CO_2 marine transportation: an energy & techno-economic analysis

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Abstract:
Anthropogenic carbon dioxide (CO_2) emissions have raised the global average temperature in 1.0 °C with respect to pre-industrial levels and this increase is likely to reach 1.5 °C before 2050, according to Intergovernmental Panel on Climate Change (IPCC, 2021).
To limit the temperature rise, most envisioned policies regarding CO_2 emissions rely on carbon capture, use and storage (CCUS), being essential to keep its concentration in the atmosphere below 450 ppm by 2100. IPCC forecasts 12 Gt/y of CO_2 removal in 2050 but the current capacity is 40 Mt/y. CCUS play a vital role in decarbonization, and it may be impossible to get emissions to net-zero fast enough without them.
For the marine industry, CCUS facilitate both CO_2 capture and transport. Ships fitted with this technology can capture carbon from burning fossil fuels. Among the newbuilding ships in 2021, 88% of them were fuelled with fossil fuels and according to ABS, in 2050 still 40% of them will be in this situation. Therefore, CO_2 capture onboard is necessary. Ships can also transport captured CO_2 to facilities for its use and/or storage.

This article investigates the value of ships as CO_2 carriers, focusing on the transport conditions of CO_2. An energy and techno-economic analysis is performed, considering several combinations of pressure and temperature. From an exclusive transport perspective, results show that lower pressures of CO_2 are likely to be more economic. From the pre-processing point of view, results suggest that higher pressures of CO_2 will imply energy savings and potentially cost savings. From the whole logistic chain perspective, the trade-off pressure is still unknown. More research is advised.

Keywords:
Carbon dioxide, shipping, CCUS, decarbonization, Sustainable Development Goals, Climate Change, Circular economy

1. Introduction

Carbon dioxide (CO_2) is an essential gas for the presence of life on our planet. It is also the main "greenhouse gas" (GHG). These gases absorb and emit infrared radiation that reaches Earth from the Sun, heating the planet's surface as well as the lower layers of the atmosphere.

It is present in the Earth's atmosphere naturally, historically, in concentrations of approximately 300 parts per million (ppm) or 0.03%. During the ice ages, the levels were around 200 ppm and during the interglacial periods, slightly less than 300 ppm. the concentration of other GHGs has increased very significantly in the Earth's atmosphere in recent decades. Scientists attribute most of this increase in CO_2 concentration to human sources.

Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate, according to the Intergovernmental Panel on Climate Change (IPCC).

Most of net CO_2 emission models developed by the IPCC [1] require significant use of CCUS. According to the IPCC, carbon capture, utilization and storage (CCUS) is essential to maintain the concentration of CO_2 in the atmosphere below 450 ppm in the year 2100.

According to the International Energy Agency (IEA) [2], currently CCUS facilities around the world have the capacity to annually capture more than 40 $MtCO_2$. However, the mean of IPCC global net CO_2 emissions scenarios predicts 12 $GtCO_2$/yr sequestration from the energy sector in 2050. Therefore, CCUS technologies

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play a vital role in decarbonization and it may be impossible to reduce net emissions down to zero fast enough without them.

It shall be noted that CO_2 is a commodity but still without a market. Moreover, according to IEA [3], CO_2 utilisation is a complement but it is not an alternative to CO_2 storage. Mac Dowell et al. [4] estimated that the contribution of carbon capture and utilisation (CCU) to the global CO_2 emissions reduction would be negligible (0.2 $GtCO_2$/year in 2050) and it could not compete with carbon capture and storage (CCS) as it has a much higher CO_2 capture potential, which was estimated at 7.8 Gt CO_2/year in 2050 [5]. In the IEA Net Zero Scenario [6], over 85% of BECC (Bio-energy with Carbon capture) and DAC (Direct Air Capture) CO_2 is permanently stored, and under 15% is used as feedstock.

