Mobile Source Carbon Capture – Overview and FECM Activities

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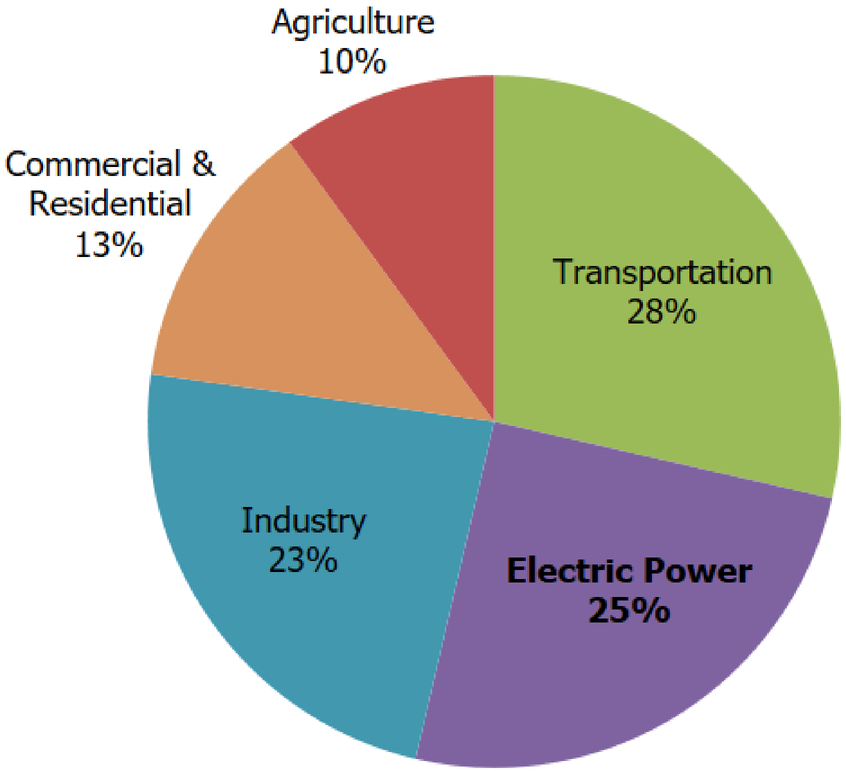
U.S. DEPARTMENT OF ENERGY

Fossil Energy and Carbon Management

Motivation for Mobile Source Carbon Capture (MCC)

- **Transportation sector responsible > 25 % global CO_2 emissions**
  - Heavy-duty overland and long-range marine transportation ***hard to decarbonize***
- Ambitious **decarbonization targets**
  - International Maritime Organization (IMO) goal to reduce emissions marine sector (3% global emissions) by 70% 2040 and net-zero by 2050.[1]



