How is CO_2 transported?

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C4U

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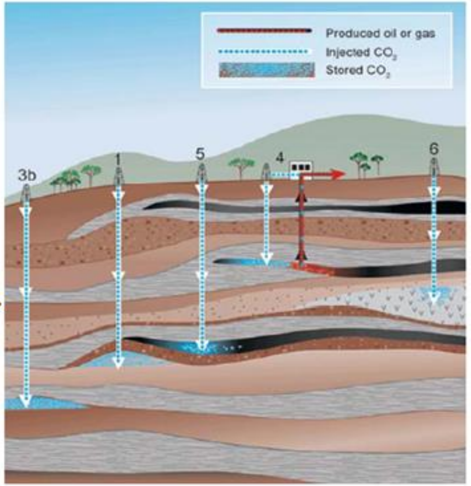
2 Modes of CO_2 transport – pipelines, trucks, trains and ships

3 CO_2 transport in CCS clusters

4 Summary

Why CO_2 transport?

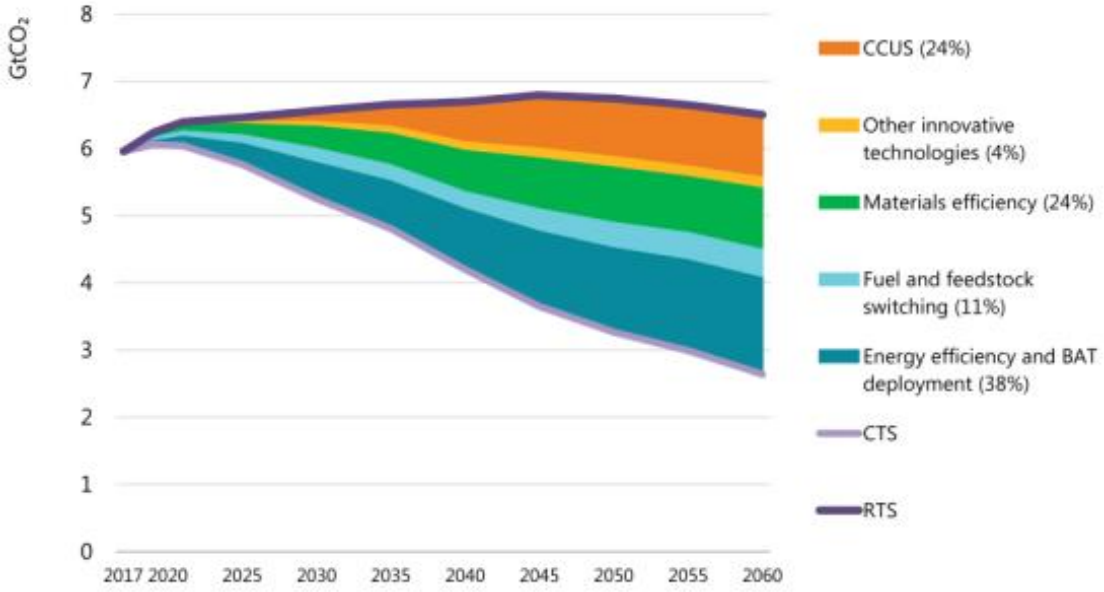
Capture of anthropogenic CO_2 emitted from industrial processes (e.g., methane reforming, ammonia production, steel, cement, etc) and power plants



CO_2 geological storage

Implementation of CCS requires not only capture and storage facilities, but also the development of *robust, safe and economic CO_2 transport infrastructure*

Demand for transport of CO_2 for CCUS



Capture of
ca 1 Gt CO_2 / year
as part of CCS
in 2050

Global CO_2 emission reduction scenarios for key industry subsectors (cement, iron and steel, chemicals) (IEA, 2019)

Demand for transport of CO_2 for CCUS

CO_2 commercial use:

- ✓ Enhanced oil recovery (EoR),
- ✓ food and beverage industries,
- ✓ horticulture,
- ✓ refrigeration (R744),
- ✓ supercritical solvent extraction,
- ✓ fire extinguishing,
- ✓ welding
- ✓ …