Roussanaly et al. [7] stated that CO_2 shipping can be expected to play an important role in early CCS development, for "small" capacities, and/or long distance transport. According to the Global Global CCS Institute [8], CCUS technology facilitates both CO_2 capture and transport for the marine industry. First, ships fitted with carbon capture technologies can catch carbon emissions released from burning fossil fuels onboard. This is done via the use of scrubbers, which already clean emissions from exhaust gas and can be adapted to capture CO_2. This would enable shipowners to remove significant quantities of CO_2 from the exhaust. Second, ships can transport captured CO_2 to its drop-off point or offshore. Technology providers have developed safe solutions for storing CO_2 during transport at the right temperature and pressure, similar to those for ammonia and liquid petroleum gas (LPG). As stated by Xing et al. [9], shipowners can choose among materials for CO_2 storage tanks and optimize onboard space with either a single large tank or several smaller tanks. CCS technologies in maritime applications are still at an early stage, and their future prospects depend on reasonable technological innovation in combination with policy support.

Transport is that stage of carbon value chain that links sources and storage sites. Alongside pipelines, CO_2 shipping can enable flexible and scalable CCS infrastructure that can adapt to future capture projects and storage sites. Ships are also preferable for small or short lifetime CO_2 sources that cannot justify a dedicated pipeline.

Gas transported at pressure close to atmospheric ones occupies such a large volume that very large facilities are needed. Gas occupies less volume if it is compressed, and compressed gas is transported by pipeline. Volume can be further reduced by liquefaction, solidification or hydration [10].

At atmospheric pressure, CO_2 is as gas phase or as solid phase depending on the temperature. Lowering the temperature at atmospheric pressure cannot by itself liquefy CO_2, only make so-called 'dry-ice'. Liquid CO_2 can only exist at a combination of low temperature and pressure well above atmospheric [11].

CO_2 can be liquified at various pressures between the triple point (5.18 bar, −56.6°C) and critical point (83.8 bar, 31.1°C). When pressured above its critical temperature and pressure, the CO_2 can be compressed to reach supercritical form that has a higher density and can avoid two-phase flow [12].

Currently there are three ways of transporting CO_2 to onshore reception facilities and or offshore underground storages [6]:

- Gaseous transportation: CO_2 is compressed up to 35 bar and transported by pipeline, with intermediate boosters.
- Liquid transportation: CO_2 is compressed and transported by ship or pipeline.
- Supercritical transportation: CO_2 is compressed up to 250 bar and transported by pipeline.

CO_2 transport by ships is based on the shipping experience in the food and beverage industries and it a mature technology (TRL 9) as it has been practised for over 30 years at small-scale, with only 3 Mt CO_2/year. According to Hong [5], CO_2 shipping is now considered for large-scale transport of CO_2 because it may be more economical when CO_2 needs to be transported on a large-scale over large distances or overseas than constructing new long-distance pipelines or repurposing gas pipelines at existing loading facilities and unloading platform.

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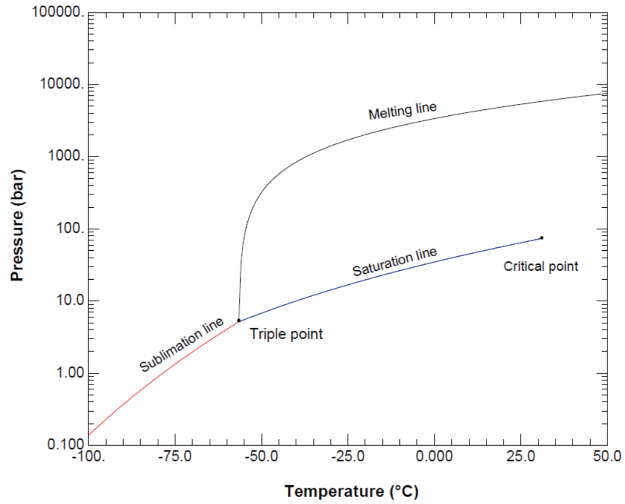

Figure. 1. CO_2 pressure-temperature diagram [13].

Liquefied CO_2 is the most obvious choice for ship transport, but even ships carrying compressed, gas phase CO_2 have been suggested. Transporting compressed CO_2 can be compared to transport of CO_2 in pipelines. Transport conditions will therefore be similar to that of pipelines, but with more flexibility and ease of inspection than pipelines. The temperature should be about 25°C and the pressure above 75 bar. The concept of compressed CO_2 on ships has been developed by ship companies, but remains untested and no international regulations exist for such transport of CO_2 [14].

Most literature recommends conditions near the triple point for shipping of liquefied CO_2, for the benefit of lower storage costs and enhanced density. However, other research suggests a higher liquefaction pressure for higher energy efficiency. Thus, there is no set optimal liquefaction pressure for all conditions; it should instead be determined from individual needs and the wider chain and project variables [12].

