, p. 301–315, 2019.

[139] K. Orchard, M. Hay, I. Ombudstvedt, R. Skagestad, M. Joos, G. Nysaeter, C. Sjobris, A. Gimnes Jaroy, E. Durusut and J. Craig, "The Status and Challenges of CO2 Shipping Infrastructures," in *Proceedings of the 15th Greenhouse Gas Control Technologies Conference*, Abu Dhabi, UAE, March 15–18, 2021.

[140] S. Bond, "London Convention/Protocol Scientific Groups Science Day Symposium 2024," 18 April 2024. [Online]. Available: https://www.imo.org/en/About/Events/Pages/Science-Day-2024.aspx. [Accessed 16 August 2024].

[141] Knutsen NYK Carbon Carriers AS, "Press release - KNCC," 21 08 2024. [Online]. Available: https://www.kn-cc.com/news/press-release-21-08-2024. [Accessed 21 August 2024].

[142] HGK Shipping, "2024_08_21_PR_HGK_Shipping_Vanguard_EN.pdf," 21 08 2024. [Online]. Available: https://hgkshipping.de/wp-content/uploads/2024/08/2024_08_21_PR_HGK_Shipping_Vanguard_EN.pdf. [Accessed 21 August 2024].

[143] HGK Shipping, "HGK Shipping - Innovatives fluss-seegängiges Gastankschiff / river-seagoing gas tanker „Vanguard“," 21 August 2024. [Online]. Available: https://www.youtube.com/watch?v=8H_Iu-KwSy4. [Accessed 21 August 2024].

[144] HGK Shipping, "Future-oriented pioneering project in inland waterway shipping: HGK Shipping develops Europe’s first gas tanker for transporting cold liquefied ammonia and LCO2," 17 April 2024. [Online]. Available: https://hgkshipping.de/wp-content/uploads/2024/04/2024_04_17_PR_HGK_Shipping_Pioneer_EN.pdf. [Accessed 21 August 2024].

[145] HGK Shipping, "HGK Shipping GmbH — PIONEER Animation Video," 17 April 2024. [Online]. Available: https://www.youtube.com/watch?v=hJV0RUfbCVc. [Accessed 21 August 2024].

[146] R. de Kler, F. Neele, M. Nienoord, P. Brownsort, J. Koomneef, S. Belfroid, L. Peters, A. van Wijhe and D. Loeve, "Transportation and unloading of CO2 by ship - a comparative assessment," 09 April 2016. [Online]. Available: https://co2-cato.org/publications/transportation-unloading-co2-ship/. [Accessed 21 August 2024].

[147] F. Neele, R. de Kler, M. Nienoord, P. Brownsort, J. Koomneef, S. Belfroid, L. Peters, A. van Wijhe and D. Loeve, "CO2 transport by ship: the way forward in Europe," *Energy Procedia,* vol. 114, p. 6824–6834, 2017.

[148] K. Simonsen, D. S. Hansen and S. Pedersen, "Challenges in CO2 transportation: trends and perspective," *Renewable and Sustainable Energy Reviews,* vol. 191, p. 14, 2024.

[149] R. James, "CO2 impurity design parameters," DOE, Washington, D.C., 2019.

[150] C. Aizhu, "Focus: China shipyards feast on record LNG tanker orders as South Korea builders are full up," Reuters, 11 December 2022. [Online]. Available: https://www.reuters.com/business/china-shipyards-feast-record-lng-tanker-orders-skorea-builders-are-full-up-2022-12-12/. [Accessed 6 September 2024].

[151] The Oxford Institute for Energy Studies, "What do we need to know to make CO2 shipping for CCS a reality?," March 2024. [Online]. Available: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2024/03/Insight-146-CO2-Shipping-for-CCS.pdf. [Accessed 29 August 2024].

[152] EPA, "Class VI - Wells used for Geologic Sequestration of Carbon Dioxide," [Online]. Available: https://www.epa.gov/uic/class-vi-wells-used-geologic-sequestration-carbon-dioxide.

[153] EPA, "Underground Injection Control (UIC) Class VI Permit Tracker," EPA, 5 July 2024. [Online]. Available: https://awsedap.epa.gov/public/single/?appid=8c074297-7f9e-4217-82f0-fb05f54f28e7&sheet=51312158-636f-48d5-8fe6-a21703ca33a9&theme=horizon&bookmark=6218ffed-bb6e-42e4-a4f1-52d87e036a1b&opt=ctxmenu. [Accessed 16 September 2024].

[154] CO2LOS, "CO2LOS - CO2 ship transport - new solutions," 20 September 2019. [Online]. Available: https://www.sintef.no/en/projects/2019/co2los-co2-ship-transport-new-solutions/. [Accessed 17 September 2024].

[155] DOE, "Technology Readiness Assessment Guide (DOE G 413.3-4A)," DOE, 2011.

[156] Danish Technological Institute and Maersk Broker Advisory Services, "Maritime Transport of CO2," 2022.

[157] D. Kearns, H. Liu and C. Consoli, "Technology Readiness and Costs of CCS," Global CCS Institute, 2021.

[158] DNV, "CO2 offshore injection," [Online]. Available: https://www.dnv.com/article/co2-offshore-injection-joint-industry-project/. [Accessed 19 August 2024].

[159] CO2 Logistics by Ship Phase III, "CO2LOS III - Final Report," Brevik Engineering AS and SINTEF Industry, Porsgrunn, Norway, 2023.

[160] M. Bui, C. S. Adjiman, A. Bardow, E. Anthony, A. Boston, S. Brown, P. Fennell, S. Fuss, A. Galindo, L. Hackett, J. Hallett, H. Herzog, G. Jackson, J. Kemper, S. Krevor, G. Maitland, M. Matuszewski, I. Metcalfe, C. Petit, G. Puxty, J. Reimer, D. Reiner, E. Rubin, S. Scott, N. Shah, B. Smit, J. Trusler, P. Webley, J. Wilcox and N. Mac Dowell, "Carbon capture and

storage (CCS): the way forward," *Energy & Environmental Science,* vol. 11, no. 5, p. 1062–1176, 2018.

[161] Clarksons, "What is an LNG ship?," [Online]. Available: https://www.clarksons.com/glossary/what-is-an-lng-ship/. [Accessed September 2024].

[162] International Standards Organization, ISO 20815:2018: Petroleum, petrochemical and natural gas industries, 2018.

[163] S. Trædal, J. H. G. Stang, I. Snustad, M. V. Johansson and D. Berstad, "CO2 Liquefaction Close to the Triple Point Pressure," *Energies,* vol. 14, no. 24, p. 8220, 2021.

[164] B. H. Morland, A. Dugstad and G. Svenningsen, "Experimental based CO2 transport specification ensuring material integrity," *International Journal of Greenhouse Gas Control,* vol. 119, p. 103697, 2022.

[165] F. Engel and A. Kather, "Improvements on the liquefaction of a pipeline CO2 stream for ship transport," *International Journal of Greenhouse Gas Control,* vol. 72, pp. 214-221, 2018.

[166] Northern Lights, "Webinar on updated CO2 specifications for the Northern Lights value chain," 15 February 2024. [Online]. Available: https://norlights.com/news/webinar-on-updated-co2-specifications-for-the-northern-lights-value-chain/.

[167] J. Gernert and R. Span, "EOS–CG: A Helmholtz energy mixture model for humid gases and CCS mixtures," *The Journal of Chemical Thermodynamics,* vol. 93, pp. 274-293, 2016.

[168] W. Li, G. Di and R. Wang, "The Cause Analysis of a Liquid CO2 Tank Explosion on a Ship," *Materials Science Forum,* vol. 689, p. 461–467, 2011.

[169] Northern Lights, "Northern Lights celebrates completion of world's first commercial CO2 transport and storage service," September 2024. [Online]. Available: https://norlights.com/news/northern-lights-celebrates-completion-of-worlds-first-commercial-co2-transport-and-storage-service/. [Accessed October 2024].

[170] S&P Global, "Japan set for world's first transport of liquefied CO2," April 2024. [Online]. Available: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/042624-japan-set-for-worlds-first-transport-of-liquefied-co2. [Accessed 2024 June].

[171] K.E.D. Global, "Hyundai Heavy, Glovis to make world's largest liquefied CO2 carrier," June 2022. [Online]. Available: https://www.kedglobal.com/shipping-shipbuilding/newsView/ked202206070013. [Accessed October 2024].

[172] S. Roussanaly, H. Deng, G. Skaugen and T. Gundersen, "At what Pressure Shall CO2 Be Transported by Ship? An in-Depth Cost Comparison of 7 and 15 Barg Shipping," *Energies,* vol. 15, no. 18, p. 1–27, 2021.

[173] Global CCS Institute, "State of the Art: CCS Technologies 2024," 2024.

[174] Y. Seo, C. Huh, S. Lee and D. Chang, "Comparison of CO2 liquefaction pressures for ship-based carbon capture and storage (CCS) chain," *International Journal of Greenhouse Gas Control,* vol. 52, p. 1–12, 2016.

[175] NOAA, "Implementing the National Charting Plan," Office of Coast Survey, 2019.

[176] NOAA Office of Coast Survey, "ENC Direct to GIS," 2024. [Online]. Available: https://www.nauticalcharts.noaa.gov/data/gis-data-and-services.html#enc-direct-to-gis. [Accessed 2 July 2024].

[177] Maritime Safety Office, "WORLD PORT INDEX," June 2024. [Online]. Available: https://msi.nga.mil/Publications/WPI. [Accessed 8 July 2024].

[178] DNR, "Pipeline 1:63,360," 25 July 2023. [Online]. Available: https://gis.data.alaska.gov/datasets/SOA-DNR::pipeline-163360/explore. [Accessed 9 July 2024].

[179] DOI, "Submerged Lands Act Boundary - Alaska Region," BOEM, 2024.

[180] Alaska Railroad Corporation, "Track Centerline," 24 January 2024. [Online]. Available: https://data-arrc.opendata.arcgis.com/datasets/708e21fcb5d14027a8915a79c6a5bc8a_0/explore. [Accessed 15 July 2024].

[181] Alaska Department of Transportation and Public Facilities, "Alaska Highway System," 21 March 2024. [Online]. Available: https://data-soa-akdot.opendata.arcgis.com/search?tags=roads. [Accessed 9 July 2024].

[182] EIA, "Power Plants," 15 April 2024. [Online]. Available: https://atlas.eia.gov/datasets/bf5c5110b1b944d299bb683cdbd02d2a_0/explore. [Accessed 14 July 2024].

[183] USGS, "Search Earthquake Catalog," 2024. [Online]. Available: https://earthquake.usgs.gov/earthquakes/search/. [Accessed 15 July 2024].

[184] USGS: Coastal and Marine Hazards and Resources Program, "Coastal Change Mapping and Research in Alaska," 30 November 2020. [Online]. Available: https://www.usgs.gov/programs/cmhrp/news/coastal-change-mapping-and-research-alaska. [Accessed 8 July 2024].

[185] National Park Service, "Oceans, Coasts & Seashores: Alaska," 8 June 2022. [Online]. Available: https://www.nps.gov/subjects/oceans/alaska.htm. [Accessed 8 July 2024].

[186] University of Alaska Fairbanks, "Historical Sea Ice Atlas," Alaska Center for Climate Assessment and Policy, Undated. [Online]. Available: https://snap.uaf.edu/tools/sea-ice-atlas/. [Accessed 13 September 2024].

[187] J. Turner, "The cold war: how sea ice impacts on Arctic operations," Offshore Technology, 14 August 2013. [Online]. Available: https://www.offshore-technology.com/features/feature-arctic-sea-ice-decline-climate-change-nersc/?cf-view. [Accessed 1 October 2024].

[188] USCG, "Major Icebreakers of the World," 2017. [Online]. Available: https://www.dco.uscg.mil/Portals/9/DCO%20Documents/Office%20of%20Waterways%20and%20Ocean%20Policy/20170501%20major%20icebreaker%20chart.pdf?ver=2017-06-08-091723-907. [Accessed 13 September 2024].

[189] Advanced Resources International, "Basin Oriented Strategies for CO2 Enhanced Oil Recovery: Alaska," DOE, Washington, D.C., 2005.

[190] USGS, "Geologic CO2 Sequestration," DOI, Undated. [Online]. Available: https://co2public.er.usgs.gov/viewer/. [Accessed 21 August 2024].

[191] M. Juliano, "Port of Alaska declared safe after earthquake," TradeWinds, 2 December 2018. [Online]. Available: https://www.tradewindsnews.com/safety/port-of-alaska-declared-safe-after-earthquake/2-1-490438. [Accessed 13 September 2024].

[192] S. Tobben and R. Tuttle, "Alaska Earthquake Threatens Oil Exports," Bloomberg and Rig Zone, 30 November 2018. [Online]. Available: https://www.rigzone.com/news/wire/alaska_earthquake_threatens_oil_exports-30-nov-2018-157613-article/. [Accessed 13 September 2024].

[193] Global CCS Institute, "Induced seismicity and CO2 geological storage," 16 April 2016. [Online]. Available: https://www.globalccsinstitute.com/news-media/insights/induced-seismicity-and-co2-geological-storage/. [Accessed 12 September 2024].

[194] S. Hosseini, S. Hovorka, A. Savvaidis, F. Kavoura and J. Nicot, "Current State of Knowledge Regarding the Risk of Induced Seismicity at CO2 Storage Projects," Gulf Coast Carbon Center, the Bureau of Economic Geology at the University of Texas, IEAGHG Technical Report, Austin, Texas, 2022.

[195] B. S. Halpern, M. Frazier, J. Potapenko, K. S. Casey and K. Koenig, "Cumulative human impacts: raw stressor data (2008 and 2013)," 2015.

[196] DOT Bureau of Transportation Statistics, "Marine Highways," 1 July 2018. [Online]. Available: https://geodata.bts.gov/datasets/usdot::marine-highways/explore. [Accessed 17 June 2024].

[197] U.S. Central Intelligence Agency, "Map of the world oceans," October 2012. [Online]. Available: https://github.com/newzealandpaul/Shipping-Lanes?tab=readme-ov-file. [Accessed 18 June 2024].

[198] USACE, "Draft Integrated Feasibility Report, Draft Environmental Assessment (EA), and Draft Finding of No Significant Impact (FONSI) - Alaska Deep-Draft Artic Port System Study," USACE Alaska District, 2015.

[199] D. M. Fraga, R. Skagestad, N. Henrik Eldrup, A. Korre, H. Askel Haugen, Z. Nie and S. Durucan, "Design of a multi-user CO2 intermediate storage facility in the Grenland region of Norway," *International Journal of Greenhouse Gas Control,* vol. 112, p. 103514, 2021.

[200] IEAGHG, "Ship Transport of CO2, Report PH4/30," IEAGHG, Cheltenham, 2004.

[201] G. F. Weihs, K. Kunmar and D. Wiley, "Understanding the Economic Feasibility of Ship Transport of CO2 within the CCS Chain," *Energy Procedia,* vol. 63, p. 2630–2637, 2014.

[202] H. Noh, K. Kang, C. Huh, S.-G. Kang, S. Han and H. Kim, "Conceptualization of CO2 Terminal for Offshore CCS Using System Engineering Process," *Energies,* vol. 12, no. 22, p. 4350, 2019.

[203] Global Centre for Maritime Decarbonisation, "Concept Study to Offload Onboard Captured CO2," 2024.

[204] D. M. Fraga, R. Skagestad, N. H. Eldrup, A. Korre, H. A. Haugen, Z. Nie and S. Durucan, "Design of a multi-user CO2 intermediate storage facility in the Grenland region of Norway," *International Journal of Greenhouse Gas Control,* vol. 112, no. ISSN 1750-5836, 2021.

[205] Element Energy, "CO2 Shipping Cost Model commissioned by the UK Department for Business, Energy, & Industrial Strategy (BEIS)," 2018. [Online]. Available: https://www.gov.uk/government/publications/shipping-carbon-dioxide-co2-uk-cost-estimation-study.

[206] Maersk Broker Advisory Services & Danish Technological Institute, "Maritime Transport of CO2," Danish Technological Institute, Aarhus, 2022.

[207] V. S. Bjerketvedt, A. Tomasgard and S. Roussanaly, "Deploying a shipping infrastructure to enable carbon capture and storage from Norwegian industries," *Journal of Cleaner Production,* vol. 33, no. 129586, 2022.

[208] DNV, "DNV supports innovations in CO2 carrier design," [Online]. Available: https://www.dnv.com/expert-story/maritime-impact/DNV-supports-innovations-in-CO2-carrier-design.

[209] IMO, "International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)," [Online]. Available: https://www.imo.org/en/ourwork/safety/pages/igc-code.aspx.

[210] United Nations, "United Nations Framework Convention," [Online]. Available: https://unfccc.int/sites/default/files/convention_text_with_annexes_english_for_posting.pdf.

[211] United Nations, "Paris Agreement," 2015. [Online]. Available: https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

[212] S. Eggelston, L. Buendia, K. Miwa, T. Ngara and K. Tanabe, "2006 IPCC Guidelines for National Greenhouse Gas Inventories," Institute for Global Environmental Strategies (IGES) for the IPCC, 2006.

[213] D. M. Bartram, B. Cai, E. C. Buendia and et al., "2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories," Intergovernmental Panel on Climate Change, 2019.

[214] IPCC, Expert Meeting on Carbon Dioxide Removal Technologies and Carbon Capture, Utilization, and Storage Background Paper, Eds: Enoki, T., Hayat, M., Report of the IPCC Expert Meeting: IGES, Japan, 2024.

[215] UN environment programme, "Basel Convention," [Online]. Available: https://www.basel.int/TheConvention/Overview/tabid/1271/Default.aspx.

[216] UN Environment Programme, "BASEL CONVENTION ON THE CONTROL OF TRANSBOUNDARY MOVEMENTS OF HAZARDOUS WASTES AND THEIR DISPOSAL, PROTOCOL ON LIABILITY AND COMPENSATION FOR DAMAGE RESULTING FROM TRANSBOUNDARY MOVEMENTS OF HAZARDOUS WASTES AND THEIR DISPOSAL, TEXTS AND ANNEXES," 2019. [Online]. Available: https://www.basel.int/TheConvention/Overview/TextoftheConvention/tabid/1275/Default.aspx.

[217] C. Arlota, M. B. Gerrard and P. D. Mahadevan, "Legal Issues in Oceanic Transport of Carbon Dioxide for Sequestration," 2024. [Online]. Available: https://scholarship.law.columbia.edu/faculty_scholarship/4447/.

[218] United Nations, "United Nations Convention on the Law of the Sea," [Online]. Available: https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf.

[219] IMO, Reports of the Consultative Meeting of the Parties of the London Convention: LC 21/23, LC 26/15, LC 27/16, LC 28/15, and LC 29/17.

[220] V. Weber, "Are We Ready for the Ship Transport of CO2 for CCS? Crude Solutions from International and European Law," *Review of European, Comparative & International Environmental Law,* vol. 30, no. 3, p. 387–395, 2021.

[221] I. Havercroft and R. Purdy, Carbon Capture and Storage – A Legal Perspective, 2007.

[222] EPA, "1996 PROTOCOL TO THE CONVENTION ON THE PREVENTION OF MARINE POLLUTION BY DUMPING OF WASTES AND OTHER MATTER, 1972 (as amended in 2006)," 2006. [Online]. Available: https://www.epa.gov/sites/default/files/2015-10/documents/lpamended2006.pdf.

[223] Protocol (1996) to the Convention of the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972, Flanders Chancellery & Foreign Office, 2006.

[224] EPA, "London Convention and London Protocol: International Treaties to Prevent Marine Pollution," 24 September 2024. [Online]. Available: https://www.epa.gov/ocean-dumping/london-convention-and-london-protocol-international-treaties-prevent-marine-pollution. [Accessed 15 November 2024].

[225] NISHIMURA & ASAHI, "Development of CCS Regulations in Japan — Necessary Steps to Enable CCS Projects Involving Cross-Border Transport of CO2," 5 September 2024. [Online]. Available: https://www.nishimura.com/sites/default/files/newsletters/file/natural_resources_energy_competition_law_international_trade_240905_en.pdf. [Accessed 15 November 2024].

[226] T. Dixon, "Transnational CCS Value Chain Developments," 2024.

[227] U. Nations, "Marine genetic resources, including the fair and equitable sharing of benefits.," July 2024. [Online]. Available: https://www.un.org/bbnjagreement/sites/default/files/2024-07/BBNJAgreementFactsheet2MGRs.pdf.

[228] United Nations, "Agreement on Marine Biodiversity of Areas beyond National Jurisdiction BBNJ Agreement," [Online]. Available: https://www.un.org/bbnjagreement/en.

[229] IMO, "MARPOL," [Online]. Available: https://www.imo.org/en/KnowledgeCentre/ConferencesMeetings/Pages/Marpol.aspx.

[230] IMO, "International Convention for the Safety of Life at Sea (SOLAS), 1974," [Online]. Available: https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx.

[231] IMO, "The HNS Convention," [Online]. Available: https://www.imo.org/en/MediaCentre/HotTopics/Pages/HNS-2010.aspx.

[232] OECD, "Transboundary movements of waste," [Online]. Available: https://www.oecd.org/en/data/tools/transboundary-movements-of-waste.html.

[233] EPA, "Organization for Economic Cooperation and Development (OECD) Council Decision," [Online]. Available: https://www.epa.gov/hwgenerators/international-agreements-transboundary-shipments-hazardous-waste#oecd.

[234] DOT Office of Environmental Quality, "Basel Convention on Hazardous Wastes," [Online]. Available: https://www.state.gov/key-topics-office-of-environmental-quality-and-transboundary-issues/basel-convention-on-hazardous-wastes/.

[235] IMO, "Convention on Limitation of Liability for Maritime Claims (LLMC)," [Online]. Available: https://www.imo.org/en/About/Conventions/Pages/Convention-on-Limitation-of-Liability-for-Maritime-Claims-(LLMC).aspx.

[236] EPA, "International Agreements on Transboundary Shipments of Hazardous Waste - Basel Convention," 26 September 2024. [Online]. Available: https://www.epa.gov/hwgenerators/international-agreements-transboundary-shipments-hazardous-waste#basel. [Accessed 15 November 2024].

[237] Ministry of the Environment Government of Japan, "Conservation of Marine Environment," [Online]. Available: https://www.env.go.jp/en/earth/marine/conservation.html. [Accessed 15 November 2024].

[238] FAO, "Law Relating to the Prevention of Marine Pollution and Maritime Disaster (Law No. 136)," [Online]. Available: https://www.fao.org/faolex/results/details/en/c/LEX-FAOC073561/.

[239] Ministry of Foreign Affairs of Japan, "Maritime Safety, Maritime Pollution Prevention and Japan's Contribution," [Online]. Available: https://www.mofa.go.jp/policy/maritime/safety/pollution.html.

[240] J. OIJMA, "Features of the Japanese Industrial Safety and Health Act: some key points regarding the organization of safety and health management," [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7557416/.

[241] High Pressure Gas Safety Institute of Japan, "High Pressure Gas Safety Act," [Online]. Available: https://www.cas.go.jp/jp/seisaku/hourei/data/HPGSA.pdf.

[242] White & Case, "On the path to decarbonisation: Japan enacts its first legislation on hydrogen and CCS," [Online]. Available: https://www.whitecase.com/insight-alert/path-decarbonisation-japan-enacts-its-first-legislation-hydrogen-and-ccs.

[243] Nishimura & Asahi, "Japan’s CCS Bill in Brief," [Online]. Available: https://www.nishimura.com/sites/default/files/newsletters/file/natural_resources_energy_240306_en.pdf.

[244] Baker McKenzie, "Japan: Publication of Draft Interim Summary of CCS Regulatory Framework," [Online]. Available: https://insightplus.bakermckenzie.com/bm/projects/japan-publication-of-draft-interim-summary-of-ccs-regulatory-framework.

[245] Industrial Safety and Health Institute of Japan, "Industrial Safety and Health Act," [Online]. Available: https://www.cas.go.jp/jp/seisaku/hourei/data/isha_2.pdf.

[246] U.S. Congress, "United States Code, 2011 Edition, Title 49 – TRANSPORTATION, SUBTITLE III - GENERAL AND INTERMODAL PROGRAMS, CHAPTER 51 - TRANSPORTATION OF HAZARDOUS MATERIAL," [Online]. Available: https://www.govinfo.gov/content/pkg/USCODE-2011-title49/html/USCODE-2011-title49-subtitleIII-chap51.htm.