The global current market for CO_2 as an industrial gas is several **10 Mt/year** (excluding EOR and urea production) is very small compared to ***ca*** **1Gt/ year** planned CO_2 capture in CCS

Although mature CO_2 transportation solutions already exist, the roll-out of CCS requires highly efficient and economic solutions at **high TRL** for **large scale transport of CO_2**, with improved efficiency, operability and safety

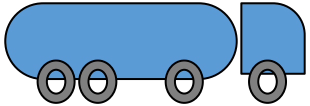
Modes of transport of industrial fluids

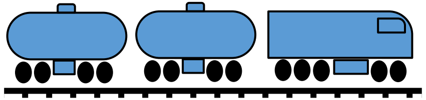
Onshore transport:

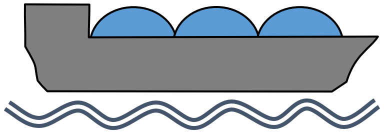
- Modular transport: Tanks carried by trucks, railway carriages, barges (solids, liquid, compressed gas cylinders);
- Pipelines: Stainless steel/ carbon steel pipelines/ composite corrosion resistant pipelines (low-pressure gas-phase and high-pressure dense-phase, slurries);

Offshore transport:

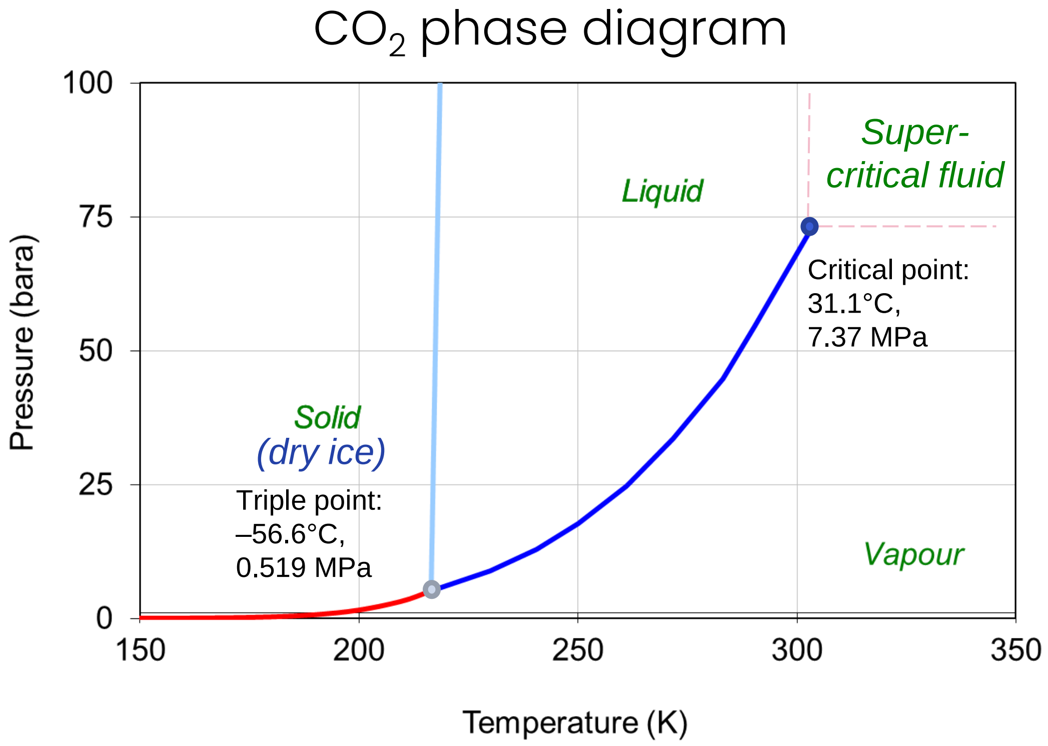
- Shipping of liquefied gases
- Subsea pipelines