The code which applies to new gas carriers (built after 1986) is the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk. In brief, this Code is known as the IGC Code. The IGC Code, under amendments to Safety of Life at Sea Convention (SOLAS), is mandatory for all new ships since 1986 [15]. Kokubun et al. [16] stated that the physical properties of CO_2, specifically the vapor liquid equilibrium properties of CO_2, are such that the design of a storage tank for the containment of liquid carbon dioxide is very similar to existing designs for intermediate pressure liquefied petroleum gas (LPG) containment systems. The design methodology for LPG cargo tanks is well understood and is regulated by international standards (specifically the IGC code) and those of Classification Societies, such as Det Norske Veritas (DNV), Bureau Veritas (BV) and Lloyd's Register (LR).

As mentioned above, there is not enough number of CO_2 carriers for a realistic comparison. For this reason, it is assumed that similar ships can be a good starting point for energy and techno-economic comparison. The most similar ship to CO_2 carriers are LPG ships (pressurized or semi-pressurized) for liquid transportation and compressed natural gas (CNG) ships for gas transportation. However, there is only one existing CNG ship in the world fleet and compressed CO_2 transportation has not been developed yet as a practical solution.

The object of this article is to perform a comparison of transport conditions of liquid CO_2 by ship, considering several pressures of CO_2 (defined in Table 2), a common ship model and two different cargo tanks configuration, as defined in Section 2. The following CO_2 conditions have been considered:

Table 1. Thermophysical properties of CO_2 for pressures from 6 to 45 bar [17].

Case No.	Pressure, bar	Temperature, ºC	Density, kg/m^3
#1	6	-53.12	1166.00
#2	10	-40.12	1116.90
#3	15	-28.52	1069.50
#4	20	-19.50	1029.40
#5	25	-12.01	993.20
#6	30	-55.52	959.25
#7	35	0.16	926.47
#8	40	5.30	894.05
#9	45	9.98	861.27

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2. Methods

Focusing on the maritime transport part of the CCUS chain, and in order to investigate the value of ships as CO_2 carriers, some Key Performance Indicators (KPI) are presented and discussed, considering a specific ship as a comparison element.

2.1 Ship definition

First of all, a ship has been identified and chosen as a model to compare transport cases defined in Section 1. Based on the information provided yearly by the Royal Institution of Naval Architects (RINA) in its publication “Significant Ships” [18], a LPG carried named “Alkaid” (named “Sibur Voronezh” until 2022) has been selected as a reference ship to compare the different transport conditions of CO_2 from a common base.

This ship was designed to carry liquefied gases such as propane, butylene, propylene, anhydrous ammonia, butadiene and vinyl chloride monomer (VCM). The cargo space is divided into four cargo holds to accommodate four independent self-supporting cargo tanks built to International Maritime Organization (IMO) type C standard of bi-lobe shape with a centre longitudinal bulkhead; along with one cylindrical type deck tank. The vapour pressure range of the cargoes carried is up to 5.3 bar, the minimum cargo temperature is -40 ºC and the maximum specific gravity 0.972. The main technical particulars and ship drawings are presented in Table 2 and Fig 2.

Table 2. Technical particulars and characteristics of LPG carrier “Alkaid” [18], [19].

IMO number	9655509
Length (overall) (m)	159.97
Length (between perpendiculars) (m)	152.20
Breadth (moulded) (m)	25.60
Depth (moulded) (m)	16.40
Draught (scantling) (m)	10.90
Deadweight (design) (t)	13 650
Deadweight (scantling) (t)	22 700
Cargo capacity (m^3)	20 800
EEDI [$gCO_2/(t \cdot nm)$]	10.7

