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Ship-based Carbon Dioxide Capture and Storage for Enhanced Oil Recovery

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Abstract

This report presents details of a proposed ship-based carbon dioxide capture and storage (CCS) method. CCS is one of the key technologies essential to achieve greenhouse gas reduction. This technology can also contribute to enhanced oil recovery (EOR) efforts by increasing oil production in mature fields. The liquefied CO_2 (LCO_2) to be sequestered is injected directly into subseabed geological formations through a flexible riser pipe using injection facilities contained onboard an LCO_2 carrier ship. The primary characteristics of this LCO_2 subseabed injection system are as follows: the presence of LCO_2 injection equipment onboard the LCO_2 carrier ship, a direct injection into subseabed geological formations through a flexible riser pipe, and the absence of any stationary sea surface structures at the offshore CO_2 injection site. The advantage of ship-based transportation is flexibility in regard to *i)* multiple CO_2 shipping locations and storage sites, *ii)* multiple injection sites from a large CO_2 storage port, and *iii)* relocation of the injection site resulting from either termination of oil production or the site becoming filled with CO_2. That is, ships can easily alter their shipping ports and routes to the offshore injection site(s), depending on requirements.

Introduction

Ship-based Carbon Dioxide Capture and Storage.

Carbon dioxide capture and storage (CCS), one of the key technologies for greenhouse gas reduction, can be accomplished by the injection of liquefied CO_2 (LCO_2) into geological formations, both inland and offshore in subseabeds, a method that has been studied by the petroleum industry and national organizations. The proposed ship-based LCO_2 subseabed injection system described herein is characterized by the presence of LCO_2 injection equipment located onboard the LCO_2 carrier ship, the absence of any stationary sea surface structures at the offshore CO_2 storage site, and direct LCO_2 injection into subseabed geological formations through a flexible riser pipe which remains submerged on the seabed until it is pulled up and connected to the LCO_2 carrier ship for the LCO_2 injection. The main stages and components needed for the proposed system are the following: initial liquefaction of CO_2 and temporary storage at ports, offloading to a shuttle ship equipped with a dynamic positioning system (DPS) and injection equipment, and at the injection site, a flexible riser pipe whose ends are connected with the wellhead on the seafloor and the pickup system. The use of an unmanned offshore facility for mooring and injection results in lower facility construction/maintenance costs as well as increased safety of the entire operation. **Figure 1** illustrates LCO_2 injection directly from the ship to the storage layer via the proposed flexible riser pipe.

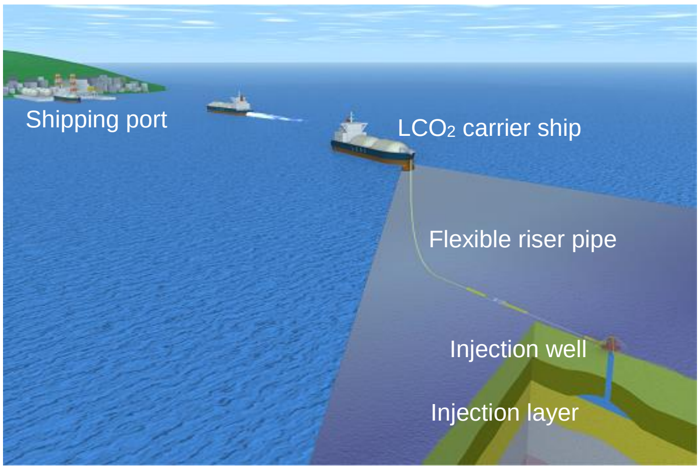


Fig.1 Illustration showing direct LCO_2 injection from the ship to the storage layer via the proposed flexible riser pipe.

A Japanese research consortium (project director, Prof. Masahiko Ozaki of the University of Tokyo) has been studying offshore CCS since 2011 under the sponsorship of the Global CCS Institute (GCCSI). This report is a component of the *Preliminary Feasibility Study on CO_2 Carrier for Ship-based CCS* (2011) [1] and its follow-up study *...Phase-2 - unmanned offshore facility* (2013) [2] sponsored by the Global CCS Institute. Other technical aspects of the study were presented in the 11th International Conference on Greenhouse Gas Control Technologies (GHGT-11) [3], [4], [5], [6], [7].

CCS-based Enhanced Oil Recovery.

Currently, about 130 commercial CO_2-EOR operations have been deployed around the world, with the vast majority, 123 projects by 2012, in the United States [8]. A study by Kuuskraa et al. [9] reported that *i)* CO_2-EOR currently provides about 284,000 barrels of oil per day (bbl/d) in the U.S., equal to 6% of U.S. crude oil production, and *ii)* a total of 62 million metric tons (MMmt) of CO_2 was supplied to EOR operations in the U.S. in 2010. A study by Sweatman et al. [10] reported that CO_2 injection into oil reservoirs for EOR has been safely and effectively applied in 18,077 active wells worldwide (17,112 in the U.S.) over the past 58 years, according to the latest EOR survey (O&GJ, 2010). In addition, the report indicated that offshore CCS-EOR may be more viable than onshore options in areas where population densities are high, where offshore reservoirs are within reasonable distances from land, or where there are existing offshore oil and gas facilities and wells. A recent report prepared by the U.S. Department of Energy (DOE) [11] states that while a number of nearshore CO_2-EOR pilot projects were undertaken in the early 1980s, there is not yet a commercial-scale CO_2 project in the more distant offshore regions of the U.S. In contrast, a number of significant offshore CO_2-EOR efforts are underway in Brazil, the UAE, Vietnam and Malaysia. This DOE report also assessed the oil recovery and CO_2 demand from the Gulf of Mexico Outer Continental Shelf (GOM OCS) by comparing “current” and “next generation” (improvement of oil recovery efficiency by about half) CO_2-EOR technology: total 810 million barrels (MMbbl) of incremental oil and 310 million metric tons (MMmt) of CO_2 demand with today’s moderate performance technology (Current Technology); total 14,920 MMbbl of incremental oil and 3,910 MMmt of CO_2 demand with the higher performing “Next Generation” technology. The CCS-based EOR projects mentioned above are summarized in **Table 1**.