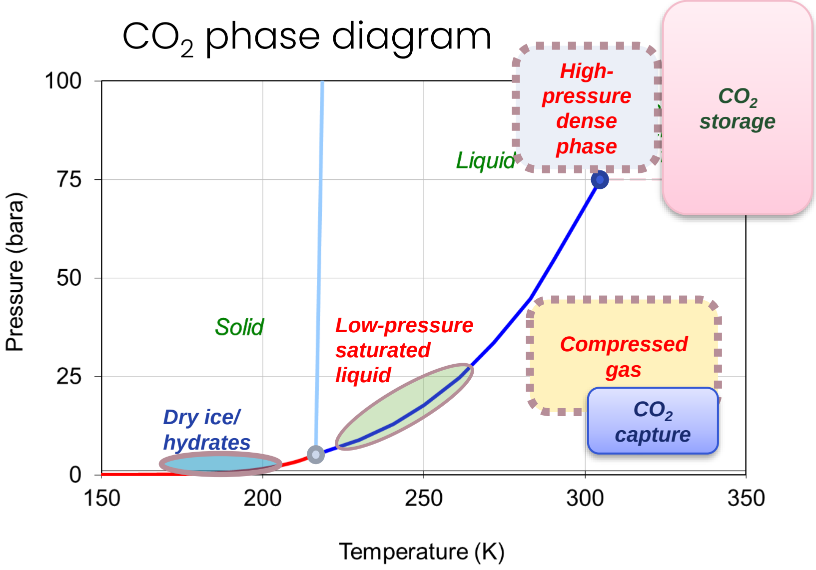


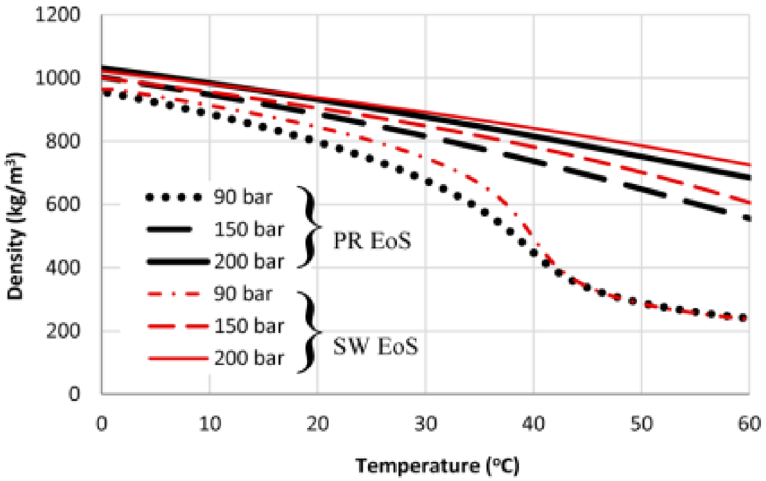


Properties of CO_2 fluid



Properties of CO_2 fluid



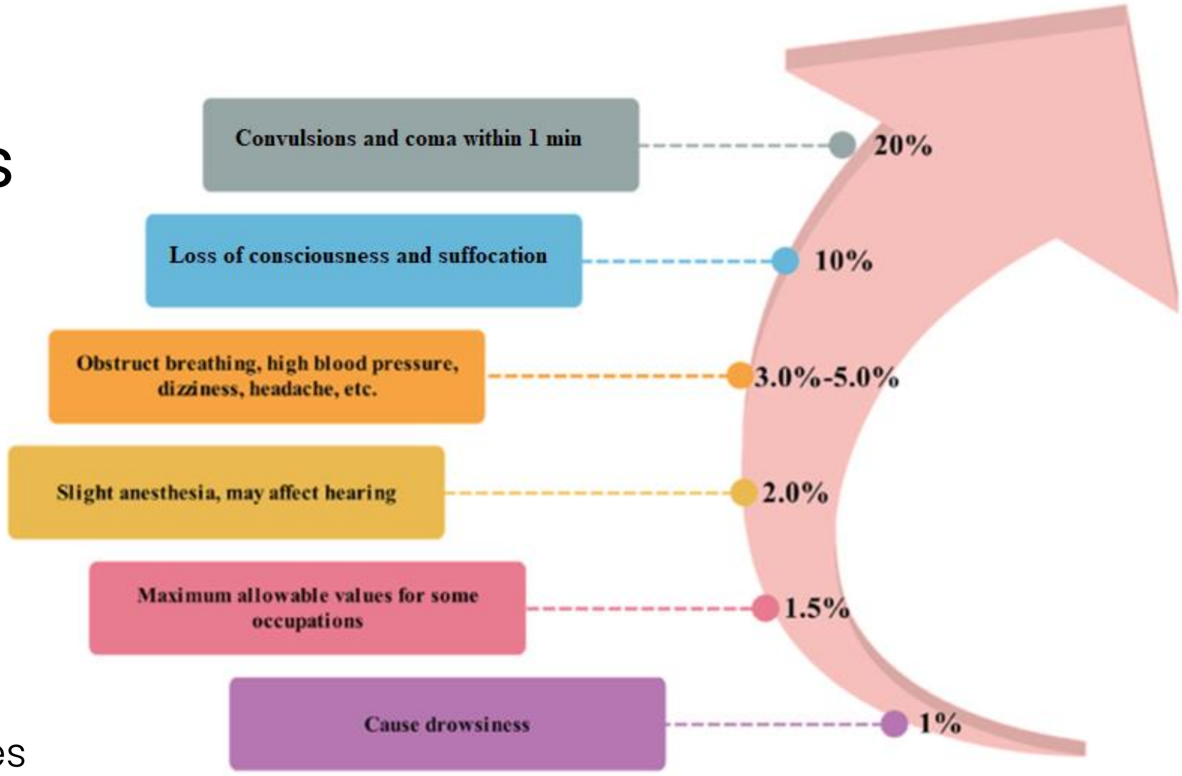


CO_2 properties in dense-phase and supercritical states may differ significantly from those of gases and liquids.

CO_2 processing facilities hazards

CO_2 as a substance is not toxic, but CO_2 facilities can carry hazards due to:

- CO_2 asphyxiation,
- high pressure,
- low temperature,
- presence of toxic impurities in the CO_2 stream



Impacts of CO_2 concentration in air on human health

Lu, H., Ma, X., Huang, K., Fu, L., & Azimi, M. (2020). Carbon dioxide transport via pipelines: A systematic review. *Journal of Cleaner Production*, *266*, 121994.

CO_2 pipeline transportation – existing experience

CO_2 pipelines in North America (USA and Canada):

- since 1972 (Canyon Reef pipeline),
- more than **6,500 km** of onshore high-pressure pipelines,