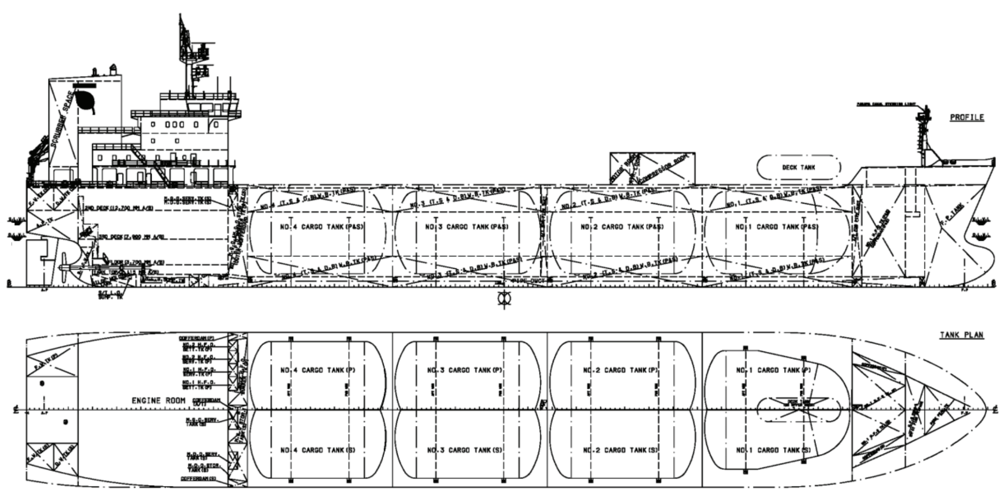

Figure. 2. **“**Alkaid” side and top views [18].

The dimensions of the cargo holds and LPG tanks (No.2-4) are shown in Fig 3. For calculation purposes, it is assumed that the fore tank (No. 1) has the same shape and volume as cargo tanks 2-4.

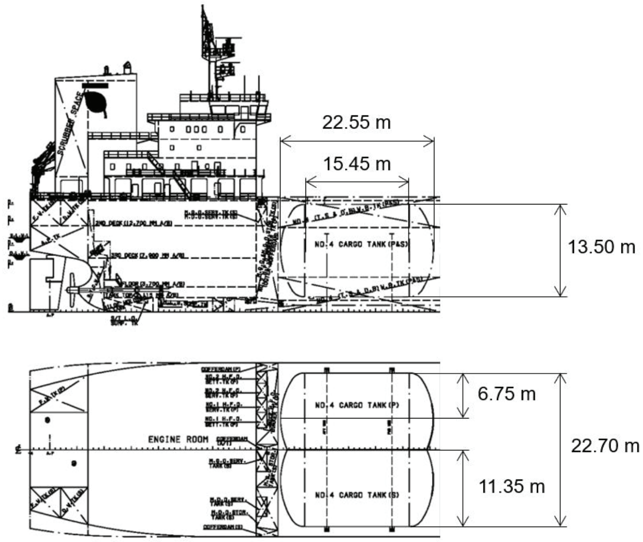

Figure. 3. Cargo hold and bi-lobe tank main dimensions [18].

As a general constraint for the different proposed arrangements, the following control volume has been defined, considering the maximum dimensions of the bi-lobe tank, as shown in Fig 3 and detailed in Table 3. In order to establish a common basis for comparison, the new redesigned tanks can occupy the complete control volume, despite its shape (bi-lobe, cylindrical) or its position (vertical, horizontal), thickness included.

Table 3. Dimensions of cargo hold control volume.

Dimension	Value
Length (m)	22.5
Breadth (m)	22.7
Height (m)	13.5

Redesigned bi-lobular tanks are arranged as in the existing ship. As the design pressures considered are higher than the LPG storage pressure (5.3 bar), the thickness growth will reduce the net volume of the cargo. The key parameter of the new configuration of the bi-lobular tanks for CO_2 storage is summarized in Table 4.

Table 4. Configuration and dimensions of bi-lobular tanks.

Characteristic	Value
Number of tanks per cargo hold	1
Total number of tanks	4
Length (thickness included) (m)	22.5
Breadth (thickness included) (m)	22.7
Height (thickness included) (m)	13.5
Main axis direction	Horizontal

Another proposed configuration is to store CO_2 in cylindrical tanks of smaller diameter, within the same control volume. New calculated cylindrical tanks can be transported vertically or horizontally. There are several variables (diameter, number of tanks per cargo hold, etc.) so the different potential configurations shall be considered carefully. Considering the boiloff management, and free-surface area to prevent sloshing and stability issues, a vertical arrangement seems preferable. In addition, a minimum clearance between cylindrical tanks must be considered for isolation, supporting structures, etc. Table 5 displays the key assumptions of the vertical cylinders. A 6x6 tank grid per hold has been deemed a good tradeoff considering a small free-surface area, while keeping the number of the ancillary components (pumps, valves, manifolds etc.) of all the tanks within reasonable levels.