[247] USCG, "Design Basis Agreement Submission Guidance," 17 March 2023. [Online]. Available: https://www.dco.uscg.mil/Portals/9/OCSNCOE/References/Policy-Letters/HQ/ENG/CG-ENG-PL-01-23.pdf?ver=epiSuGJrfdcDJ0tJ2Kq6_w%3D%3D.

[248] U.S. Congress, "Pipeline Safety Reauthorization Act of 1988," [Online]. Available: https://www.congress.gov/100/statute/STATUTE-102/STATUTE-102-Pg2805.pdf.

[249] S. C. f. C. C. Law, "PHMSA Advances CO2 Pipeline Safety Regulations," 1 February 2024. [Online]. Available: https://climate.law.columbia.edu/content/phmsa-advances-co2-pipeline-safety-regulations. [Accessed 12 December 2024].

[250] Federal Maritime Commission, "Federal Maritime Commission," [Online]. Available: https://www.fmc.gov/about/.

[251] U.S. Senate Committee on Commerce Science and Transportation, "President Biden Signs Cantwell-Championed Ocean Shipping Reform Act," 16 June 2022. [Online]. Available:

https://www.commerce.senate.gov/2022/6/president-biden-signs-cantwell-championed-ocean-shipping-reform-act.

[252] U.S. Coast Guard, "Ports and Waterways Safety Act," 2012. [Online]. Available: https://coast.noaa.gov/data/Documents/OceanLawSearch/PortsandWaterwaysSafetyAct.pdf.

[253] Cornell Law School, "33 CFR § 6.01-3 - Captain of the Port," [Online]. Available: https://www.law.cornell.edu/cfr/text/33/6.01-3.

[254] DOJ Office of Justice Programs, "Maritime Transportation Security Act," [Online]. Available: https://www.ojp.gov/ncjrs/virtual-library/abstracts/maritime-transportation-security-act.

[255] U.S. Congress, "46 USC App Ch. 24: MERCHANT MARINE ACT," 1920. [Online]. Available: https://uscode.house.gov/view.xhtml?req=granuleid%3AUSC-2000-title46a-chapter24&edition=2000.

[256] M. Woodruff, "Topic Paper #3-8 The Merchant Marine Act of 1920," 12 December 2019. [Online]. Available: https://www.energy.gov/sites/default/files/2022-10/Infra_Topic_Paper_3-8_FINAL.pdf.

[257] Congressional Research Service, "Shipping Under the Jones Act: Legislative and Regulatory Background," 21 November 2019. [Online]. Available: https://crsreports.congress.gov/product/pdf/R/R45725.

[258] U.S. Customs and Border Protection, "The Jones Act," September 2020. [Online]. Available: https://www.cbp.gov/sites/default/files/assets/documents/2020-Oct/Jones-Act-Informed-Compliance-Publication-September-2020.pdf.

[259] DOT, "Cargo Preference Laws and Regulations," [Online]. Available: https://www.maritime.dot.gov/cargo-preference/military-cargoes/cargo-preference-laws-and-regulations.

[260] EPA, "MARPOL Annex VI and the Act To Prevent Pollution From Ships (APPS)," [Online]. Available: https://www.epa.gov/enforcement/marpol-annex-vi-and-act-prevent-pollution-ships-apps.

[261] EPA, "MARPOL Annex VI Air Pollution Prevention Requirements," 27 June 2011. [Online]. Available: https://www.epa.gov/sites/default/files/documents/jointletter062711.pdf.

[262] EPA, "Primary Enforcement Authority for the Underground Injection Control Program," [Online]. Available: https://www.epa.gov/uic/primary-enforcement-authority-underground-injection-control-program-0.

[263] U.S. Congress, 40 CFR Parts 124, 144, 145, 146, and 147 Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide (CO2) Geologic Sequestration (GS) Wells, 2010.

[264] U.S. Congress, "CFR Part 261-Identification and Listing of Hazardous Waste," 1980. [Online]. Available: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-I/part-261.

[265] R. Malischek and S. McCulloch, "The world has vast capacity to store CO2: Net zero means we'll need it," IEA, 1 April 2021. [Online]. Available: https://www.iea.org/commentaries/the-world-has-vast-capacity-to-store-co2-net-zero-means-we-ll-need-it. [Accessed 24 June 2024].

[266] U.S. Congress, "Hazardous Waste Management System: Conditional Exclusion for Carbon Dioxide (CO2) Streams in Geologic Sequestration Activities," 03 January 2014. [Online]. Available: https://www.federalregister.gov/documents/2014/01/03/2013-31246/hazardous-waste-management-system-conditional-exclusion-for-carbon-dioxide-co2-streams-in-geologic.

[267] NOAA, "Outer Continental Shelf Lands Act," [Online]. Available: https://coast.noaa.gov/data/Documents/OceanLawSearch/Summary%20of%20Law%20-%20Outer%20Continental%20Shelf%20Lands%20Act.pdf.

[268] U.S. Congress, "Infrastructure Investment and Jobs Act," 15 November 2021. [Online]. Available: https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf.

[269] Department of the Interior , "Carbon Sequestration," Office of Management and Budget, 15 November 2022. [Online]. Available: https://www.reginfo.gov/public/do/eAgendaViewRule?pubId=202304&RIN=1082-AA04.

[270] BOEM, "Regulatory Framework and Guidelines," Bureau of Ocean Energy Management, [Online]. Available: https://www.boem.gov/environment/regulatory-framework-and-guidelines.

[271] FEMA, "1899 Rivers and Harbors Act," [Online]. Available: https://emilms.fema.gov/is_0727/groups/160.html.

[272] USACE, "What is the Regulatory Program?," [Online]. Available: https://www.swl.usace.army.mil/Missions/Regulatory/What-is-the-Regulatory-Program/.

[273] EPA, "What is the National Environmental Policy Act?," [Online]. Available: https://www.epa.gov/nepa/what-national-environmental-policy-act.

[274] U.S. Fish and Wildlife Service, "National Environmental Policy Act: Frequently Asked Questions," [Online]. Available: https://www.fws.gov/node/266179.

[275] EPA, "National Environmental Policy Act Review Process," [Online]. Available: https://www.epa.gov/nepa/national-environmental-policy-act-review-process.

[276] U.S. Congress, Fiscal Responsibility Act of 2023, Pub. L. No. 118-5 (2023), 2023.

[277] CCUS Map, "CCUS Map," Energy Corridor Imaging, Undated. [Online]. Available: https://ccusmap.com/. [Accessed 8 August 2023].

[278] Permitting Dashboard Federal Infrastructure Projects, "Permitting Council," [Online]. Available: https://www.permits.performance.gov/fpisc-content/permitting-council-0.

[279] EPA, "Reviewing National Ambient Air Quality Standards (NAAQS): Scientific and Technical Information," [Online]. Available: https://www.epa.gov/naaqs.

[280] Congressional Research Service, "Clean Air Act: A Summary of the Act and Its Major Requirements," 2022. [Online]. Available: https://crsreports.congress.gov/product/pdf/RL/RL30853.

[281] EPA, "Summary of the Clean Water Act," [Online]. Available: https://www.epa.gov/laws-regulations/summary-clean-water-act.

[282] S. Kerschner and T. Pullins, "How US environmental laws and regulations affect carbon capture and storage," 29 January 2021. [Online]. Available: https://www.whitecase.com/insight-our-thinking/how-us-environmental-laws-and-regulations-affect-carbon-capture-and-storage.

[283] NOAA Office for Coastal Management, "Coastal Zone Management Act," [Online]. Available: https://coast.noaa.gov/czm/act/.

[284] NOAA Office for Coastal Management, "The Coastal and Estuarine Land Conservation Program," [Online]. Available: https://coast.noaa.gov/czm/landconservation/.

[285] Michigan State University, "United States Code Annotated. Title 16. Conservation. Chapter 49. Fish and Wildlife Conservation," [Online]. Available: https://www.animallaw.info/statute/us-conservation-fish-wildlife-conservation-act.

[286] FWS, "Fish and Wildlife Coordination Act," [Online]. Available: https://www.fws.gov/law/fish-and-wildlife-coordination-act.

[287] EPA, "Summary of the Endangered Species Act," [Online]. Available: https://www.epa.gov/laws-regulations/summary-endangered-species-act.

[288] S. Kane, "Which state is closer to Japan, Alaska or Hawaii? The answer may surprise you," Business Insider, 21 July 2016. [Online]. Available: https://www.businessinsider.com/which-state-nearest-japan-2016-7#:~:text=It's%20easy%20to%20assume%20Hawaii,closer%20to%20Japan%20than%20Hawaii. [Accessed 2 October 2024].

[289] FWS, "Migratory Bird Treaty Act of 1918," [Online]. Available: https://www.fws.gov/law/migratory-bird-treaty-act-1918.

[290] S. Kerschner and T. Pullins, "How US environmental laws and regulations affect carbon capture and storage," White & Case, 29 January 2021. [Online]. Available: https://www.whitecase.com/insight-our-thinking/how-us-environmental-laws-and-regulations-affect-carbon-capture-and-storage.

[291] U.S. Department of Justice, "Executive Orders," [Online]. Available: https://bja.ojp.gov/program/it/privacy-civil-liberties/authorities/executive-orders. [Accessed 15 November 2024].

[292] Executive Order 13175, Summary of Executive Order 12898 - Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations, Washington DC, 1994.

[293] The White House, Executive Order on Revitalizing Our Nation's Commitment to Environmental Justice for All, 2023.

[294] M. Gracz and P. Glaser, "Evaluation of a wetland classification system devised for management in a region with a high cover of peatlands: an example from the Cook Inlet Basin, Alaska," *Wetlands Ecol Manage,* p. 87–104, 2017.

[295] DOT Federal Highway Administration, Environmental Review Toolkit Section 4(f) Tutorial.

[296] U.S. Federal Regulation, "Wild and Scenic Rivers Act," [Online]. Available: https://www.govinfo.gov/content/pkg/COMPS-1758/pdf/COMPS-1758.pdf.

[297] Cultural Property News, "A Primer: NAGPRA, ARPA, and the Antiquities Act," [Online]. Available: https://culturalpropertynews.org/a-primer-nagpra-arpa-and-the-antiquities-act.

[298] "The American Indian Religious Freedom Act of 1978," [Online]. Available: https://coast.noaa.gov/data/Documents/OceanLawSearch/Summary%20of%20Law%20-%20American%20Indian%20Religious%20Freedom%20Act.pdf.

[299] Federal Infrastructure Projects Dashboard, "The FAST-41 Process," [Online]. Available: https://www.permits.performance.gov/fpisc-content/fast-41-process.

[300] NOAA, "Marine Mammal Protection," [Online]. Available: https://www.fisheries.noaa.gov/topic/marine-mammal-protection.

[301] A. DeMarban, "Dunleavy signs three bills to address high energy costs and promote renewable power in Alaska," *Anchorage Daily News,* 31 July 2024.

[302] Alaska DEC Division of Water, "Antidegradation," [Online]. Available: https://dec.alaska.gov/water/water-quality/standards/antidegradation/.

[303] Alaska Division of Air Quality, "Air Permit Program," [Online]. Available: https://dec.alaska.gov/air/air-permit/.

[304] Alaska Department of Fish and Game, "Fish Habitat Permits," [Online]. Available: https://www.adfg.alaska.gov/index.cfm?adfg=uselicense.fish_habitat_permits.

[305] American Bureau of Shipping, "Requirements for Liquefied Carbon Dioxide Carriers," 2024. [Online]. Available: https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/344-requirements-for-liquefied-carbon-dioxide-carriers-2024/344-liquefied-co2-carriers-reqts-jan24.pdf.

[306] MarineLog, "ABS publishes its requirements for LCO2 carriers," 15 February 2024. [Online]. Available: https://www.marinelog.com/news/abs-publishes-its-requirements-for-lco2-carriers/. [Accessed 15 August 2024].

[307] Mitsuir O.S.K. Lines. Ltd. (MOL), "Approval in Principle (AiP) Acquired from Two Classification Societies for Low-Pressure Type Liquefied CO2 Carriers undergoing Pursuit of Standardization toward Realization of Large-Scale International Transportation from 2028 onwards," 18 September 2024. [Online]. Available: https://www.mol.co.jp/en/pr/2024/24107.html. [Accessed 29 September 2024].

[308] SIGTTO, "Carbon Dioxide Cargo on Gas Carriers, First Edition," [Online]. Available: https://www.sigtto.org/media/4004/sigtto-carbon-dioxide-cargo-on-gas-carriers.pdf.

[309] NYK Line, "Joint Study to Establish Standard Specifications and Designs for LCO2 Carriers in Japan Towards Large-Scale International Marine Transport of Liquefied CO2 by 2028," [Online]. Available: https://www.nyk.com/english/news/2024/20240827.html.

[310] The Maritime Executive, "Japanese Companies to Standardize LCO2 Carriers to Meet Anticipated Demand," [Online]. Available: https://maritime-executive.com/article/japanese-companies-to-standardize-lco2-carriers-to-meet-anticipated-demand.

[311] Alaska LNG, "Alaska LNG," Alaska LNG, [Online]. Available: https://alaska-lng.com/. [Accessed 2 August 2024].

[312] S. Søreide, "Northern Lights jetty – photo by Svein Ove Søreide," Northern Lights, Øygarden, 2024.

[313] F. T. Richards, P.E., AGDC President, "Alaska LNG Project," 11 May 2022. [Online]. Available: https://alaska-lng.com/wp-content/uploads/2022/05/NSPE_Alaska-LNG-Project-Update_11May2022_PUBLIC.pdf.

[314] FPISC, "Alaska LNG Project," Federal Permitting Improvement Steering Council, [Online]. Available: https://www.permits.performance.gov/permitting-project/fast-41-covered-projects/alaska-lng-project. [Accessed 2 August 2024].

[315] Federal Infrastructure Projects Permitting Dashboard, "Biden-Harris Administration Announces First of Its Kind State Permitting Collaboration with the New Mexico Renewable Energy Transmission Authority (RETA) to Advance Grid Infrastructure Projects," [Online]. Available: https://www.permits.performance.gov/fpisc-content/biden-harris-administration-announces-first-its-kind-state-permitting-collaboration.

[316] Office of Fossil Energy and Carbon Management, "Funding Notice: Bipartisan Infrastructure Law: Carbon Capture Technology Program, Front-End Engineering Design for Carbon Dioxide (CO2) Transport," 9 May 2024. [Online]. Available: https://www.fedconnect.net/FedConnect/default.aspx?ReturnUrl=%2ffedconnect%3fdoc%3dDE-FOA-0002730%26agency%3dDOE&doc=DE-FOA-0002730&agency=DOE.

[317] Council on Environmental Quality, "National Environmental Policy Act Implementing Regulations Revisions Phase 2," 1 May 2024. [Online]. Available: https://www.regulations.gov/document/CEQ-2023-0003-82043.

[318] Y. Lee, K. Baek, S. Lee, K. Cha and C. Han, "Design of boil-off CO2 re-liquefaction processes for a large-scale liquid CO2 transport ship," *International Journal of Greenhouse Gas Control,* vol. 67, p. 93–102, 2017.

[319] C. Zevenhoven and J. Fagerlund, "Controlling evaporation of liquid CO2 during transport as part of CCS," in *33rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*, June 29–July 3, 2020.

[320] B. Chu, D. Chang and H. Chung, "Optimum liquefaction fraction for boil-off gas reliquefaction system of semi-pressurized liquid CO2 carriers based on economic evaluation," *International Journal of Greenhouse Gas Control,* vol. 10, p. 46–55, 2012.

[321] The Maritime Executive, "55 Vessels Required by 2030 for Emerging CO2 Transport and Storage," 4 September 2023. [Online]. Available: https://maritime-executive.com/article/55-vessels-required-by-2030-for-emerging-co2-transport-and-storage. [Accessed 28 August 2024].

[322] S. Geschwindt, "This UK startup can capture 95% of a ship's carbon emissions," TNW, 8 February 2024. [Online]. Available: https://thenextweb.com/news/uk-startup-seabound-carbon-capture-shipping. [Accessed 3 September 2024].

[323] ERMA FIRST, "Carbon Fit Carbon Capture & Storage," 2024. [Online]. Available: https://www.ermafirst.com/wp-content/uploads/2024/06/CARBON-FIT-Flyer.pdf. [Accessed 3 September 2024].

[324] MundoMaritimo, "Onboard CO2 capture can revolutionize the path to decarbonization," 22 April 2024. [Online]. Available: https://www.mundomaritimo.net/noticias/onboard-co2-capture-can-revolutionize-the-path-to-decarbonization. [Accessed 3 September 2024].

[325] Pietro Fiorentini, "CO2 Recovery and Liquefaction," Undated. [Online]. Available: https://www.fiorentini.com/en/solutions/systems/solutions-renewable-energies/bioco2/co2-recovery-and-liquefaction/. [Accessed 22 August 2024].

[326] B. Wagg and M. Stephens, "State-of-the-Art in Transporting CO2 in Pipelines," C-FER Technologies, 2024.

[327] IPCC, "Chapter 4: Transport of CO2," in *Carbon Capture and Storage*, New York, Cambridge University Press, 2005, p. 179–194.

[328] Y. Seo, H. You, S. Lee, C. Huh and D. Chang, "Evaluation of CO2 liquefaction processes for ship-based carbon capture and storage (CCS) in terms of life cycle cost (LCC) considering availability," *International Journal of Greenhouse Gas Control,* vol. 35, pp. 1-12, 2015.

[329] H. Deng, S. Roussanaly and G. Skaugen, "Better understanding of CO_2 liquefaction (Towards identifying optimal transport conditions for ship-based CCS)," SINTEF, 16 September 2019. [Online]. Available: https://blog.sintef.com/sintefenergy/co2-liquefaction-transport-conditions-ship-based-ccs/. [Accessed 22 August 2024].

[330] Zero Emissions Platform, "The Costs of CO2 Transport," European Technology Platform for Zero Emissions Fossil Fuel Power Plants, 2011.

[331] B. Yoo, S. Lee, K. Rhee, H. Na and J. Park, "New CCS system integration with CO2 carrier and liquefaction process," *Energy Procedia,* vol. 4, p. 2308–2314, 2011.

[332] Amager Resource Center, "Pre-feasibility study for CO2 pipeline and storage," Niras, 2020.

[333] P. Brownsort, "Ship transport of CO for Enhanced Oil Recovery – Literature Survey," Enhanced Oil Recovery Joint Industry Project, no. WP-15, 2015.

[334] B. Berger, O. Kaarstad and H. Askel Haugen, "Creating a large-scale CO2 infrastructure for enhanced oil recovery," in *Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies 5*, Vancouver, Canada, 2004.

[335] Offshore Engineer, "Northern Lights Installs 12 CO2 Storage Tanks in Øygarden," 2 June 2023. [Online]. Available: https://www.oedigital.com/news/505550-northern-lights-installs-12-co2-storage-tanks-in-ygarden. [Accessed 19 August 2024].

[336] B. Yoo, D. Choi, H. Kim, Y. Moon, H. Na and S. Lee, "Development of CO2 terminal and CO2 carrier for future commercialized CCS market," *International Journal of Greenhouse Gas Control,* vol. 12, no. https://doi.org/10.1016/j.ijggc.2012.11.008, p. 323–332, 2013.

[337] Wobo Industrial Group Corp., "Factory Supply Liquid CO2 Storage Spherical Tank," Undated. [Online]. Available: https://wobogroup.en.made-in-china.com/product/lZRGBjFuhafE/China-Factory-Supply-Liquid-CO2-Storage-Spherical-Tank.html. [Accessed 19 August 2024].

[338] R. Svensson, M. Oldenberger, F. Johnsson and L. Strömberg, "Transportation infrastructure for CCS —Experiences and expected development," in *7th International Conference on Greenhouse Gas Control Technologies*, Vancouver, Canada, 2004.

[339] K. Patchigolla and J. Oakey, "Design overview of high pressure dense phase CO2 pipeline transport in flow mode," *Energy Procedia,* vol. 37, p. 3123–3130, 2013.

[340] E. Lindeberg, "Modelling pressure and temperature profile in a CO2 injection well," *Energy Procedia,* vol. 4, p. 3935–3941, 2011.

[341] F. Pariso and V. Vilarrasa, "Sinking CO2 in Supercritical Reservoirs," *Geophysical Research Letters,* vol. 47, p. 1–10, 2020.

[342] Ministry of Petroleum and Energy, "Feasibility study for full-scale CCS in Norway," GASSNOVA and GASSCO, 2016.

[343] A. Aspelund, "12 - Developments and Innovation in Carbon Dioxide (CO2) Capture and Storage Technology," in *Developments and Innovation in Carbon Dioxide (CO2) Capture and Storage Technology*, Woodhead Publishing Series in Energy, 2010, p. 383–407.

[344] NOAA, "Coastal Water Temperature Guide," National Centers for Environmental Information, Undated. [Online]. Available: https://www.ncei.noaa.gov/products/coastal-water-temperature-guide. [Accessed 16 August 2024].

[345] EPA, "Regulatory and Statutory Authorities Relevant to Carbon Capture and Sequestration (CCS) Projects," [Online]. Available: https://www.regulations.gov/document/EPA-HQ-OAR-2023-0072-8772.

[346] Lloyd's Register, "Materials, Equipment and Components Certification - Approval in Principle," 2024. [Online]. Available: https://www.lr.org/en/services/classification-certification/materials-equipment-components-product-certification/approval-in-principle/. [Accessed 5 August 2024].

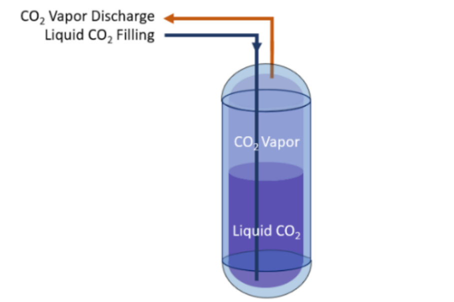
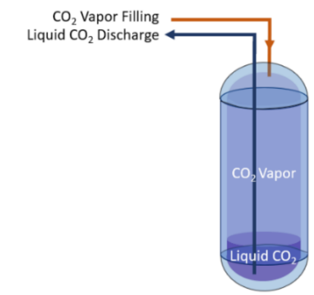
[347] EIA, "U.S. Energy-Related Carbon Dioxide Emissions, 2023," 25 April 2024. [Online]. Available: https://www.eia.gov/environment/emissions/carbon/. [Accessed 14 January 2025].

[348] International Organization for Standardization, "Transportation of CO2 by ship," 2024.

APPENDIX A: SUPPLEMENTARY INFORMATION FOR LCO_2 VESSEL AND LOADING AND OFFLOADING TERMINAL DESIGN CONSIDERATIONS

This appendix provides additional content related to the design considerations for liquefied carbon dioxide (LCO_2) vessels described in Section 2.1.2 and port terminals described in Section 2.1.3. Table A-1 summarizes cycling rate, boil-off gas management, and fuel type in the context of LCO_2 vessel design implications. It provides a compliment to Table 2-3 by providing content on the purpose of each component along with design and operational considerations. The ensuing subsections in this appendix discuss liquefaction, temporary intermediate storage, and conditioning in detail. These write-ups provide additional context for the role each component plays in the collective carbon capture, utilization, and storage (CCUS) value chain with maritime CO_2 transport.