- transport **ca 68 Mt/yr** of CO_2 for EOR,
- purified CO_2 (>95% CO_2): naturally occurring (Cortez, Sheep Mt, Bravo, Central Basin pipelines) and from gasification plants (Canyon Reef, Weyburn, Val Verde, Bairoil pipleines),
- in sparsely populated areas.

Kinder Morgan to expand CO2 pipeline network. https://www.worldpipelines.com/

Pipeline	Location	Operator	Capacity ($MtCO_2\ yr^{-1}$)	Length (km)	Year finished	Origin of CO_2
Cortez	USA	Kinder Morgan	19.3	808	1984	McElmoDome
Sheep Mountain	USA	BP Amoco	9.5	660	-	Sheep Mountain
Bravo	USA	BP Amoco	7.3	350	1984	Bravo Dome
Canyon Reef Carriers	USA	Kinder Morgan	5.2	225	1972	Gasification plants
Val Verde	USA	Petrosource	2.5	130	1998	Val Verde Gas Plants
Bati Raman	Turkey	Turkish Petroleum	1.1	90	1983	Dodan Field
Weyburn	USA & Canada	North Dakota Gasification Co.	5	328	2000	Gasification Plant
Total			49.9	2591		

Doctor, et al (2005). Transport of CO2. In IPCC Special Report on Carbon dioxide Capture and Storage.

