Ship Design for CO2 Transportation

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Classification Societies

- Independent arbiters of standards
- Mission – promote the security of life and property and preserve the natural environment
- Achieved by establishing and administering standards known as Rules for marine vessels and structures:
  - Design
  - Construction
  - Operational maintenance

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Class and Government

- The role of classification has been recognized in SOLAS and the International Convention on Load Lines
- Classification societies also act as Recognized Organizations (ROs) performing statutory inspections on behalf of flag States
- This statutory activity is distinct from but complementary to class requirements

What is Classification?

A stakeholder in the network of maritime safety

Drivers for Involvement in CO2

IPCC Report 2019

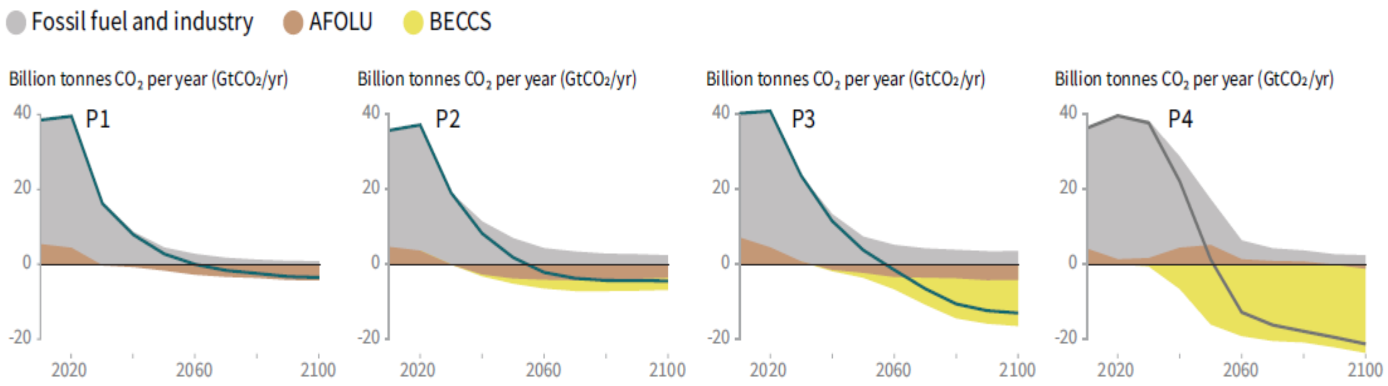
IPCC for limiting global temperature rise to 1.5^{o}C:

- anticipates future of carbon capture
- Three scenarios require major use of Carbon Capture

Carbon Capture and Storage projects recently gained momentum for expanding development

BECCS: Bioenergy with Carbon Capture and Storage
AFOLU: removals in the Agriculture, Forestry and Other Land Use
CDR: Carbon Dioxide Removal

Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways



P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

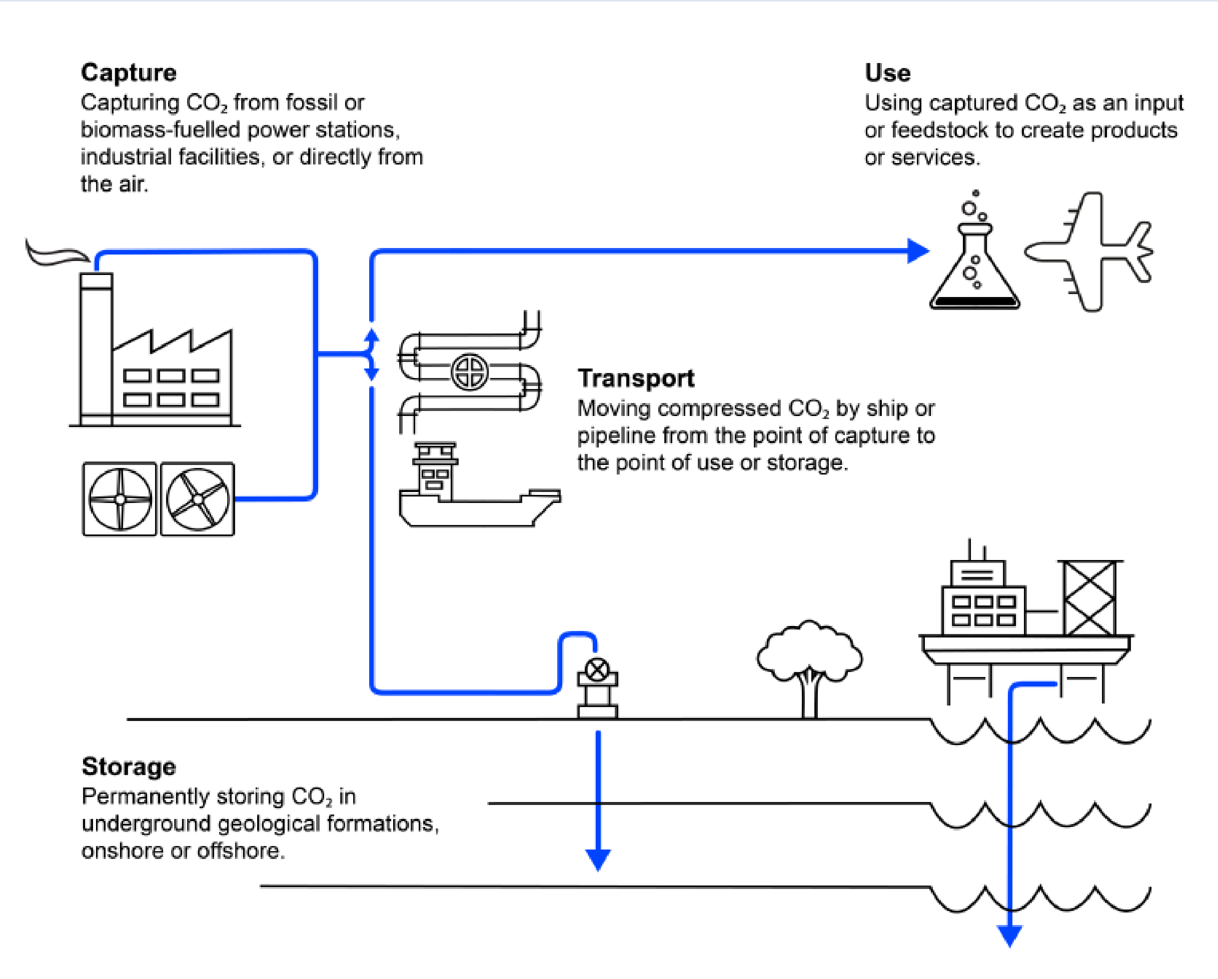
CCUS

The captured carbon can be :

- Either reused that helps reduce necessity of further release of fossil carbon

- Or locked in a reservoir to remove from the active carbon cycle (sequestration)

Schematic of CCUS



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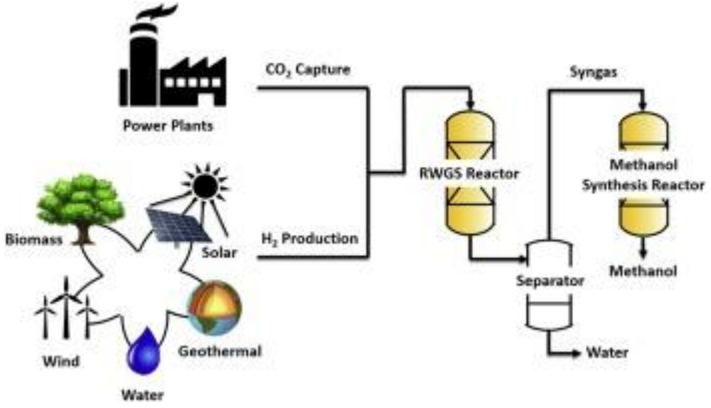
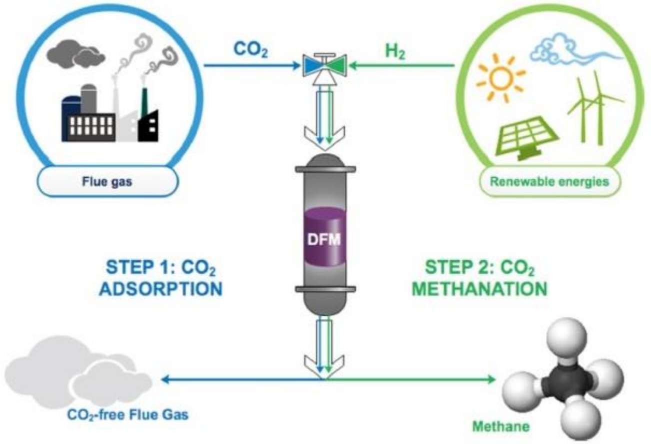
Capture Reuse

CO2 is a key input in many industries

- Feedstock for urea manufacturing on fertilizer industry.
- Small quantities in food and beverage production, cooling system and water treatment.
- New demand anticipated as feedstock for producing green methane and green methanol as new generation low carbon fuel.



https://www.sciencedirect.com/science/article/abs/pii/S221334371830736X

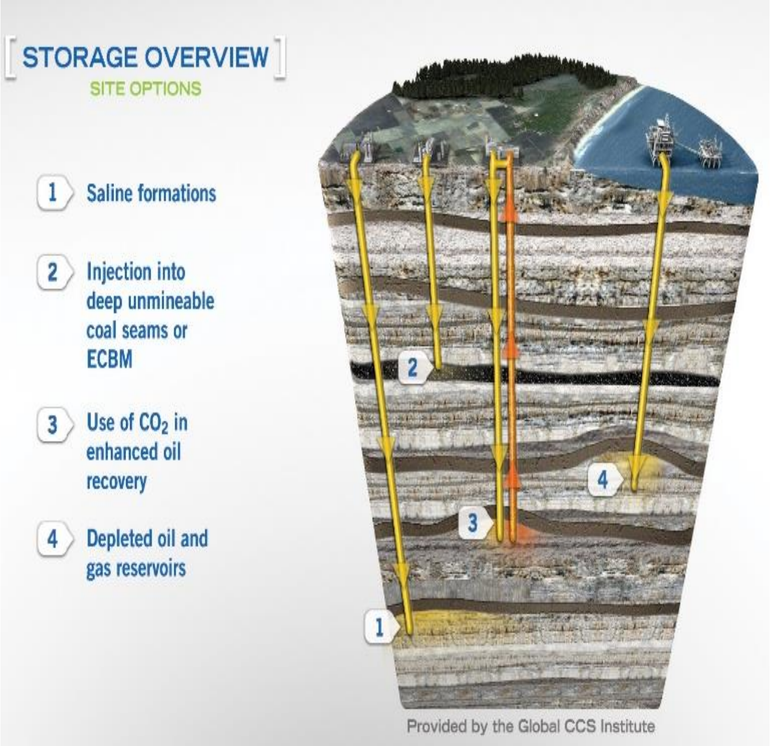


https://damiendebecker.wordpress.com/2019/10/21/co2-capture-it-and-turn-it-into-methane/

Capture Storage

- Long term storage by injection into natural porous rock formations such as;
  - Depleted oil or gas reservoirs
  - Coal beds
  - Saline aquifers

This allows both sequestration and enhancing oil/gas recovery.