Table A-1. Additional LCO_2 vessel components and associated design considerations

Component	Description/Purpose	Design and Operational Consideration
Cycling Rate	The time (in days) it takes an LCO_2 vessel of a given size to load cargo, travel to its destination, offload cargo, and return to a CO_2 export loading terminal	Cycle rate is influenced by several factors, including the round-trip distance between loading and offloading locations, vessel traveling speed capability (in knots), and cargo loading and offloading time. Improving vessel transit speed enables transportation of more cargo but has trade-offs associated with requiring more engine power, increased emissions, and larger fuel storage needs [151]. Existing and proposed LCO_2 vessels are reported to travel at speeds on the order of 12–14 knots (Table 2-4). LCO_2 loading and offloading rates noted from the literature range 2,500–3,000 tonnes per hour. For perspective, a 20,000 m^3 (706,290 ft^3) vessel (roughly 22,000 tonnes of CO_2) loading (or offloading) would take 7.5–9 hours to transfer the contents of its cargo depending on rate [96, 146]. Additional influencing factors include the per-trip time spent in port (separate from loading or offloading), time traversing at lower speeds than intended, and added trip time caused by any foreseen or unforeseen delays.
Boil-Off Gas (BOG) Management	BOG is CO_2 that evaporates from a liquid state into gas within storage tanks due to either external heat transfer from the surrounding environment or liquid sloshing in the storage tanks	Pressure inside storage tanks increases as BOG accumulates, which can be dangerous. Pressure safety valves are used to manage tank pressure under circumstances of BOG accumulation and increased pressurization. To avoid venting of CO_2 under these circumstances, systems can be installed to capture and re-liquefy BOG to maintain safe operating conditions and prevent venting and loss of cargo [318]. BOG generated for LCO_2 transport is has been assumed on the order of 0.01–0.15% per day. Total BOG would be proportional to the total time of transit (increasing with one-way route distances) as well as any delay time associated with congestion caused by marine traffic around ports [151, 319, 320]. BOG can additionally be affected by distance travelled, level of impurities in the storage tank, ambient temperature and sea conditions, tank pressure design, and operational modes. A low filling level in tanks can also lead to higher evaporation rates of the liquid. Sufficient tank insulation is a critical safeguard to minimize BOG generation. BOG is important in the CO_2 loading and offloading process. As steel tanks are filled with LCO_2, BOG serves as a CO_2 vapor cap. The BOG cap pressure is maintained to avoid rapid pressure fluctuations from heat ingress, commonly referred to as "hydraulic lock," which can damage equipment. During tank filling, pressure is maintained by decreasing BOG using a CO_2 vapor discharge line (graphic A). During tank discharge, pressure is maintained by adding BOG using the same CO_2 vapor line, which avoids CO_2 solidification within the tank from dropping pressures (graphic B). Under low-pressure storage conditions, the pressure operating margin is smaller compared to other pressure and temperature (P/T) regimes given proximity to the triple point.  ***A. Simultaneous discharge of CO_2 vapor and filling of LCO_2***  ***B. Simultaneous filling of CO_2 vapor and discharge of LCO_2***
Fuel Type	LCO_2 vessels can be powered with several types of fuel, including maritime diesel, low-sulfur fuel oil, liquefied natural gas (LNG), liquefied petroleum gas (LPG), and biodiesel being the most matured options. Hydrogen, methanol, ammonia, and battery-powered vessels are also considered but still require maturation [100].	New LCO_2 vessel builds are equipped with engines capable of utilizing LNG as a primary fuel [31]. Engines capable of operating on carbon-neutral green fuels can reduce the CO_2 footprint of the vessel compared to conventionally-fueled vessels. Additional efficiency-enabling mechanisms are available to the maritime industry being considered for LCO_2 transport. These include the use of wind-assisted propulsion systems and air lubrication approaches to help reduce drag on the hull [321, 100]. New technologies also exist that enable onboard capture of CO_2 from vessel exhaust gas produced by engines utilizing hydrocarbon fuel [322, 323, 324, 95]. These technologies provide a means to minimize the carbon footprint of the transportation segment of the CCUS value chain.

A.1 LIQUEFACTION

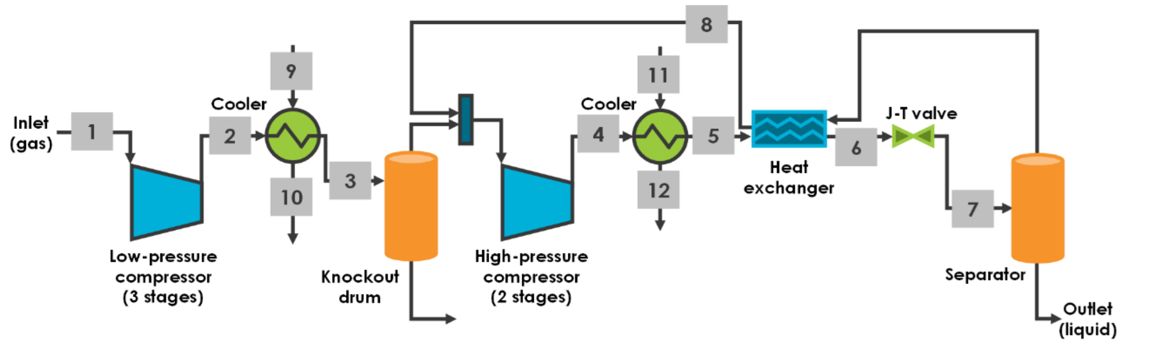
At the head of the LCO_2 shipping supply chain battery is the CO_2 liquefaction step located at an export terminal facility. Liquefaction is the process of turning CO_2 into a liquid state [325]. It involves compressing and cooling the CO_2 until it achieves a temperature below its critical point of 31 °C (87.8 °F) and a corresponding pressure amendable to liquefy the CO_2 (P/T regimes for LCO_2 showed in Figure 2-2). In this state, CO_2 is a colorless liquid affords efficient transportation and storage. The CO_2 will remain liquid as long as its temperature persists below the critical point and the pressure applied is sufficient to prevent CO_2 from turning back into a gas.

Captured CO_2 can essentially arrive at the port terminal liquefaction facility in one of three possible states, including the supercritical/high-pressure liquid phase or the gaseous state, common in pipeline transport [326, 327], or in the medium-pressure liquid phase common to truck/rail transport. The CO_2 arriving onsite must be converted to a compatible P/T condition required for temporary intermediate storage and shipboard containment (driven by the vessel configuration). The CO_2 liquefaction process involves a series of compression stages and cooling, through which the CO_2 stream is liquefied to reach the conditions intended for temporary storage and vessel transport. The number of compression stages and cooling cycles is project-specific and based on the design configuration implemented; however, in the literature, the number of compression stages generally ranges 3–5 [138, 328]. In the compression train, the CO_2 stream is compressed to the desired liquefaction pressure and water is removed by condensation to prevent hydration. The process can also include an impurity removal unit to purify the CO_2 stream to the desired transport conditions for vessel transport and eventual utilization [329]. Liquefaction is a mature and established technology that has been utilized for gas transport of LPG and LNG via ship.

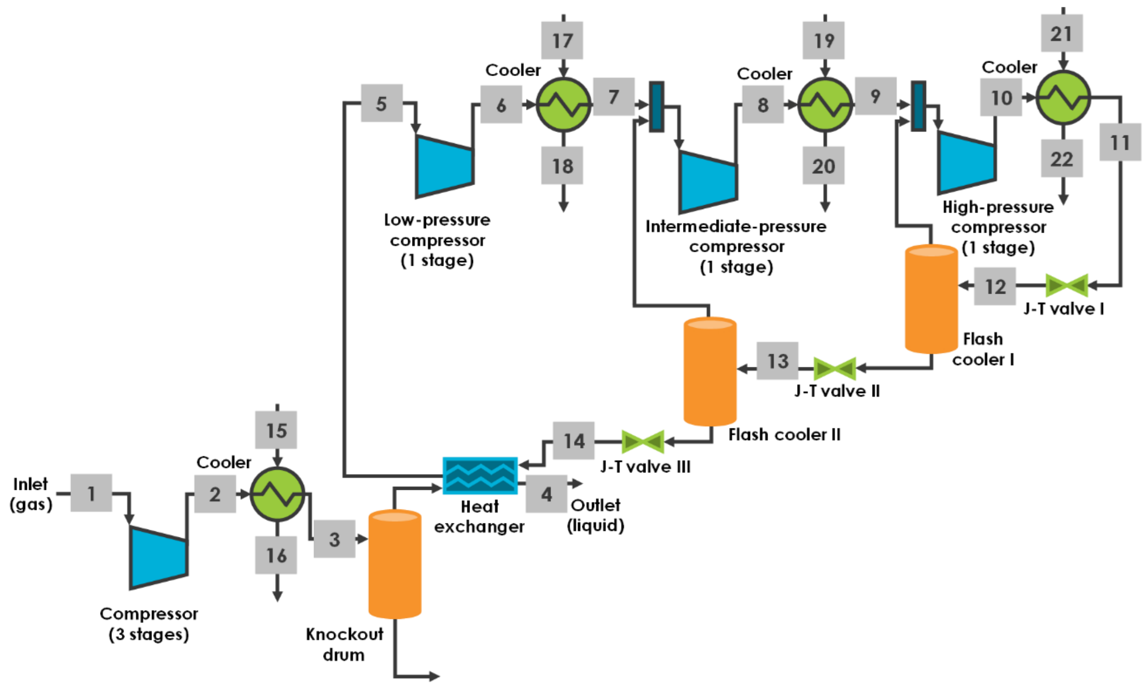
There are two main types of liquefaction systems, depending on whether external working fluids (refrigerants) are incorporated. The first system type is based on an open system concept and the second system type is based on a closed system concept [16, 328, 199]; the open liquefaction system is generally simpler than the closed system because it does not require the refrigerant.

- In an open system, the CO_2 is compressed to 70 bar (1,015 psi) and expanded to the intended transport pressure: low or medium pressure. Flash gas from this process must be recompressed, while the latter utilizes a refrigerant.
- In an external cooling loop, the CO_2 is compressed to the transport pressure and cooled with an external cooling loop, such as cold ammonia.

Internal cooling loop systems are simpler but considered less efficient than external cooling loop systems. For reference, Figure A-1 outlines two proposed CO_2 liquefaction configurations by Seo et al. [328] for open and closed systems designed to process 1 Mt CO_2/yr with exit P/Ts of 15 bar and -28 °C, respectively. Additionally, Figure A-1 also summarizes the P/T ranges varying across each system as well as the portion of total CO_2 in the system at each numbered component.



Stream Component Number	1	2	3	4	5	6	7	8	9	10	11	12
Pressure (bar)	1	15	15	100	100	100	15	15	3	3	3	3
Temperature (°C)	35	121	35	128	35	29	-28	24	30	35	30	35
Fraction of CO_2 in System Handled (%)	54%	54%	54%	100%	100%	100%	100%	46%	C	C	C	C
C = Coolant												



Stream Component Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Pressure (bar)	1	15	15	15	1	2.5	2.5	6	6	14	14	6	2.5	1	3	3	3	3	3	3	3	3
Temperature (°C)	35	121	35	-28	-31	42	35	117	35	118	35	9	-13	-32	30	35	30	35	30	35	30	35
Fraction of CO_2 in System Handled (%)	100%	100%	100%	100%	28%	28%	30%	30%	30%	33%	33%	33%	30%	28%	C	C	C	C	C	C	C	C
C = Coolant or refrigerant																						

Figure A-1. Example of an open system (top) and closed system (bottom) process flow for CO_2 liquefaction

A.2 Temporary Intermediate Storage

Due to the continuous nature of CO_2 capture and the intermittency of vessel availability and loading, storage tanks (otherwise called containers) that can temporarily house liquefied CO_2 are required. Having these intermediate and temporary storage tanks provides a means to ensure continuous operations of all value chain components by balancing CO_2 supply variability given the differences in CO_2 handling/processing temporalities across components. The storage tanks afford a buffer between value chain components that generally provide a constant supply of CO_2 (i.e., output from liquefaction facilities and subsurface injection of CO_2) and processes that provide a more batch-wise supply of CO_2 (i.e., vessel availability and loading/offloading rates and durations) [172, 199]. As mentioned in Section 2.1, this type of buffer storage is required prior to shipping at the export terminal and post shipping at the receiving/import terminal. Intermediate storage has also been proposed for application in offshore settings via LCO_2 receiving vessels and floating storage and offloading units [203]. This study discussion will focus largely on onshore intermediate storage options. Considering analogous technologies, LCO_2 shares many commonalities and is largely comparable with vessel transport of LPG and LNG, in which both products are similarly transported in refrigerated and pressurized (applicable to LPG) storage tanks. Additionally, the LPG and LNG industries utilize onshore tanks to similarly store product on a temporary basis as a means to ensure timely distribution to geologic storage sites or CO_2 utilization end users.

Several tank design options exist for temporary storage facilities. Cylindrical or spherical steel tanks are common buffer storage options. Tank size and configuration designs require some level of optimization to ensure compatibility with the multiple interdependencies that exist in a given CCUS value chain [199]. Critical design considerations for temporary intermediate storage infrastructure include the targeted LCO_2 transport P/T regime, CO_2 flow rate (average and maximum), vessel onboard storage capacity, vessel fleet size, loading and offloading durations, and round-trip time per vessel between export and import terminals. Generally, for a given storage facility, one common tank geometry is employed, influenced by the needed storage capacity and the tank design (operating) pressure. The advantages and disadvantages to each are described in Table A-2.

To enable operational flexibility, the design capacity for storage facilities must have sufficient margin beyond the expected capacity of the ship(s). For instance, the size of the storage facility must correspond to at least the full capacity of the vessel and should also be able to store additional CO_2 in case the turn-around cycle of the ship(s) is delayed for any reason (like break-downs, scheduled maintenance, or inclement weather events). The literature has proposed a range of potential storage capacity margin design targets for consideration beyond batch-wise transport capacity. These span from 100 percent of the vessel capacity [330, 174] to 120 percent (similar to the LNG industry) [331], upwards of even 150 and 200 percent of the vessel capacity [332, 333, 334, 199]. Ultimately, the margin of design buffer relative to batch/vessel capacity can be influenced by balancing the cost/benefit of system operational flexibility and cost-effectiveness, given that storage system capital and operational expenses scale with design capacity. From a siting design perspective, bulk storage of CO_2 at terminals additionally requires consideration of spacing needs. The Northern Lights project, for example, has completed the installation of 12 vertically oriented, cylindrical CO_2 storage tanks at its import facility in Øygarden. The tanks are 32.5 m (107 ft) tall and have the capacity to store nearly 700 tonnes of CO_2 each [335]. These tanks afford the Northern Lights project roughly 100 percent of buffer storage capacity relative to the project's dedicated LCO_2 vessels design capacity [114]. These tanks occupy roughly 1,880 square meters (m^2) (6,170 square feet [ft^2]) of surface area at the import terminal site.

Storage tank designs require the use of material and equipment capable of withstanding a range of CO_2 pressures and temperatures. A variety of classes of steel are used for the storage tanks, depending on the P/T regime implemented. Forged carbon steel is used for high-pressure conditions. Carbon steel is used in combination with either foam insulation or double-skin vacuum insulation for medium-pressure conditions. Tanks expected to operate under low-temperature conditions require the use of specialized low-temperature materials, including carbon manganese steel, stainless steel, and low-temperature steel grades [336, 174, 96].

In their 2024 study titled "Concept Study to Offload Onboard Captured CO_2," the Global Centre for Maritime Decarbonisation listed several design standards related to LCO_2 temporary storage [85]. These standards, summarized in Table A-3, require future consideration when planning temporary storage facilities at a terminal site.

Table A-2. Advantages and disadvantages for different pressurized LCO_2 storage container types

Item	Cylindrical Pressure Tanks	Spherical Pressure Tanks
Advantages	Fabrication is straightforward Can be oriented in vertical or horizontal fashion Low cost to construct relative to spherical tanks Enables efficient arrangement configurations in buildings (or on vessels) Low surface footprint when arranged in a vertical (vs. horizontal) fashion Greater structural integrity under pressure	At same design pressure, can be designed with reduced wall thickness compared to cylindrical tanks Largest storage volume per unit surface area of any container design Improved resistance to corrosion Minimalized concentration of stress on surface of tank from internal loading Can be designed upwards of 10,000 m^3, equating to roughly 9,030–11,150 tonnes of CO_2 depending on P/T regime
Disadvantages	Maximum capacity of larger tanks is approximately 1,000 m^3, equating to roughly 930–1,115 tonnes of CO_2 depending on P/T regime	Higher fabrication cost relative to cylindrical pressure tanks Requires larger surface footprint per container relative to cylindrical tanks

Note: Data are from Fraga et al. [199] and Wobo Industrial Group Corp. [337]

Table A-3. Summary of applicable onshore LCO_2 temporary storage design standards

Standard Identifier	Standard Title	Summary	Relevance to LCO_2 Onshore Storage
Compressed Gas Association G-6.1	Standard for Large Insulated Liquid Carbon Dioxide Systems at User Sites	The standard covers the design, location, installation, operation, and maintenance of LCO_2 supply systems located at user sites where each container has a liquid capacity of greater than 1,000 pounds, which the industry often refers to as bulk systems. It addresses the system design components, from the container fill connections to process piping.	The guidance is applicable to the design and construction of insulated LCO_2 bulk storage tanks or containers for storage of captured LCO_2, transportation of offloaded LCO_2, and storage of LCO_2 at onshore installations. Overall, it aims to ensure safe handling and operation of these systems, particularly regarding the potential hazards associated with low temperatures and high pressures associated with LCO_2 storage.
ISO 20421-1: 2019	Cryogenic vessels – Large transportable vacuum insulated vessels – Part 1: Design, fabrication, inspection and testing	The standard specifies requirements for the design, fabrication, inspection, and testing of large transportable vacuum-insulated cryogenic vessels of more than 450-liter volume, which are permanently (fixed tanks) or not permanently (demountable tanks	LCO_2 is one of the fluids covered under the standard. It provides requirements for the design, fabrication, inspection, and testing of large, transportable, vacuum-insulated cryogenic vessels, even if the temperatures are not essentially at cryogenic levels.

Standard Identifier	Standard Title	Summary	Relevance to LCO_2 Onshore Storage
		and portable tanks) attached to a means of transport, for one or more modes of transport.	
ISO 21028-2: 2018	Cryogenic vessels – Toughness requirements for materials at cryogenic temperature – Part 2: Temperatures between -80 °C and -20 °C	The standard specifies the toughness requirements of metallic materials for use at temperatures between −20 °C and −80 °C to ensure their suitability for cryogenic vessels. This document is applicable to fine-grain and low-alloyed steels with specified yield strength < 460 Newton per square millimeter, aluminum and aluminum alloys, copper and copper alloys, and austenitic stainless steels.	This standard is relevant to the handling and storage of substances like LCO_2, which must be stored at low temperatures, even though not essentially at cryogenic temperatures. The standard can be used in the selection of metallic materials for LCO_2 storage vessels onboard vessels with a toughness commensurate with the design temperatures anticipated for LCO_2 and without risk of failure due to the low temperatures and considerations for the equipment in the transfer process.
British Compressed Gasses Association Code of Practice 26	Bulk Liquid Carbon Dioxide Storage at Users' Premises	The code of practice provides guidance for the design, installation, operation, and maintenance of static, insulated, bulk LCO_2 storage systems at users' premises of an individual capacity of up to 250,000 liters (250 m^3).	The guidance is applicable to static insulated bulk storage of LCO_2 onshore storage tanks and ensures compliance with safety standards related to the storage and handling of bulk LCO_2.
ISO 21013 - 1 & 2	Cryogenic vessels – Pressure-relief accessories for cryogenic service	The standard specifies the requirements for the design, manufacturing, and testing of pressure-relief valves for cryogenic service.	Applicable to valves not exceeding a size of nominal diameter of 150 millimeters designed to relieve single-phase vapors or gases for systems operation with cryogenic fluids below −10 °C in addition to operation at ambient temperatures from ambient to cryogenic.
ASME Boiler and Pressure Vessel Code	ASME Boiler and Pressure Vessel Code Section VIII - Rules for Construction of Pressure Vessels, Division 1 or 2	ASME BPVC Section VIII provides requirements for the design, fabrication, inspection, testing, and certification of pressure vessels that operate at either internal or external pressures exceeding 15 psig (1 bar). This makes it directly relevant for pressure vessels used in bulk liquid storage if they are pressurized.	The guidance is applicable to the design and construction of insulated LCO_2 bulk storage tanks for onshore storage and transport, all of which will be pressurized above 1 bar. It is incorporated by reference by other industry societies or shipping codes.

A.3 Gas Conditioning

Gas conditioning is a step that involves pressurization and heating of the CO_2 to conditions that would be amenable with offsite transport (like a CO_2 pipeline) or for direct injection into the subsurface via the U.S. Environmental Protection Agency (EPA) Underground Injection Control injection well (Class II for enhanced oil recovery and Class VI for long-term storage). This equipment includes heating and pumping and could be located on the import terminal or platform or directly on transport vessels used for direct-injection applications.

As outlined in prior sections, LCO_2 is transported via vessel and intermediately stored in the range of 6–18 bar (87–261 psi) and -50 to -25 °C (-58 to -13 °F) depending on the use of low- or medium-pressure storage regimes (Table 2-2). For context, CO_2 pipelines typically operate at conditions around 75–150 bar (1,100–2,200 psi) and 15–30 °C (60–86 °F) [338, 339]. The injection pressures at wellheads are typically even higher than pipeline pressures, often exceeding the critical pressure needed to ensure the CO_2 reaches the reservoir in a supercritical phase [340, 341]. As a result, the CO_2 stream must undergo substantial pressurization and heating to overcome these P/T deficits prior to transport to storage sites or be directly injected.

From a design and operational perspective, the P/T conditions at which the CO_2 will be transported on the vessels will directly influence the subsequent capital and operational costs of appropriately sized CO_2 conditioning equipment [342]. In general, costs decrease as less pressurization and heating is needed [16]. The medium- and high-pressure vessel designs would prompt the lowest P/T condition requirements relative to the low-pressure design case and as a result, offer a cost saving regarding the conditioning step [100].

In the case of direct injection from the ship, heating could be provided from waste heat available from seawater (>15 °C; 60 °F) or from the ship's engine. Combustion of an alternative fuel (like oil) can be used if the waste heat or warm sea water is not appropriate given site conditions [83, 343]. In the case of Alaska, extracting waste heat from seawater requires further consideration given the ranges in local seawater temperatures. Depending on location, seawater temperatures near Alaska can swing from 10–15 °C (50–60 °F) to -1.7 °C (28 °F) in the Arctic Ocean (near the freezing point of seawater) depending on the time of year [344].

A.4 Pilot-Scale Testing: Summary of CETO Report Results

This section expands the technical discussion that is summarized in Section 2.2.2. Among the most thorough technology readiness level (TRL) assessments to date of LCO_2 shipping technologies specific to low-P/T transport is the 2024 CO_2 Efficient Transport via Ocean (CETO) report published by Det Norske Veritas (DNV) in partnership with SINTEF, Brevik Engineering, and other research and development (R&D) agencies [22]. The report assesses TRL 4 on a 7-point scale [162] for nearly all component technologies of the LCO_2 shipping value chain (see Figure 2-10), which qualifies as "large scale version of technology built, and technology qualified for use within specified operating conditions/limits, through testing in intended environment simulated or actual" [162]. This description is in broad agreement with TRL 5–6 in the U.S. Department of Energy (DOE) scale [155] that qualifies a technology demonstrated at pilot scale

(~10 percent of full commercial scale). Experimental configurations, key results of the pilot testing, and implications for component technology TRLs are summarized in the following subsections.

Lab/Pilot Systems Testing for Low-Pressure LCO_2 Transport

Pilot-scale R&D (TRL 5–6) aims to integrate the components of a technology in a configuration that approximates the final application at roughly 10 percent scale. Component technologies that have been developed and tested separately with realistic materials (e.g., a compression and refrigeration unit for low-pressure LCO_2 liquefaction or a low-pressure LCO_2 cargo tank) are interfaced and the system operated as a whole using process feedstocks that are either a simulant(s) (e.g., pure CO_2 mixed with impurities) or real (e.g., LCO_2 from a representative capture source). Pilot-scale testing is a critical stage in technology development that applies learnings from bench-top experiments to the first operations of the final system configuration and enables collection of important process data across a range of scenarios to inform development of the technology toward full commercial scale.

Low-P/T LCO_2 Transfer System

SINTEF and Norwegian CCS successfully operated an original experimental system to transfer low-P/T LCO_2 between a simulated onshore (vertical) tank and shipboard cargo (horizontal) tank (see Figure A-2). The test system attempted to replicate the final technology by including a realistic valve configuration including pressure-release valves. The system was tested in roughly 40 scenarios across a range of operating conditions including induced dry ice formation in tanks and valves as well as four scenarios with simulated, impure LCO_2 cargo (0.5 mol% methane [CH_4]). Target P/T in various segments of the system was determined by process modeling and monitored in real time. The testing identified several operational impacts (Table A-4) that the report links to heat ingress from ambient air and non-pre-cooled tanks and piping that, the report states, are likely to have a reduced effect at full-scale. The report concludes that the pilot study results demonstrate successful LCO_2 transfer in low-pressure conditions and support the feasibility of commercial-scale port terminal systems for low-pressure LCO_2 on-/offloading.