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Table 5. Configuration and dimensions of vertical cylindrical vessels.

Characteristic	Value
Number of vessels per cargo hold	36 (6x6)
Total number of tanks	144
Length (m)	13.5
Diameter (thickness included) (m)	3.5
Main axis direction	Vertical

Both CO_2 type of tanks proposed are based on ships in operation or projects under development, such as Samsung Heavy Industries (bi-lobular tanks) or KNCC (cylindrical tanks), both Approved in Principle by DNV in 2022 [20], [21].

According to American Bureau of Shipping (ABS) [22], both bi-lobe and cylindrical tanks are "pressure vessels", which are designed and built to meet the requirements of recognized pressure vessel standards such as the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC), as well as additional classification society requirements and statutory regulations.

The nominal body and head wall thicknesses are calculated based on ASME VIII Div. 1 UG-27 (Thickness of shell under internal pressure) and UG-32 (Formed heads and Sections, pressure on concave side). The main inputs and assumptions are listed below:

- For thickness calculations, the bi-lobe tank thickness has been calculated considering a cylinder with a radius of 6.75 m, in order to avoid complex strength calculations.
- The welded joint efficiency factor to be used is 0.875.
- The allowance for corrosion is 1 mm.
- The material selected for both types of tanks is American Society for Testing and Materials (ASTM) A537 Class 2 (quenched and tempered), a higher yield and tensile strength carbon steel used in the fabrication of pressurised vessels and steel boilers and a lowest usual service temperature −60 ºC.

Table 6. Mechanical properties of carbon steel ASTM A537 class 2 [23].

Material	Thickness, mm	Yield strength, MPa	Tensile strength, MPa
ASTM A537 class 2	< 65	415	550
	> 65 < 100	380	515
	> 100	315	485

2.2. Key Performance Indicators (KPI) definition

The following Key Performance Indicators (KPI) are analysed and discussed, considering the transport pressures described in Section 1.

- Preconditioning of CO_2 (liquefaction):
  - Thermomechanical Exergy
- Transport of CO_2:
  - Mass of CO_2
  - Ratio mass of CO_2 vs. tank structure
  - Ratio volume of cargo vs. cargo hold
  - Energy Efficiency Design Index

The first KPI is the *thermomechanical exergy* of the preconditioning phase of the CO_2. In this case it represents the minimum work required to change a substance from the restricted dead state to a particular state using the ambient as the only heat source [24]. This KPI is defined by Eq. 1, where U is internal energy, V volume and S entropy of a closed system that is in nonequilibrium with the environment, T_0 is the reference temperature of the surroundings environment (so called "restricted dead state"), and index 0 refers to the values of the parameters when the system is in thermomechanical equilibrium with the environment. The restricted dead state conditions are described in Table 7.

$$Ex = (E - U_0) + p_0(V - V_0) - T_0(S - S_0) \tag{1}$$

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Table 7. Restricted dead state conditions.

Property	Value
Pressure (kPa)	100
Temperature (K)	288.15

The mass of CO_2 transported is calculated considering the two tank types defined in Section 2. The thickness of shell and head are calculated and the gross and net volume and mass of the CO_2 and tank are obtained, considering the size limitations. Mass and volume ratios are then calculated based on this. It is assumed that the balance of mass of LPG cargo and tanks of “Alkaid” shall remain invariant. Hence, if the mass of CO_2 and tanks is bigger than “Alkaid” cargo mass (to be called “Maximum CO_2”), the exceeding mass is considered as a cargo loss and will be deducted from the CO_2 mass.

$$Mass\ LPG + Mass\ LPG\ tanks = Mass\ CO_2 + Mass\ CO_2\ tanks \quad (2)$$

The last KPI considered is the Energy Efficiency Design Index (EEDI). It provides a specific figure for an individual ship design, expressed in grams of CO_2 per ship's capacity-mile and is calculated by a formula based on the technical design parameters for a given ship. EEDI was made mandatory by the IMO [25] for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships at Marine Environment Protection Committee No. 62 with the adoption of amendments to International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI.