Table 1. Summary of CCS-based Enhanced Oil Recovery.

Authors	CO2-EOR project	Achievement/assessment	Remarks
Whittaker et al., [8]	CO_2-EOR projects (worldwide)	130 commercial operations deployed	Mostly in the U.S.
Kuuskraa et al., [9]	CO_2-EOR production in the U.S.	284,000 bbl/d of crude oil 62 MMmt of CO_2 supplied in 2010	6% of the U.S. crude oil production in 2010
Sweatman et al. [10]	CO2-EOR over the past 58 years	18,077 active wells worldwide	17,112 in the U.S.
U.S. DOE, [11]	CO_2-EOR offshore the U.S.	No commercial-scale project	
	CO_2-EOR in GOM OCS future assessment	810 MMbbl of incremental oil 310 MMmt of CO_2 demand	“Current” technology
		14,920 MMbbl of incremental oil 3,910 MMmt of CO_2 demand	“Next Generation” technology

Many of the onshore injection projects in the U.S. were started in the 1970s and, thus, the pipeline transportation and injection technologies are already well established. Examples of more recent as well as planned onshore and offshore CO_2-EOR projects are listed in **Table 2**. The CO_2 injection volumes are less than 3,000 mt/d (metric tons per day) in the U.S. onshore injection projects, except the 8,200 mt/d of the Weyburn-Midale project. Uthmaniyah (2,000 mt/d est., start in 2015) (Saudi Arabia, onshore) and Don Valley (14,000 mt/d est., under study) (England, offshore to North Sea) are both pipeline projects. The only offshore injection project currently operating is the Sleipner Project (in-situ CCS, 2,500 mt/d) in the North Sea (started in 1996). This project was the world’s first demonstration of injecting CO_2 into a deep saline reservoir specifically for CCS, i.e., not for EOR, and remains the only development where the CO_2 is both captured and injected offshore [12]. The 3,000 mt/d in the present study of the proposed ship-based transportation of LCO_2 to offshore injection wells is greater than the injection rate of the other projects listed in Table 2, except for the Weyburn-Midale and Don Valley projects.

Table 2. Examples of Onshore and Offshore CO_2-EOR Projects (current and under study).

Project (start year)	Country	CO_2 injection (metric tons per day)	Transportation type	References
Weyburn-Midale (2000)	USA to Canada	8,200	Pipeline (onshore)	MIT CC&ST, [13]
Coffeyville (2013)	USA, Kansas	2,400	Pipeline (onshore)	GCCSI database, [14]
Enid Fertilizer (2003)	USA, Oklahoma	2,300	Pipeline (onshore)	MIT CC&ST, [15]
LaBarge (1986)	USA, Wyoming	1,100	Pipeline (onshore)	MIT CC&ST, [16]
Uthmaniyah (2015)	Saudi Arabia	2,000 (est.)	Pipeline (onshore)	GCCSI database, [17]
Don Valley (under study)	England to North Sea	14,000 (est.)	Pipeline (offshore)	U.S. DOE, [11]
Abu Dhabi (under study)	Abu Dhabi	2,200 (est.)	Pipeline (offshore)	U.S. DOE, [11]
Present study	Japan	3,000 (est.)	Ship (offshore)	[1], [2], [3], [4], [5], [6], [7]

Scenarios of Ship-based CCS/EOR

As methods of transporting CO_2 from onshore to an offshore injection site, both pipelines and ships can be considered depending on the distances and costs involved. A pipeline can provide a steady supply of CO_2 to the injection site, being unaffected by rough sea states. The offshore pipeline, however, cannot be relocated when oil production terminates or the injection site becomes filled with CO_2. The method proposed in this study is characterized by transporting CO_2 with a relatively small-sized LCO_2 carrier ship and direct injection into subseabed geological formations through a flexible riser pipe using facilities contained onboard the ship.

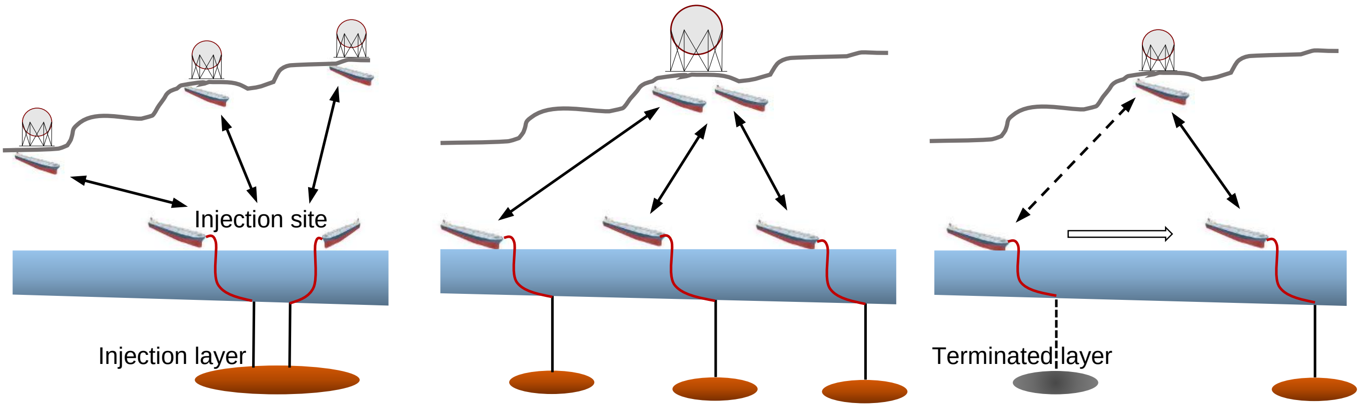
The advantage of ship-based transportation is flexibility in regard to the following:

