Ship transport of CO_2 An Overview

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Talk outline

- Introduction – literature survey
- Existing CO_2 shipping experience
- Process technology
- Regulation and HSE aspects
- Financial factors, cost comparisons

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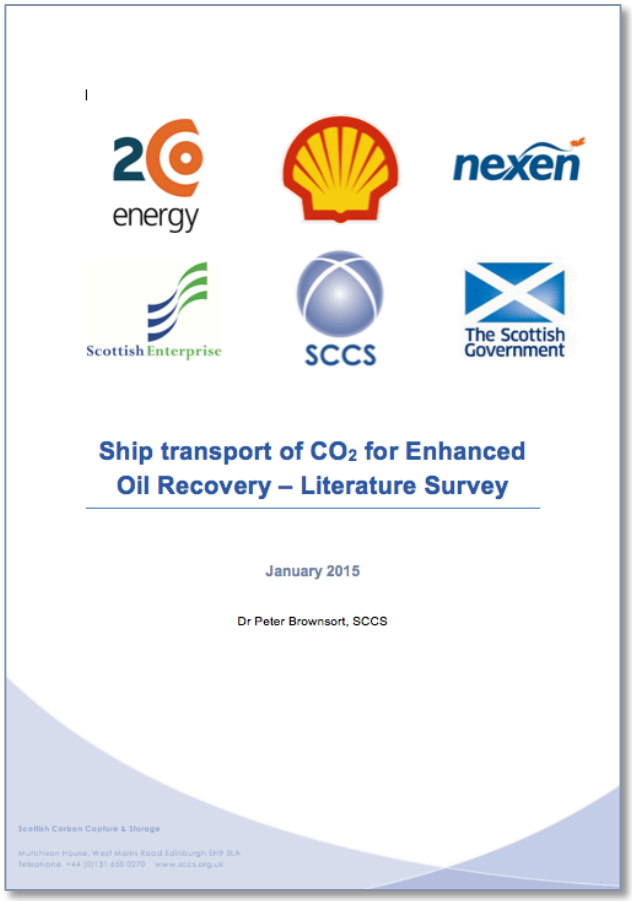
CO_2 shipping literature survey

- SCCS Joint Industry Project on CO_2-EOR commissioned literature survey, 2014
  - Extent and scope of literature on transport of CO_2 by ship
  - Key findings for EOR



http://www.sccs.org.uk/images/expertise/reports/co2-eor-jip/SCCS-CO2-EOR-JIP-WP15-Shipping.pdf

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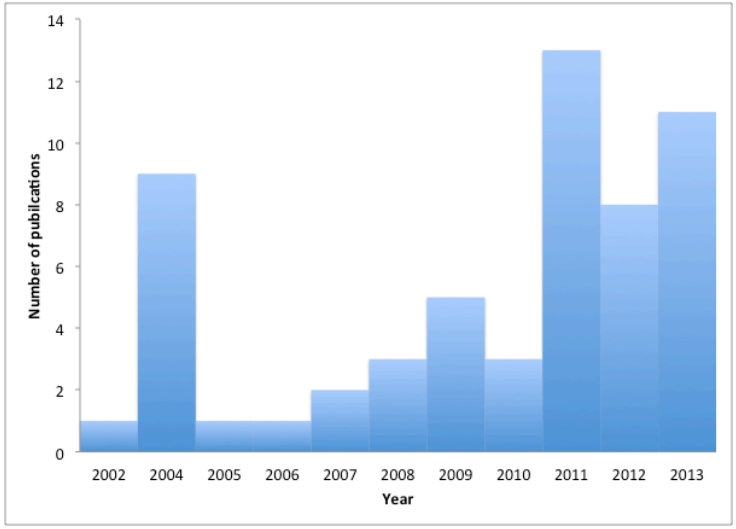
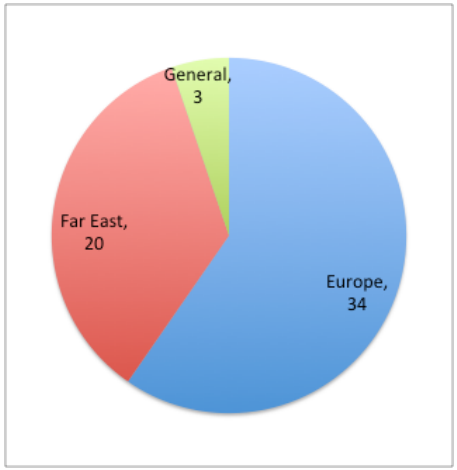
Introduction – literature survey