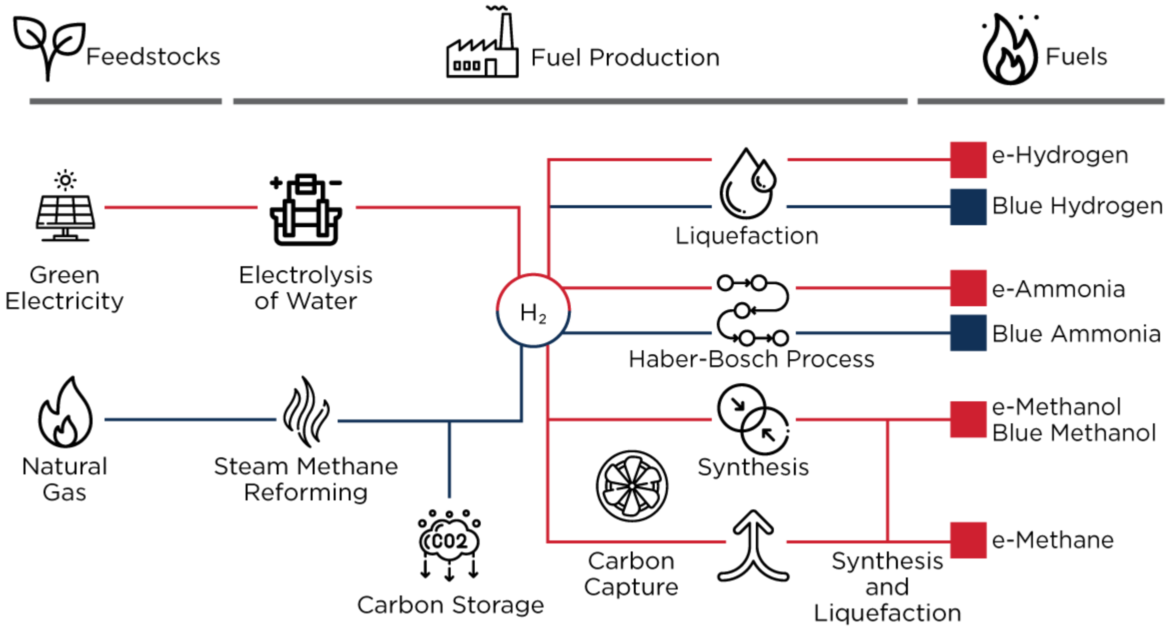
- For many years, CO2 has been injected during hydrocarbon production as
  - Enhanced oil recovery (EOR)
  - Enhanced coal bed methane (ECBM) recovery.
- London Protocol Convention
  - Article 6 does not allow export of wastes or other matter to other countries for dumping or incineration at sea
  - 2009 Amendments proposed for allowing transboundary transportation under agreement (tripartite agreement). Not ratified yet by the 2/3 of signatories

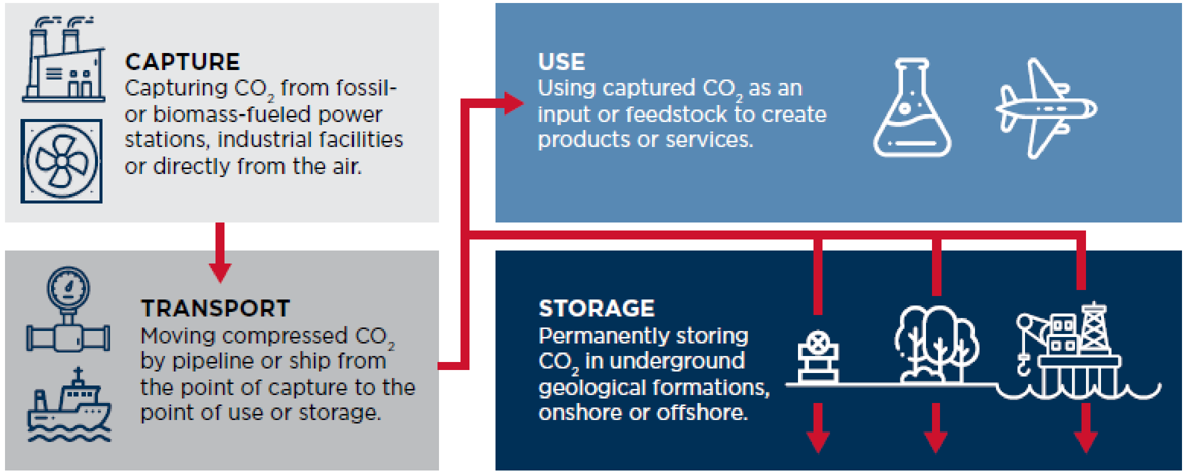
Hydrogen Value Chain – Carbon Value Chain

The value chain includes all activities related to producing Green (and Blue) Hydrogen, conversion of Hydrogen into other fuels/carriers (e.g., Ammonia and E-fuels), transportation and distribution to the final consumers.

Net Zero cannot realistically be delivered without the availability of Carbon Capture, Utilization and Storage (CCUS) technology.

This value chain includes capturing CO_2 at generation points, transporting it, collecting captured CO_2 at hubs, sequestering/storing CO_2 or using it as a feedstock.