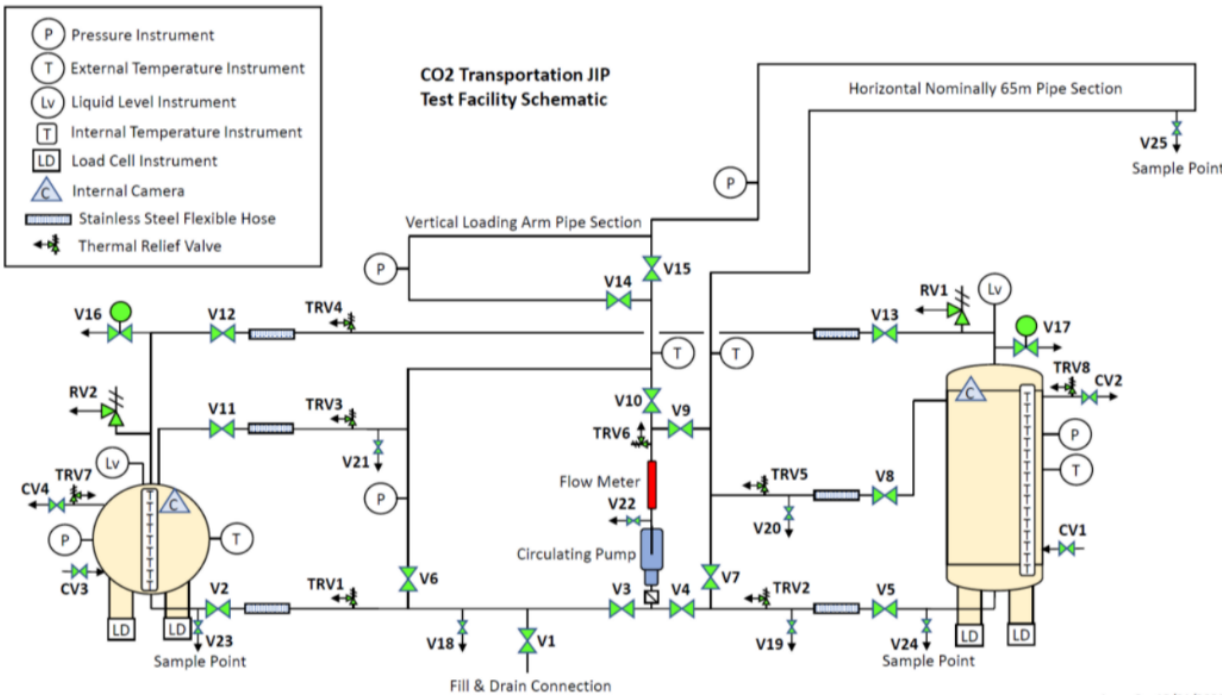


Figure A-2. Process flow diagram for pilot-scale low-pressure LCO_2 cargo transfer system

Permission pending from Notaro et al. [22]

Table A-4. Details of the integrated LCO_2 storage and transfer system configuration and testing presented in the CETO report

Parameter	Full-Scale Operation Target*	Range of Pilot-Scale Testing
Pressure	7–8 bara	5.2–10 bara
Temperature	-49.4 to -46 °C	-49 to -46 °C
Transfer time	varies	>1 hr
Tank heel	2%	5%
Flowrate	2,500 m^3/hr	3–4 m^3/hr
Conduit length	300 m	50 m
System component	**Configuration**	
Piping	Insulated, vertical “loading arm” segment, pressure drop of 1–2 bar	
Tanks	Two tanks at least 1 m^3; one tank vertical (onshore simulant), one tank horizontal (shipboard simulant)	
LCO_2	Pure LCO_2; impure LCO_2 simulant with 0.5 mol% CH_4 added	
Process Impact	**Observed Effects**	**Learning/Conclusion**
Two-phase flow in vertical “loading arm” segment	Gradual reduction in flowrate	Flaw of test rig; piping in full-scale application would have stronger submerged pumps, lower heat ingress (lower surface area/volume ratio), pre-cooling

Parameter	Full-Scale Operation Target*	Range of Pilot-Scale Testing
Impure LCO_2 cargo (0.5 mol% CH_4)	Increased system pressure response to heat ingress; temperature gradient in liquid phase	Did not increase risk of dry ice formation; light impurities like CH_4 must be removed prior to shipping
Heat ingress/non-equilibrium vapor formation	Gradual increase in system pressure (~2 bar/hr)	

*Based on 30,000 m^3 LCO_2 tanker concept; see tables 6-5, 6-6 in Notaro et al. [22]

Liquefaction to Low-Pressure LCO_2 Transport Conditions

CO_2 liquefaction to medium-P/T conditions is technologically mature (TRL 9). Low-P/T CO_2 liquefaction, however, requires cooling to temperatures well below (~-50 °C) the requirements for medium-P/T shipping (~-30 °C) and, therefore, faces process uncertainty such as the role of variable
LCO_2-phase equilibria caused by impure CO_2 streams that have not been extensively modeled or validated at low-P/T conditions.

SINTEF and partners conducted a pilot-scale study of CO_2 liquefaction to low-P/T conditions using a closed-loop system with test scenarios using pure CO_2 and nitrogen (N_2)-CO_2 mixtures (6–25 mol% N_2) that mimic impurity concentrations of CO_2 streams from different capture methods [22, 163]. N_2 is a common non-compressible gas impurity in captured CO_2 streams that can alter the triple-point P/T conditions at which dry ice formation occurs and serves here as an analog to other common non-compressible gas impurities such as O_2, CH_4, and H_2 [163, 90]. The experimental liquefaction system, which is configured after concept designs for commercial low-P/T liquefaction, uses conventional CO_2 liquefaction stages to achieve medium-P/T conditions and adds a throttling step (Joule-Thomson cooling) to achieve low-P/T conditions [90]. The system processes a maximum 200 kg CO_2/hr, which is <10 percent of the rate expected for a full-scale liquefaction facility handling 1 Mt/yr of CO_2 [138].

The results of the pilot study demonstrated, for both pure and N_2-contaminated CO_2 streams, successful liquefaction to common low-P/T conditions for LCO_2 shipping (7–8 bar at ~-50 °C; see Section 2.1.1) with conditions held stable for five hours without dry ice formation. In each test scenario, once operational low-P/T conditions were demonstrated, LCO_2 P/T was decreased until dry ice formation was observed at triple-point conditions that varied with N_2 content (5.6–6.5 bar; -55 °C to -56.5 °C) and progressed until the system was plugged (5.4–5.6 bar). The results of this pilot study support the feasibility of commercial-scale liquefaction of impure CO_2 streams to low-P/T shipping conditions. The study assesses a TRL 4 on a 7-point scale for low-P/T CO_2 liquefaction based on the pilot study results. With respect to DOE TRL assessment criteria [155], this pilot study may achieve TRL 4–5 reflective of successful operation with simulant inputs at <10 percent of commercial scale. This TRL assessment, however, should be considered preliminary until a full technology readiness assessment is completed [155].

Low-P/T LCO_2 Cargo Tank Material and Construction

The temperature of low-P/T LCO_2 transport is near the lower limit of carbon-manganese steel. The CETO report confirmed acceptable results of impact and deformation (cracked tip opening displacement) behavior on unwelded plates of two P690-equivalent high-manganese steel chemistries (1.5 percent and 2 percent nickel) using realistic design parameters including 50-millimeter plate thickness, post-weld heat-treated submerged arc welds, and low-P/T temperature regimes [22]; however, low-temperature fracture testing revealed embrittlement of tank steel near welds to the support structure that failed standardized qualification criteria. In response to this design flaw, a new tank concept was designed that attempted to redistribute critical stresses to avoid failure at embrittled weld-affected zones. Dynamic simulations of the updated tank design, performed for the purpose of DNV Class review, revealed material strength and fatigue parameters within an acceptable range with notable caveats and future testing guidance issued in the DNV review [22].

APPENDIX B: REGULATORY AND STATUTORY AUTHORITIES

Table B-1 and Table B-2, developed by the U.S. EPA, present the regulatory and statutory authorities (along with action(s) required, affected medium, and authorizing/implementing agency) related to CO_2 transportation, site selection, and CO_2 storage for additional review and consideration [345].

Table B-1. Regulatory and statutory authorities potentially applicable to CO_2 transportation

Authority	Action(s) Required	Affected Medium	Authorizing/Implementing Agency
Hazardous Materials Transportation Act	Permitting and packaging procedures for covered hazardous materials	Surface (pipelines, roads, rails) including on the seabed	U.S. Department of Transportation (DOT), Pipeline & Hazardous Materials Safety Administration
Hazardous Liquid Pipeline Safety Act	Developing/implementing public education programs about pipeline safety	Surface (pipelines, roads, rails)	DOT, Pipeline & Hazardous Materials Safety Administration
Clean Air Act	Prevention of Significant Deterioration/New Source, including Ambient Air Quality Standards, Nonattainment New Source Review permitting	Air	U.S. Environmental Protection Agency (EPA), Office of Air and Radiation, Office of Air Quality Planning and Standards
Various Alaska state acts/regulations	Permitting for truck/carrier, rail transport, or shipping of CO_2	Surface (pipelines, roads, rails)	DOT and Alaska State Department of Transportation
National Environmental Policy Act	Environmental Assessments (EAs) and Environmental Impact Statements (EISs) for major federal actions	Air, surface (e.g., emissions source, pipeline), subsurface	Agencies responsible for permitting major federal actions
National Historic Preservation Act	Tribal consultations and evaluations of impacts to sites on the National Register of Historic Places	Surface (developed/community area), subsurface, seabed	Agencies responsible for permitting major actions in collaboration with National Park Service, Alaska State and Tribal Historic Preservation Officers, and local governments certified as having qualified preservation programs
Fish and Wildlife Conservation Act/ Fish and Wildlife Coordination Act	Consultations about non-game fish and wildlife species and their habitats	Surface (water bodies, forested area)	U.S. Department of the Interior (DOI), U.S. Fish and Wildlife Service (FWS); Alaska State wildlife agencies
Coastal Zone Management Act	Requires federal actions that are reasonably likely to affect any land or water use or natural resource of the coastal zone be consistent with enforceable policies of Alaska's federally-approved coastal management program	Surface (coastal and ocean), subsurface (coastal and ocean)	U.S. Department of Commerce (DOC), National Oceanic and Atmospheric Administration (NOAA), Office for Coastal Management in collaboration with Alaska State agencies
Magnuson-Stevens Fishery Conservation and Management Act	Consultations regarding adverse effects to essential fish habitats	Surface, subsurface	DOC, NOAA Fisheries
Marine Mammal Protection Act	Incidental Take Authorization for unintentional taking of small numbers of marine mammals. Requires public review/comment, monitoring, and reporting of take to verify negligible impact	Waters under the jurisdiction of the United States (oceans)	DOC, NOAA Fisheries
General Military Law; Part IV: Service Supply and Property	Issuance of leases of non-excess military property; easements for rights-of-way for military departments; and acceptance of funds to cover administrative expenses	Air, surface (land and water bodies), subsurface (federal lands)	U.S. Department of Defense (DOD), U.S. Army Corps of Engineers (USACE)
Endangered Species Act	Consultations regarding endangered or threatened species and their habitats	Surface (water bodies, forested areas), air	DOI, FWS; DOC, NOAA Fisheries

Authority	Action(s) Required	Affected Medium	Authorizing/Implementing Agency
Rights-of-way for pipelines through federal lands	Obtaining special use permits or rights-of-way on federal lands	Surface (federal lands as defined by the authority)	U.S. Department of Agriculture (USDA), U.S. Forest Service (USFS); USACE; DOI; applies on federal lands
Federal Land Policy and Management Act	Development of Resource Management Plans	Surface (any lands or interest managed by the Bureau of Land Management [BLM])	DOI, BLM; applies on federal lands
National Forest Management Act	Land and Resource Management Planning for multiple uses within national forests and grasslands	Surface (federal lands)	USDA, USFS; applies on federal lands
Mineral Leasing Act	Leasing for federal minerals	Surface (land)	DOI, BLM, USDA, USFS; applies on federal lands
Outer Continental Shelf Lands Act	Grant of a lease, easement, or right-of-way on the Outer Continental Shelf (OCS) for activities that provide for, support, or are directly related to the injection of a CO_2 stream into sub-seabed geologic formations for the purpose of long-term carbon storage	Air and surface (ocean waters)	DOI, Bureau of Ocean Energy Management (BOEM), Bureau of Safety and Environmental Enforcement (BSEE)
Comprehensive Environmental Response Compensation and Liability Act	Responding in the event contaminants are released that present an imminent and substantial danger to the environment	Surface, subsurface	EPA, Office of Emergency Management (applies only if contamination occurs)
Resource Conservation and Recovery Act	Compliance with DOT and other conditions in the regulation (e.g., certification). If applicable, Alaska state authority requirements for transportation of conditionally excluded CO_2 streams that are hazardous from the definition of hazardous waste	Surface (pipelines, roads, rails) and subsurface	EPA, Office of Land and Emergency Management, Office of Resource Conservation and Recovery
Emergency Planning and Community Right to Know Act	Reporting and emergency planning in the event of releases of listed extremely hazardous substances	Surface, subsurface	EPA, with involvement of Alaska state/local government and tribes (applies only if contamination occurs)
Title 41 of the Fixing America's Surface Transportation Act	Voluntary program governed by the statutory eligibility criteria to coordinate interagency efforts, eliminate needless duplication, and engage federal agencies and project sponsors to foster improved communication and clarify expectations	Air, surface (e.g., emissions source, pipeline), subsurface	Federal Permitting Improvement Steering Council in collaboration with federal agencies
Consultation and Coordination with Indian Tribal Governments (E.O. 13175)	Regular and meaningful consultation and collaboration with tribes	Air, surface (land and water bodies), subsurface	Federal agencies undertaking actions with tribal implications
Environmental Justice (E.O. 12898)	Identify and address disproportionately high and adverse human health or environmental effects of actions on minority and low-income populations and promote nondiscrimination in federal programs that affect human health and the environment, as well as provide minority and low-income communities access to public information and public participation	Air, surface (land and water bodies), subsurface	Federal agencies undertaking action that may impact communities with environmental justice concerns
Various local regulations	Local land use permitting	Surface (developed area)	Local government agencies
Various local regulations	Condemnation procedures for eminent domain authority	Surface (emissions source, pipeline, road), subsurface	Alaska state-specific authorities

Table B-2. Regulatory and statutory authorities related to site selection

Authority	Action(s) Required	Affected Medium	Authorizing/Implementing Agency
Various local regulations	Local land use permitting and zoning	Surface (developed area)	Local government agencies
Various Alaska state and local regulations	Surface and groundwater use/rights permitting	Surface (water bodies); subsurface (groundwater)	Various Alaska state-specific authorities (i.e., based on individual Alaska state riparian rights or ground water management rules)
National Environmental Policy Act	EAs and EISs for major federal actions	Air, surface (e.g., emissions source, pipeline), subsurface	Agencies responsible for permitting major federal actions
Endangered Species Act	Consultations regarding endangered or threatened species and their habitats	Surface (water bodies, forested areas) and air	DOI, FWS, DOC, NOAA fisheries
Fish and Wildlife Conservation Act/Fish and Wildlife Coordination Act	Consultations about non-game fish and wildlife species and their habitats	Surface (water bodies, forested area)	DOI, FWS, Alaska state wildlife agencies
National Historic Preservation Act	Tribal consultations and evaluations of impacts to sites on the National Register of Historic Places	Surface (developed/community area), subsurface, seabed	Agencies responsible for permitting major actions in collaboration with National Park Service, Alaska State and Tribal Historic Preservation Officers, and local governments certified as having qualified preservation programs
Various Alaska state authorities, acts, or regulations	Pore space use or ownership	Subsurface	Alaska state/local agencies
Various Alaska state oil and gas (O&G) authorities, acts, or regulations	Pooling, spacing, unitization, and/or associated mineral rights or lease holds in depleted O&G fields	Subsurface	Alaska state-specific O&G regulatory entities
Emergency Planning and Community Right to Know Act	Reporting and emergency planning in the event of releases of listed extremely hazardous substances	Surface, subsurface	EPA, with involvement of Alaska state/local government and tribes (applies only if contamination occurs)
Federal Land Policy and Management Act	Development of Resource Management Plans	Surface (any lands or interest managed by the Bureau of Land Management)	DOI, BLM; applies on federal lands
Rights-of-way for pipelines through federal lands	Obtaining special use permits or rights-of-way on federal lands	Surface (federal lands)	USDA, USFS, DOD, USACE, DOI; applies on federal lands
Mineral Leasing Act	Leasing for federal minerals	Surface (lands)	DOI, BLM, USDA, USFS
National Forest Management Act	Land and resource management planning for multiple uses within national forests and grasslands	Surface (federal lands)	USDA, USFS; applies on federal lands
General Military Law; Part IV: Service Supply and Property	Issuance of leases of non-excess military property; easements for rights-of-way for military departments; and acceptance of funds to cover administrative expenses	Air, surface (land and water bodies), subsurface (federal lands)	DOD, USACE
Comprehensive Environmental Response Compensation and Liability Act	Responding in the event of releases of contaminants that present an imminent and substantial danger to the environment	Surface, subsurface	EPA, Office of Emergency Management (applies only if contamination occurs)

Authority	Action(s) Required	Affected Medium	Authorizing/Implementing Agency
Title 41 of the Fixing America's Surface Transportation Act	Voluntary program governed by the statutory eligibility criteria to coordinate interagency efforts, eliminate needless duplication, and engage federal agencies and project sponsors to foster improved communication and clarify expectations	Air, surface (land and water bodies) (e.g., emissions source, pipeline), subsurface	Federal Permitting Improvement Steering Council in collaboration with federal agencies
Consultation and Coordination with Indian Tribal Governments (E.O. 13175)	Regular and meaningful consultation and collaboration with tribes	Air, surface (land and water bodies), subsurface	Federal agencies undertaking actions with tribal implications
Environmental Justice (E.O. 12898)	Identify and address disproportionately high and adverse human health or environmental effects of actions on minority and low-income populations and promote nondiscrimination in federal programs that affect human health and the environment, as well as provide minority and low-income communities access to public information and public participation	Air, surface (land and water bodies), subsurface	Federal agencies undertaking action that may impact communities with environmental justice concerns
Coastal Zone Management Act	Requires that federal actions that are reasonably likely to affect any land or water use or natural resource of the coastal zone be consistent with enforceable policies of Alaska's federally-approved coastal management program	Surface (coastal and ocean), subsurface (coastal and ocean)	DOC, NOAA, Office for Coastal Management in collaboration with Alaska state agencies
Magnuson-Stevens Fishery Conservation and Management Act	Consultations regarding adverse effects to essential fish habitats	Surface (water bodies), subsurface	DOC, NOAA fisheries
Marine Mammal Protection Act	Incidental Take Authorization for unintentional taking of small numbers of marine mammals. Requires public review/comment, monitoring, and reporting of take to verify negligible impact	Waters under the jurisdiction of the United States (ocean)	DOC, NOAA fisheries
The Bald and Golden Eagle Protection Act	Consultations regarding bald eagles and their habitats if these species are present in the project area	Surface	DOI, FWS
The Migratory Bird Treaty Act	Consultations regarding migratory birds and their habitats if these species are present in the project area	Surface	DOI, FWS
Clean Water Act	Section 404/Section 401 permitting for discharge of dredge or fill materials	Surface (water bodies) on federal or non-federal lands	DOD, USACE, EPA, Office of Wetlands, Oceans and Watersheds
Rivers and Harbors Act of 1899	Permitting for construction of any structure or other alterations in or over any navigable waters of the United States	Surface (water bodies) on federal or non-federal lands	DOD, USACE
10 U.S.C. Sections 2667 and 2668	Obtaining rights-of-way on military or civil works lands	Surface	DOD, USACE
33 U.S.C. Section 408	Section 408 program verifies that changes to authorized Civil Works projects will not be injurious to the public interest and will not impair the usefulness of a project; applies to taking possession of, use of, or injury to harbor or river improvements.	Surface	DOD, USACE
Outer Continental Shelf Lands Act	Grant a lease, easement, or right-of-way on the OCS for activities that provide for, support, or are directly related to the injection of a CO_2 stream into sub-seabed geologic formations for the purpose of long-term carbon storage	Air, surface (ocean waters), and subsurface (offshore)	DOI, BOEM, BSEE

APPENDIX C: LCO_2 SHIPPING COST DATA

Table C-1 presents a simplified version of the lookup table from the "Shipping infrastructure costs" sheet in the BEIS shipping cost tool developed by Element Energy [205]. The original 17 CAPEX and OPEX categories have been consolidated into 8 cost categories. While Section 3.2 of this report focuses on an annual transport capacity of 1 Mt per year, Table C-1 also includes estimated costs for 0.1, 0.2, 0.5, 2, 5, and 10 Mt/year. The table provides cost data for 4 offloading options, 3 P/T regimes, and 9 vessel size classifications. For medium- and high-P/T scenarios, costs are only estimated for vessel sizes of 10,000 tonnes or less, as larger vessels are generally considered technically unfeasible for medium-P/T, and high-P/T technology is still in the laboratory testing phase [96, 204, 205, 100]. All costs are estimated for a shipping transport distance of 6,402 km, representing shipping from the east coast of Japan to the southern coast of Alaska.