- Around 60 references found (more since)
- Europe > Asia
- Conference > Journal > Report





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Literature survey – some key references

- **MITSUBISHI HEAVY INDUSTRIES LTD. (2004)**. *Ship Transport of CO_2.* Cheltenham, IEA-GHG. Report number: PH4/30.
- **ASPELUND, A., MØLNVIK, M. J. & DE KOEIJER G.** (2006). Ship Transport of CO_2. *Chemical Engineering Research and Design.* 84(9): 847-855.
- **ASPELUND, A.** (2010). Gas purification, compression and liquefaction processes and technology for carbon dioxide (CO_2) transport. In: Maroto-Valer, M. M. (Ed) *Developments and innovation in CCS technology*, Cambridge, Woodhead Publishing Ltd. pp. 383-407.
- **VERMEULEN, T. N.** (2011). *Overall Supply Chain Optimization. CO_2 Liquid Logistics Shipping Concept.* Tebodin Netherlands BV, Vopak, Anthony Veder and GCCSI. Report number: 3112001.
- **ZEP** (2011). *The Costs of CO_2 Transport.* Brussels, European Technology Platform for Zero Emission Fossil Fuel Power Plants.

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Literature survey – key findings

- Ship transport of CO_2 feasible using known technologies, related to LPG
- Established on small scale
- Can be cost competitive
- Some advantages over pipeline transport
- Focus of studies for CCS, not EOR
- Some knowledge gaps

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Existing experience of CO_2 shipping

- EU market for bulk CO_2 c.3 Mt/yr, transported by truck, train, ship.
- Yara International trades CO_2 from Nor and NL through 7 import and distribution terminals around western European coasts
- Larvik shipping – Yara I, II, III – 900-1200 t
- Yara Embla, Yara Froya – 1800 t
- Anthony Vader – 1250 m^3 dual purpose LPG/CO_2
- IM Skaugen – six 10,000 m^3 dual purpose LPG/CO_2

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Images: Larvik; Yara; Anthony Vader; IM Skaugen

Experience of CO_2 shipping vs. LPG, LNG

	CO_2	LPG	LNG
Number of ships	≤ 12	≥600 (?)	≥ 350
Capacity	Most ≤ 1800t, up to 10,000 m^3	Up to 80,000 m^3	Up to 266,000 m^3
Type	Semi-pressurised/ refrigerated	Pressurised, Semi-pressurised/ refrigerated, or Refrigerated	Refrigerated, atmospheric pressure
Typical conditions	-30°C, 20 bara (existing fleet)	Varied: to -55°C, 20 bara	-161°C, 1 bara
Loading/unloading	In port	In port, offshore	In port, offshore

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Process technology

- Shipping of CO_2 as liquid near triple point generally proposed – 6.5 bara, -52°C
  - Other liquid conditions sometimes proposed
  - Transport as compressed gas also considered
- Technology can be adapted from LPG
- Process blocks:

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Liquefaction

- Compression, cooling, dehydration and distillation
- Most energy intensive and costly step
- Several process options depending on cooling available
  - Cooling water or seawater at <15°C
  - External refrigeration
  - Over-compression and expansion
  - Combination