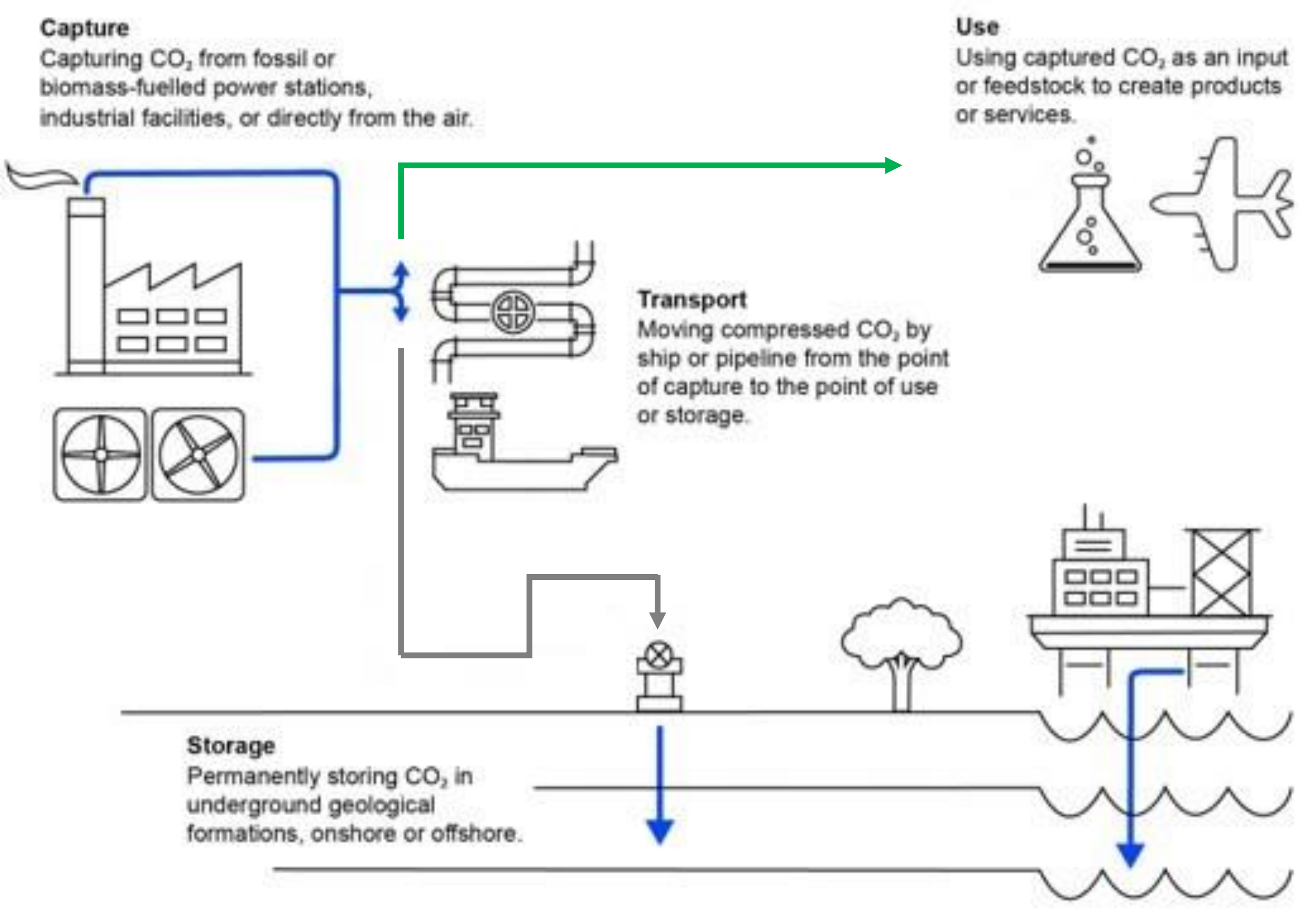




Assuming that green fuels can be produced from renewable energy at 60 percent efficiency, the required renewable power production would be 4,582 GW or an amount approximately equal to **seven times** the wind power produced in 2019, and **eight times** the solar power produced that year.

Carbon Value Chain

- **Net Zero** cannot realistically be delivered without the availability of Carbon Capture, Utilization and Storage (CCUS) technology.
- This value chain includes capturing CO_2 at generation points, transporting captured CO_2, collecting captured CO_2 at hubs, Sequestrating/Storing CO_2 or Using CO_2 as a feedstock.



Source: Adapted from https://www.iea.org/reports/ccus-in-clean-energy-transitions/a-new-era-for-ccus

Shipping's Role in the CCUS Value Chain

CAPTURE

Onboard carbon capture systems are becoming increasingly important for meeting the shipping industry's commitment to reduce greenhouse gas emissions. Hydrocarbon-fueled ships will be in service in the coming years, so onboard CCS will be necessary in order to avoid excess pollution until zero-carbon fuels become viable options.

TRANSPORT

Innovative shipping infrastructure has to be established that could **transport CO_2 efficiently and economically** across long distances then this would represent an essential step towards solving the global problem.

UTILIZATION

Shipping has an opportunity to lead the way in adopting e-fuels to compete the value chain.

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Transportation and Vessel Design

CO_2 Shipping Background

- Current CO_2 transportation relies heavily on pipeline network.
- Liquefied CO_2 shipping is mostly used in food/beverage industry with fairly pure CO_2:
  - Existing fleet limited to four LCO_2 carriers of small capacity (~1,800 tons CO_2) and high operational pressure (~15 bara / -25^{o}C).
- Need of LCO_2 transport by ships is expected to increase especially for emitters without close access to storage or existing pipelines.
- Scaling up LCO_2 carriers essential to support CCUS applications efficiently:
  - Main challenge for high operational pressure (~15-20 bara) is the larger capacity tanks construction complexity (increased tank shell plate thickness, weldability issues etc.).
  - Lower pressure options are being considered in feasibility studies (6-8 bara).
- Composition varies for captured CO_2 from CCUS => Impurities impact should be taken into consideration during design process.