Table C-1. Simplified Element Energy's BEIS CO_2 shipping cost lookup table (2023$)

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Onshore	6,402	0.1	Low	1,000	6	83.2	187.9	1.7	5.0	0.6	10.8	2.1	1.0	87.6	204.7	10.2	297.73
Onshore	6,402	0.1	Low	2,000	3	60.4	104.4	1.7	5.0	0.6	6.2	4.2	2.1	66.9	117.6	5.9	187.87
Onshore	6,402	0.1	Low	4,000	2	58.4	68.0	1.7	5.0	0.6	3.8	8.5	4.2	69.2	80.9	4.0	152.89
Onshore	6,402	0.1	Low	8,000	1	42.3	41.7	1.7	5.0	0.6	2.7	17.0	8.3	61.6	57.7	2.9	121.57
Onshore	6,402	0.1	Low	10,000	1	47.7	40.0	1.7	5.0	0.6	2.4	21.2	10.4	71.3	57.8	2.9	131.46
Onshore	6,402	0.1	Low	20,000	1	69.3	43.5	1.7	5.0	0.6	1.9	42.5	20.9	114.0	71.2	3.6	188.70
Onshore	6,402	0.1	Low	30,000	1	86.1	50.8	1.7	5.0	0.6	2.0	63.7	31.3	152.1	89.1	4.5	245.65
Onshore	6,402	0.1	Low	40,000	1	100.5	56.5	1.7	5.0	0.6	1.9	85.0	41.7	187.7	105.0	5.3	298.20
Onshore	6,402	0.1	Low	50,000	1	113.3	60.8	1.7	5.0	0.6	1.7	106.2	52.1	221.8	119.6	6.0	347.70
Onshore	6,402	0.1	Medium	1,000	6	188.5	239.6	1.3	3.9	0.6	10.8	3.3	1.6	193.7	255.9	12.8	457.91
Onshore	6,402	0.1	Medium	2,000	3	133.1	140.1	1.3	3.9	0.6	6.1	6.5	3.2	141.6	153.3	7.7	300.39
Onshore	6,402	0.1	Medium	4,000	2	125.4	100.9	1.3	3.9	0.6	3.8	13.1	6.4	140.4	115.0	5.8	260.10
Onshore	6,402	0.1	Medium	8,000	1	88.5	64.4	1.3	3.9	0.6	2.7	26.2	12.9	116.6	83.8	4.2	204.18
Onshore	6,402	0.1	Medium	10,000	1	98.9	65.1	1.3	3.9	0.6	2.4	32.7	16.1	133.6	87.5	4.4	225.18
Onshore	6,402	0.1	High	1,000	6	380.8	333.9	0.8	3.1	0.6	10.7	12.7	6.2	394.8	353.9	17.7	762.55
Onshore	6,402	0.1	High	2,000	3	268.9	206.7	0.8	3.1	0.6	6.0	25.3	12.4	295.6	228.2	11.4	533.50
Onshore	6,402	0.1	High	4,000	2	253.2	163.6	0.8	3.1	0.6	3.6	50.6	24.8	305.2	195.2	9.8	509.66
Onshore	6,402	0.1	High	8,000	1	178.8	108.7	0.8	3.1	0.6	2.6	101.2	49.7	281.4	164.0	8.2	453.67
Onshore	6,402	0.1	High	10,000	1	199.8	114.7	0.8	3.1	0.6	2.2	126.5	62.1	327.8	182.1	9.1	519.27
Onshore	6,402	0.2	Low	1,000	12	166.4	375.7	3.4	9.9	1.2	21.7	2.1	1.0	173.1	408.4	20.4	296.12
Onshore	6,402	0.2	Low	2,000	6	120.7	208.7	3.4	9.9	1.2	12.3	4.2	2.1	129.5	233.0	11.7	184.64
Onshore	6,402	0.2	Low	4,000	3	87.6	120.2	3.4	9.9	1.2	7.6	8.5	4.2	100.6	141.9	7.1	123.50
Onshore	6,402	0.2	Low	8,000	2	84.7	83.4	3.4	9.9	1.2	5.3	17.0	8.3	106.3	107.0	5.3	108.59
Onshore	6,402	0.2	Low	10,000	2	95.5	80.0	3.4	9.9	1.2	4.8	21.2	10.4	121.3	105.2	5.3	115.33
Onshore	6,402	0.2	Low	20,000	1	69.3	53.0	3.4	9.9	1.2	3.9	42.5	20.9	116.3	87.6	4.4	103.86
Onshore	6,402	0.2	Low	30,000	1	86.1	57.2	3.4	9.9	1.2	3.7	63.7	31.3	154.4	102.1	5.1	130.63

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Onshore	6,402	0.2	Low	40,000	1	100.5	61.2	3.4	9.9	1.2	3.4	85.0	41.7	190.0	116.2	5.8	155.98
Onshore	6,402	0.2	Low	50,000	1	113.3	66.1	3.4	9.9	1.2	3.3	106.2	52.1	224.1	131.4	6.6	181.05
Onshore	6,402	0.2	Medium	1,000	12	377.0	479.1	2.6	7.8	1.2	21.6	3.3	1.6	384.1	510.2	25.5	455.42
Onshore	6,402	0.2	Medium	2,000	6	266.2	280.2	2.6	7.8	1.2	12.3	6.5	3.2	276.6	303.5	15.2	295.42
Onshore	6,402	0.2	Medium	4,000	3	188.0	169.5	2.6	7.8	1.2	7.6	13.1	6.4	204.9	191.3	9.6	201.80
Onshore	6,402	0.2	Medium	8,000	2	177.1	128.8	2.6	7.8	1.2	5.2	26.2	12.9	207.1	154.7	7.7	184.22
Onshore	6,402	0.2	Medium	10,000	2	197.9	130.3	2.6	7.8	1.2	4.8	32.7	16.1	234.4	158.9	7.9	200.33
Onshore	6,402	0.2	High	1,000	12	761.5	667.9	1.7	6.1	1.1	21.3	12.7	6.2	777.0	701.5	35.1	752.94
Onshore	6,402	0.2	High	2,000	6	537.8	413.5	1.7	6.1	1.1	12.0	25.3	12.4	565.9	444.0	22.2	514.29
Onshore	6,402	0.2	High	4,000	3	379.8	263.6	1.7	6.1	1.1	7.3	50.6	24.8	433.2	301.9	15.1	374.34
Onshore	6,402	0.2	High	8,000	2	357.6	217.4	1.7	6.1	1.1	5.0	101.2	49.7	461.6	278.1	13.9	376.74
Onshore	6,402	0.2	High	10,000	2	399.7	229.3	1.7	6.1	1.1	4.5	126.5	62.1	529.0	302.0	15.1	423.21
Onshore	6,402	0.5	Low	1,000	30	416.0	939.4	8.4	24.8	3.1	54.2	2.1	1.0	429.6	1,019.4	51.0	295.15
Onshore	6,402	0.5	Low	2,000	15	301.8	521.8	8.4	24.8	3.1	30.8	4.2	2.1	317.5	579.5	29.0	182.71
Onshore	6,402	0.5	Low	4,000	8	233.5	308.3	8.4	24.8	3.1	19.1	8.5	4.2	253.5	356.3	17.8	124.22
Onshore	6,402	0.5	Low	8,000	4	169.4	186.1	8.4	24.8	3.1	13.3	17.0	8.3	197.8	232.5	11.6	87.67
Onshore	6,402	0.5	Low	10,000	3	143.2	154.8	8.4	24.8	3.1	12.1	21.2	10.4	175.9	202.1	10.1	76.99
Onshore	6,402	0.5	Low	20,000	2	138.5	117.3	8.4	24.8	3.1	9.7	42.5	20.9	192.5	172.6	8.6	74.37
Onshore	6,402	0.5	Low	30,000	1	86.1	78.6	8.4	24.8	3.1	9.1	63.7	31.3	161.3	143.7	7.2	62.12
Onshore	6,402	0.5	Low	40,000	1	100.5	80.2	8.4	24.8	3.1	8.8	85.0	41.7	196.9	155.4	7.8	71.78
Onshore	6,402	0.5	Low	50,000	1	113.3	81.7	8.4	24.8	3.1	8.3	106.2	52.1	230.9	167.0	8.3	81.06
Onshore	6,402	0.5	Medium	1,000	30	942.5	1,197.8	6.5	19.6	3.0	54.1	3.3	1.6	955.3	1,273.1	63.7	453.93
Onshore	6,402	0.5	Medium	2,000	15	665.6	700.4	6.5	19.6	3.0	30.6	6.5	3.2	681.7	753.9	37.7	292.43
Onshore	6,402	0.5	Medium	4,000	8	501.4	439.8	6.5	19.6	3.0	18.9	13.1	6.4	524.1	484.8	24.2	205.51
Onshore	6,402	0.5	Medium	8,000	4	354.1	276.8	6.5	19.6	3.0	13.2	26.2	12.9	389.8	322.4	16.1	145.09
Onshore	6,402	0.5	Medium	10,000	3	296.8	230.2	6.5	19.6	3.0	11.9	32.7	16.1	339.1	277.8	13.9	125.66
Onshore	6,402	0.5	High	1,000	30	1,903.8	1,669.7	4.2	15.3	2.8	53.4	12.7	6.2	1,923.4	1,744.5	87.2	747.18
Onshore	6,402	0.5	High	2,000	15	1,344.5	1,033.7	4.2	15.3	2.8	29.9	25.3	12.4	1,376.8	1,091.3	54.6	502.76
Onshore	6,402	0.5	High	4,000	8	1,012.8	690.9	4.2	15.3	2.8	18.2	50.6	24.8	1,070.4	749.2	37.5	370.67
Onshore	6,402	0.5	High	8,000	4	715.3	454.1	4.2	15.3	2.8	12.5	101.2	49.7	823.5	531.5	26.6	276.01
Onshore	6,402	0.5	High	10,000	3	599.5	378.8	4.2	15.3	2.8	11.2	126.5	62.1	733.0	467.4	23.4	244.53
Onshore	6,402	1	Low	1,000	60	832.0	1,878.7	16.8	49.5	6.2	108.4	2.1	1.0	857.0	2,037.7	101.9	294.83
Onshore	6,402	1	Low	2,000	30	603.5	1,043.6	16.8	49.5	6.2	61.6	4.2	2.1	630.7	1,156.8	57.8	182.06
Onshore	6,402	1	Low	4,000	15	437.8	600.8	16.8	49.5	6.2	38.2	8.5	4.2	469.2	692.7	34.6	118.34
Onshore	6,402	1	Low	8,000	8	338.8	372.3	16.8	49.5	6.2	26.5	17.0	8.3	378.7	456.6	22.8	85.08
Onshore	6,402	1	Low	10,000	6	286.4	309.6	16.8	49.5	6.2	24.1	21.2	10.4	330.6	393.7	19.7	73.77
Onshore	6,402	1	Low	20,000	3	207.8	198.7	16.8	49.5	6.2	19.4	42.5	20.9	273.2	288.5	14.4	57.21
Onshore	6,402	1	Low	30,000	2	172.2	157.1	16.8	49.5	6.2	18.1	63.7	31.3	258.9	256.1	12.8	52.45
Onshore	6,402	1	Low	40,000	2	201.0	160.4	16.8	49.5	6.2	17.1	85.0	41.7	308.9	268.8	13.4	58.83
Onshore	6,402	1	Low	50,000	2	226.5	163.5	16.8	49.5	6.2	16.6	106.2	52.1	355.7	281.8	14.1	64.93

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Onshore	6,402	1	Medium	1,000	60	1,885.0	2,395.7	13.0	39.2	6.1	108.1	3.3	1.6	1,907.4	2,544.5	127.2	453.44
Onshore	6,402	1	Medium	2,000	30	1,331.2	1,400.9	13.0	39.2	6.1	61.3	6.5	3.2	1,356.9	1,504.5	75.2	291.44
Onshore	6,402	1	Medium	4,000	15	940.1	847.4	13.0	39.2	6.1	37.9	13.1	6.4	972.3	930.9	46.5	193.85
Onshore	6,402	1	Medium	8,000	8	708.2	553.6	13.0	39.2	6.1	26.2	26.2	12.9	753.5	631.8	31.6	141.10
Onshore	6,402	1	Medium	10,000	6	593.6	460.4	13.0	39.2	6.1	23.8	32.7	16.1	645.4	539.5	27.0	120.69
Onshore	6,402	1	High	1,000	60	3,807.6	3,339.5	8.3	30.5	5.6	106.7	12.7	6.2	3,834.2	3,482.9	174.1	745.26
Onshore	6,402	1	High	2,000	30	2,689.0	2,067.4	8.3	30.5	5.6	59.9	25.3	12.4	2,728.2	2,170.2	108.5	498.92
Onshore	6,402	1	High	4,000	15	1,899.0	1,318.1	8.3	30.5	5.6	36.5	50.6	24.8	1,963.6	1,410.0	70.5	343.60
Onshore	6,402	1	High	8,000	8	1,430.6	908.2	8.3	30.5	5.6	24.8	101.2	49.7	1,545.7	1,013.2	50.7	260.63
Onshore	6,402	1	High	10,000	6	1,199.1	757.6	8.3	30.5	5.6	22.4	126.5	62.1	1,339.5	872.7	43.6	225.32
Onshore	6,402	2	Low	1,000	119	1,650.0	3,726.1	33.5	99.1	12.3	216.8	2.1	1.0	1,698.0	4,043.0	202.2	292.37
Onshore	6,402	2	Low	2,000	60	1,207.0	2,087.3	33.5	99.1	12.3	123.2	4.2	2.1	1,257.1	2,311.6	115.6	181.74
Onshore	6,402	2	Low	4,000	30	875.6	1,201.6	33.5	99.1	12.3	76.3	8.5	4.2	930.0	1,381.2	69.1	117.70
Onshore	6,402	2	Low	8,000	15	635.2	722.1	33.5	99.1	12.3	52.9	17.0	8.3	698.0	882.5	44.1	80.49
Onshore	6,402	2	Low	10,000	12	572.8	619.2	33.5	99.1	12.3	48.2	21.2	10.4	639.9	777.0	38.8	72.16
Onshore	6,402	2	Low	20,000	6	415.5	397.4	33.5	99.1	12.3	38.9	42.5	20.9	503.9	556.2	27.8	53.99
Onshore	6,402	2	Low	30,000	4	344.4	314.3	33.5	99.1	12.3	35.9	63.7	31.3	454.0	480.5	24.0	47.59
Onshore	6,402	2	Low	40,000	3	301.4	269.1	33.5	99.1	12.3	34.2	85.0	41.7	432.3	444.1	22.2	44.63
Onshore	6,402	2	Low	50,000	3	339.8	276.6	33.5	99.1	12.3	33.3	106.2	52.1	491.9	461.1	23.1	48.53
Onshore	6,402	2	Medium	1,000	119	3,738.6	4,751.4	26.1	78.3	12.1	216.2	3.3	1.6	3,780.0	5,047.6	252.4	449.55
Onshore	6,402	2	Medium	2,000	60	2,662.5	2,801.7	26.1	78.3	12.1	122.6	6.5	3.2	2,707.2	3,005.9	150.3	290.94
Onshore	6,402	2	Medium	4,000	30	1,880.3	1,694.8	26.1	78.3	12.1	75.8	13.1	6.4	1,931.6	1,855.3	92.8	192.85
Onshore	6,402	2	Medium	8,000	15	1,327.9	1,062.2	26.1	78.3	12.1	52.4	26.2	12.9	1,392.3	1,205.7	60.3	132.31
Onshore	6,402	2	Medium	10,000	12	1,187.2	920.8	26.1	78.3	12.1	47.7	32.7	16.1	1,258.2	1,062.9	53.1	118.20
Onshore	6,402	2	High	1,000	119	7,551.7	6,623.3	16.7	61.0	11.2	213.4	12.7	6.2	7,592.2	6,903.9	345.2	738.23
Onshore	6,402	2	High	2,000	60	5,378.0	4,134.8	16.7	61.0	11.2	119.8	25.3	12.4	5,431.2	4,328.0	216.4	497.00
Onshore	6,402	2	High	4,000	30	3,798.1	2,636.3	16.7	61.0	11.2	73.0	50.6	24.8	3,876.6	2,795.1	139.8	339.76
Onshore	6,402	2	High	8,000	15	2,682.3	1,727.0	16.7	61.0	11.2	49.6	101.2	49.7	2,811.4	1,887.3	94.4	239.29
Onshore	6,402	2	High	10,000	12	2,398.2	1,515.3	16.7	61.0	11.2	44.9	126.5	62.1	2,552.5	1,683.3	84.2	215.71
Onshore	6,402	5	Low	1,000	296	4,104.3	9,268.3	83.8	247.7	30.8	542.0	2.1	1.0	4,221.0	10,059.0	503.0	290.89
Onshore	6,402	5	Low	2,000	148	2,977.4	5,148.6	83.8	247.7	30.8	307.9	4.2	2.1	3,096.2	5,706.2	285.3	179.31
Onshore	6,402	5	Low	4,000	74	2,159.9	2,964.0	83.8	247.7	30.8	190.8	8.5	4.2	2,282.9	3,406.7	170.3	115.90
Onshore	6,402	5	Low	8,000	37	1,566.8	1,781.2	83.8	247.7	30.8	132.3	17.0	8.3	1,698.4	2,169.6	108.5	78.79
Onshore	6,402	5	Low	10,000	30	1,432.1	1,548.0	83.8	247.7	30.8	120.6	21.2	10.4	1,567.9	1,926.7	96.3	71.19
Onshore	6,402	5	Low	20,000	15	1,038.9	993.5	83.8	247.7	30.8	97.2	42.5	20.9	1,195.9	1,359.3	68.0	52.05
Onshore	6,402	5	Low	30,000	10	861.0	785.7	83.8	247.7	30.8	89.5	63.7	31.3	1,039.3	1,154.2	57.7	44.68
Onshore	6,402	5	Low	40,000	8	803.9	698.6	83.8	247.7	30.8	85.5	85.0	41.7	1,003.4	1,073.5	53.7	42.31
Onshore	6,402	5	Low	50,000	6	679.6	600.2	83.8	247.7	30.8	83.2	106.2	52.1	900.4	983.3	49.2	38.37
Onshore	6,402	5	Medium	1,000	296	9,299.3	11,818.6	65.2	195.8	30.3	540.6	3.3	1.6	9,398.0	12,556.6	627.8	447.23
Onshore	6,402	5	Medium	2,000	148	6,567.4	6,910.9	65.2	195.8	30.3	306.5	6.5	3.2	6,669.4	7,416.5	370.8	286.94

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Onshore	6,402	5	Medium	4,000	74	4,638.0	4,180.5	65.2	195.8	30.3	189.5	13.1	6.4	4,746.6	4,572.2	228.6	189.83
Onshore	6,402	5	Medium	8,000	37	3,275.5	2,620.0	65.2	195.8	30.3	130.9	26.2	12.9	3,397.2	2,959.6	148.0	129.49
Onshore	6,402	5	Medium	10,000	30	2,968.1	2,302.0	65.2	195.8	30.3	119.2	32.7	16.1	3,096.3	2,633.2	131.7	116.71
Onshore	6,402	5	High	1,000	296	18,784.0	16,474.7	41.7	152.5	27.9	533.5	12.7	6.2	18,866.3	17,167.0	858.3	734.01
Onshore	6,402	5	High	2,000	148	13,265.7	10,199.2	41.7	152.5	27.9	299.5	25.3	12.4	13,360.7	10,663.6	533.2	489.39
Onshore	6,402	5	High	4,000	74	9,368.6	6,502.8	41.7	152.5	27.9	182.4	50.6	24.8	9,488.9	6,862.6	343.1	333.09
Onshore	6,402	5	High	8,000	37	6,616.3	4,260.0	41.7	152.5	27.9	123.9	101.2	49.7	6,787.2	4,586.1	229.3	231.68
Onshore	6,402	5	High	10,000	30	5,995.4	3,788.2	41.7	152.5	27.9	112.2	126.5	62.1	6,191.6	4,115.0	205.7	209.95
Onshore	6,402	10	Low	1,000	591	8,194.7	18,505.4	167.7	495.4	61.5	1,083.9	2.1	1.0	8,426.0	20,085.7	1,004.3	290.40
Onshore	6,402	10	Low	2,000	296	5,954.7	10,297.1	167.7	495.4	61.5	615.8	4.2	2.1	6,188.2	11,410.4	570.5	179.24
Onshore	6,402	10	Low	4,000	148	4,319.7	5,927.9	167.7	495.4	61.5	381.7	8.5	4.2	4,557.4	6,809.2	340.5	115.77
Onshore	6,402	10	Low	8,000	74	3,133.6	3,562.4	167.7	495.4	61.5	264.6	17.0	8.3	3,379.8	4,330.8	216.5	78.53
Onshore	6,402	10	Low	10,000	60	2,864.2	3,096.0	167.7	495.4	61.5	241.2	21.2	10.4	3,114.6	3,843.1	192.2	70.87
Onshore	6,402	10	Low	20,000	30	2,077.7	1,987.0	167.7	495.4	61.5	194.4	42.5	20.9	2,349.4	2,697.7	134.9	51.41
Onshore	6,402	10	Low	30,000	20	1,722.0	1,571.4	167.7	495.4	61.5	179.0	63.7	31.3	2,015.0	2,277.1	113.9	43.72
Onshore	6,402	10	Low	40,000	15	1,507.2	1,345.4	167.7	495.4	61.5	171.0	85.0	41.7	1,821.4	2,053.6	102.7	39.47
Onshore	6,402	10	Low	50,000	12	1,359.3	1,200.5	167.7	495.4	61.5	166.3	106.2	52.1	1,694.7	1,914.4	95.7	36.76
Onshore	6,402	10	Medium	1,000	591	18,567.1	23,597.3	130.4	391.7	60.6	1,081.1	3.3	1.6	18,761.4	25,071.6	1,253.6	446.45
Onshore	6,402	10	Medium	2,000	296	13,134.8	13,821.8	130.4	391.7	60.6	613.0	6.5	3.2	13,332.3	14,829.7	741.5	286.84
Onshore	6,402	10	Medium	4,000	148	9,276.1	8,361.0	130.4	391.7	60.6	378.9	13.1	6.4	9,480.2	9,138.0	456.9	189.63
Onshore	6,402	10	Medium	8,000	74	6,551.0	5,240.0	130.4	391.7	60.6	261.9	26.2	12.9	6,768.2	5,906.4	295.3	129.09
Onshore	6,402	10	Medium	10,000	60	5,936.2	4,604.1	130.4	391.7	60.6	238.5	32.7	16.1	6,159.9	5,250.3	262.5	116.22
Onshore	6,402	10	High	1,000	591	37,504.5	32,893.8	83.5	305.0	55.9	1,067.1	12.7	6.2	37,656.6	34,272.1	1,713.6	732.61
Onshore	6,402	10	High	2,000	296	26,531.5	20,398.4	83.5	305.0	55.9	598.9	25.3	12.4	26,696.1	21,314.8	1,065.7	489.00
Onshore	6,402	10	High	4,000	148	18,737.2	13,005.6	83.5	305.0	55.9	364.8	50.6	24.8	18,927.2	13,700.3	685.0	332.32
Onshore	6,402	10	High	8,000	74	13,232.7	8,520.1	83.5	305.0	55.9	247.8	101.2	49.7	13,473.2	9,122.6	456.1	230.14
Onshore	6,402	10	High	10,000	60	11,990.8	7,576.3	83.5	305.0	55.9	224.4	126.5	62.1	12,256.7	8,167.8	408.4	208.03
Direct injection	6,402	0.1	Low	1,000	7	97.1	200.3	1.7	5.0	29.1	19.9	1.1	0.5	128.9	225.7	11.3	361.20
Direct injection	6,402	0.1	Low	2,000	4	80.5	116.4	1.7	5.0	29.1	17.6	2.1	1.0	113.4	140.0	7.0	258.02
Direct injection	6,402	0.1	Low	4,000	2	58.4	68.3	1.7	5.0	29.1	16.4	4.2	2.1	93.4	91.8	4.6	188.64
Direct injection	6,402	0.1	Low	8,000	1	42.3	41.9	1.7	5.0	29.1	15.9	8.5	4.2	81.6	66.9	3.3	151.26
Direct injection	6,402	0.1	Low	10,000	1	47.7	40.1	1.7	5.0	29.1	15.7	10.6	5.2	89.1	66.0	3.3	158.05
Direct injection	6,402	0.1	Low	20,000	1	69.3	43.6	1.7	5.0	29.1	15.5	21.2	10.4	121.3	74.4	3.7	199.34
Direct injection	6,402	0.1	Low	30,000	1	86.1	50.9	1.7	5.0	29.1	15.5	31.9	15.6	148.7	87.0	4.4	240.11
Direct injection	6,402	0.1	Low	40,000	1	100.5	56.5	1.7	5.0	29.1	15.5	42.5	20.9	173.7	97.8	4.9	276.57
Direct injection	6,402	0.1	Low	50,000	1	113.3	60.9	1.7	5.0	29.1	15.4	53.1	26.1	197.2	107.3	5.4	310.05
Direct injection	6,402	0.1	Medium	1,000	7	219.9	260.6	1.3	3.9	29.1	19.9	1.6	0.8	251.9	285.3	14.3	547.17
Direct injection	6,402	0.1	Medium	2,000	4	177.5	164.0	1.3	3.9	29.1	17.6	3.3	1.6	211.2	187.1	9.4	405.64
Direct injection	6,402	0.1	Medium	4,000	2	125.4	101.2	1.3	3.9	29.1	16.4	6.5	3.2	162.3	124.8	6.2	292.37
Direct injection	6,402	0.1	Medium	8,000	1	88.5	64.6	1.3	3.9	29.1	15.9	13.1	6.4	132.0	90.8	4.5	226.90