CO_2 pipeline transportation – existing experience

CO_2 pipeline systems worldwide

Country	System	Length (km)	Capacity (Mt/year)
United States	Permian Basin (West Texas, New Mexico, Colorado)	4 180	
	Gulf Coast (Mississippi, Louisiana, East Texas)	1 190	
	Rocky Mountains (Colorado, Wyoming, Montana)	1 175	
	Midcontinent (Oklahoma, Kansas)	770	
	Other (North Dakota, Michigan)	345	
Canada	Alberta Carbon Trunk Line	240	14.6
	Quest	84	1.2
	Saskatchewan	66	1.2
	Weyburn	330	2
Norway	Hammerfest	153	0.7
Netherlands	Rotterdam	85	0.4
United Arab Emirates	Abu Dhabi	45	
Saudi Arabia	Uthmaniyah	85	

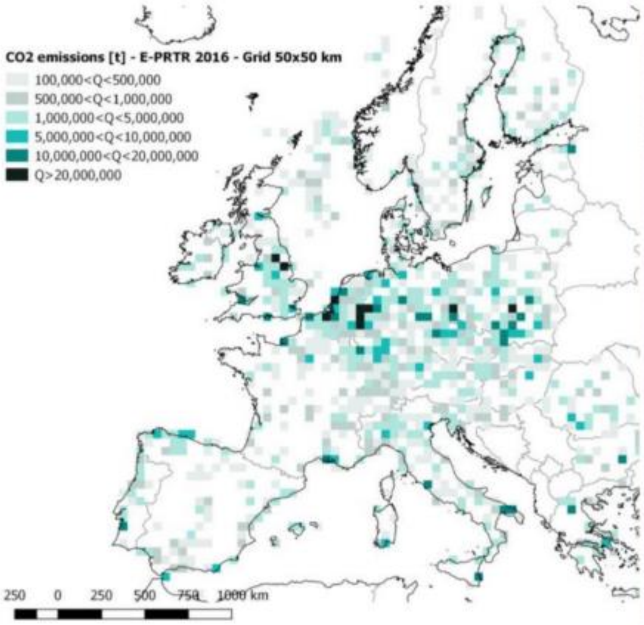
Source: IEA analysis based on IEAGHG (2013), CO_2 pipeline infrastructure report 2013/18 and Peletiri, Rahmanian and Mujtaba (2018), CO_2 Pipeline Design: A Review.

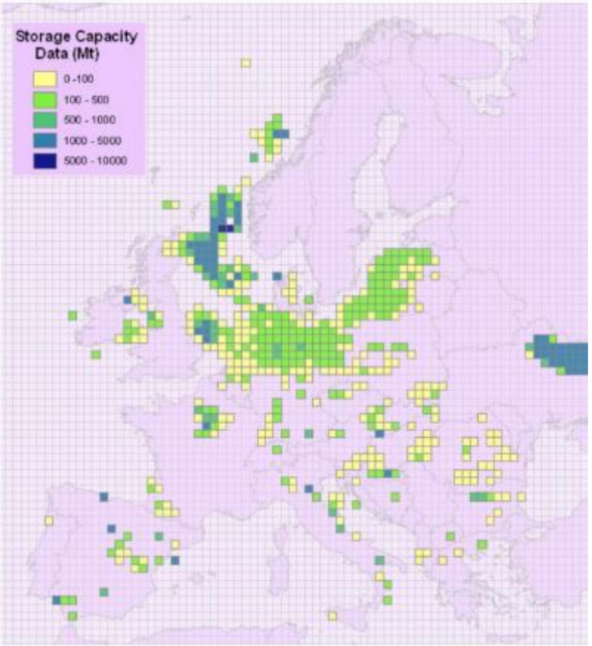
Typical specifications for dense phase CO_2 (liquid/ supercritical) transport pipelines:

- Temperatures: 4°C to 40°C
- Pressures: 86 bar to 200 bar
- Flow speed: ca 1.5 m/s

IEA. (2020). Energy Technology Perspectives 2020. Special Report on Carbon Capture Utilisation and Storage. CCUS in clean energy transitions. In *Energy Technology Perspectives*.