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LCO_2 Carriers Orderbook

Shipyard	IMO	Operator	Delivery	Capacity (m^3)
Dalian Shipbuilding Offshore Co. (DSOC)	9954228	Northern Lights JV	2024-02	7,500
Dalian Shipbuilding Offshore Co. (DSOC)	9954230	Northern Lights JV	2024-02	7,500
Dalian Shipbuilding Offshore Co. (DSOC)	1034668	Northern Lights JV	2024-09	7,500
Dalian Shipbuilding Offshore Co. (DSOC)	1045265	BSM	2026-06	7,500
Hyundai Mipo Dockyard	1029974	Capital Gas Ship Management Corp	2025-11	22,000
Hyundai Mipo Dockyard	1029986	Capital Gas Ship Management Corp	2026-03	22,000

Orderbook of LCO2 carriers, as of Jan 2024

LCO_2 Carriers Existing Fleet

Operator	Name of Ship	Shipbuilder	Built
Sanyu Kisen	EXCOOL	**Mitsubishi Heavy Industries Shimonoseki**	2023-11
Larvik Shipping	FROYA	**Marine Projects Ltd.**	2005-09
Larvik Shipping	EMBLA	**Marine Projects Ltd.**	2005-01
Larvik Shipping	GERDA	**Marine Projects Ltd.**	2004-02
Larvik Shipping	HELLE	**Frisian**	1999-12

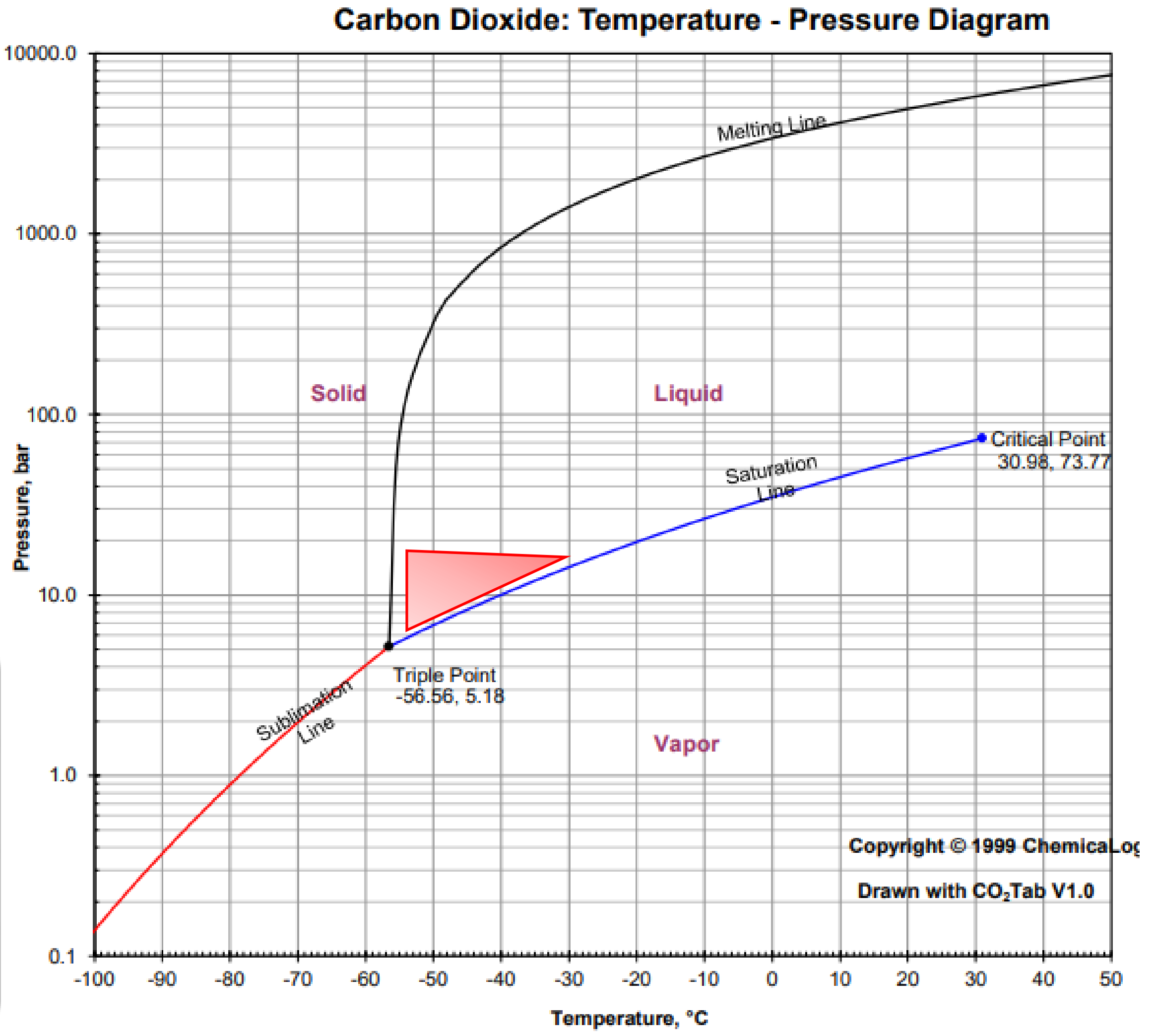
CO_2 Characteristics

- CO_2 Properties:
  - Non-flammable
  - Asphyxiant
  - Heavier than air
- Triple Point (-56.6°C, 5.18 bara for pure CO2)
- Saturation temperature at ambient pressure -78.5°C (dry ice)
- Toxicity concerns at high concentrations

Concentration	References
5,000 ppm (0.5%)	OSHA PEL and ACGIH Threshold Limit Value (TLV) for 8-hour exposure
30,000 ppm (3.0%)	ACGIH TLV- Short Term (STEL)
40,000 ppm (4.0%)	Immediately Dangerous to Life or Health (IDLH)