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Direct injection	6,402	0.1	Medium	10,000	1	98.9	65.3	1.3	3.9	29.1	15.7	16.4	8.0	145.7	92.9	4.6	243.05
Direct injection	6,402	0.1	High	1,000	7	444.2	370.7	0.8	3.1	29.1	19.8	6.3	3.1	480.5	396.7	19.8	893.43
Direct injection	6,402	0.1	High	2,000	4	358.5	252.9	0.8	3.1	29.1	17.5	12.7	6.2	401.1	279.6	14.0	693.33
Direct injection	6,402	0.1	High	4,000	2	253.2	164.0	0.8	3.1	29.1	16.3	25.3	12.4	308.4	195.8	9.8	513.54
Direct injection	6,402	0.1	High	8,000	1	178.8	108.9	0.8	3.1	29.1	15.8	50.6	24.8	259.4	152.5	7.6	419.52
Direct injection	6,402	0.1	High	10,000	1	199.8	114.8	0.8	3.1	29.1	15.6	63.3	31.1	293.0	164.5	8.2	466.03
Direct injection	6,402	0.2	Low	1,000	13	180.3	390.9	3.4	9.9	30.1	26.1	1.1	0.5	214.7	427.4	21.4	327.04
Direct injection	6,402	0.2	Low	2,000	7	140.8	224.3	3.4	9.9	30.1	21.4	2.1	1.0	176.4	256.7	12.8	220.54
Direct injection	6,402	0.2	Low	4,000	4	116.7	136.7	3.4	9.9	30.1	19.1	4.2	2.1	154.4	167.7	8.4	164.07
Direct injection	6,402	0.2	Low	8,000	2	84.7	83.8	3.4	9.9	30.1	17.9	8.5	4.2	126.6	115.7	5.8	123.42
Direct injection	6,402	0.2	Low	10,000	2	95.5	80.3	3.4	9.9	30.1	17.7	10.6	5.2	139.5	113.1	5.7	128.63
Direct injection	6,402	0.2	Low	20,000	1	69.3	53.1	3.4	9.9	30.1	17.2	21.2	10.4	123.9	90.7	4.5	109.28
Direct injection	6,402	0.2	Low	30,000	1	86.1	57.3	3.4	9.9	30.1	17.1	31.9	15.6	151.4	100.0	5.0	128.02
Direct injection	6,402	0.2	Low	40,000	1	100.5	61.3	3.4	9.9	30.1	17.0	42.5	20.9	176.4	109.0	5.5	145.35
Direct injection	6,402	0.2	Low	50,000	1	113.3	66.2	3.4	9.9	30.1	16.9	53.1	26.1	199.8	119.0	6.0	162.38
Direct injection	6,402	0.2	Medium	1,000	13	408.4	502.9	2.6	7.8	30.1	26.0	1.6	0.8	442.7	537.6	26.9	499.24
Direct injection	6,402	0.2	Medium	2,000	7	310.6	307.7	2.6	7.8	30.1	21.3	3.3	1.6	346.6	338.5	16.9	348.87
Direct injection	6,402	0.2	Medium	4,000	4	250.7	202.4	2.6	7.8	30.1	19.0	6.5	3.2	289.9	232.5	11.6	266.05
Direct injection	6,402	0.2	Medium	8,000	2	177.1	129.1	2.6	7.8	30.1	17.8	13.1	6.4	222.8	161.2	8.1	195.58
Direct injection	6,402	0.2	Medium	10,000	2	197.9	130.6	2.6	7.8	30.1	17.6	16.4	8.0	246.9	164.0	8.2	209.28
Direct injection	6,402	0.2	High	1,000	13	825.0	707.4	1.7	6.1	30.1	25.8	6.3	3.1	863.0	742.5	37.1	817.62
Direct injection	6,402	0.2	High	2,000	7	627.4	463.2	1.7	6.1	30.1	21.2	12.7	6.2	671.8	496.7	24.8	595.08
Direct injection	6,402	0.2	High	4,000	4	506.4	328.0	1.7	6.1	30.1	18.8	25.3	12.4	563.5	365.3	18.3	472.98
Direct injection	6,402	0.2	High	8,000	2	357.6	217.8	1.7	6.1	30.1	17.6	50.6	24.8	440.0	266.3	13.3	359.71
Direct injection	6,402	0.2	High	10,000	2	399.7	229.6	1.7	6.1	30.1	17.4	63.3	31.1	494.7	284.2	14.2	396.66
Direct injection	6,402	0.5	Low	1,000	31	429.8	977.3	8.4	24.8	33.0	44.5	1.1	0.5	472.3	1,047.1	52.4	309.50
Direct injection	6,402	0.5	Low	2,000	16	321.9	536.4	8.4	24.8	33.0	32.8	2.1	1.0	365.4	595.0	29.8	195.64
Direct injection	6,402	0.5	Low	4,000	8	233.5	310.0	8.4	24.8	33.0	26.9	4.2	2.1	279.1	363.8	18.2	130.97
Direct injection	6,402	0.5	Low	8,000	4	169.4	187.0	8.4	24.8	33.0	24.1	8.5	4.2	219.3	240.0	12.0	93.56
Direct injection	6,402	0.5	Low	10,000	4	190.9	180.6	8.4	24.8	33.0	23.4	10.6	5.2	243.0	234.1	11.7	97.17
Direct injection	6,402	0.5	Low	20,000	2	138.5	117.7	8.4	24.8	33.0	22.3	21.2	10.4	201.1	175.2	8.8	76.66
Direct injection	6,402	0.5	Low	30,000	2	172.2	123.3	8.4	24.8	33.0	21.9	31.9	15.6	245.5	185.7	9.3	87.82
Direct injection	6,402	0.5	Low	40,000	1	100.5	80.5	8.4	24.8	33.0	21.8	42.5	20.9	184.4	147.9	7.4	67.68
Direct injection	6,402	0.5	Low	50,000	1	113.3	82.0	8.4	24.8	33.0	21.6	53.1	26.1	207.8	154.4	7.7	73.77
Direct injection	6,402	0.5	Medium	1,000	31	973.9	1,244.4	6.5	19.6	33.0	44.4	1.6	0.8	1,015.1	1,309.1	65.5	473.45
Direct injection	6,402	0.5	Medium	2,000	16	710.0	726.9	6.5	19.6	33.0	32.7	3.3	1.6	752.8	780.8	39.0	312.40
Direct injection	6,402	0.5	Medium	4,000	8	501.4	441.5	6.5	19.6	33.0	26.8	6.5	3.2	547.5	491.1	24.6	211.57
Direct injection	6,402	0.5	Medium	8,000	4	354.1	277.7	6.5	19.6	33.0	23.9	13.1	6.4	406.7	327.6	16.4	149.60
Direct injection	6,402	0.5	Medium	10,000	4	395.7	281.2	6.5	19.6	33.0	23.3	16.4	8.0	451.6	332.1	16.6	159.65
Direct injection	6,402	0.5	High	1,000	31	1,967.2	1,732.0	4.2	15.3	33.0	43.9	6.3	3.1	2,010.8	1,794.2	89.7	775.09

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Direct injection	6,402	0.5	High	2,000	16	1,434.1	1,082.4	4.2	15.3	33.0	32.2	12.7	6.2	1,484.0	1,136.1	56.8	533.71
Direct injection	6,402	0.5	High	4,000	8	1,012.8	692.6	4.2	15.3	33.0	26.3	25.3	12.4	1,075.3	746.6	37.3	371.13
Direct injection	6,402	0.5	High	8,000	4	715.3	455.0	4.2	15.3	33.0	23.4	50.6	24.8	803.1	518.5	25.9	269.22
Direct injection	6,402	0.5	High	10,000	4	799.4	479.3	4.2	15.3	33.0	22.8	63.3	31.1	899.8	548.4	27.4	295.02
Direct injection	6,402	1	Low	1,000	62	859.7	1,954.6	16.8	49.5	37.9	75.2	1.1	0.5	915.4	2,079.8	104.0	305.07
Direct injection	6,402	1	Low	2,000	31	623.6	1,085.1	16.8	49.5	37.9	51.8	2.1	1.0	680.4	1,187.5	59.4	190.26
Direct injection	6,402	1	Low	4,000	16	467.0	620.0	16.8	49.5	37.9	40.1	4.2	2.1	525.9	711.7	35.6	126.06
Direct injection	6,402	1	Low	8,000	8	338.8	374.0	16.8	49.5	37.9	34.2	8.5	4.2	401.9	462.0	23.1	87.99
Direct injection	6,402	1	Low	10,000	7	334.2	339.5	16.8	49.5	37.9	33.1	10.6	5.2	399.4	427.3	21.4	84.21
Direct injection	6,402	1	Low	20,000	4	277.0	235.5	16.8	49.5	37.9	30.7	21.2	10.4	352.9	326.2	16.3	69.17
Direct injection	6,402	1	Low	30,000	3	258.3	204.3	16.8	49.5	37.9	30.1	31.9	15.6	344.8	299.6	15.0	65.64
Direct injection	6,402	1	Low	40,000	2	201.0	160.9	16.8	49.5	37.9	29.6	42.5	20.9	298.1	260.9	13.0	56.94
Direct injection	6,402	1	Low	50,000	2	226.5	163.9	16.8	49.5	37.9	29.3	53.1	26.1	334.3	268.9	13.4	61.44
Direct injection	6,402	1	Medium	1,000	62	1,947.8	2,488.7	13.0	39.2	37.9	74.9	1.6	0.8	2,000.4	2,603.7	130.2	468.93
Direct injection	6,402	1	Medium	2,000	31	1,375.6	1,454.3	13.0	39.2	37.9	51.5	3.3	1.6	1,429.8	1,546.6	77.3	303.15
Direct injection	6,402	1	Medium	4,000	16	1,002.8	883.1	13.0	39.2	37.9	39.8	6.5	3.2	1,060.3	965.3	48.3	206.31
Direct injection	6,402	1	Medium	8,000	8	708.2	555.4	13.0	39.2	37.9	34.0	13.1	6.4	772.2	635.0	31.7	143.33
Direct injection	6,402	1	Medium	10,000	7	692.6	515.5	13.0	39.2	37.9	32.8	16.4	8.0	759.9	595.5	29.8	138.04
Direct injection	6,402	1	High	1,000	62	3,934.5	3,464.0	8.3	30.5	37.9	74.0	6.3	3.1	3,987.1	3,571.6	178.6	769.86
Direct injection	6,402	1	High	2,000	31	2,778.6	2,143.0	8.3	30.5	37.9	50.6	12.7	6.2	2,837.5	2,230.3	111.5	516.17
Direct injection	6,402	1	High	4,000	16	2,025.6	1,385.2	8.3	30.5	37.9	38.8	25.3	12.4	2,097.2	1,466.9	73.3	363.02
Direct injection	6,402	1	High	8,000	8	1,430.6	910.0	8.3	30.5	37.9	33.0	50.6	24.8	1,527.4	998.4	49.9	257.25
Direct injection	6,402	1	High	10,000	7	1,398.9	862.2	8.3	30.5	37.9	31.8	63.3	31.1	1,508.4	955.6	47.8	250.97
Direct injection	6,402	2	Low	1,000	124	1,719.4	3,909.1	33.5	99.1	47.7	136.6	1.1	0.5	1,801.6	4,145.4	207.3	302.86
Direct injection	6,402	2	Low	2,000	62	1,247.3	2,170.3	33.5	99.1	47.7	89.8	2.1	1.0	1,330.6	2,360.2	118.0	187.96
Direct injection	6,402	2	Low	4,000	31	904.8	1,248.6	33.5	99.1	47.7	66.4	4.2	2.1	990.3	1,416.2	70.8	122.55
Direct injection	6,402	2	Low	8,000	16	677.5	748.1	33.5	99.1	47.7	54.7	8.5	4.2	767.3	906.0	45.3	85.21
Direct injection	6,402	2	Low	10,000	13	620.6	652.3	33.5	99.1	47.7	52.4	10.6	5.2	712.4	808.9	40.4	77.47
Direct injection	6,402	2	Low	20,000	7	484.8	438.8	33.5	99.1	47.7	47.7	21.2	10.4	587.3	596.0	29.8	60.26
Direct injection	6,402	2	Low	30,000	5	430.5	362.1	33.5	99.1	47.7	46.2	31.9	15.6	543.6	523.0	26.2	54.32
Direct injection	6,402	2	Low	40,000	4	401.9	321.9	33.5	99.1	47.7	45.3	42.5	20.9	525.6	487.1	24.4	51.58
Direct injection	6,402	2	Low	50,000	3	339.8	277.6	33.5	99.1	47.7	44.9	53.1	26.1	474.1	447.6	22.4	46.94
Direct injection	6,402	2	Medium	1,000	124	3,895.6	4,977.5	26.1	78.3	47.7	136.1	1.6	0.8	3,971.0	5,192.7	259.6	466.67
Direct injection	6,402	2	Medium	2,000	62	2,751.2	2,908.6	26.1	78.3	47.7	89.3	3.3	1.6	2,828.2	3,077.8	153.9	300.77
Direct injection	6,402	2	Medium	4,000	31	1,943.0	1,758.2	26.1	78.3	47.7	65.9	6.5	3.2	2,023.3	1,905.7	95.3	200.09
Direct injection	6,402	2	Medium	8,000	16	1,416.4	1,110.8	26.1	78.3	47.7	54.2	13.1	6.4	1,503.3	1,249.7	62.5	140.20
Direct injection	6,402	2	Medium	10,000	13	1,286.2	979.0	26.1	78.3	47.7	51.8	16.4	8.0	1,376.3	1,117.2	55.9	126.98
Direct injection	6,402	2	High	1,000	124	7,869.0	6,928.0	16.7	61.0	47.7	134.1	6.3	3.1	7,939.7	7,126.3	356.3	767.25
Direct injection	6,402	2	High	2,000	62	5,557.3	4,286.1	16.7	61.0	47.7	87.3	12.7	6.2	5,634.3	4,440.6	222.0	513.08
Direct injection	6,402	2	High	4,000	31	3,924.7	2,731.1	16.7	61.0	47.7	63.9	25.3	12.4	4,014.4	2,868.4	143.4	350.51

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Direct injection	6,402	2	High	8,000	16	2,861.1	1,820.0	16.7	61.0	47.7	52.2	50.6	24.8	2,976.1	1,958.1	97.9	251.28
Direct injection	6,402	2	High	10,000	13	2,598.0	1,623.0	16.7	61.0	47.7	49.8	63.3	31.1	2,725.6	1,764.9	88.2	228.69
Direct injection	6,402	5	Low	1,000	309	4,284.6	9,741.3	83.8	247.7	77.0	320.8	1.1	0.5	4,446.5	10,310.4	515.5	300.60
Direct injection	6,402	5	Low	2,000	155	3,118.2	5,425.7	83.8	247.7	77.0	203.8	2.1	1.0	3,281.2	5,878.3	293.9	186.58
Direct injection	6,402	5	Low	4,000	78	2,276.6	3,141.7	83.8	247.7	77.0	145.3	4.2	2.1	2,441.7	3,536.7	176.8	121.78
Direct injection	6,402	5	Low	8,000	39	1,651.5	1,886.8	83.8	247.7	77.0	116.0	8.5	4.2	1,820.9	2,254.7	112.7	83.02
Direct injection	6,402	5	Low	10,000	31	1,479.8	1,607.2	83.8	247.7	77.0	110.2	10.6	5.2	1,651.3	1,970.3	98.5	73.77
Direct injection	6,402	5	Low	20,000	16	1,108.1	1,033.6	83.8	247.7	77.0	98.5	21.2	10.4	1,290.2	1,390.2	69.5	54.60
Direct injection	6,402	5	Low	30,000	11	947.1	844.0	83.8	247.7	77.0	94.6	31.9	15.6	1,139.9	1,202.0	60.1	47.70
Direct injection	6,402	5	Low	40,000	8	803.9	701.2	83.8	247.7	77.0	92.6	42.5	20.9	1,007.2	1,062.4	53.1	42.16
Direct injection	6,402	5	Low	50,000	7	792.9	666.1	83.8	247.7	77.0	91.4	53.1	26.1	1,006.9	1,031.3	51.6	41.52
Direct injection	6,402	5	Medium	1,000	309	9,707.7	12,403.6	65.2	195.8	77.0	319.5	1.6	0.8	9,851.6	12,919.8	646.0	463.86
Direct injection	6,402	5	Medium	2,000	155	6,878.0	7,271.4	65.2	195.8	77.0	202.5	3.3	1.6	7,023.5	7,671.3	383.6	299.34
Direct injection	6,402	5	Medium	4,000	78	4,888.8	4,424.0	65.2	195.8	77.0	144.0	6.5	3.2	5,037.5	4,767.0	238.3	199.72
Direct injection	6,402	5	Medium	8,000	39	3,452.6	2,770.9	65.2	195.8	77.0	114.7	13.1	6.4	3,607.9	3,087.9	154.4	136.40
Direct injection	6,402	5	Medium	10,000	31	3,067.0	2,386.4	65.2	195.8	77.0	108.9	16.4	8.0	3,225.6	2,699.1	135.0	120.69
Direct injection	6,402	5	High	1,000	309	19,609.0	17,264.2	41.7	152.5	77.0	314.6	6.3	3.1	19,734.1	17,734.4	886.7	763.25
Direct injection	6,402	5	High	2,000	155	13,893.2	10,715.2	41.7	152.5	77.0	197.6	12.7	6.2	14,024.6	11,071.5	553.6	511.22
Direct injection	6,402	5	High	4,000	78	9,875.0	6,871.8	41.7	152.5	77.0	139.0	25.3	12.4	10,019.1	7,175.7	358.8	350.27
Direct injection	6,402	5	High	8,000	39	6,974.0	4,499.6	41.7	152.5	77.0	109.8	50.6	24.8	7,143.4	4,786.7	239.3	243.02
Direct injection	6,402	5	High	10,000	31	6,195.2	3,922.0	41.7	152.5	77.0	103.9	63.3	31.1	6,377.3	4,209.5	210.5	215.66
Direct injection	6,402	10	Low	1,000	618	8,569.1	19,482.7	167.7	495.4	126.0	627.9	1.1	0.5	8,863.8	20,606.5	1,030.3	300.16
Direct injection	6,402	10	Low	2,000	309	6,216.3	10,816.4	167.7	495.4	126.0	393.8	2.1	1.0	6,512.0	11,706.7	585.3	185.56
Direct injection	6,402	10	Low	4,000	155	4,524.0	6,243.0	167.7	495.4	126.0	276.8	4.2	2.1	4,821.9	7,017.3	350.9	120.58
Direct injection	6,402	10	Low	8,000	78	3,303.0	3,773.5	167.7	495.4	126.0	218.2	8.5	4.2	3,605.1	4,491.4	224.6	82.46
Direct injection	6,402	10	Low	10,000	62	2,959.6	3,214.4	167.7	495.4	126.0	206.5	10.6	5.2	3,263.9	3,921.6	196.1	73.19
Direct injection	6,402	10	Low	20,000	31	2,147.0	2,061.9	167.7	495.4	126.0	183.1	21.2	10.4	2,461.9	2,750.9	137.5	53.09
Direct injection	6,402	10	Low	30,000	21	1,808.1	1,611.3	167.7	495.4	126.0	175.4	31.9	15.6	2,133.6	2,297.8	114.9	45.14
Direct injection	6,402	10	Low	40,000	16	1,607.7	1,402.4	167.7	495.4	126.0	171.4	42.5	20.9	1,943.8	2,090.1	104.5	41.09
Direct injection	6,402	10	Low	50,000	13	1,472.5	1,271.3	167.7	495.4	126.0	169.1	53.1	26.1	1,819.3	1,961.9	98.1	38.51
Direct injection	6,402	10	Medium	1,000	618	19,415.4	24,807.2	130.4	391.7	126.0	625.2	1.6	0.8	19,673.4	25,824.9	1,291.2	463.41
Direct injection	6,402	10	Medium	2,000	309	13,711.6	14,495.9	130.4	391.7	126.0	391.2	3.3	1.6	13,971.3	15,280.4	764.0	297.93
Direct injection	6,402	10	Medium	4,000	155	9,714.8	8,791.2	130.4	391.7	126.0	274.1	6.5	3.2	9,977.7	9,460.2	473.0	197.98
Direct injection	6,402	10	Medium	8,000	78	6,905.1	5,541.8	130.4	391.7	126.0	215.6	13.1	6.4	7,174.6	6,155.5	307.8	135.77
Direct injection	6,402	10	Medium	10,000	62	6,134.1	4,772.7	130.4	391.7	126.0	203.9	16.4	8.0	6,406.8	5,376.3	268.8	120.01
Direct injection	6,402	10	High	1,000	618	39,217.9	34,528.4	83.5	305.0	126.0	615.4	6.3	3.1	39,433.7	35,451.9	1,772.6	762.73
Direct injection	6,402	10	High	2,000	309	27,696.7	21,361.3	83.5	305.0	126.0	381.3	12.7	6.2	27,918.8	22,053.9	1,102.7	508.98
Direct injection	6,402	10	High	4,000	155	19,623.4	13,655.4	83.5	305.0	126.0	264.3	25.3	12.4	19,858.2	14,237.1	711.9	347.27
Direct injection	6,402	10	High	8,000	78	13,948.0	8,999.2	83.5	305.0	126.0	205.7	50.6	24.8	14,208.0	9,534.8	476.7	241.83
Direct injection	6,402	10	High	10,000	62	12,390.5	7,844.1	83.5	305.0	126.0	194.0	63.3	31.1	12,663.2	8,374.2	418.7	214.27

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Platform with storage	6,402	0.1	Low	1,000	6	83.2	189.2	1.7	5.0	120.0	64.9	2.1	1.0	207.0	260.0	13.0	475.67
Platform with storage	6,402	0.1	Low	2,000	3	60.4	105.0	1.7	5.0	120.0	62.6	4.2	2.1	186.3	174.6	8.7	367.55
Platform with storage	6,402	0.1	Low	4,000	2	58.4	68.3	1.7	5.0	120.0	61.4	8.5	4.2	188.5	138.9	6.9	333.45
Platform with storage	6,402	0.1	Low	8,000	1	42.3	41.9	1.7	5.0	120.0	60.8	17.0	8.3	181.0	116.0	5.8	302.52
Platform with storage	6,402	0.1	Low	10,000	1	47.7	40.1	1.7	5.0	120.0	60.7	21.2	10.4	190.6	116.2	5.8	312.53
Platform with storage	6,402	0.1	Low	20,000	1	69.3	43.6	1.7	5.0	120.0	60.4	42.5	20.9	233.4	129.8	6.5	369.95
Platform with storage	6,402	0.1	Low	30,000	1	86.1	50.9	1.7	5.0	120.0	60.5	63.7	31.3	271.5	147.6	7.4	426.86
Platform with storage	6,402	0.1	Low	40,000	1	100.5	56.5	1.7	5.0	120.0	60.4	85.0	41.7	307.1	163.6	8.2	479.45
Platform with storage	6,402	0.1	Low	50,000	1	113.3	60.9	1.7	5.0	120.0	60.3	106.2	52.1	341.2	178.3	8.9	529.05
Platform with storage	6,402	0.1	Medium	1,000	6	188.5	240.8	1.3	3.9	120.0	64.9	3.3	1.6	313.1	311.2	15.6	635.86
Platform with storage	6,402	0.1	Medium	2,000	3	133.1	140.7	1.3	3.9	120.0	62.5	6.5	3.2	261.0	210.4	10.5	480.08
Platform with storage	6,402	0.1	Medium	4,000	2	125.4	101.2	1.3	3.9	120.0	61.4	13.1	6.4	259.7	172.9	8.6	440.67
Platform with storage	6,402	0.1	Medium	8,000	1	88.5	64.6	1.3	3.9	120.0	60.8	26.2	12.9	236.0	142.1	7.1	385.14
Platform with storage	6,402	0.1	Medium	10,000	1	98.9	65.3	1.3	3.9	120.0	60.7	32.7	16.1	253.0	145.9	7.3	406.26
Platform with storage	6,402	0.1	High	1,000	6	380.8	335.2	0.8	3.1	120.0	64.8	12.7	6.2	514.2	409.3	20.5	940.59
Platform with storage	6,402	0.1	High	2,000	3	268.9	207.4	0.8	3.1	120.0	62.4	25.3	12.4	415.0	285.3	14.3	713.28
Platform with storage	6,402	0.1	High	4,000	2	253.2	164.0	0.8	3.1	120.0	61.3	50.6	24.8	424.6	253.1	12.7	690.32
Platform with storage	6,402	0.1	High	8,000	1	178.8	108.9	0.8	3.1	120.0	60.7	101.2	49.7	400.9	222.3	11.1	634.72
Platform with storage	6,402	0.1	High	10,000	1	199.8	114.8	0.8	3.1	120.0	60.6	126.5	62.1	447.2	240.5	12.0	700.45
Platform with storage	6,402	0.2	Low	1,000	12	166.4	378.3	3.4	9.9	121.4	71.6	2.1	1.0	293.2	460.8	23.0	384.01