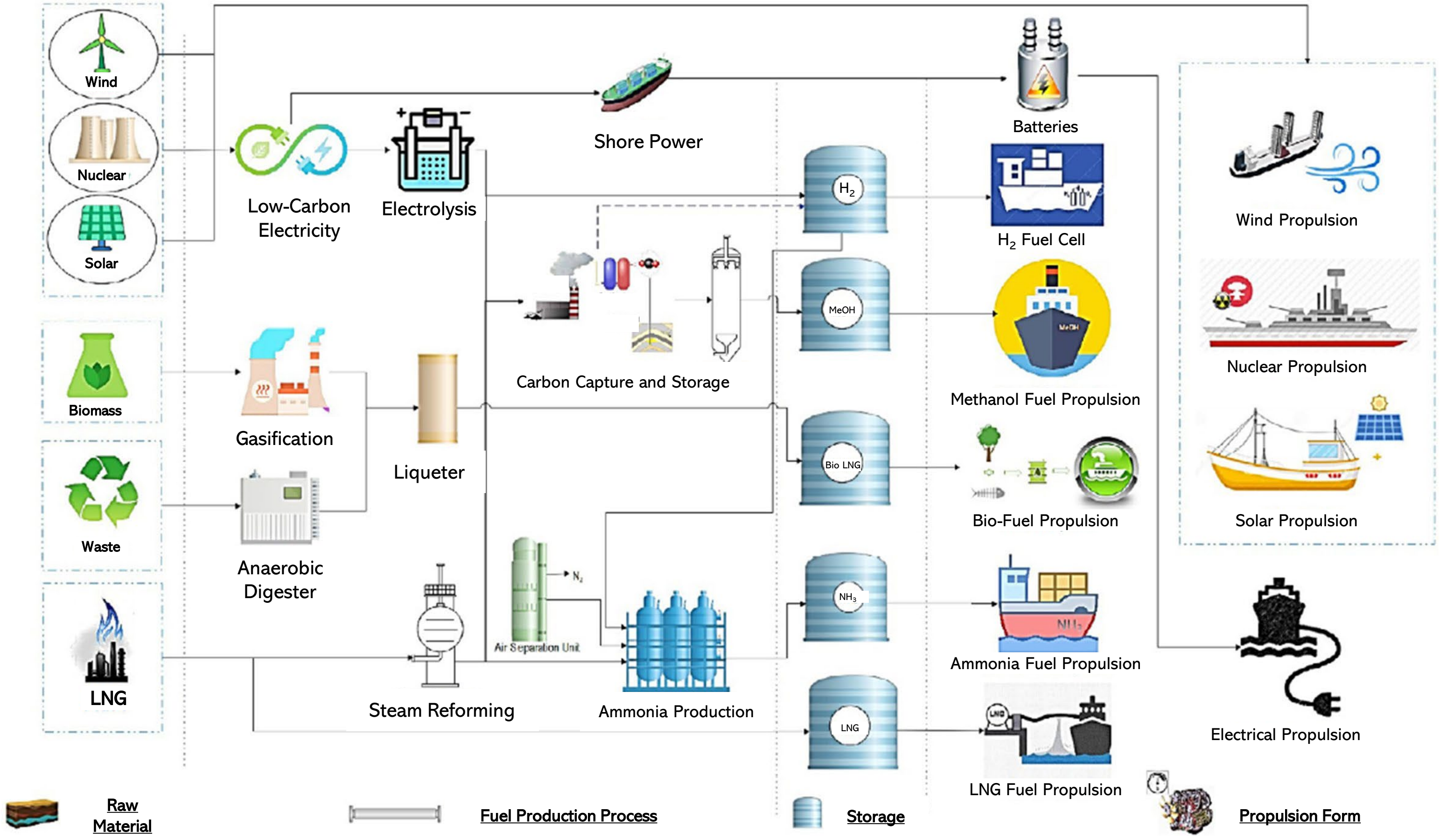
U.S. Environmental Protection Agency (2023)

(1) IMO Strategy on Reduction of GHG Emissions from Ships. International Maritime Organization (2023)

Motivation for Mobile Source Carbon Capture (MCC)

- **Multiple alternatives to decarbonize transportation**: batteries, ammonia, hydrogen, biofuels and e-fuels

- **Different challenges**: low TRL, infrastructure changes, cost-competitiveness