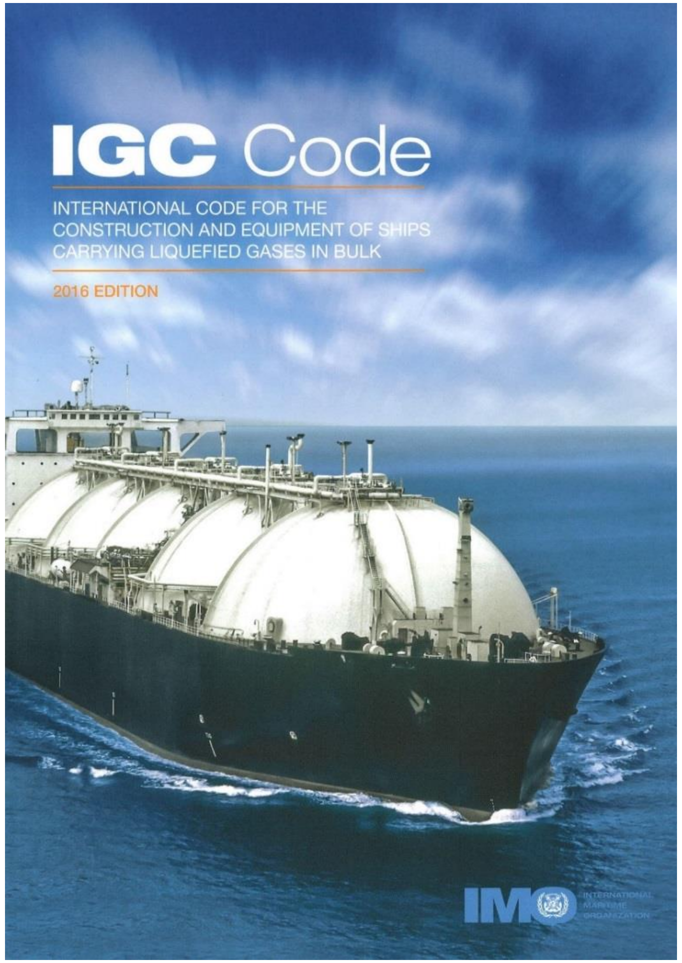
Carbon Dioxide Toxicity Levels

- OSHA: Occupational Safety and Health Administration
- ACGIH: American Conference of Governmental Industrial Hygienists



Rules & Regulations for CO_2 Carriers

- International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)
- ABS Marine Vessel Rules



a	b	c	d	e	f	g	h	i
Product name		Ship type	Independent tank type C required	Control of vapour space within cargo tanks	Vapour detection	Gauging		Special requirements
Acetaldehyde		2G/2PG	–	Inert	F + T	C		14.4.3, 14.3.3.1, 17.4.1, 17.6.1
Ammonia, anhydrous		2G/2PG	–	–	T	C		14.4, 17.2.1, 17.12
Butadiene (all isomers)		2G/2PG	–	–	F + T	C		14.4, 17.2.2, 17.4.2, 17.4.3, 17.6, 17.8
Butane (all isomers)		2G/2PG	–	–	F	R		
Butane-propane mixture		2G/2PG	–	–	F	R		
Butylenes (all isomers)		2G/2PG	–	–	F	R		
Carbon Dioxide (high purity)		3G	–	–	A	R		17.21
Carbon Dioxide (Reclaimed quality)		3G	–	–	A	R		17.22
Chlorine		1G	Yes	Dry	T	I		14.4, 17.3.2, 17.4.1, 17.5, 17.7, 17.9, 17.13
Diethyl ether*		2G/2PG	–	Inert	F + T	C		14.4.2, 14.4.3, 17.2.6, 17.3.1, 17.6.1, 17.9, 17.10, 17.11.2, 17.11.3
Dimethylamine		2G/2PG	–	–	F + T	C		14.4, 17.2.1
Dimethyl Ether		2G/2PG			F + T	C		
Ethane		2G	–	–	F	R		
Ethyl Chloride		2G/2PG	–	–	F + T	C		
Ethylene		2G	–	–	F	R		

IGC - Specific Requirements for CO_2

IGC 17.21 & 17.22

- Risk of cargo solidifying (Sublimation)
  - Low Pressure alarm 0.05 MPa above triple point
  - On Low Low Pressure automatically closure all cargo manifold liquid and vapour valves and stop all cargo compressors and cargo pumps
  - Means of isolating the cargo tank safety valves shall be provided
  - Discharge piping from safety relief valves shall be designed so they remain free from obstructions that could cause clogging. Protective screens shall not be fitted to the outlets of relief valve discharge piping.
- All materials used in cargo tanks and cargo piping system shall be suitable for the lowest temperature that may occur in service (saturation temperature at set pressure of the automatic safety system).
- Continuous monitoring for CO_2 build-up for cargo hold spaces, cargo compressor rooms and other enclosed spaces where CO_2 could accumulate.
  (Including Type C tank hold spaces).
- In case of reclaimed quality CO_2 17.22.1 the materials of construction used in the cargo system shall also take account of the possibility of corrosion, in case the reclaimed quality carbon dioxide cargo contains impurities such as water, sulphur dioxide, etc., which can cause acidic corrosion or other problems.