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Liquefaction

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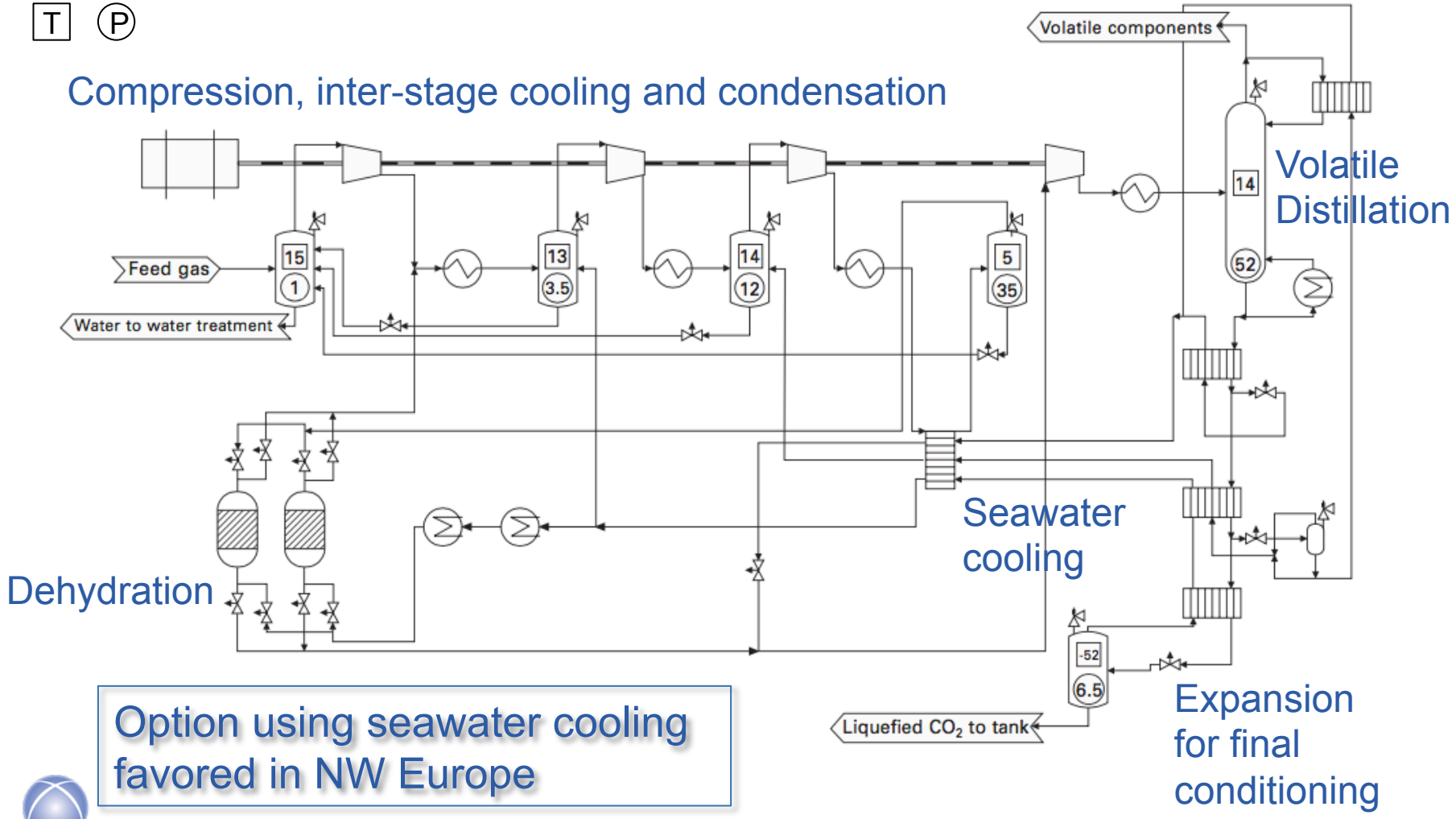
Compression, inter-stage cooling and condensation



Volatile Distillation

Seawater cooling

Dehydration

Expansion for final conditioning

Option using seawater cooling favored in NW Europe

Source: Aspelund, 2010

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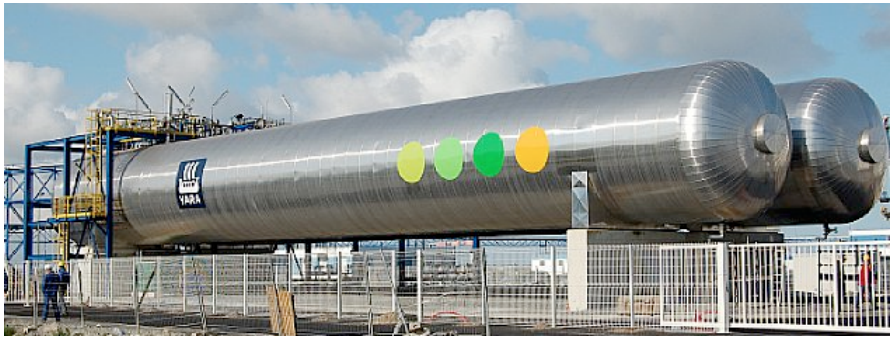
Shore storage

- Liquefaction is continuous, shipping is batch ➔ buffer storage needed before loading
  - Cylinders or spheres
  - Onshore or on barge in port
- Shore storage volume, 1.0 to 1.5 x ship volume