i) multiple CO_2 shipping locations and injection site~~s~~,
ii) multiple injection sites from a large CO_2 storage port, and
iii) ability to relocate the injection site in cases of the termination of oil production or the site becoming filled with CO_2.

That is, ships can change shipping ports and routes to the offshore injection site as illustrated in **Fig. 2**.

In addition, ship-based transportation may have advantages in regard to the following:

iv) cost benefit relative to a pipeline installation when the injection site is located far offshore or distant from the onshore facility,
v) injection sites where new pipeline installation may be difficult/expensive because of the presence of obstructing bathymetric features or previously installed pipelines on the sea floor,
vi) ability to control injection CO_2 volume by adjusting ship size (i.e., transporting capacity) or shipping frequency, and
vii) no necessity for costly removal of pipelines in cases of the termination of oil production or the site becoming filled with CO_2.



a) Multiple CO_2 shipping locations. **b) Multiple CO_2 injection sites.** **c) Relocation of the injection site.**

Fig. 2 Flexibility of ship accessibility to (a single/multiple) offshore injection site(s) from (a single/multiple) shipping port(s).

Preliminary Design of the LCO_2-CCS Component

Design Basis of the Ship-based Concept

The design basis is derived from the comprehensive plan developed in this study that includes transportation method, onboard cargo tank, water depth, LCO_2 injection volume and design pressure of the LCO_2, as summarized in **Table 3**.

Table 3. Design basis of the ship-based LCO_2-CCS concept.

Facility / Design parameter	Component/Condition
Transport method	Shuttle tanker
Offshore facility	Unmanned
Injection site water depth	500 m
LCO_2 injection volume	3,000 metric tons per day (about one MMmt/year of LCO_2)
Onshore tank	3,000 metric tons of LCO_2
Cargo tank	1,500 metric tons per tank, 2 tanks onboard
LCO_2 in tanks	Minus 20 °C, 1.97 MPa
LCO_2 during injection operation	5 °C, 10 MPa
Significant wave height	3.0 m
Current speed	1.0 m/sec.
Wind speed	15 m/sec.

Onshore Operations

CO_2 captured from electric power and other industrial plants is fed to the CO_2 compression and liquefier facility, where the CO_2 is compressed to 1.97 MPa, dehydrated, liquefied at minus 20ºC, and then stored in an onshore LCO_2 tank of 3,000 metric tons capacity. LCO_2 is pumped from the tank through a loading arm into the onboard LCO_2 cargo tanks of the carrier ship. The onshore operations from the CO_2 source to delivering the LCO_2 to the onboard LCO_2 cargo tanks are illustrated in **Fig. 3**.

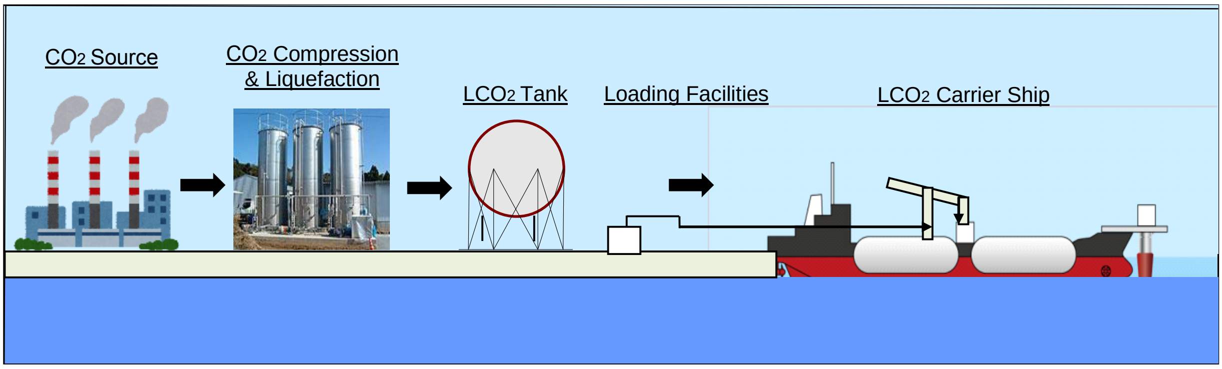


Fig. 3 Illustration: Onshore operations from the CO_2 source to the onboard LCO_2 cargo tanks.

Offshore Operations

The LCO_2 carrier ship features, besides the LCO_2 cargo tanks, an onboard injection pump capable of delivering pressurized LCO_2 directly from the ship to the seafloor injection well through a flexible riser pipe that remains connected to the wellhead. The shuttle ship, containing about 3,000 metric tons of LCO_2 maintained at minus 20 ºC and 1.97 MPa in two cargo tanks, is designed to be capable of injecting about 3,000 metric tons per day (about one MMmt of LCO_2 per year) into the target reservoir via a flexible riser pipe. At the injection site, the temperature of the LCO_2 is increased from minus 20 ºC to 5 ºC before the injection through the flexible riser pipe into the seafloor well at an LCO_2 pressure of 10 MPa. A combination of the heat from sea water and exhaust gas from the diesel generator is used to increase LCO_2 temperature in this study. First, the LCO_2 is heated from minus 20 ºC to minus 4 ºC by a heat exchanger using seawater with a temperature in the range from 3 ºC to 8 ºC; the LCO_2 is further heated to 5 ºC using water heated by the exhaust gases of the diesel generator.