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Platform with storage	6,402	0.2	Low	2,000	6	120.7	210.0	3.4	9.9	121.4	66.9	4.2	2.1	249.7	288.9	14.4	274.27
Platform with storage	6,402	0.2	Low	4,000	3	87.6	120.8	3.4	9.9	121.4	64.5	8.5	4.2	220.8	199.4	10.0	214.01
Platform with storage	6,402	0.2	Low	8,000	2	84.7	83.8	3.4	9.9	121.4	63.4	17.0	8.3	226.4	165.4	8.3	199.53
Platform with storage	6,402	0.2	Low	10,000	2	95.5	80.3	3.4	9.9	121.4	63.1	21.2	10.4	241.4	163.8	8.2	206.35
Platform with storage	6,402	0.2	Low	20,000	1	69.3	53.1	3.4	9.9	121.4	62.7	42.5	20.9	236.5	146.6	7.3	195.06
Platform with storage	6,402	0.2	Low	30,000	1	86.1	57.3	3.4	9.9	121.4	62.6	63.7	31.3	274.6	161.1	8.1	221.86
Platform with storage	6,402	0.2	Low	40,000	1	100.5	61.3	3.4	9.9	121.4	62.4	85.0	41.7	310.2	175.4	8.8	247.26
Platform with storage	6,402	0.2	Low	50,000	1	113.3	66.2	3.4	9.9	121.4	62.4	106.2	52.1	344.2	190.6	9.5	272.35
Platform with storage	6,402	0.2	Medium	1,000	12	377.0	481.7	2.6	7.8	121.4	71.5	3.3	1.6	504.2	562.6	28.1	543.32
Platform with storage	6,402	0.2	Medium	2,000	6	266.2	281.5	2.6	7.8	121.4	66.8	6.5	3.2	396.8	359.3	18.0	385.06
Platform with storage	6,402	0.2	Medium	4,000	3	188.0	170.2	2.6	7.8	121.4	64.5	13.1	6.4	325.1	248.9	12.4	292.31
Platform with storage	6,402	0.2	Medium	8,000	2	177.1	129.1	2.6	7.8	121.4	63.3	26.2	12.9	327.2	213.1	10.7	275.17
Platform with storage	6,402	0.2	Medium	10,000	2	197.9	130.6	2.6	7.8	121.4	63.1	32.7	16.1	354.6	217.5	10.9	291.36
Platform with storage	6,402	0.2	High	1,000	12	761.5	670.5	1.7	6.1	121.4	71.3	12.7	6.2	897.2	754.1	37.7	840.93
Platform with storage	6,402	0.2	High	2,000	6	537.8	414.8	1.7	6.1	121.4	66.6	25.3	12.4	686.1	499.9	25.0	604.02
Platform with storage	6,402	0.2	High	4,000	3	379.8	264.3	1.7	6.1	121.4	64.3	50.6	24.8	553.4	359.5	18.0	464.94
Platform with storage	6,402	0.2	High	8,000	2	357.6	217.8	1.7	6.1	121.4	63.1	101.2	49.7	581.9	336.7	16.8	467.78
Platform with storage	6,402	0.2	High	10,000	2	399.7	229.6	1.7	6.1	121.4	62.9	126.5	62.1	649.2	360.7	18.0	514.34
Platform with storage	6,402	0.5	Low	1,000	30	416.0	945.8	8.4	24.8	125.5	91.6	2.1	1.0	552.0	1,063.1	53.2	329.01
Platform with storage	6,402	0.5	Low	2,000	15	301.8	525.1	8.4	24.8	125.5	79.9	4.2	2.1	439.9	631.8	31.6	218.31

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Platform with storage	6,402	0.5	Low	4,000	8	233.5	310.0	8.4	24.8	125.5	74.0	8.5	4.2	375.9	413.0	20.6	160.69
Platform with storage	6,402	0.5	Low	8,000	4	169.4	187.0	8.4	24.8	125.5	71.1	17.0	8.3	320.3	291.3	14.6	124.57
Platform with storage	6,402	0.5	Low	10,000	3	143.2	155.5	8.4	24.8	125.5	70.5	21.2	10.4	298.3	261.2	13.1	113.99
Platform with storage	6,402	0.5	Low	20,000	2	138.5	117.7	8.4	24.8	125.5	69.3	42.5	20.9	314.9	232.7	11.6	111.54
Platform with storage	6,402	0.5	Low	30,000	1	86.1	78.9	8.4	24.8	125.5	69.0	63.7	31.3	283.7	203.9	10.2	99.34
Platform with storage	6,402	0.5	Low	40,000	1	100.5	80.5	8.4	24.8	125.5	68.8	85.0	41.7	319.3	215.8	10.8	109.01
Platform with storage	6,402	0.5	Low	50,000	1	113.3	82.0	8.4	24.8	125.5	68.6	106.2	52.1	353.4	227.5	11.4	118.33
Platform with storage	6,402	0.5	Medium	1,000	30	942.5	1,204.2	6.5	19.6	125.5	91.4	3.3	1.6	1,077.8	1,316.8	65.8	487.80
Platform with storage	6,402	0.5	Medium	2,000	15	665.6	703.7	6.5	19.6	125.5	79.7	6.5	3.2	804.2	806.2	40.3	328.04
Platform with storage	6,402	0.5	Medium	4,000	8	501.4	441.5	6.5	19.6	125.5	73.9	13.1	6.4	646.5	541.4	27.1	241.99
Platform with storage	6,402	0.5	Medium	8,000	4	354.1	277.7	6.5	19.6	125.5	71.0	26.2	12.9	512.3	381.1	19.1	182.00
Platform with storage	6,402	0.5	Medium	10,000	3	296.8	230.9	6.5	19.6	125.5	70.4	32.7	16.1	461.6	337.0	16.8	162.66
Platform with storage	6,402	0.5	High	1,000	30	1,903.8	1,676.1	4.2	15.3	125.5	90.9	12.7	6.2	2,046.1	1,788.5	89.4	781.14
Platform with storage	6,402	0.5	High	2,000	15	1,344.5	1,037.0	4.2	15.3	125.5	79.2	25.3	12.4	1,499.5	1,143.9	57.2	538.46
Platform with storage	6,402	0.5	High	4,000	8	1,012.8	692.6	4.2	15.3	125.5	73.4	50.6	24.8	1,193.1	806.1	40.3	407.24
Platform with storage	6,402	0.5	High	8,000	4	715.3	455.0	4.2	15.3	125.5	70.5	101.2	49.7	946.2	590.4	29.5	313.01
Platform with storage	6,402	0.5	High	10,000	3	599.5	379.6	4.2	15.3	125.5	69.9	126.5	62.1	855.7	526.8	26.3	281.62
Platform with storage	6,402	1	Low	1,000	60	832.0	1,891.5	16.8	49.5	132.4	124.9	2.1	1.0	983.2	2,067.0	103.4	310.67
Platform with storage	6,402	1	Low	2,000	30	603.5	1,050.1	16.8	49.5	132.4	101.5	4.2	2.1	756.9	1,203.2	60.2	199.65
Platform with storage	6,402	1	Low	4,000	15	437.8	604.2	16.8	49.5	132.4	89.8	8.5	4.2	595.5	747.7	37.4	136.80

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Platform with storage	6,402	1	Low	8,000	8	338.8	374.0	16.8	49.5	132.4	83.9	17.0	8.3	504.9	515.9	25.8	103.97
Platform with storage	6,402	1	Low	10,000	6	286.4	311.1	16.8	49.5	132.4	82.8	21.2	10.4	456.8	453.8	22.7	92.75
Platform with storage	6,402	1	Low	20,000	3	207.8	199.5	16.8	49.5	132.4	80.4	42.5	20.9	399.4	350.4	17.5	76.37
Platform with storage	6,402	1	Low	30,000	2	172.2	157.8	16.8	49.5	132.4	79.7	63.7	31.3	385.1	318.3	15.9	71.65
Platform with storage	6,402	1	Low	40,000	2	201.0	160.9	16.8	49.5	132.4	79.2	85.0	41.7	435.1	331.4	16.6	78.07
Platform with storage	6,402	1	Low	50,000	2	226.5	163.9	16.8	49.5	132.4	79.0	106.2	52.1	481.9	344.6	17.2	84.19
Platform with storage	6,402	1	Medium	1,000	60	1,885.0	2,408.5	13.0	39.2	132.4	124.6	3.3	1.6	2,033.7	2,573.9	128.7	469.29
Platform with storage	6,402	1	Medium	2,000	30	1,331.2	1,407.4	13.0	39.2	132.4	101.2	6.5	3.2	1,483.2	1,551.0	77.5	309.04
Platform with storage	6,402	1	Medium	4,000	15	940.1	850.8	13.0	39.2	132.4	89.5	13.1	6.4	1,098.7	985.9	49.3	212.32
Platform with storage	6,402	1	Medium	8,000	8	708.2	555.4	13.0	39.2	132.4	83.7	26.2	12.9	879.8	691.1	34.6	160.00
Platform with storage	6,402	1	Medium	10,000	6	593.6	461.9	13.0	39.2	132.4	82.5	32.7	16.1	771.8	599.6	30.0	139.68
Platform with storage	6,402	1	High	1,000	60	3,807.6	3,352.3	8.3	30.5	132.4	123.6	12.7	6.2	3,961.0	3,512.6	175.6	761.20
Platform with storage	6,402	1	High	2,000	30	2,689.0	2,073.9	8.3	30.5	132.4	100.2	25.3	12.4	2,855.1	2,217.1	110.9	516.61
Platform with storage	6,402	1	High	4,000	15	1,899.0	1,321.5	8.3	30.5	132.4	88.5	50.6	24.8	2,090.4	1,465.4	73.3	362.16
Platform with storage	6,402	1	High	8,000	8	1,430.6	910.0	8.3	30.5	132.4	82.7	101.2	49.7	1,672.5	1,072.9	53.6	279.63
Platform with storage	6,402	1	High	10,000	6	1,199.1	759.1	8.3	30.5	132.4	81.5	126.5	62.1	1,466.3	933.2	46.7	244.40
Platform with storage	6,402	2	Low	1,000	119	1,650.0	3,751.5	33.5	99.1	146.2	191.6	2.1	1.0	1,831.9	4,043.2	202.2	299.20
Platform with storage	6,402	2	Low	2,000	60	1,207.0	2,100.3	33.5	99.1	146.2	144.7	4.2	2.1	1,391.0	2,346.2	117.3	190.32
Platform with storage	6,402	2	Low	4,000	30	875.6	1,208.3	33.5	99.1	146.2	121.3	8.5	4.2	1,063.9	1,432.9	71.6	127.15
Platform with storage	6,402	2	Low	8,000	15	635.2	725.7	33.5	99.1	146.2	109.6	17.0	8.3	831.9	942.7	47.1	90.38

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Platform with storage	6,402	2	Low	10,000	12	572.8	622.1	33.5	99.1	146.2	107.3	21.2	10.4	773.8	838.9	41.9	82.13
Platform with storage	6,402	2	Low	20,000	6	415.5	399.1	33.5	99.1	146.2	102.6	42.5	20.9	637.8	621.6	31.1	64.14
Platform with storage	6,402	2	Low	30,000	4	344.4	315.5	33.5	99.1	146.2	101.1	63.7	31.3	587.9	547.0	27.4	57.80
Platform with storage	6,402	2	Low	40,000	3	301.4	270.1	33.5	99.1	146.2	100.3	85.0	41.7	566.2	511.2	25.6	54.87
Platform with storage	6,402	2	Low	50,000	3	339.8	277.6	33.5	99.1	146.2	99.8	106.2	52.1	625.8	528.6	26.4	58.79
Platform with storage	6,402	2	Medium	1,000	119	3,738.6	4,776.8	26.1	78.3	146.2	191.0	3.3	1.6	3,914.1	5,047.8	252.4	456.39
Platform with storage	6,402	2	Medium	2,000	60	2,662.5	2,814.7	26.1	78.3	146.2	144.2	6.5	3.2	2,841.3	3,040.5	152.0	299.54
Platform with storage	6,402	2	Medium	4,000	30	1,880.3	1,701.5	26.1	78.3	146.2	120.8	13.1	6.4	2,065.7	1,907.1	95.4	202.32
Platform with storage	6,402	2	Medium	8,000	15	1,327.9	1,065.7	26.1	78.3	146.2	109.1	26.2	12.9	1,526.4	1,266.0	63.3	142.21
Platform with storage	6,402	2	Medium	10,000	12	1,187.2	923.8	26.1	78.3	146.2	106.8	32.7	16.1	1,392.3	1,124.9	56.2	128.19
Platform with storage	6,402	2	High	1,000	119	7,551.7	6,648.7	16.7	61.0	146.2	189.1	12.7	6.2	7,727.2	6,905.0	345.2	745.16
Platform with storage	6,402	2	High	2,000	60	5,378.0	4,147.8	16.7	61.0	146.2	142.2	25.3	12.4	5,566.2	4,363.5	218.2	505.68
Platform with storage	6,402	2	High	4,000	30	3,798.1	2,643.0	16.7	61.0	146.2	118.8	50.6	24.8	4,011.6	2,847.7	142.4	349.32
Platform with storage	6,402	2	High	8,000	15	2,682.3	1,730.6	16.7	61.0	146.2	107.1	101.2	49.7	2,946.4	1,948.4	97.4	249.28
Platform with storage	6,402	2	High	10,000	12	2,398.2	1,518.2	16.7	61.0	146.2	104.8	126.5	62.1	2,687.6	1,746.1	87.3	225.79
Platform with storage	6,402	5	Low	1,000	297	4,118.2	9,363.0	83.8	247.7	187.6	391.6	2.1	1.0	4,391.7	10,003.4	500.2	293.23
Platform with storage	6,402	5	Low	2,000	149	2,997.5	5,215.7	83.8	247.7	187.6	274.5	4.2	2.1	3,273.2	5,740.0	287.0	183.60
Platform with storage	6,402	5	Low	4,000	75	2,189.0	3,020.8	83.8	247.7	187.6	216.0	8.5	4.2	2,469.0	3,488.7	174.4	121.36
Platform with storage	6,402	5	Low	8,000	38	1,609.2	1,838.4	83.8	247.7	187.6	186.8	17.0	8.3	1,897.6	2,281.2	114.1	85.12
Platform with storage	6,402	5	Low	10,000	30	1,432.1	1,555.3	83.8	247.7	187.6	180.9	21.2	10.4	1,724.8	1,994.4	99.7	75.76

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Platform with storage	6,402	5	Low	20,000	15	1,038.9	997.7	83.8	247.7	187.6	169.2	42.5	20.9	1,352.8	1,435.5	71.8	56.80
Platform with storage	6,402	5	Low	30,000	10	861.0	788.8	83.8	247.7	187.6	165.3	63.7	31.3	1,196.2	1,233.2	61.7	49.49
Platform with storage	6,402	5	Low	40,000	8	803.9	701.2	83.8	247.7	187.6	163.3	85.0	41.7	1,160.3	1,154.0	57.7	47.14
Platform with storage	6,402	5	Low	50,000	6	679.6	602.6	83.8	247.7	187.6	162.2	106.2	52.1	1,057.3	1,064.6	53.2	43.22
Platform with storage	6,402	5	Medium	1,000	297	9,330.7	11,921.9	65.2	195.8	187.6	390.3	3.3	1.6	9,586.8	12,509.6	625.5	450.11
Platform with storage	6,402	5	Medium	2,000	149	6,611.8	6,989.9	65.2	195.8	187.6	273.2	6.5	3.2	6,871.1	7,462.2	373.1	291.98
Platform with storage	6,402	5	Medium	4,000	75	4,700.7	4,253.8	65.2	195.8	187.6	214.7	13.1	6.4	4,966.6	4,670.8	233.5	196.32
Platform with storage	6,402	5	Medium	8,000	38	3,364.0	2,699.9	65.2	195.8	187.6	185.4	26.2	12.9	3,643.0	3,094.0	154.7	137.24
Platform with storage	6,402	5	Medium	10,000	30	2,968.1	2,309.4	65.2	195.8	187.6	179.6	32.7	16.1	3,253.6	2,700.9	135.0	121.30
Platform with storage	6,402	5	High	1,000	297	18,847.5	16,593.8	41.7	152.5	187.6	385.3	12.7	6.2	19,089.5	17,137.8	856.9	737.97
Platform with storage	6,402	5	High	2,000	149	13,355.4	10,300.4	41.7	152.5	187.6	268.3	25.3	12.4	13,610.0	10,733.7	536.7	495.89
Platform with storage	6,402	5	High	4,000	75	9,495.2	6,607.5	41.7	152.5	187.6	209.8	50.6	24.8	9,775.1	6,994.6	349.7	341.61
Platform with storage	6,402	5	High	8,000	38	6,795.2	4,384.2	41.7	152.5	187.6	180.5	101.2	49.7	7,125.7	4,766.9	238.3	242.26
Platform with storage	6,402	5	High	10,000	30	5,995.4	3,795.5	41.7	152.5	187.6	174.6	126.5	62.1	6,351.3	4,184.8	209.2	214.62
Platform with storage	6,402	10	Low	1,000	593	8,222.5	18,694.6	167.7	495.4	256.6	724.9	2.1	1.0	8,648.9	19,915.9	995.8	290.94
Platform with storage	6,402	10	Low	2,000	297	5,974.9	10,396.3	167.7	495.4	256.6	490.8	4.2	2.1	6,403.4	11,384.7	569.2	181.18
Platform with storage	6,402	10	Low	4,000	149	4,348.9	6,001.4	167.7	495.4	256.6	373.8	8.5	4.2	4,781.7	6,874.7	343.7	118.72
Platform with storage	6,402	10	Low	8,000	75	3,176.0	3,628.4	167.7	495.4	256.6	315.3	17.0	8.3	3,617.2	4,447.4	222.4	82.14
Platform with storage	6,402	10	Low	10,000	60	2,864.2	3,110.7	167.7	495.4	256.6	303.6	21.2	10.4	3,309.7	3,920.1	196.0	73.64
Platform with storage	6,402	10	Low	20,000	30	2,077.7	1,995.4	167.7	495.4	256.6	280.2	42.5	20.9	2,544.5	2,791.8	139.6	54.35

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Platform with storage	6,402	10	Low	30,000	20	1,722.0	1,577.7	167.7	495.4	256.6	272.5	63.7	31.3	2,210.0	2,376.9	118.8	46.72
Platform with storage	6,402	10	Low	40,000	15	1,507.2	1,350.7	167.7	495.4	256.6	268.5	85.0	41.7	2,016.5	2,156.3	107.8	42.50
Platform with storage	6,402	10	Low	50,000	12	1,359.3	1,205.1	167.7	495.4	256.6	266.1	106.2	52.1	1,889.7	2,018.8	100.9	39.81
Platform with storage	6,402	10	Medium	1,000	593	18,630.0	23,803.7	130.4	391.7	256.6	722.3	3.3	1.6	19,020.2	24,919.2	1,246.0	447.53
Platform with storage	6,402	10	Medium	2,000	297	13,179.1	13,933.0	130.4	391.7	256.6	488.2	6.5	3.2	13,572.7	14,816.1	740.8	289.15
Platform with storage	6,402	10	Medium	4,000	149	9,338.8	8,450.9	130.4	391.7	256.6	371.2	13.1	6.4	9,738.9	9,220.2	461.0	193.10
Platform with storage	6,402	10	Medium	8,000	75	6,639.5	5,328.7	130.4	391.7	256.6	312.6	26.2	12.9	7,052.7	6,045.8	302.3	133.41
Platform with storage	6,402	10	Medium	10,000	60	5,936.2	4,618.8	130.4	391.7	256.6	300.9	32.7	16.1	6,355.9	5,327.4	266.4	119.00
Platform with storage	6,402	10	High	1,000	593	37,631.5	33,131.6	83.5	305.0	256.6	712.4	12.7	6.2	37,984.2	34,155.3	1,707.8	734.76
Platform with storage	6,402	10	High	2,000	297	26,621.1	20,531.7	83.5	305.0	256.6	478.3	25.3	12.4	26,986.5	21,327.5	1,066.4	492.09
Platform with storage	6,402	10	High	4,000	149	18,863.8	13,126.8	83.5	305.0	256.6	361.3	50.6	24.8	19,254.5	13,818.0	690.9	336.85
Platform with storage	6,402	10	High	8,000	75	13,411.5	8,653.1	83.5	305.0	256.6	302.8	101.2	49.7	13,852.8	9,310.6	465.5	235.92
Platform with storage	6,402	10	High	10,000	60	11,990.8	7,591.0	83.5	305.0	256.6	291.1	126.5	62.1	12,457.4	8,249.2	412.5	210.90
Existing platform with storage	6,402	0.1	Low	1,000	6	83.2	189.2	1.7	5.0	1.4	64.9	2.1	1.0	88.4	260.0	13.0	354.87
Existing platform with storage	6,402	0.1	Low	2,000	3	60.4	105.0	1.7	5.0	1.4	62.6	4.2	2.1	67.7	174.6	8.7	246.75
Existing platform with storage	6,402	0.1	Low	4,000	2	58.4	68.3	1.7	5.0	1.4	61.4	8.5	4.2	69.9	138.9	6.9	212.65
Existing platform with storage	6,402	0.1	Low	8,000	1	42.3	41.9	1.7	5.0	1.4	60.8	17.0	8.3	62.4	116.0	5.8	181.72
Existing platform with storage	6,402	0.1	Low	10,000	1	47.7	40.1	1.7	5.0	1.4	60.7	21.2	10.4	72.0	116.2	5.8	191.73
Existing platform with storage	6,402	0.1	Low	20,000	1	69.3	43.6	1.7	5.0	1.4	60.4	42.5	20.9	114.8	129.8	6.5	249.15
Existing platform with storage	6,402	0.1	Low	30,000	1	86.1	50.9	1.7	5.0	1.4	60.5	63.7	31.3	152.9	147.6	7.4	306.05

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Existing platform with storage	6,402	0.1	Low	40,000	1	100.5	56.5	1.7	5.0	1.4	60.4	85.0	41.7	188.5	163.6	8.2	358.65
Existing platform with storage	6,402	0.1	Low	50,000	1	113.3	60.9	1.7	5.0	1.4	60.3	106.2	52.1	222.5	178.3	8.9	408.25
Existing platform with storage	6,402	0.1	Medium	1,000	6	188.5	240.8	1.3	3.9	1.4	63.9	3.3	1.6	194.5	310.3	15.5	514.10
Existing platform with storage	6,402	0.1	Medium	2,000	3	133.1	140.7	1.3	3.9	1.4	61.6	6.5	3.2	142.4	209.5	10.5	358.32
Existing platform with storage	6,402	0.1	Medium	4,000	2	125.4	101.2	1.3	3.9	1.4	60.4	13.1	6.4	141.1	172.0	8.6	318.91
Existing platform with storage	6,402	0.1	Medium	8,000	1	88.5	64.6	1.3	3.9	1.4	59.9	26.2	12.9	117.4	141.2	7.1	263.38
Existing platform with storage	6,402	0.1	Medium	10,000	1	98.9	65.3	1.3	3.9	1.4	59.7	32.7	16.1	134.4	145.0	7.2	284.50
Existing platform with storage	6,402	0.1	High	1,000	6	380.8	335.2	0.8	3.1	1.4	63.9	12.7	6.2	395.6	408.4	20.4	818.93
Existing platform with storage	6,402	0.1	High	2,000	3	268.9	207.4	0.8	3.1	1.4	61.6	25.3	12.4	296.4	284.5	14.2	591.63
Existing platform with storage	6,402	0.1	High	4,000	2	253.2	164.0	0.8	3.1	1.4	60.4	50.6	24.8	306.0	252.3	12.6	568.66
Existing platform with storage	6,402	0.1	High	8,000	1	178.8	108.9	0.8	3.1	1.4	59.9	101.2	49.7	282.2	221.5	11.1	513.06
Existing platform with storage	6,402	0.1	High	10,000	1	199.8	114.8	0.8	3.1	1.4	59.7	126.5	62.1	328.6	239.7	12.0	578.79
Existing platform with storage	6,402	0.2	Low	1,000	12	166.4	378.3	3.4	9.9	2.8	71.6	2.1	1.0	174.6	460.8	23.0	323.61
Existing platform with storage	6,402	0.2	Low	2,000	6	120.7	210.0	3.4	9.9	2.8	66.9	4.2	2.1	131.1	288.9	14.4	213.87
Existing platform with storage	6,402	0.2	Low	4,000	3	87.6	120.8	3.4	9.9	2.8	64.5	8.5	4.2	102.2	199.4	10.0	153.60
Existing platform with storage	6,402	0.2	Low	8,000	2	84.7	83.8	3.4	9.9	2.8	63.4	17.0	8.3	107.8	165.4	8.3	139.13
Existing platform with storage	6,402	0.2	Low	10,000	2	95.5	80.3	3.4	9.9	2.8	63.1	21.2	10.4	122.8	163.8	8.2	145.95
Existing platform with storage	6,402	0.2	Low	20,000	1	69.3	53.1	3.4	9.9	2.8	62.7	42.5	20.9	117.9	146.6	7.3	134.65
Existing platform with storage	6,402	0.2	Low	30,000	1	86.1	57.3	3.4	9.9	2.8	62.6	63.7	31.3	155.9	161.1	8.1	161.46
Existing platform with storage	6,402	0.2	Low	40,000	1	100.5	61.3	3.4	9.9	2.8	62.4	85.0	41.7	191.6	175.4	8.8	186.86