CO_2 pipeline transportation – future needs





On a global scale the CO_2 transport for CCS would require

95,000 – 550,000 km

of pipes

(Element Energy, 2010)

IOGP (2019). *The potential for CCS and CCU in Europe.*

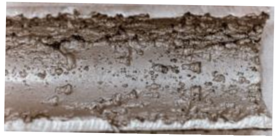
Is CO_2 pipeline transportation safe?

CO_2 specific design and operation considerations made to minimise the risks of:

- formation of two-phase liquid-vapour flow;
- rapid transients in the flow,
- significant cooling in the flow, causing:
  - formation of solid phase CO_2 (dry ice);
  - embrittlement of the pipeline materials.
- fracture propagation along the pipeline;
- accidental discharge of CO_2 from a pipeline constructed in populated areas;
- corrosion in presence of H_2O, SO_x, O_2;
- hydrates formation.

Propagated rupture in CO_2 pipeline
Aursand et al. /Engineering Structures 123 (2016) 192–212

Release of 3.8 tons of Supercritical CO_2 from a large-scale pipeline (DUT, CO2QUEST)



CO2 pipeline corrosion
https://www.aboutcorrosion.com/2014/11/12/carbon-dioxide-corrosion-definition/

Hydrates formation in pipelines
Zarinabadi & Samimi (2011). Australian J. of Basic & Applied Sci, 5(12): 741-745

- *ISO 27913:2016 Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems.*
- *DNV (2010). Design and Operation of CO2 Pipelines. Recommended Practice DNV-RP-J202.*

CO_2 road transport

Existing experience:
Refrigerated liquid CO_2 transport in tanks mounted on trucks or trailers

Pressure: ca 20 bar
Temperature: saturation (ca -20 ^oC)
Capacity: 2 m^3 to 35 m^3

Vehicle speed: up to *ca* 100 km/hr

Similar applies to railway/ barge transport

https://tomcosystems.com/product/co2-transportation/

https://www.bnhgastanksindia.com/liquid-carbon-dioxide-transport-tanks

CO_2 ship transport

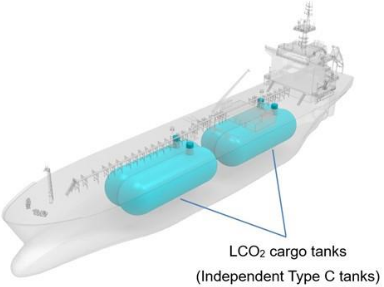
https://www.energynewsbulletin.net/

Past experience: LNG transport

Developing solutions:
transport of refrigerated liquid CO_2

Pressure: 7 bar to 15 bar
Temperature: -50 °C to -30 °C
Capacity: 4,500 m^3 to 30,000 m^3

Vessel speed: 16.5 knots ~ 30 km/hr

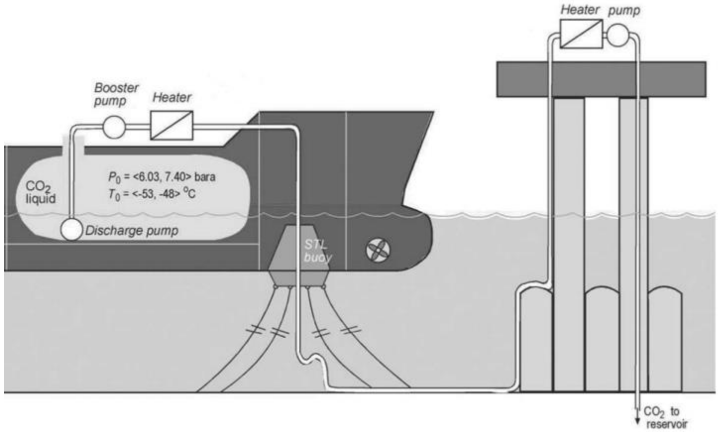


https://www.offshore-energy.biz/mitsubishi-shipbuilding-secures-aip-for-lco2-carrier-cargo-tank/