The EEDI is calculated based on a complex formula, taking the ship’s emissions, capacity, and speed into account. The lower a ship’s EEDI, the more energy-efficient it is and the lower its negative impact on the environment. IMO regulations stipulate that ships must meet a minimum energy efficiency requirement, so their EEDI must not exceed a given limit.

$$EEDI = \frac{grams\ of\ emmited\ CO_2}{tonne\ of\ cargo \cdot nautical\ mile} = \frac{Power \times Fuel\ consumption \times CO_2\ emission\ factor}{Capacity \times Ship\ speed} \quad (3)$$

Aiming to compare EEDI of “Alkaid” with the calculated CO_2 cases, it is assumed that all factors of the equation remain equal except the cargo mass (capacity) so the following relation applies:

$$(EEDI \times Capacity)_{ALKAID} = (EEDI \times Capacity)_{CASE} \quad (4)$$

$$EEDI_{CASE} = \frac{EEDI_{ALKAID} \times Capacity_{ALKAID}}{Capacity_{CASE}} \quad (5)$$

According to the IMO, the EEDI reference line for gas carriers is calculated as follows [26]:

$$EEDI = 1120 \times DWT^{-0.456} \quad (6)$$

For gas carriers with 10000 DWT (deadweight) and above, the reduction factors are 20% in phase 2 (January 2020 to December 2024) and 30% in phase 3 (starting January 2025).

3. Results & Discussion

Figures 4 to 9 show the results of the analysis, giving the overview, and the results in detail.

In Fig 4 it is shown the specific exergy (kJ/kg) for the different cases studied, despite its packing conditions. Considering the dead state defined in Section 2, it is observed that the exergy is greater for low temperatures and low pressures than for higher temperatures and pressures. This means that the higher the pressure, the less energy is expected to be required to drive CO_2 from a restricted dead state to the saturated liquid state corresponding to the pressure. For example, the exergy of case #9 (45 bar, 10ºC) is 6.4% lower than case #1 (6 bar, -53ºC). Only from the exergetic point of view, liquefaction up to the highest range of pressures considered in this study is more convenient than low pressures close to the triple point. This metric reflects that the processes required to produce liquid CO_2 at 45 bar will foreseeably require less energy than the lower pressure alternatives. Energy savings at this stage are key considering they will have an associated cost that will impact for the whole lifetime of the logistic chain, which could easily span for 30 years.

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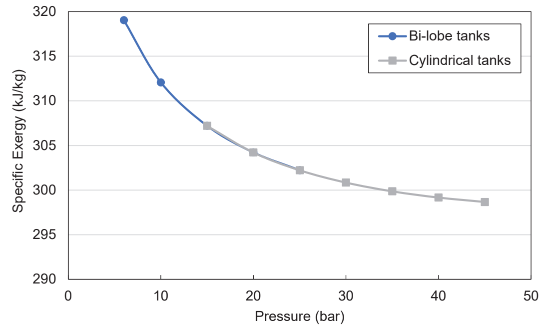
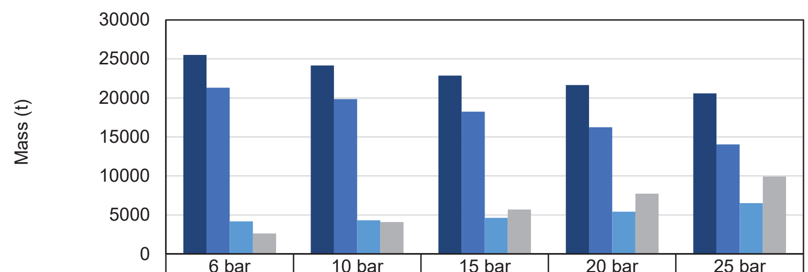


Figure. 4. Specific Exergy of CO_2 as a function of CO_2 pressure.