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Existing platform with storage	6,402	0.2	Low	50,000	1	113.3	66.2	3.4	9.9	2.8	62.4	106.2	52.1	225.6	190.6	9.5	211.95
Existing platform with storage	6,402	0.2	Medium	1,000	12	377.0	481.7	2.6	7.8	2.8	69.6	3.3	1.6	385.6	560.8	28.0	481.97
Existing platform with storage	6,402	0.2	Medium	2,000	6	266.2	281.5	2.6	7.8	2.8	64.9	6.5	3.2	278.2	357.5	17.9	323.70
Existing platform with storage	6,402	0.2	Medium	4,000	3	188.0	170.2	2.6	7.8	2.8	62.6	13.1	6.4	206.5	247.0	12.4	230.96
Existing platform with storage	6,402	0.2	Medium	8,000	2	177.1	129.1	2.6	7.8	2.8	61.4	26.2	12.9	208.6	211.2	10.6	213.81
Existing platform with storage	6,402	0.2	Medium	10,000	2	197.9	130.6	2.6	7.8	2.8	61.2	32.7	16.1	236.0	215.7	10.8	230.00
Existing platform with storage	6,402	0.2	High	1,000	12	761.5	670.5	1.7	6.1	2.8	69.6	12.7	6.2	778.6	752.4	37.6	779.67
Existing platform with storage	6,402	0.2	High	2,000	6	537.8	414.8	1.7	6.1	2.8	64.9	25.3	12.4	567.5	498.3	24.9	542.76
Existing platform with storage	6,402	0.2	High	4,000	3	379.8	264.3	1.7	6.1	2.8	62.6	50.6	24.8	434.8	357.9	17.9	403.69
Existing platform with storage	6,402	0.2	High	8,000	2	357.6	217.8	1.7	6.1	2.8	61.4	101.2	49.7	463.3	335.0	16.7	406.53
Existing platform with storage	6,402	0.2	High	10,000	2	399.7	229.6	1.7	6.1	2.8	61.2	126.5	62.1	530.6	359.0	18.0	453.08
Existing platform with storage	6,402	0.5	Low	1,000	30	416.0	945.8	8.4	24.8	6.9	91.6	2.1	1.0	433.4	1,063.1	53.2	304.85
Existing platform with storage	6,402	0.5	Low	2,000	15	301.8	525.1	8.4	24.8	6.9	79.9	4.2	2.1	321.3	631.8	31.6	194.14
Existing platform with storage	6,402	0.5	Low	4,000	8	233.5	310.0	8.4	24.8	6.9	74.0	8.5	4.2	257.3	413.0	20.6	136.53
Existing platform with storage	6,402	0.5	Low	8,000	4	169.4	187.0	8.4	24.8	6.9	71.1	17.0	8.3	201.7	291.3	14.6	100.41
Existing platform with storage	6,402	0.5	Low	10,000	3	143.2	155.5	8.4	24.8	6.9	70.5	21.2	10.4	179.7	261.2	13.1	89.83
Existing platform with storage	6,402	0.5	Low	20,000	2	138.5	117.7	8.4	24.8	6.9	69.3	42.5	20.9	196.3	232.7	11.6	87.38
Existing platform with storage	6,402	0.5	Low	30,000	1	86.1	78.9	8.4	24.8	6.9	69.0	63.7	31.3	165.1	203.9	10.2	75.18
Existing platform with storage	6,402	0.5	Low	40,000	1	100.5	80.5	8.4	24.8	6.9	68.8	85.0	41.7	200.7	215.8	10.8	84.85
Existing platform with storage	6,402	0.5	Low	50,000	1	113.3	82.0	8.4	24.8	6.9	68.6	106.2	52.1	234.8	227.5	11.4	94.17

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Existing platform with storage	6,402	0.5	Medium	1,000	30	942.5	1,204.2	6.5	19.6	6.9	86.7	3.3	1.6	959.2	1,312.2	65.6	462.68
Existing platform with storage	6,402	0.5	Medium	2,000	15	665.6	703.7	6.5	19.6	6.9	75.0	6.5	3.2	685.6	801.5	40.1	302.93
Existing platform with storage	6,402	0.5	Medium	4,000	8	501.4	441.5	6.5	19.6	6.9	69.2	13.1	6.4	527.9	536.7	26.8	216.87
Existing platform with storage	6,402	0.5	Medium	8,000	4	354.1	277.7	6.5	19.6	6.9	66.3	26.2	12.9	393.7	376.4	18.8	156.88
Existing platform with storage	6,402	0.5	Medium	10,000	3	296.8	230.9	6.5	19.6	6.9	65.7	32.7	16.1	343.0	332.3	16.6	137.55
Existing platform with storage	6,402	0.5	High	1,000	30	1,903.8	1,676.1	4.2	15.3	6.9	86.7	12.7	6.2	1,927.5	1,784.3	89.2	756.12
Existing platform with storage	6,402	0.5	High	2,000	15	1,344.5	1,037.0	4.2	15.3	6.9	75.0	25.3	12.4	1,380.9	1,139.7	57.0	513.45
Existing platform with storage	6,402	0.5	High	4,000	8	1,012.8	692.6	4.2	15.3	6.9	69.2	50.6	24.8	1,074.5	801.9	40.1	382.22
Existing platform with storage	6,402	0.5	High	8,000	4	715.3	455.0	4.2	15.3	6.9	66.3	101.2	49.7	827.6	586.2	29.3	288.00
Existing platform with storage	6,402	0.5	High	10,000	3	599.5	379.6	4.2	15.3	6.9	65.7	126.5	62.1	737.1	522.6	26.1	256.61
Existing platform with storage	6,402	1	Low	1,000	60	832.0	1,891.5	16.8	49.5	13.8	124.9	2.1	1.0	864.6	2,067.0	103.4	298.59
Existing platform with storage	6,402	1	Low	2,000	30	603.5	1,050.1	16.8	49.5	13.8	101.5	4.2	2.1	638.3	1,203.2	60.2	187.57
Existing platform with storage	6,402	1	Low	4,000	15	437.8	604.2	16.8	49.5	13.8	89.8	8.5	4.2	476.9	747.7	37.4	124.72
Existing platform with storage	6,402	1	Low	8,000	8	338.8	374.0	16.8	49.5	13.8	83.9	17.0	8.3	386.3	515.9	25.8	91.89
Existing platform with storage	6,402	1	Low	10,000	6	286.4	311.1	16.8	49.5	13.8	82.8	21.2	10.4	338.2	453.8	22.7	80.67
Existing platform with storage	6,402	1	Low	20,000	3	207.8	199.5	16.8	49.5	13.8	80.4	42.5	20.9	280.8	350.4	17.5	64.29
Existing platform with storage	6,402	1	Low	30,000	2	172.2	157.8	16.8	49.5	13.8	79.7	63.7	31.3	266.5	318.3	15.9	59.57
Existing platform with storage	6,402	1	Low	40,000	2	201.0	160.9	16.8	49.5	13.8	79.2	85.0	41.7	316.5	331.4	16.6	65.99
Existing platform with storage	6,402	1	Low	50,000	2	226.5	163.9	16.8	49.5	13.8	79.0	106.2	52.1	363.3	344.6	17.2	72.11
Existing platform with storage	6,402	1	Medium	1,000	60	1,885.0	2,408.5	13.0	39.2	13.8	115.3	3.3	1.6	1,915.1	2,564.5	128.2	456.26

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Existing platform with storage	6,402	1	Medium	2,000	30	1,331.2	1,407.4	13.0	39.2	13.8	91.8	6.5	3.2	1,364.6	1,541.6	77.1	296.00
Existing platform with storage	6,402	1	Medium	4,000	15	940.1	850.8	13.0	39.2	13.8	80.1	13.1	6.4	980.1	976.5	48.8	199.28
Existing platform with storage	6,402	1	Medium	8,000	8	708.2	555.4	13.0	39.2	13.8	74.3	26.2	12.9	761.2	681.7	34.1	146.97
Existing platform with storage	6,402	1	Medium	10,000	6	593.6	461.9	13.0	39.2	13.8	73.1	32.7	16.1	653.2	590.2	29.5	126.65
Existing platform with storage	6,402	1	High	1,000	60	3,807.6	3,352.3	8.3	30.5	13.8	115.3	12.7	6.2	3,842.4	3,504.2	175.2	748.27
Existing platform with storage	6,402	1	High	2,000	30	2,689.0	2,073.9	8.3	30.5	13.8	91.8	25.3	12.4	2,736.5	2,208.7	110.4	503.67
Existing platform with storage	6,402	1	High	4,000	15	1,899.0	1,321.5	8.3	30.5	13.8	80.1	50.6	24.8	1,971.8	1,457.0	72.8	349.23
Existing platform with storage	6,402	1	High	8,000	8	1,430.6	910.0	8.3	30.5	13.8	74.3	101.2	49.7	1,553.9	1,064.5	53.2	266.69
Existing platform with storage	6,402	1	High	10,000	6	1,199.1	759.1	8.3	30.5	13.8	73.1	126.5	62.1	1,347.7	924.8	46.2	231.47
Existing platform with storage	6,402	2	Low	1,000	119	1,650.0	3,751.5	33.5	99.1	27.6	191.6	2.1	1.0	1,713.3	4,043.2	202.2	293.16
Existing platform with storage	6,402	2	Low	2,000	60	1,207.0	2,100.3	33.5	99.1	27.6	144.7	4.2	2.1	1,272.4	2,346.2	117.3	184.28
Existing platform with storage	6,402	2	Low	4,000	30	875.6	1,208.3	33.5	99.1	27.6	121.3	8.5	4.2	945.2	1,432.9	71.6	121.11
Existing platform with storage	6,402	2	Low	8,000	15	635.2	725.7	33.5	99.1	27.6	109.6	17.0	8.3	713.3	942.7	47.1	84.34
Existing platform with storage	6,402	2	Low	10,000	12	572.8	622.1	33.5	99.1	27.6	107.3	21.2	10.4	655.2	838.9	41.9	76.09
Existing platform with storage	6,402	2	Low	20,000	6	415.5	399.1	33.5	99.1	27.6	102.6	42.5	20.9	519.2	621.6	31.1	58.10
Existing platform with storage	6,402	2	Low	30,000	4	344.4	315.5	33.5	99.1	27.6	101.1	63.7	31.3	469.3	547.0	27.4	51.76
Existing platform with storage	6,402	2	Low	40,000	3	301.4	270.1	33.5	99.1	27.6	100.3	85.0	41.7	447.6	511.2	25.6	48.83
Existing platform with storage	6,402	2	Low	50,000	3	339.8	277.6	33.5	99.1	27.6	99.8	106.2	52.1	507.2	528.6	26.4	52.75
Existing platform with storage	6,402	2	Medium	1,000	119	3,738.6	4,776.8	26.1	78.3	27.6	172.3	3.3	1.6	3,795.5	5,029.0	251.5	449.40
Existing platform with storage	6,402	2	Medium	2,000	60	2,662.5	2,814.7	26.1	78.3	27.6	125.5	6.5	3.2	2,722.7	3,021.8	151.1	292.54

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Existing platform with storage	6,402	2	Medium	4,000	30	1,880.3	1,701.5	26.1	78.3	27.6	102.1	13.1	6.4	1,947.1	1,888.3	94.4	195.32
Existing platform with storage	6,402	2	Medium	8,000	15	1,327.9	1,065.7	26.1	78.3	27.6	90.4	26.2	12.9	1,407.8	1,247.3	62.4	135.21
Existing platform with storage	6,402	2	Medium	10,000	12	1,187.2	923.8	26.1	78.3	27.6	88.0	32.7	16.1	1,273.6	1,106.2	55.3	121.19
Existing platform with storage	6,402	2	High	1,000	119	7,551.7	6,648.7	16.7	61.0	27.6	172.3	12.7	6.2	7,608.6	6,888.2	344.4	738.27
Existing platform with storage	6,402	2	High	2,000	60	5,378.0	4,147.8	16.7	61.0	27.6	125.5	25.3	12.4	5,447.6	4,346.7	217.3	498.79
Existing platform with storage	6,402	2	High	4,000	30	3,798.1	2,643.0	16.7	61.0	27.6	102.1	50.6	24.8	3,893.0	2,830.9	141.5	342.42
Existing platform with storage	6,402	2	High	8,000	15	2,682.3	1,730.6	16.7	61.0	27.6	90.4	101.2	49.7	2,827.8	1,931.7	96.6	242.38
Existing platform with storage	6,402	2	High	10,000	12	2,398.2	1,518.2	16.7	61.0	27.6	88.0	126.5	62.1	2,569.0	1,729.3	86.5	218.90
Existing platform with storage	6,402	5	Low	1,000	297	4,118.2	9,363.0	83.8	247.7	69.0	391.6	2.1	1.0	4,273.1	10,003.4	500.2	290.82
Existing platform with storage	6,402	5	Low	2,000	149	2,997.5	5,215.7	83.8	247.7	69.0	274.5	4.2	2.1	3,154.6	5,740.0	287.0	181.19
Existing platform with storage	6,402	5	Low	4,000	75	2,189.0	3,020.8	83.8	247.7	69.0	216.0	8.5	4.2	2,350.4	3,488.7	174.4	118.94
Existing platform with storage	6,402	5	Low	8,000	38	1,609.2	1,838.4	83.8	247.7	69.0	186.8	17.0	8.3	1,779.0	2,281.2	114.1	82.71
Existing platform with storage	6,402	5	Low	10,000	30	1,432.1	1,555.3	83.8	247.7	69.0	180.9	21.2	10.4	1,606.2	1,994.4	99.7	73.34
Existing platform with storage	6,402	5	Low	20,000	15	1,038.9	997.7	83.8	247.7	69.0	169.2	42.5	20.9	1,234.2	1,435.5	71.8	54.38
Existing platform with storage	6,402	5	Low	30,000	10	861.0	788.8	83.8	247.7	69.0	165.3	63.7	31.3	1,077.6	1,233.2	61.7	47.07
Existing platform with storage	6,402	5	Low	40,000	8	803.9	701.2	83.8	247.7	69.0	163.3	85.0	41.7	1,041.7	1,154.0	57.7	44.73
Existing platform with storage	6,402	5	Low	50,000	6	679.6	602.6	83.8	247.7	69.0	162.2	106.2	52.1	938.7	1,064.6	53.2	40.81
Existing platform with storage	6,402	5	Medium	1,000	297	9,330.7	11,921.9	65.2	195.8	69.0	343.4	3.3	1.6	9,468.2	12,462.7	623.1	446.74
Existing platform with storage	6,402	5	Medium	2,000	149	6,611.8	6,989.9	65.2	195.8	69.0	226.3	6.5	3.2	6,752.5	7,415.3	370.8	288.60
Existing platform with storage	6,402	5	Medium	4,000	75	4,700.7	4,253.8	65.2	195.8	69.0	167.8	13.1	6.4	4,848.0	4,623.9	231.2	192.95

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Existing platform with storage	6,402	5	Medium	8,000	38	3,364.0	2,699.9	65.2	195.8	69.0	138.6	26.2	12.9	3,524.4	3,047.1	152.4	133.86
Existing platform with storage	6,402	5	Medium	10,000	30	2,968.1	2,309.4	65.2	195.8	69.0	132.7	32.7	16.1	3,135.0	2,654.0	132.7	117.92
Existing platform with storage	6,402	5	High	1,000	297	18,847.5	16,593.8	41.7	152.5	69.0	343.4	12.7	6.2	18,970.9	17,095.9	854.8	734.69
Existing platform with storage	6,402	5	High	2,000	149	13,355.4	10,300.4	41.7	152.5	69.0	226.3	25.3	12.4	13,491.4	10,691.7	534.6	492.62
Existing platform with storage	6,402	5	High	4,000	75	9,495.2	6,607.5	41.7	152.5	69.0	167.8	50.6	24.8	9,656.5	6,952.6	347.6	338.34
Existing platform with storage	6,402	5	High	8,000	38	6,795.2	4,384.2	41.7	152.5	69.0	138.6	101.2	49.7	7,007.1	4,725.0	236.2	238.99
Existing platform with storage	6,402	5	High	10,000	30	5,995.4	3,795.5	41.7	152.5	69.0	132.7	126.5	62.1	6,232.6	4,142.8	207.1	211.35
Existing platform with storage	6,402	10	Low	1,000	593	8,222.5	18,694.6	167.7	495.4	138.0	724.9	2.1	1.0	8,530.2	19,915.9	995.8	289.73
Existing platform with storage	6,402	10	Low	2,000	297	5,974.9	10,396.3	167.7	495.4	138.0	490.8	4.2	2.1	6,284.8	11,384.7	569.2	179.97
Existing platform with storage	6,402	10	Low	4,000	149	4,348.9	6,001.4	167.7	495.4	138.0	373.8	8.5	4.2	4,663.1	6,874.7	343.7	117.51
Existing platform with storage	6,402	10	Low	8,000	75	3,176.0	3,628.4	167.7	495.4	138.0	315.3	17.0	8.3	3,498.6	4,447.4	222.4	80.93
Existing platform with storage	6,402	10	Low	10,000	60	2,864.2	3,110.7	167.7	495.4	138.0	303.6	21.2	10.4	3,191.1	3,920.1	196.0	72.43
Existing platform with storage	6,402	10	Low	20,000	30	2,077.7	1,995.4	167.7	495.4	138.0	280.2	42.5	20.9	2,425.9	2,791.8	139.6	53.14
Existing platform with storage	6,402	10	Low	30,000	20	1,722.0	1,577.7	167.7	495.4	138.0	272.5	63.7	31.3	2,091.4	2,376.9	118.8	45.51
Existing platform with storage	6,402	10	Low	40,000	15	1,507.2	1,350.7	167.7	495.4	138.0	268.5	85.0	41.7	1,897.9	2,156.3	107.8	41.29
Existing platform with storage	6,402	10	Low	50,000	12	1,359.3	1,205.1	167.7	495.4	138.0	266.1	106.2	52.1	1,771.1	2,018.8	100.9	38.60
Existing platform with storage	6,402	10	Medium	1,000	593	18,630.0	23,803.7	130.4	391.7	138.0	628.5	3.3	1.6	18,901.6	24,825.4	1,241.3	445.37
Existing platform with storage	6,402	10	Medium	2,000	297	13,179.1	13,933.0	130.4	391.7	138.0	394.4	6.5	3.2	13,454.1	14,722.3	736.1	286.98
Existing platform with storage	6,402	10	Medium	4,000	149	9,338.8	8,450.9	130.4	391.7	138.0	277.4	13.1	6.4	9,620.3	9,126.4	456.3	190.94
Existing platform with storage	6,402	10	Medium	8,000	75	6,639.5	5,328.7	130.4	391.7	138.0	218.9	26.2	12.9	6,934.1	5,952.1	297.6	131.25

Offloading Option	Transport Distance (km)	Transport Capacity (Mt/yr)	Transport CO_2 Pressure	Vessel Size (tCO_2)	Vessels (#)	Vessel CAPEX ($M)	Vessel OPEX ($M)	Liquefaction CAPEX ($M)	Liquefaction OPEX ($M)	Loading, Offloading, & Conditioning CAPEX ($M)	Loading, Offloading, & Conditioning OPEX ($M)	Intermediate CO_2 Storage CAPEX ($M)	Intermediate CO_2 Storage OPEX ($M)	Total CAPEX ($M)	Total Lifetime Discounted OPEX ($M)	Total Lifetime Discounted OPEX ($M/y)	Levelized Lifetime Cost of Shipping ($/$tCO_2$)
Existing platform with storage	6,402	10	Medium	10,000	60	5,936.2	4,618.8	130.4	391.7	138.0	207.2	32.7	16.1	6,237.3	5,233.7	261.7	116.83
Existing platform with storage	6,402	10	High	1,000	593	37,631.5	33,131.6	83.5	305.0	138.0	628.5	12.7	6.2	37,865.6	34,071.4	1,703.6	732.69
Existing platform with storage	6,402	10	High	2,000	297	26,621.1	20,531.7	83.5	305.0	138.0	394.4	25.3	12.4	26,867.9	21,243.6	1,062.2	490.03
Existing platform with storage	6,402	10	High	4,000	149	18,863.8	13,126.8	83.5	305.0	138.0	277.4	50.6	24.8	19,135.9	13,734.1	686.7	334.79
Existing platform with storage	6,402	10	High	8,000	75	13,411.5	8,653.1	83.5	305.0	138.0	218.9	101.2	49.7	13,734.2	9,226.7	461.3	233.86
Existing platform with storage	6,402	10	High	10,000	60	11,990.8	7,591.0	83.5	305.0	138.0	207.2	126.5	62.1	12,338.8	8,165.3	408.3	208.84

Figure C-1 illustrates the levelized cost breakdown for each cost category of the most economical shipping configurations across three offloading options, transporting 1 Mt/year under low-P/T conditions. The onshore offloading system, utilizing two 30,000-tonne vessels, proves to be the most cost-effective at $52.45/tonne. Similarly, the most economical system for offloading to a storage platform also employs two 30,000-tonne vessels, resulting in a levelized cost of $71.65/tonne. For direct injection, the optimal system comprises three 30,000-tonne vessels, with a levelized cost of $65.64/tonne.

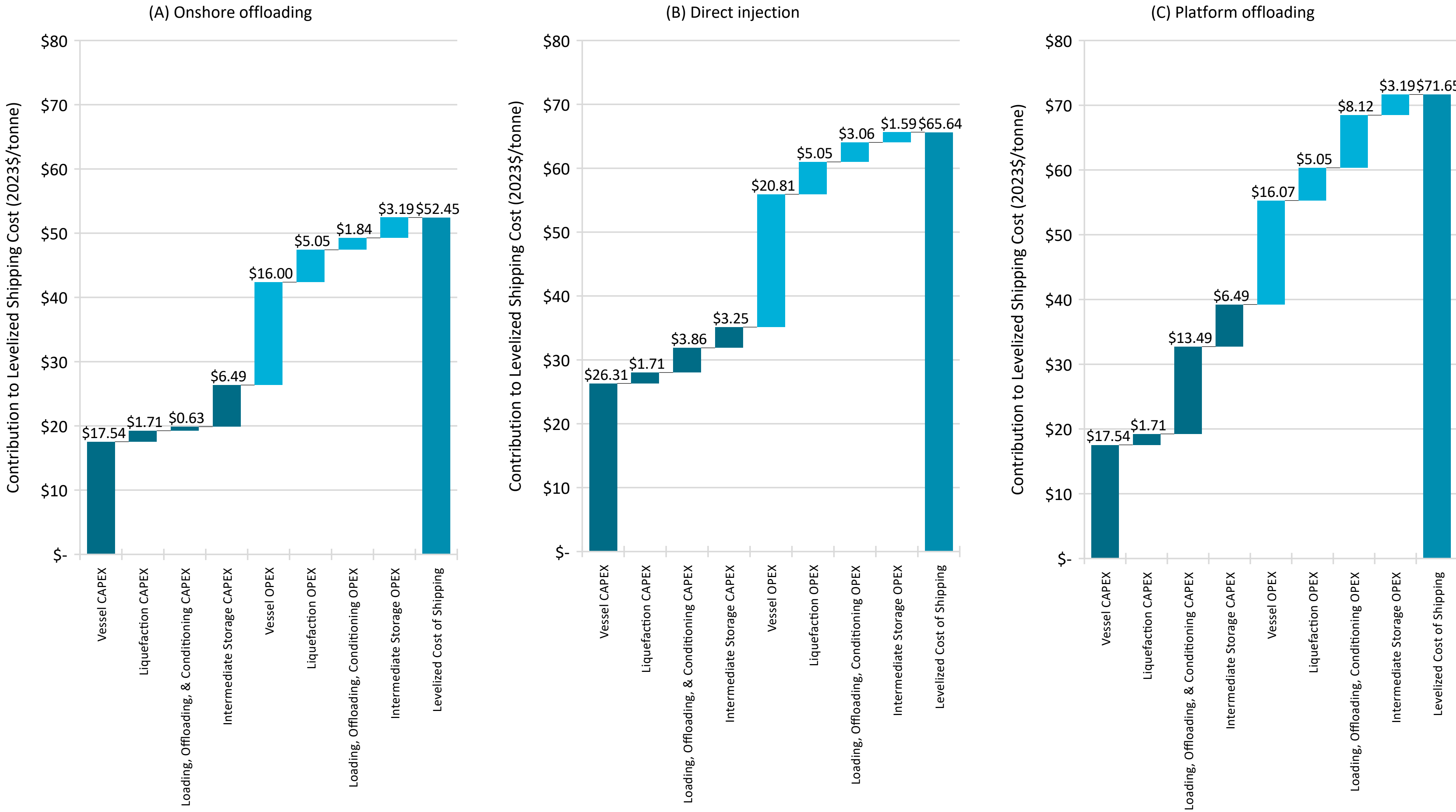


Figure C-1. Levelized shipping costs for 30,000-tonne low-P/T transport for: (A) onshore offloading, (B) direct injection, (C) platform offloading

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