Images: Yara; Liaoning Refine Technology Group

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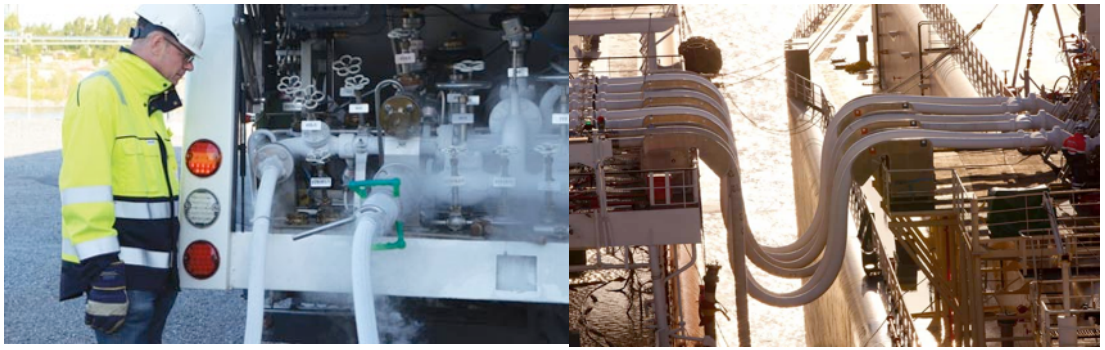
Ship loading

- Quayside loading
  - Flexible cryogenic hoses



  - Cryogenic marine loading arms

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Images: mann-tek; KLAW, Center for LNG

Ship designs

- Covered by *International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk ("IGC Code")*
- Proposed designs based on LPG carrier experience
- Typically several horizontal cylindrical cargo tanks giving 20,000 – 40,000 m3
- Alternatives – bi-lobe tanks, spherical tanks, vertical cylindrical tanks

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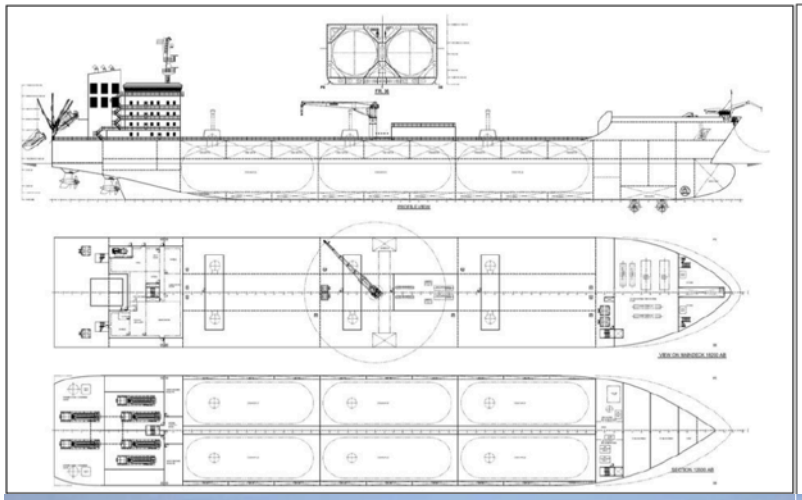
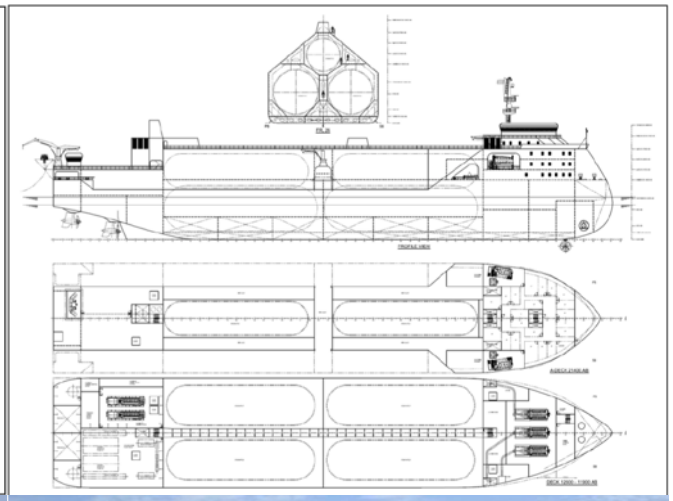
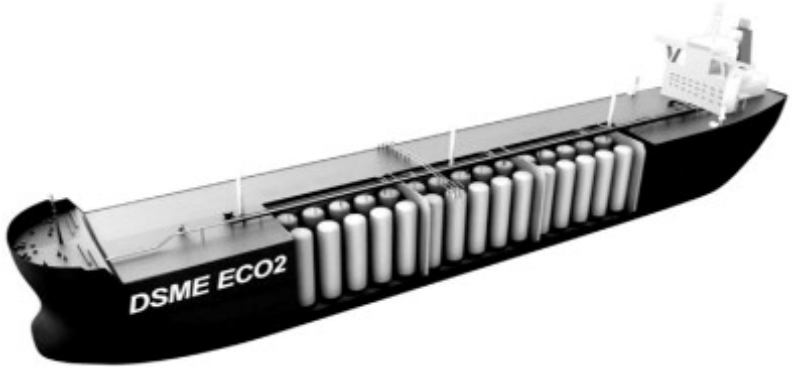
Ship designs