Liquefied CO_2 Carrier Ship

The ship is equipped with two storage tanks of LCO_2, 1,500 metric tons each. At the injection site, the ship is kept in position during the injection operation by a dynamic positioning system (DPS), consisting of one azimuth propeller (ship aft) and two side thrusters (ship fore). A simulation study was carried out under the combined disturbance conditions of wind, wave and current to determine the DPS requirements for the LCO_2 carrier ship. The dimensions of the ship, including DPS requirements, are summarized in **Table 4**; the ship is schematically illustrated in **Fig. 4**.

Table 4. Dimensions and DPS requirements of the LCO_2 carrier ship.

Ship equipment		Specification	Notes
Hull	L(overall)	94.2 m	
	L(pp)	89.6 m	
	B (mould)	14.6 m	
	D (mould)	6.9 m	
	d (design)	5.6 m	
Machinery	Side thruster (variable pitch)	1,150 kW	2 sets
	Azimuth propeller	3,000 kW	1 set (main propulsion)
	Power generator	3,500 kW	1 set (diesel driven)
Ship speed (90% NSR)		15.0 knots	7.7 m/sec.
Storage tank (bi-lobe)	Capacity	1,500 metric tons	1 bi-lobe tank
	Total capacity	3,000 metric tons	2 bi-lobe tanks
	Radius of single cylinder	3.50 m	
	Total length of each tank	26.96 m	

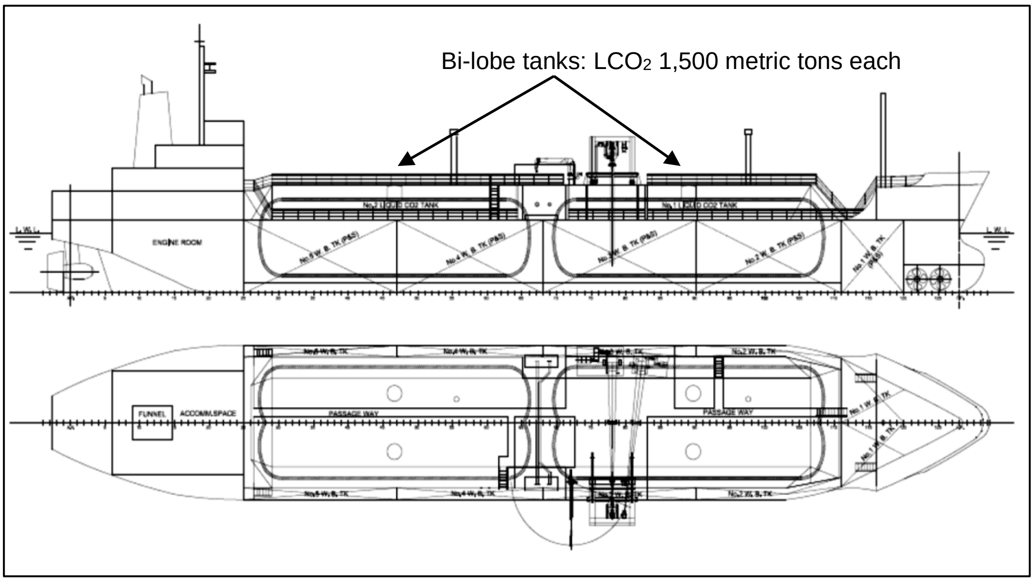


Fig.4 Schematic drawing of the LCO_2 carrier ship: two tanks, capacity of 1,500 metric tons each.

Flexible Riser Pipe Pickup System and Operation

The use of an unmanned offshore facility for mooring and injection results in lower facility construction/maintenance costs as well as increased safety of the entire operation. The flexible riser pipe, also used as a riser flow line to carry oil or gas from the seafloor wellhead, remains on the seabed and is connected to the DPS-controlled LCO_2 carrier ship only after it has arrived at the ocean site. The entire pickup buoy system is shown in **Fig. 5**. This system has the following advantages over a stationary surface structure:

- no buoy system necessary for ship mooring,
- less stringent ship handling requirements than mooring at stationary surface structures, especially in rougher sea conditions, and
- the flexible riser pipe remains on the seabed in rough seas.