CO_2 ship transport design & operation

The CO_2 interim storage and offloading in a port

https://splash247.com/japanese-utility-firm-readies-first-liquefied-co2-shipping-terminal/

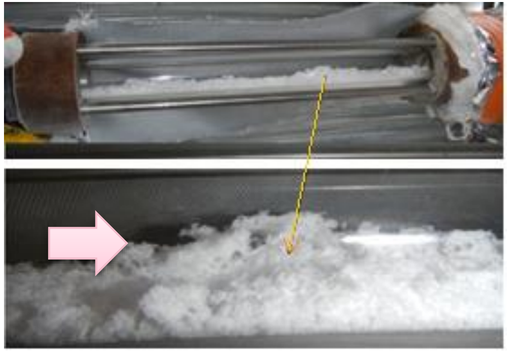


The offshore CO_2 unloading system

- a submerged turret loading (STL) system;
- cargo, booster and injection pumps;
- a CO_2 heating system on the ship;
- a flexible riser and pipelines to the platform;.

Aspelund, et al. (2006). Ship transport of CO2: Technical solutions and analysis of costs, energy utilization, exergy efficiency and CO2 emissions. *Chem Eng Res & Design, 84*(9 A), 847–855.

Safe operation of CO_2 storage tanks



Rapid decompression below the triple point:

- Very low temperatures
- ‘Dry ice’ formation inside the pipe

Very slow rate of CO_2 sublimation

FIGURE 2. Plant area close behind and to the left of the CO_2 tank after failure.

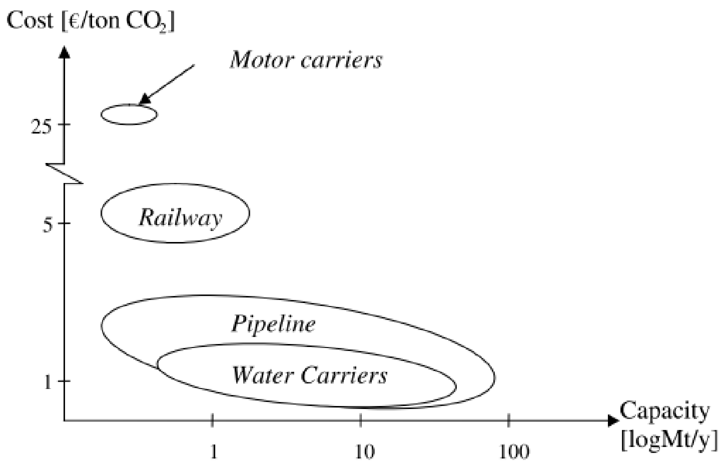
FIGURE 4. Head of CO_2 tank found soon after failure.

Clayton, W. E., & Griffin, M. L. (1994). Catastrophic failure of a liquid carbon dioxide storage vessel. *Process Safety Progress*, *13*(4), 202–209.

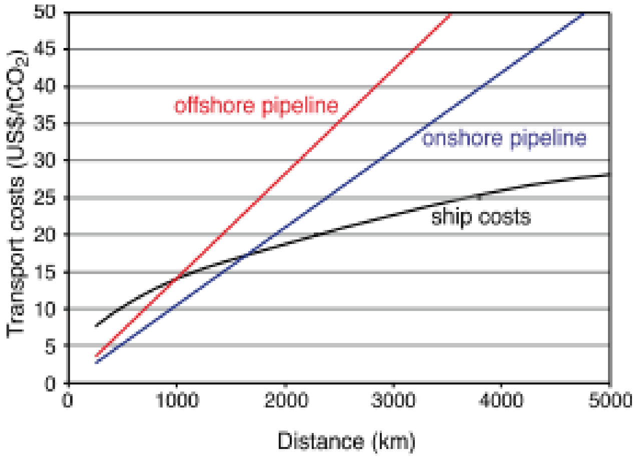
- Thermal fatigue of steel
- Brittle fracture propagation
- Blockage of safety relief valves
- Over-pressure during refilling process

Overpressure accidents and dry ice formation can be prevented by following the *standards and operation guidelines for CO_2 storage vessels and tanks*

Cost of CO_2 transport



Cost and capacity for transportation alternatives at 250 km.
Svensson et al. 2004, Energy Conv. & Managem. 45, 2343–2353



Costs for onshore pipelines, offshore pipelines and ship transport.