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Images: Vermeulen (2010), Yoo *et al* (2013), allaboutshipping.co.uk

Ship equipment

- Dynamic positioning system (DPS)
  - To maintain position during offshore offloading
- Process equipment
  - To recondition CO_2 to T and P required for offloading, and/or for well injection
    - Pumping to 50 to 400 bar
    - Warming to -15 to +20°; seawater, waste heat or fuelled system
  - Conditions needed specific to each case and depend on several factors
    - Offloading system design
    - Platform capabilities and well design
    - Reservoir conditions

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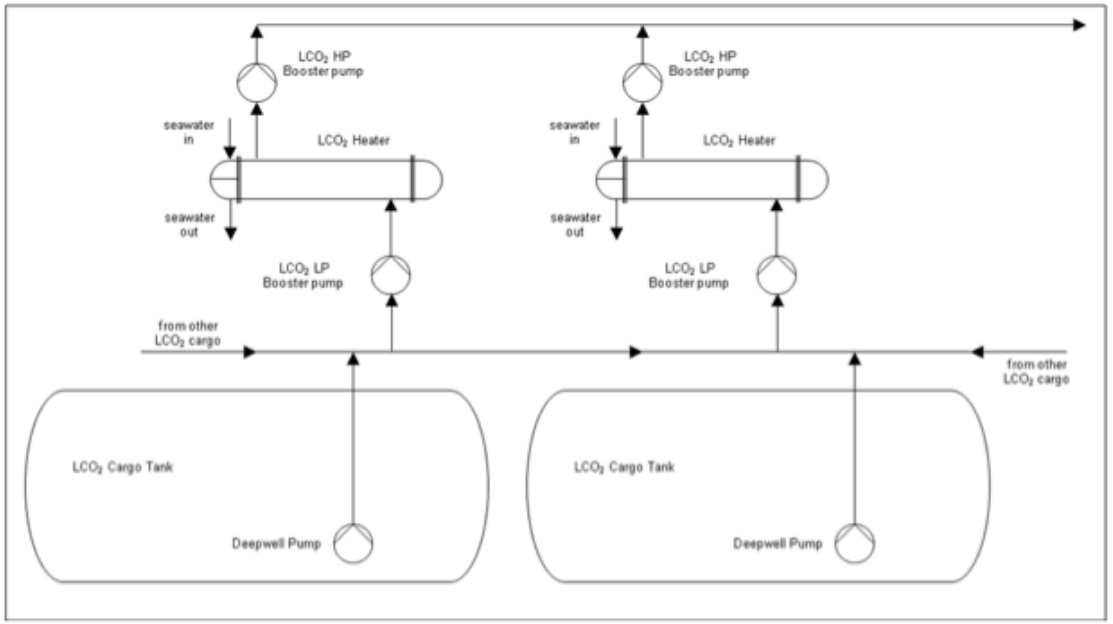
Ship-board process equipment

Example (Vermuelen, 2011)

- Cargo lift pumps
- LP pumps (45 barg) avoids vaporisation on warming
- Seawater-warmed shell and tube heat exchanger
- HP pumps to injection pressure (154-400 barg)



Alternatives and additional equipment

- Mid-pressure pump to make transfer to platform, HP pump on platform
- Waste heat or fuelled ancillary heater
- CO_2 vaporiser for tank pressure equalisation
- Dry air plant

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Offshore offloading

- Perhaps least well defined aspect
- Lots of options based on hydrocarbon transfers but will need adapting for CO_2
- Choice of single point offloading system depends on
  - CO_2 conditions – liquid or SC fluid, T and P
  - Flexible hose suitability – for environment and CO_2 conditions/properties
  - Location – sea conditions, water depth
  - Ship design – processing equipment, DPS