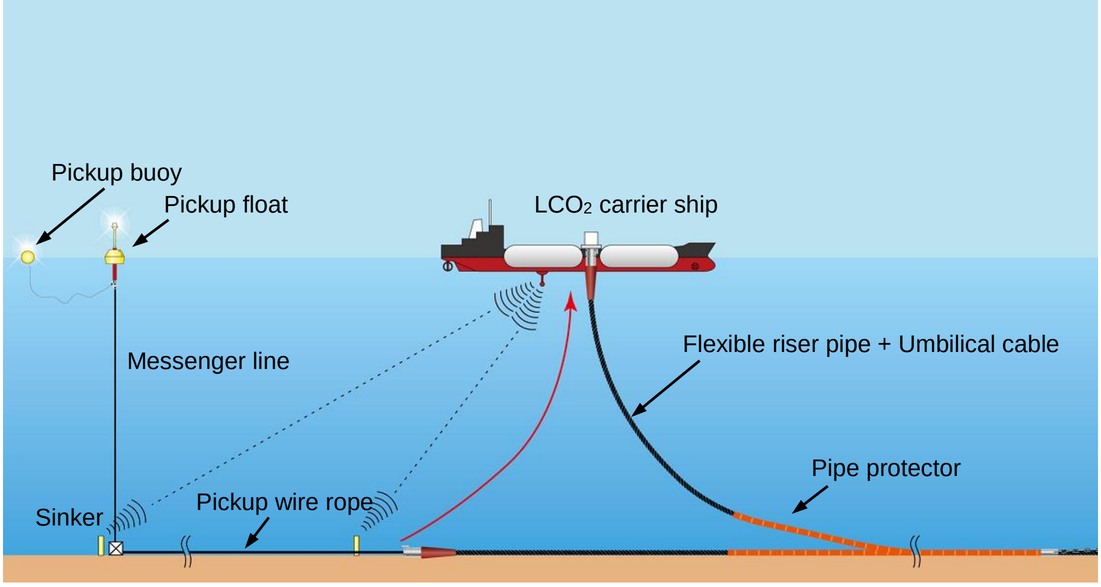


Fig. 5 Illustration showing the pickup buoy system components; the flexible riser pipe is connected to the LCO_2 carrier ship by first taking up the pickup buoy and the pickup float.

Components of the pickup buoy system are shown in **Fig. 6**. The pickup buoy is picked up first, followed by the pickup float, which is connected to the flexible riser pipe through the messenger line and the pickup wire rope. The junction of the messenger line and the pickup wire rope is kept on the seabed, using an attached sinker, except during CO_2 delivery; this system isolates the flexible riser pipe from any pickup float motions caused by waves. The pickup float, with an attached light, serves as a dan buoy (marker) for the LCO_2 carrier ship. The length of the pickup wire rope is 750 m, 1.5 times the water depth. The 550 m (1.1 times the water depth) messenger line is designed with sufficient mechanical strength to draw both the sinker and the pickup wire rope up to the LCO_2 carrier. The pickup float is designed with 10 kN buoyancy to sustain the combined weight of the messenger line and the buoy light and radar reflector.

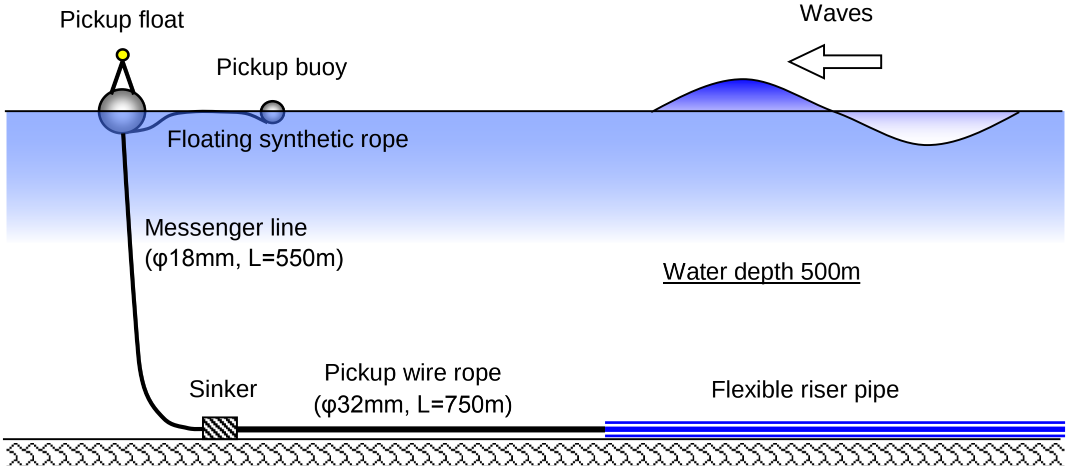


Fig. 6 Components of the pickup systems.

Submerged Flexible Riser Pipe Components

The flexible riser pipe remains submerged on the seabed until it is pulled up and connected to the LCO_2 carrier ship for the LCO_2 injection. The specifically designed components of the riser pipe as well as the design parameters are described below and illustrated in **Fig. 7**. The designed dimensions of the pipe are summarized in **Table 5**; the internal structure is schematically illustrated in **Fig. 8**.

- A bend stiffener is installed at the topmost part of the flexible riser pipe to limit the bend radius.
- The flexible riser pipe is assumed to exhibit a free catenary configuration during the injection operation.
- A pipe protector is installed around the outer sheath of the section of the flexible riser pipe that is vulnerable to wear against the seabed as a result of the motion of the DPS-controlled LCO_2 carrier ship.
- An anchor to counteract the tension in the flexible riser pipe to protect the wellhead equipment is installed at the touch down point (TDP), see location *d. Anchor* in Fig. 7.
- A bend restrictor is installed to limit bending at the joint between the riser pipe and the wellhead equipment.
- An umbilical cable, used in controlling the wellhead equipment and charging the batteries in the communication buoy as well as monitoring the downhole data, is bundled together with the flexible riser pipe.
- The location of the seafloor-lying flexible riser pipe is transmitted to the LCO_2 carrier ship by a transponder set on the pickup wire rope.