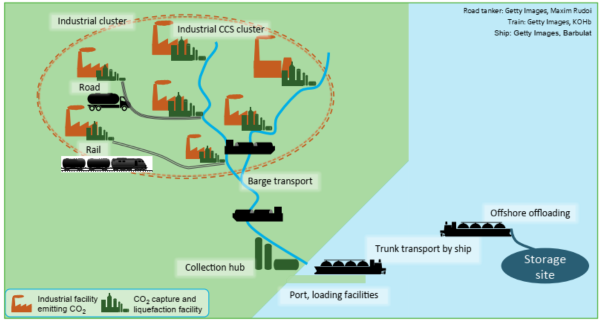
Doctor, R., et al. (2005). Transport of CO2. In *IPCC Special Report on Carbon dioxide Capture and Storage*.

CO_2 transport in CCS clusters

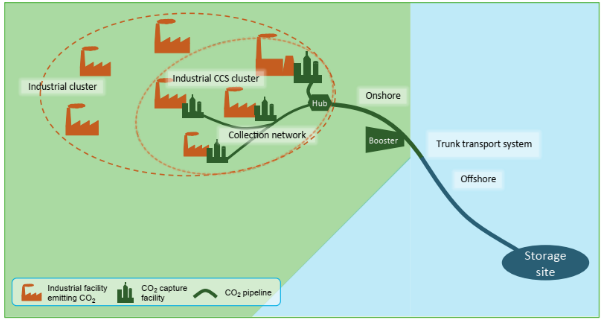
Industrial clusters (red) and storage sites (green) around the North Sea

Brownsort, P. (2019). *Methodologies for cluster development and best practices for data collection in the promising regions. Part 1.*

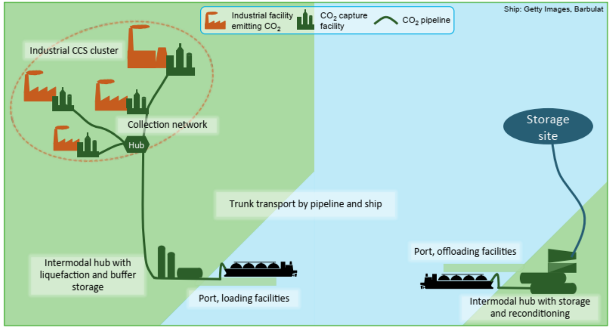
Modular transport of liquefied CO_2



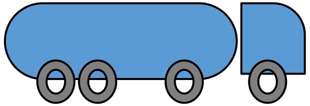
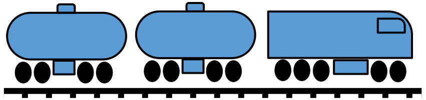
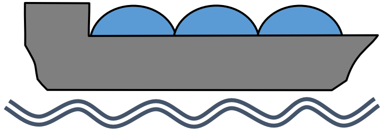
Pipeline transport of CO_2



Hybrid transport of CO_2



Comparison of CO_2 transport modes

	Advantages	Disadvantages
	• Continuous operation • Large transport capacity • Low costs	• High capital costs
	• Flexible transport route selection • Use of existing road transport infrastructure	• Low transport capacity • Affected by weather/traffic • High operating costs
	• Not dependent on weather/ traffic • Use of existing railway infrastructure	• Limited to locations with existing railways
	• Flexible transport route selection • Moderate capacities	• Temperature and pressure control for loading/unloading facilities

Thank you

Questions ?