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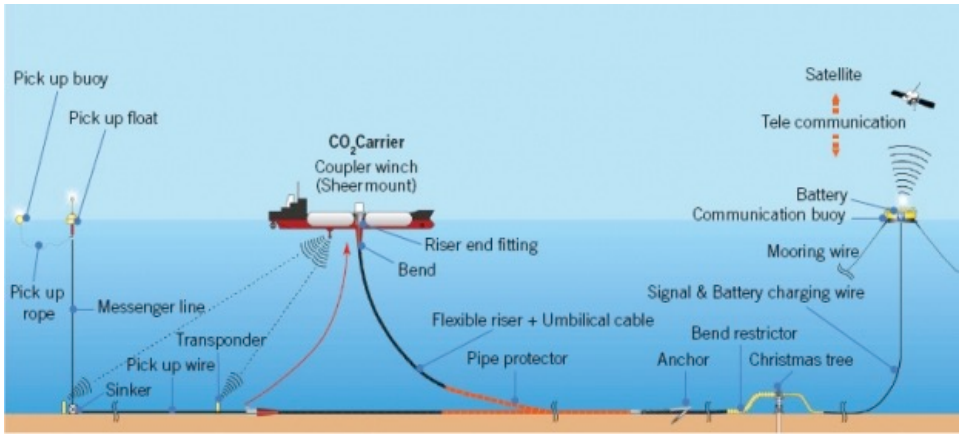
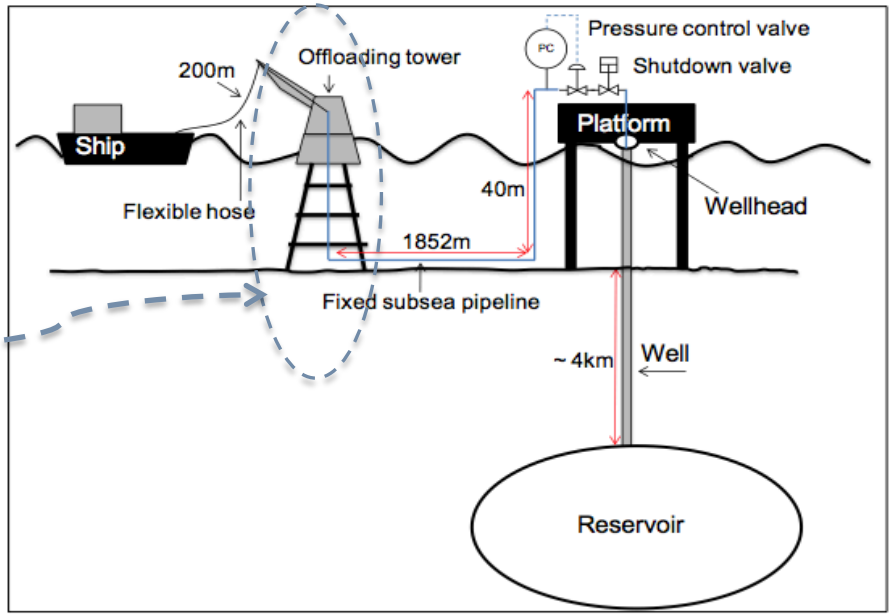
Offshore offloading

Examples of general arrangements

- Submerged offloading system (Omata, 2011)
- Single point mooring and platform (Vermeulen, 2011)
- Many alternative options for single point moorings





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Injection

- Beyond scope – a few comments only
- Injection conditions and constraints will have impacts on upstream process design, should optimise over whole system
- Literature on CO_2 shipping has little coverage of injection constraints, and very little specific to EOR

- Aim to avoid low temperature at reservoir 'entry' to avoid hydrate formation and freezing, hence need to warm CO_2 before injection
- Likely to have two-phase flow in well at times, design for it
- PCV at well head to avoid two-phases upstream
- Likely to have very low temperatures in well/wellhead at times and on emergency shutdown, design process and equipment to avoid/cope

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Regulation and HSE

- No specific regulations for CO_2 shipping
  - Covered by UNCLOS and London Protocol
  - Transport of Dangerous Goods – CO_2 non-toxic, non-flammable
  - Ship design under IGC Codes
- Carbon Footprint
  - Estimates vary widely with system boundaries and assumptions
  - Range 1.4% to 18% relative to CO_2 transported

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Regulation and HSE

- Health – CO_2 asphixiant *and* toxic, UK-WEL 5,000 ppm (8h); 15,000 ppm (15min)
- Risk assessment – DNV report for Vopak/ Veder study concluded risk levels below national (NL) risk criteria (Koers and de Looji, 2011)
- Operational issues – several potential hazard areas, all within existing scope of engineering knowledge

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Costs of CO_2 transport by ship

- Lifetime total cost estimates for North Sea distances range 10-30 €/t-CO_2, including compression and liquefaction
  - Estimates vary quite widely depending on assumptions and boundaries
- Intuitive sensitivities to scale, distance, ship capacity, utility costs
  - But relatively insensitive to distance
  - Also sensitive to cooling water temperature, CO_2 supply pressure, CO_2 purity