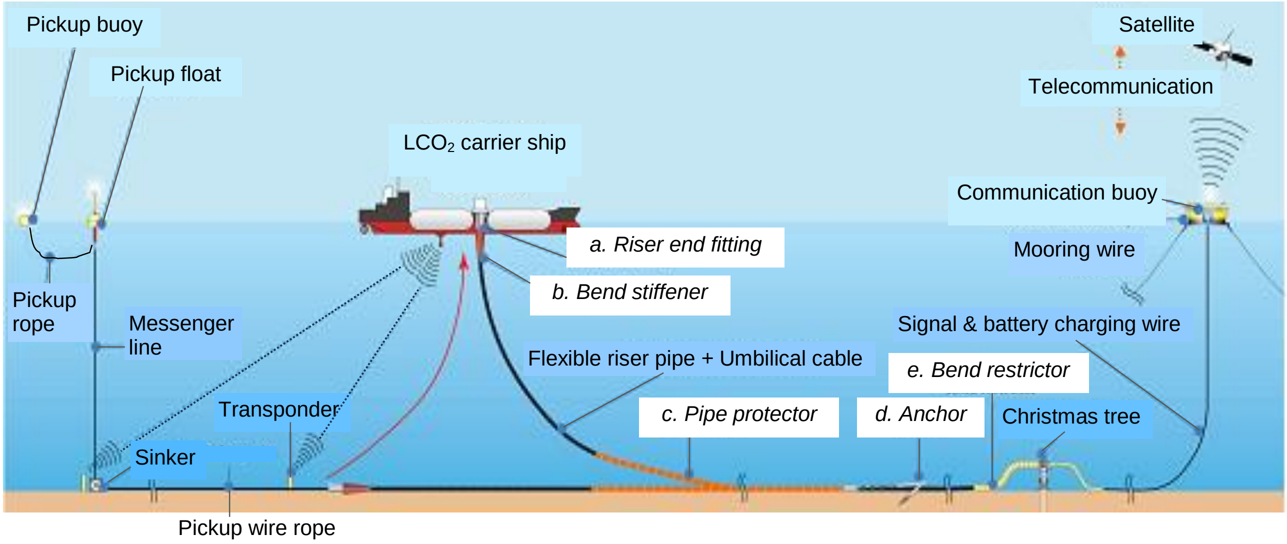


Fig. 7 Configuration of the flexible riser pipe system and its components.

Table 5. Dimensions of the flexible riser pipe.

Layer	Thickness (mm)	Outer diameter (mm)	Material
Interlock conduit	5.5	163	Stainless steel
Inner pipe	6.7	176.4	High density PE
Inner pressure armor	2.0 x 2	184.4	Carbon steel
Tensile armor	2.0 x 2	192.4	Carbon steel
Buoyant layer	51.8	295	Plastic tape
Outer sheath	7.0	309	High density PE

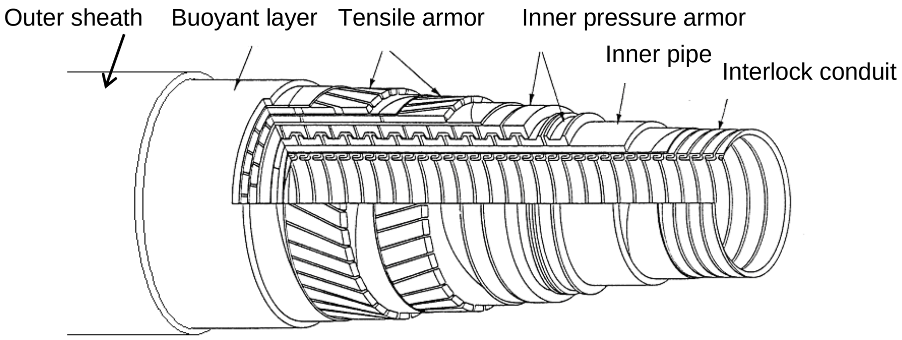


Fig. 8 Internal structure of the flexible riser pipe.

Economic Evaluation of CCS/CO_2-EOR

Ship-based LCO_2 Injection.

The economic evaluation was described in detail in a report prepared for GCCSI [2]. The cost evaluation conducted with the design basis shown in Table 3 is summarized in **Table 6** for the whole 30-year lifespan of the project. The costs were estimated using three categories; capital related cost, management cost and operational cost. The capital related cost mainly includes onshore LCO_2 loading facilities, LCO_2 carrier ship with onboard tanks, flexible riser pipe, and associated financing costs. The management cost mainly includes maintenance cost, annual insurance, satellite communication cost, and annual administration cost. The operational costs are labour wages for the operation and utility costs such as electric power, cooling water, and fuel. The total transportation costs, including onshore storage and loading as well as offshore facilities, for the transport distances of 200 km, 800 km and 1,600 km are 19.3 USD, 33.6 USD and 52.5 USD per CO_2 metric ton, respectively.

Table 6. Summary of the total transportation cost over the 30-year lifespan.

Transport distance (km)	200	800	1,600
Capital related cost (USD/Mt-CO_2)	6.50	11.70	18.00
Management cost (USD/Mt-CO_2)	7.40	12.90	20.30
Operational cost (USD/Mt-CO_2)	5.40	9.00	14.20
Total (USD/Mt-CO_2)	19.30	33.60	52.50

USD/Mt-CO_2: U.S. dollars per CO_2 metric ton.
The costs are calculated in Japanese yen in the original report. A currency exchange rate of 100 Japanese yen to one USD is used in this table.

The costs listed above include the following:

- loading section of the onshore plant: CO_2 tank, CO_2 loading pump, loading arm and related equipment,
- LCO_2 carrier ship including on-board CO_2 injection pump, sea water pump, CO_2 heater, injection control system and riser winch, and
- offshore facilities: flexible CO_2 injection riser and buoy systems.

The following items are beyond the scope of the economic analysis:

- CO_2 capture facilities,
- land-based CO_2 gathering pipelines,
- CO_2 compression and liquefier facility,
- berth onshore,
- CO_2 well head equipment,
- pipelines between well head equipment and injection well, and
- CO_2 injection wells.