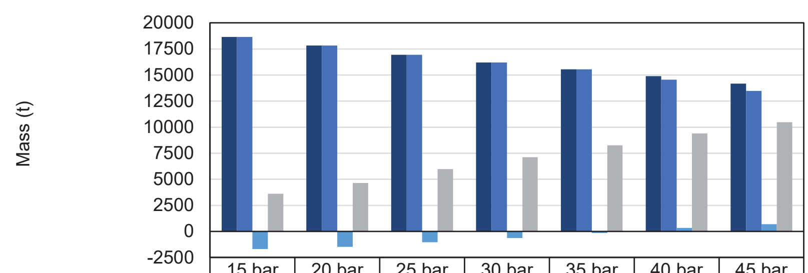
Regarding mass of cargo and tank structure, its different values are shown in Fig 5 for bi-lobe tanks (CO_2 cargo, tank structure and excess of CO_2) and Fig 6 for cylindrical tanks (CO_2 cargo, tank structure and lost mass/excess of CO_2). The maximum amount of CO_2 that can be stored in a bi-lobe and cylindrical tanks is shown in dark blue colour, called "maximum CO_2". However, as introduced in Section 2 and in order to do a consistent comparison, the balance of mass shall remain invariant with respect to the reference LPG ship. Therefore, the excess of mass compared with the LPG ship is identified and discounted, presented in blue colour, so called simply "CO_2".



	6 bar	10 bar	15 bar	20 bar	25 bar
Maximum CO2 (t)	25512	24164	22867	21664	20572
CO2 (t)	21318	19848	18241	16234	14040
Excess of CO2 (t)	4194	4316	4626	5429	6532
Steel (t)	2639	4109	5716	7723	9917

Figure. 5. Mass of CO_2, tank structure and excess of CO_2 for bi-lobe tanks.

Opposite to the situation with bi-lobe tanks and due to the lower storage volume utilization, additional ballast must be supplied to the vertical cylinder arrangement at pressures under 35 bar to keep the balance of mass invariant. The additional ballast coincides with the loss of of CO_2 mass in Fig. 6.



	15 bar	20 bar	25 bar	30 bar	35 bar	40 bar	45 bar
Maximum CO2 (t)	18656	17829	16955	16206	15545	14897	14175
CO2 (t)	18656	17829	16955	16206	15545	14559	13489
Loss/Excess of CO2 (t)	-1691	-1485	-1031	-642	-154	338	686
Steel (t)	3610	4643	5971	7109	8258	9397	10468

Figure. 6. Mass of CO_2, tank structure and lost mass or excess of CO_2 for cylindrical tanks.

With regard to the mass of transported CO_2 the best solution is to transport CO_2 at 6 bar in bi-lobe tanks as they are able to transport 21318 t while complying with the balance of mass constraint.

As shown in Fig 7, exclusively considering the amount of CO_2 transported, from pressures of 10-15 bar it is better to use cylindrical tanks as the CO_2 stored decreases rapidly from that operating pressure in bi-lobe tanks. It shall be noted that an optimized calculation of the bi-lobe tank structural strength may end up with a higher transition pressure, closer to the 15-20 bar range. Considering only the storage pressure, low pressures are more interesting, as the amount of CO_2 is higher. For example, the difference between transporting CO_2 at 10 and 45 bar is 47.1% and 70.5% (maximum CO_2).

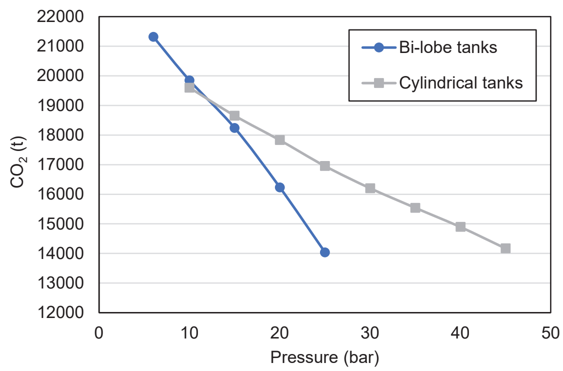


Figure. 7. Mass of CO_2.

Two ratios have been calculated: mass of CO_2 versus tank structure and volume of tank versus cargo hold, both shown in Fig 8. Both KPI serve as a measure of efficiency in the mass and volume dimensions. In both cases, the higher the ratio, the better. A low mass ratio implies that more mass of steel of the structure is being transported with respect with the CO_2. Analogously, a low volume ratio, implies that there is more empty space with regard to used space. As expected, the volume of cylindrical tanks makes much less use of available cargo hold space than bi-lobe tanks. However, bi-lobe tanks only take advantage of this for low pressures, as the mass of the structure increases rapidly. Note that for a storage pressure of 25 bar, the mass ratio of the bi-lobe tank considered is only 1.42. Under this KPIs, transporting CO_2 at low pressures, will probably result in a lower ship acquisition cost per unit mass of transported CO_2, as the mass of steel has a great influence on the final cost of a ship. The low ratios that this method yield, very likely imply that the base LPG ship main dimensions are not optimal for the transport of CO_2, thus a change of geometry in actual CO_2 could be expected Fig 2 and Fig 3 if an Ad hoc bulk CO_2 carrier was designed.