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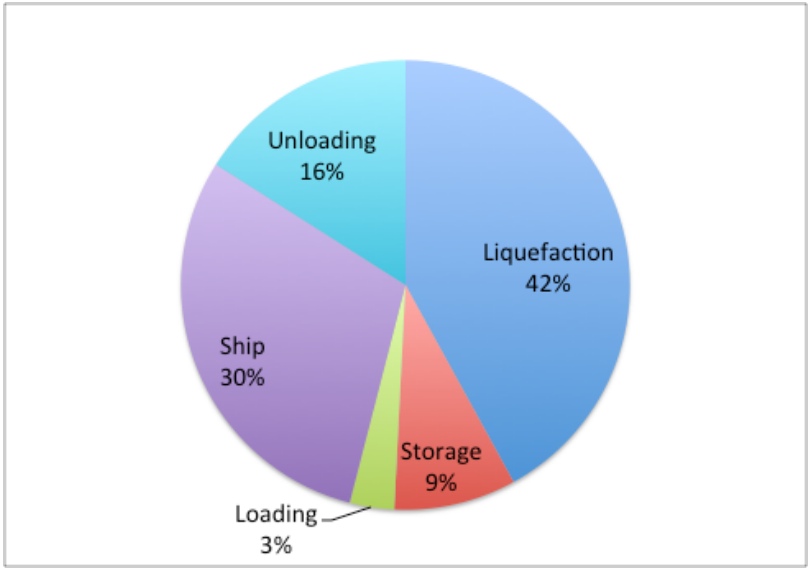
Cost breakdown

- In all estimates costs for liquefaction are highest portion
  - From both high capital costs and high operational costs due to energy consumption



Data from Aspelund, Mølnvik, de Koeijer (2006)

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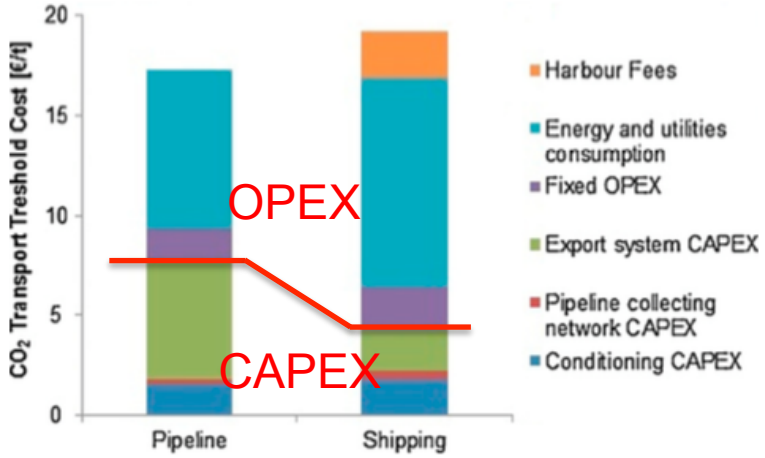
Costs of Shipping *vs.* Pipeline

- Pipeline costs more dependent on CAPEX
- Shipping costs dominated by OPEX
- Shipping less sensitive to distance
- Specific costs of shipping CO_2 higher than pipelines over short distances, lower for long distances