Onshore/offshore LCO_2 Pipeline Cost Analysis.

An example of an onshore/offshore LCO_2 pipeline cost analysis is the U.S. DOE-National Energy Technology Laboratory's calculated CO_2 pipeline transportation costs for the offshore Gulf of Mexico (GOM) region [11]. Their assumption of a pipeline with one Bcfd (billion cubic feet per day) of CO_2 capacity traversing 100 miles (160 km) onshore and 150 miles (240 km) offshore resulted in a construction cost estimate of 1.2 billion USD for the 250 mile (400 km) combined (onshore/offshore) pipeline, i.e., 20 USD/Mt-CO_2. Details concerning input parameters and calculation method can be found in reference [11].

Applicability of Ship-based CCS for EOR in the Gulf of Mexico

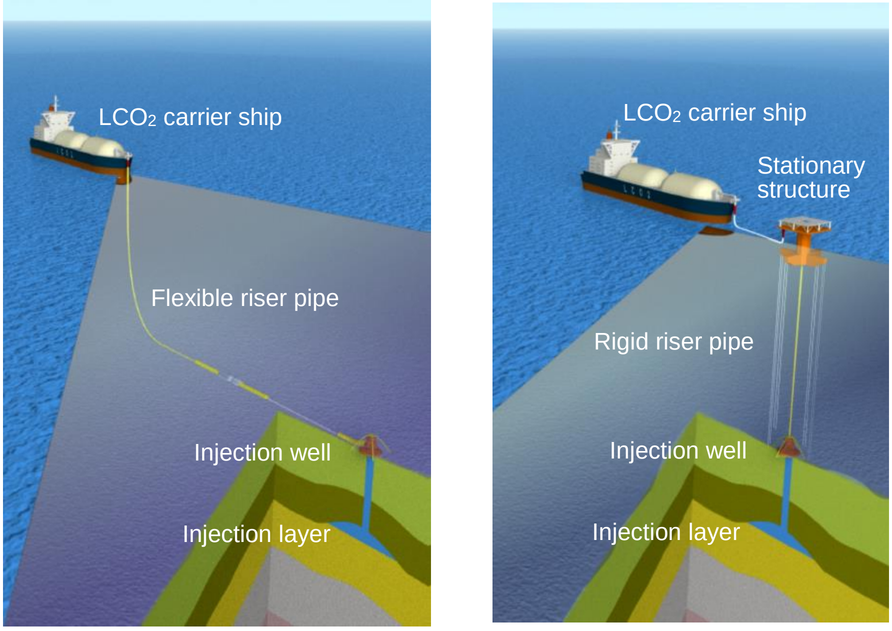
The U.S. Department of Energy has recently reported on the importance of developing CO_2-EOR in the GOM OCS region:

> *The Gulf of Mexico Outer Continental Shelf (GOM OCS) contains 1,278 discovered and proved oil and gas fields. Of these 1,278 proved oil and gas fields, 891 are active and 387 are now depleted and abandoned. These 1,278 oil and gas fields, consisting of 238 oil fields and 1,040 natural gas fields… The 238 GOM OCS oil fields contain 8,228 reservoirs with each oil field holding one to several dozen reservoirs. … Shallow water GOM offshore oil production peaked in the late 1990s at nearly 800 thousand barrels per day (MB/D). Since then, oil production has declined to 321 MB/D in 2009 (last year of oil data from BOEM* [Bureau of Ocean Energy Management] *for shallow water). …essentially all of the large GOM shallow water oilfields are mature, with only modest volumes of remaining proved reserves. As such, there is critical need for acceleration of shallow water CO_2-EOR preparation and development before this large remaining domestic resource is abandoned. (Once the offshore production platform is removed, the use of CO_2-EOR for storing CO_2 becomes much more challenging.)* [11]

Although pipeline networks are well facilitated throughout the GOM, they might still be active for oil and gas transportation. For CO_2-EOR in this area, ship-based CO_2-EOR may be useful because of the following advantages over fixed pipeline CO_2 transport:

- eliminates the need to build new pipelines specifically to transport CO_2 offshore,
- applicability of the proposed flexible riser pipe pickup system and operation for CO_2 injection at sites where platforms have been removed from wells (see Fig. 9 a), and
- easy and flexible access to existing oil and gas production platforms (see Fig. 9 b) from power plants and other industrial facilities along the Gulf Coast.

Figure 9 illustrates two methods of LCO_2 injection: *a)* directly from the ship to the storage layer via a flexible riser pipe and *b)* through the use of a stationary structure.



a. Direct LCO_2 injection through a flexible riser pipe.

b. LCO_2 injection through a stationary structure.

Fig. 9 Illustrations showing LCO_2 injection from the carrier ship to the storage layer.

With ship-based LCO$_2$ transportation, CO$_2$ injection sites can be selected flexibly to optimize the displacement of oil towards a production wellbore. In addition, the ability to control the CO$_2$ injection volume by adjusting ship size (i.e., transporting capacity) and/or shipping frequency can be used effectively to create flow channels to deliver CO$_2$ to un-swept areas of a reservoir (i.e., improve control over the mobility of the injected CO$_2$), resulting in a more productive recovery of oil production. **Figure 10** illustrates the possibility of using (a single/multiple) LCO$_2$ carrier ship(s) to access multiple injection sites to enhance oil production from a reservoir.