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LCO_2 Carriers – CO_2 Transportation

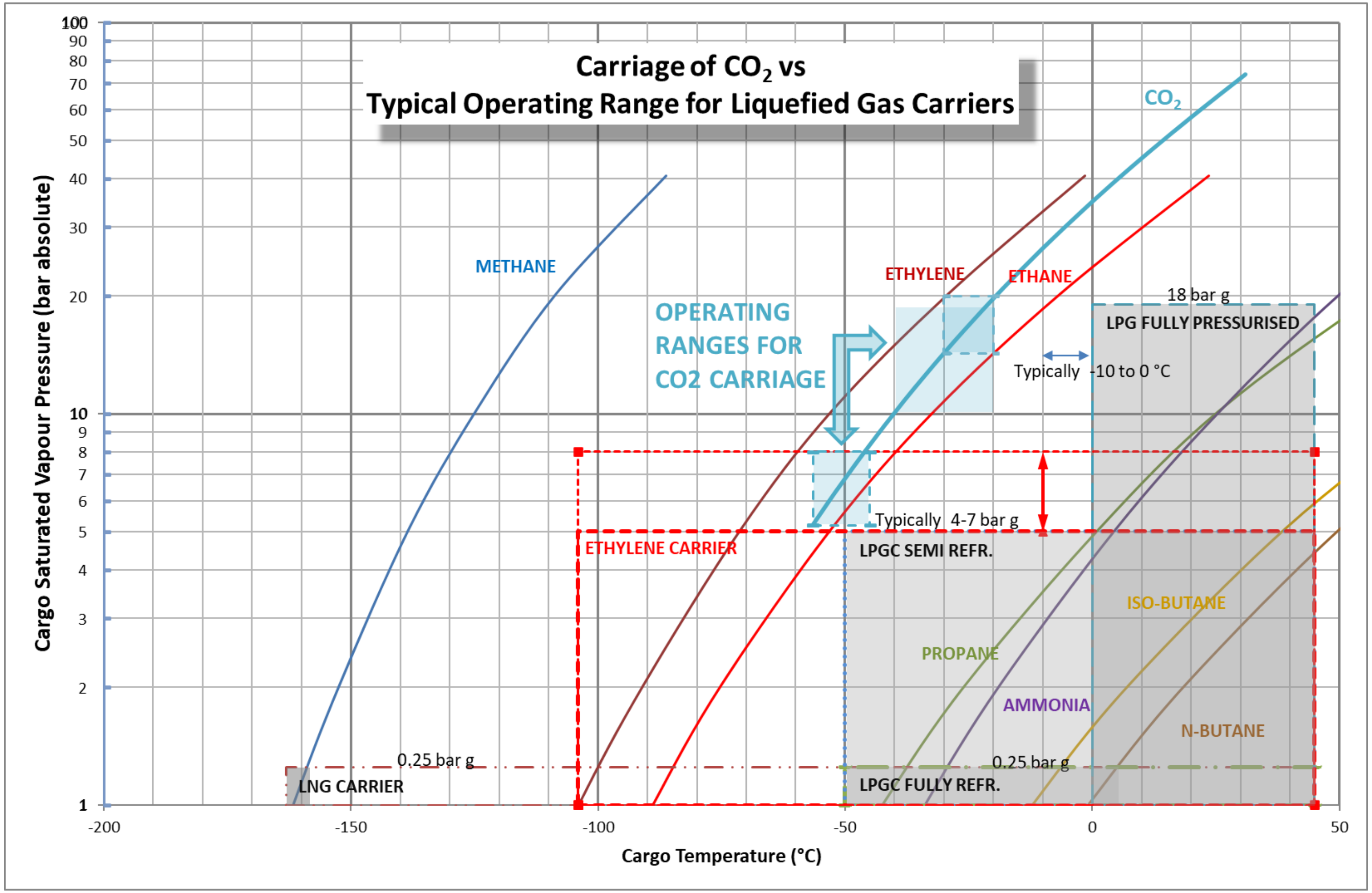
Triple Point

- LCO2 must be carried within a temperature and pressure range that will prevent formation of solid CO2:
  - Type C pressurized tanks to be used to maintain in liquid state.
  - Proximity to triple point requires additional redundancies & operational fail safes to ensure cargo does not solidify.

Density

- CO2 is **heavier than air**. Carbon dioxide vapors released into the atmosphere will accumulate in the area adjacent to the release. The highest concentration of carbon dioxide vapor will be found at the lowest point in the release area.
  - ~1,100 kg/m^3 at operational conditions close to -50^oC and 7 bara
  - ~1.98 kg/m^3 at atmospheric pressure, gas phase

Vessel Type Selection



CO_2 Composition and Purity

- IGC Code Chapter 17.22 reference to reclaimed quality CO_2.
- Annex B of ISO 27921:2020 provides indicative impurities levels (pipeline transportation)
- Cargo purity/composition depending on various parameters:
  - Carbon Capture Technology/process
  - CO_2 onshore handling and storage facilities (temperature/pressure conditions)
- Impurities effects:
  - Thermophysical effects (e.g. N_2, O_2, Ar, CH_4, H_2)
  - Corrosivity (e.g. O_2, H_2O, SO_x, NO_x, H_2S)
  - Reliquefaction plant efficiency due to non-condensable gases
  - Health & Safety considerations (NO_2, CO, H_2S, SO_2, HCN, COS, NH_3, etc.)
- Corrosion depends on Water Content & Solubility
  - CO_2 dissolves in water and forms carbonic acid. Those effects could also come from H_2S, SOx and NOx when they come in contact with free water present in the CO2 stream.