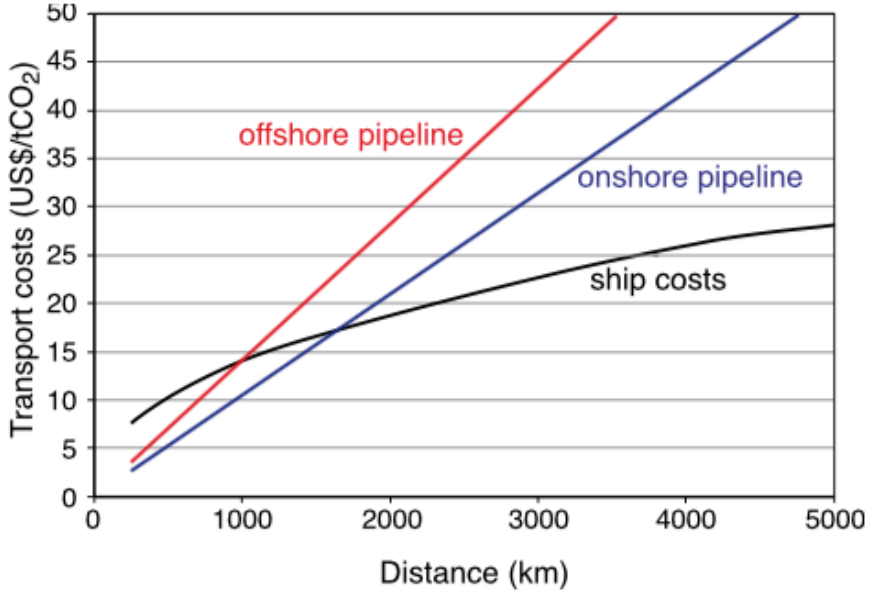
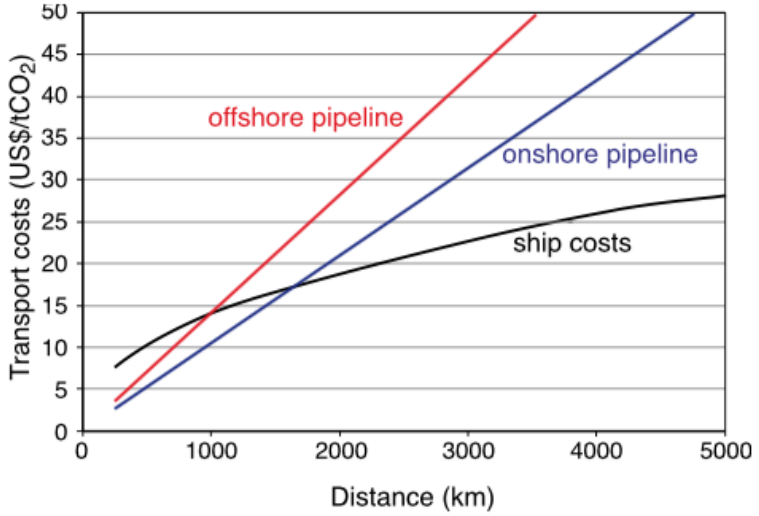


Chart sources: Rousanaly, Bureau-Cauchois, Husebye (2013); Doctor *et al* (2005)

Costs of Shipping *vs.* Pipeline

- 'Breakeven distance' beyond which shipping more cost-effective
- Breakeven distance varies with scale, and other assumptions
- Smaller volumes and longer distances favour shipping



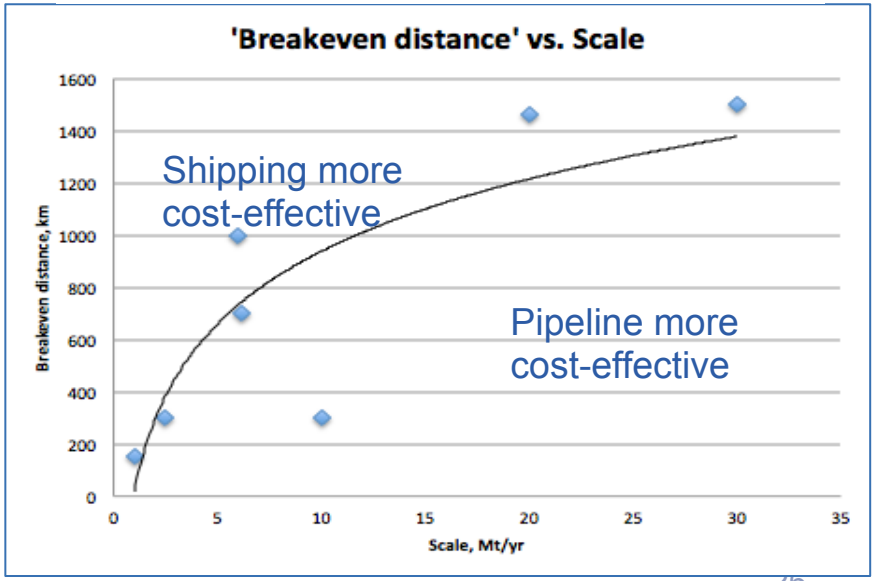


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Chart sources: Doctor *et al* (2005), author (2015)

Asset flexibility, financial risk

- Shipping allows flexibility
  - In collection points, from scattered emitters
  - In delivery points, serving different EOR fields
  - In time, EOR injection profiles and project phasing, changes to industry sources
  - In capacity, sequential addition of ship capacity
  - In asset use, dual purpose, reuse for LPG
- Low entry CAPEX for shipping and flexibility combine to give lower financial risk than pipelines
  - More attractive to investors

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Ship transport of CO_2 - Conclusions

- Ship transport of CO_2 feasible using known technologies
- Existing experience at small scale, but understanding of scale-up requirements generally good
- Published knowledge sparse for offshore offloading, EOR injection profiles and consequences, whole-chain optimisation
- No unusual regulatory or HSE issues
- Shipping cost-competitive for lower scales and greater distances
- Flexibility and low entry capital reduce financial risks

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Thank you!

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