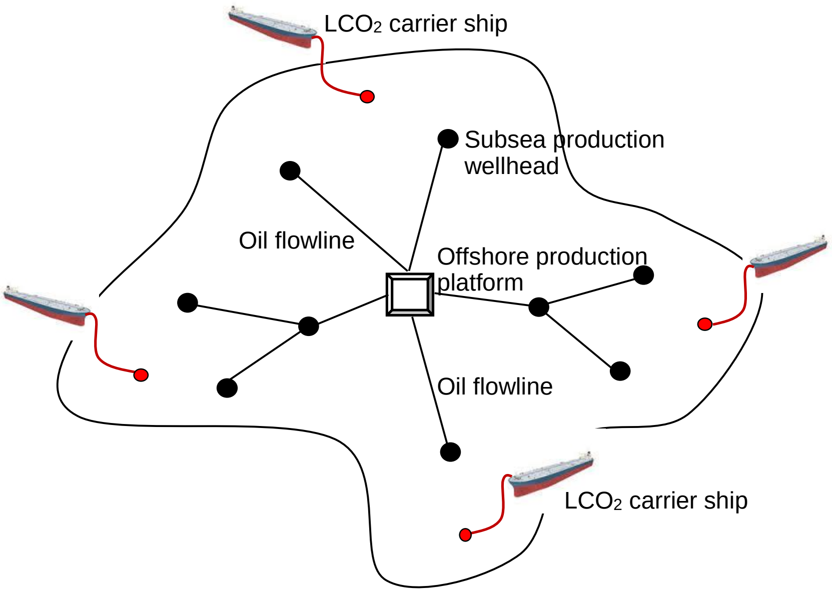
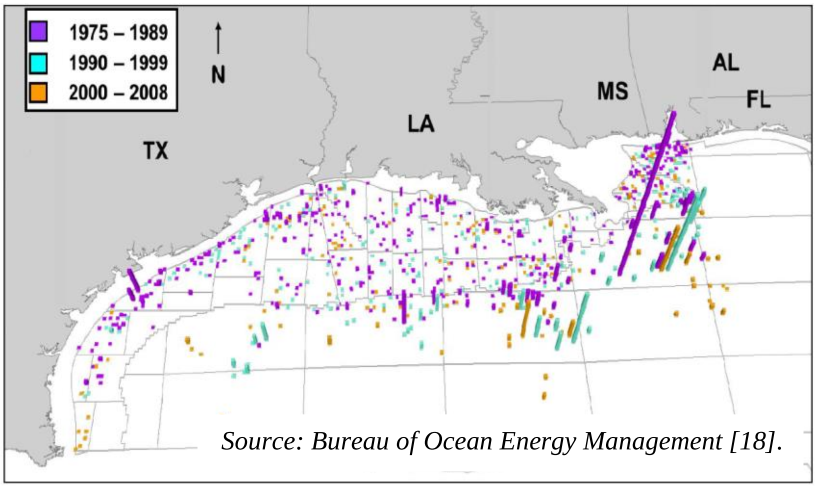


Fig. 10 Illustration showing oil production facilities at an oil reservoir: using carrier ships to transport and inject CO$_2$.

Figure 11 shows the location of the proved fields (oil and natural gas) discovered in the GOM since 1975 [11]. Of particular interest are the oil and gas fields located in shallow water along the coast that were proved in the years 1975-1989, as they might be mature and, thus, soon to be abandoned. The proposed ship-based operation is one of the effective solutions for both CCS and EOR in this region.



Source: Bureau of Ocean Energy Management [18].

Fig. 11 Location and discovery sequence for proved discovered oil and gas fields, GOM OCS [11]: To date, nearly 50,000 wells have been drilled in these fields, with 14,400 of these completions still active.

Summary and Conclusions

i) Advantages of Ship-based LCO$_2$ Injection

The proposed ship-based LCO$_2$ subseabed injection system features LCO$_2$ injection equipment onboard a shuttle ship (3,000 metric tons LCO$_2$ load capacity) that has no need for any stationary sea surface structures at offshore CO$_2$ storage sites. The advantages of this method are flexibility in accessing onshore CO$_2$ storage and shipping sites and the ease of changing the injection site if oil production is terminated or the injection layer becomes full.

ii) Offshore Facilities for LCO_2 Injection

The proposed unmanned offshore facility for both mooring and injection features lower construction/maintenance costs and a safer operational environment than found in any manned stationary facility.

iii) Liquefied CO_2 Carrier Ship

The ship is equipped with two LCO_2 storage tanks, capacity of 1,500 metric tons each. The ship is kept in position during the injection operation by a dynamic positioning system (DPS).

iv) Flexible Riser Pipe Pickup System

The LCO_2 is injected at a rate of about 3,000 metric tons per day into subseabed reservoirs via a flexible riser pipe that connects the shuttle ship to the wellhead. The riser pickup system consists of two basic elements, besides the riser pipe: shipboard equipment such as a coupling valve, crane, winches and A-frame and offshore equipment such as a pickup buoy, pickup float, messenger line, sinker and pickup wire rope.

v) Economic Evaluation of Ship-based LCO_2 Injection

The total transportation costs for offshore transporting distances of 200 km, 800 km and 1,600 km are 19.3 USD, 33.6 USD and 52.5 USD per CO_2 metric ton, respectively.

vi) Ship-based CCS for EOR in the Gulf of Mexico

Since ship-based CO_2-EOR eliminates the need to build new pipelines specifically to transport CO_2 offshore, this transport method can be an effective solution for the mature GOM shallow water oilfields because of the ease and flexibility in accessing the existing oil and gas production platforms from power plants and other industrial facilities along the Gulf Coast.

vii) Future Work

The umbilical cable, bundled with the flexible riser pipe and supplying electricity from the ship to the seabed manifold valve, has not yet been designed. In addition, a more precise and detailed economic evaluation comparing ship-based to offshore pipeline transportation systems has to be conducted.

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