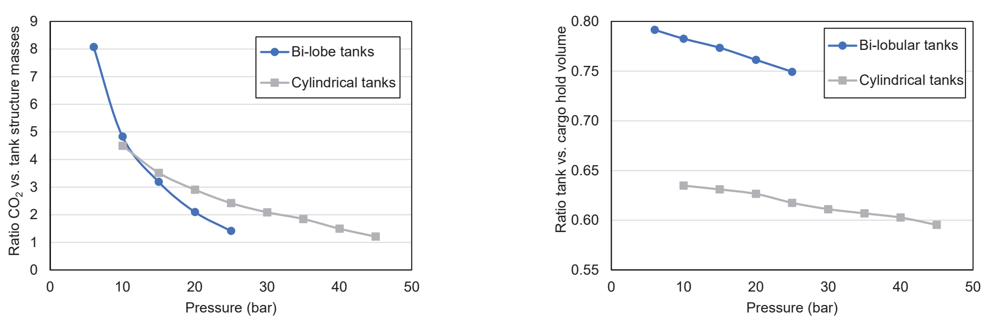


Figure. 8. Ratio of CO_2 vs. tank structure mass (left) and ratio of tank vs. cargo hold volume (right).

The last KPI is EEDI, presented in Fig 9, considering the mass of CO_2 for both type of tanks and the assumptions described in Section 2. As the storage pressure increases, so does EEDI value. In this case, the lower the value, the more efficient will be the ship. This KPI suggests that the ship with 6 bar and bi-lobe configuration will use less fuel per unit distance and unit mass of transported CO_2, probably meaning that the Voyage Cost of the low-pressure ship will be lower.

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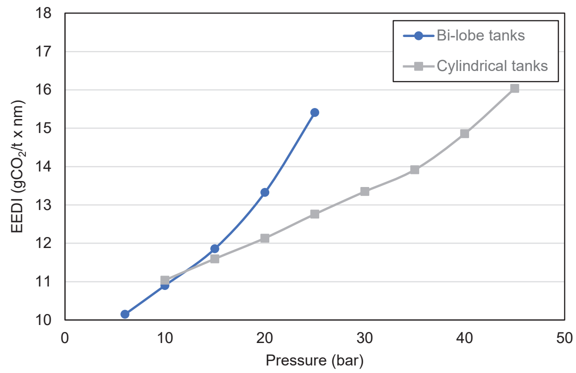

Figure. 9. EEDI of the ships proposed.

4. Conclusions

The results obtained in the different analyzes carried out establish unaligned conclusions. On one hand, from the exergetic point of view, liquefying the CO_2 to the highest range of pressures considered in this study is more efficient than lower pressures, closer to the triple point. Nevertheless, once thermoeconomy is included in the analysis, results could be different. On the other hand, lower CO_2 pressures allow more mass to be transported, and will probably result in reduced voyage costs, and the reduced steel mass in the ship's construction will probably mean cheaper acquisition costs. Considering that the whole logistic chain of CO_2 include the preprocessing costs, transport costs and post processing costs, it is not clear what the optimal transport pressure will be. Varying the pressure of the CO_2 cargo will have opposed effects in different elements of the logistic chain. Therefore, more research will have to be conducted to unveil the trade-off pressure, and the parameters that define it, considering the whole CCUS chain.
Attention should be paid to the tank design, as there is a transition pressure where bi-lobe tanks are no longer a smart option due to its mass and cylindrical tanks would be better even considering its worse volumetric efficiency. Attention should be paid to transporting CO_2 at low pressures close to the triple point, as in that region there is a higher risk of undesired CO_2 solidification, which can potentially clog pipes or damage pumps.

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Appendix A

Detail results of the calculations performed for this article are available on request.

Nomenclature

Symbols

Ex	exergy
E	energy
U	internal energy
p	pressure
V	volume
T	temperature
S	entropy

Subscripts and superscripts

0	restricted dead state

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