CO_2 Impurities

- Indicative list of CO2 impurities from published specifications

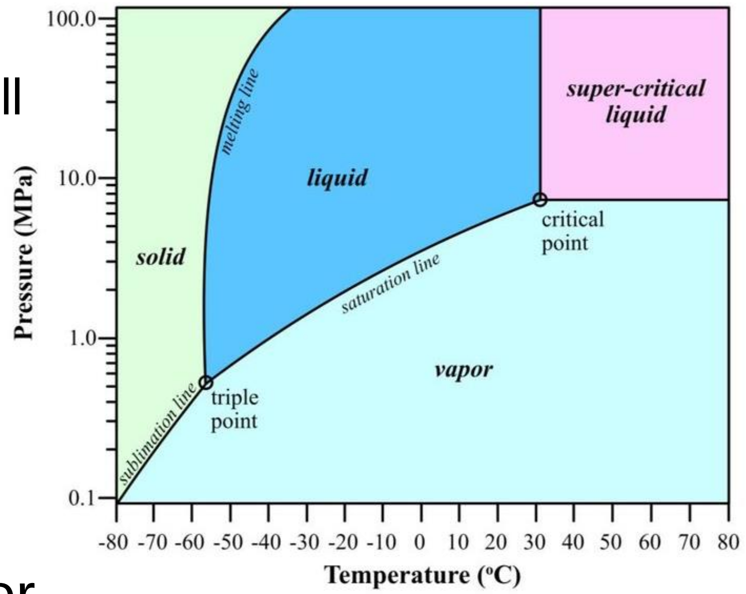
Component	Component
Water (H_2O)	Nitrogen Oxides (NOx)
Hydrogen Sulfide (H_2S)	Sulfur Oxides (SOx)
Carbon Monoxide (CO)	Acetaldehyde
Methane (CH_4)	Amine
Nitrogen (N_2)	Ammonia (NH_3)
Oxygen (O_2)	Cadmium (Cd) / Titanium (Ti)
Argon (Ar)	Formaldehydes
Hydrogen (H_2)	Mercury (Hg)

LCO_2 Carriers – Cargo Tanks Materials

- Compliance with cryogenic conditions based on operating temperature.
- Steel thickness depends on pressure. In principle, high pressure tank requires higher steel thickness.
- Compliance with IGC Code Chapter 6 to be confirmed. New materials to be approved by administration.
- Impurities in the CO_2 can potentially pose material issues.
- Development of new materials in progress for larger cargo tanks:
  - Low pressure: LT36 35mm, LT36 40mm, LT-FH51 50mm, 9%Ni 40mm,
  - High pressure: P690QL2
- Cylindrical, Bi-lobe Type C Cargo Tanks in Horizontal and Vertical configuration
- Thick low temperature steel plates require special considerations when welding

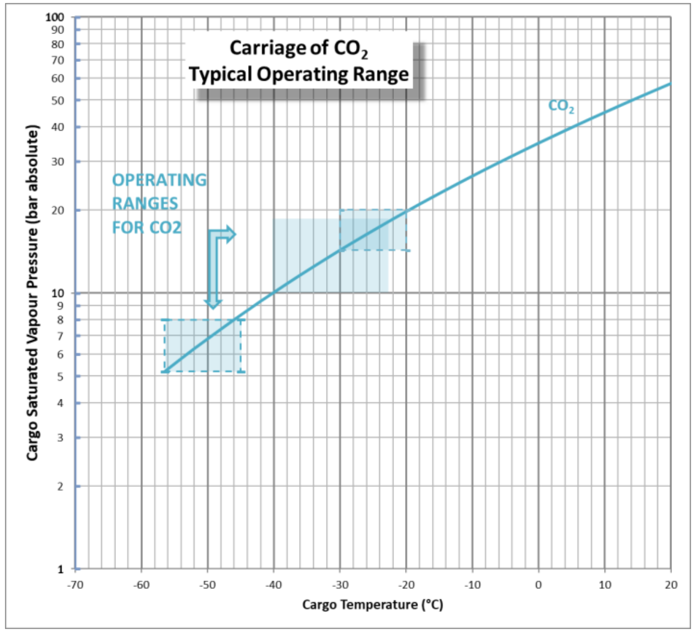
CO2 Carrier Design Requirements

- CCS design pressure higher than "triple point"
  - "Triple Point" depending on cargo purity
  - Pure CO2; 5 bara -54.4ºC (IGC notes 5barg!), density; ~1,150 kg/m^3
  - IGC Code requires additional 0.5barg for safety, avoid sublimation
- Avoid blockage of tank PRV valves due to solidification of cargo.
  - Means for PRV isolation to be provided (no interlock needed), use of full bore valves no orifice
  - Protective screens shall not be fitted on vent outlets
  - Minimize vent pipe length and avoid excessive bends or T-pieces
  - Consider the temperature drop in the vent line
- Continuous monitoring of CT pressure and ESD associated with low pressures
- Permanent fixed gas detection for CT hold spaces, CCR and other enclosed spaces where CO2 can be accumulated (CO2; asphyxiant)
- Restricted level gauging system as per IGC 13.2.3.4 is allowed



CO2 Carrier Technical / Operational Challenges

- Cargo purity/composition depending on various parameters:
  - Carbon Capture Technology / variety of resources
  - CO2 onshore handling and storage facilities (temperature/pressure conditions)
- BOG management when sailing
  - Pressure accumulation IGC 7.5 - (MARVS vs Operating pressure)
    - Holding time calculation / tank pressure rising curves
    - Operating environmental and cargo loading temperatures
    - Operational profile: loading levels, cruising range, local restrictions (US)
  - Re-liquefaction IGC 7.3
    - Highly depending on CO2 composition
    - Challenge on managing the non-condensables
- Tank pressure control during discharging
  - Compatibility with loading facilities
- Cargo Handling Operations
  - Inerting not required. Gassing up after drying
  - Gassing up after pipeline pressurization to avoid solidification of cargo



Conclusions

- Carbon capture is generating interest in CO_2 carriage by ship. This will develop depending on actual carbon projects
- Designs require project specifics from the upstream and downstream end (Capture end and storage end for CCS) to define vessel specifications
- Regulatory Frameworks including London Protocol need to be well understood by stakeholders
- Technical requirements and standards for ships are mature
- Impurities drive cargo definition and are highly relevant to ship design
- Technology is mature and available
- Early cooperation among stakeholders in full chain is the optimal path

Thank You

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