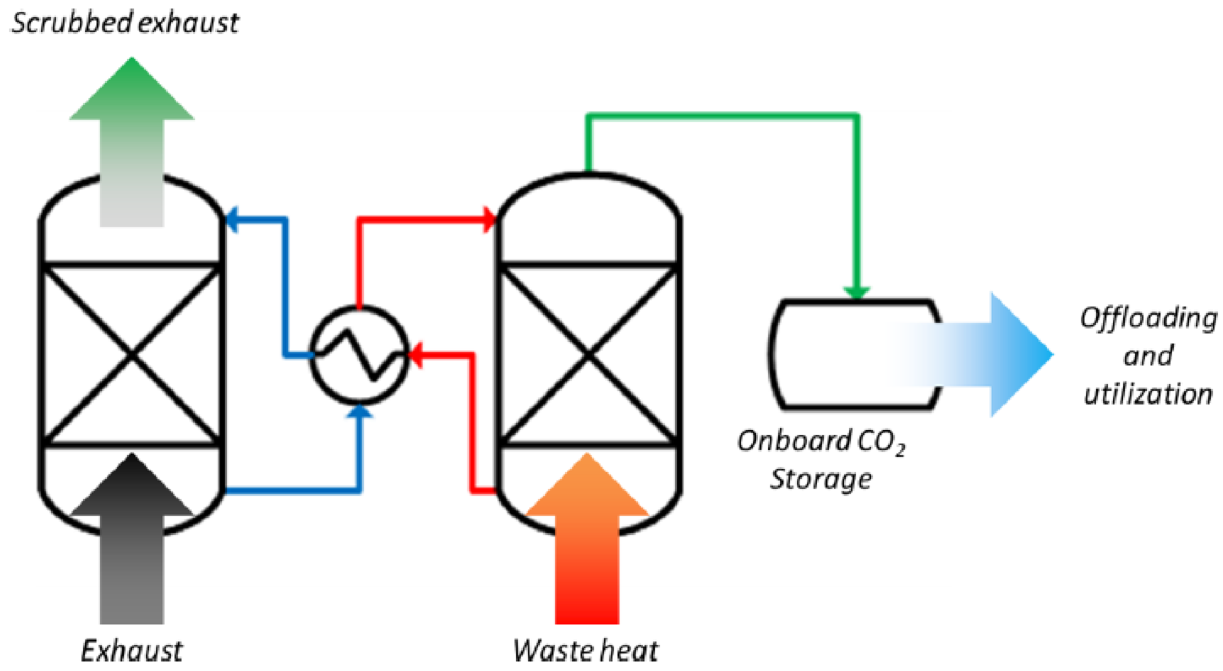


Al-Enazi et al. *A review of cleaner alternative fuels for maritime transportation*. Energy Reports (2021)

Motivation for Mobile Source Carbon Capture (MCC)

- **Mobile Carbon Capture (MCC)**: capturing CO_2 from exhaust gas onboard ships/trucks that use conventional carbon-containing fuels. Captured CO_2 stored onboard, offloaded and permanently stored.

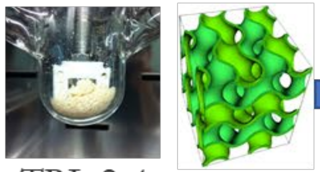
- MCC can become technologically mature sooner than alternative fuels – option to **reduce emissions from transportation sector in the near-term.**



Voice et al. *Evaluating the thermodynamic potential for carbon capture from internal combustion engines*. Transportation Engineering (2022)

Point Source Carbon Capture Technology Portfolio

Lab & Bench



TRL 2-4

Small Pilots

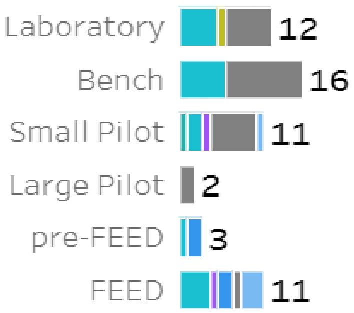
TRL 4-5

Large Pilots

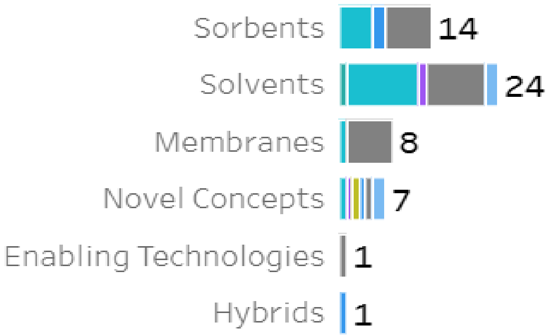
TRL 5-7

FEED Studies

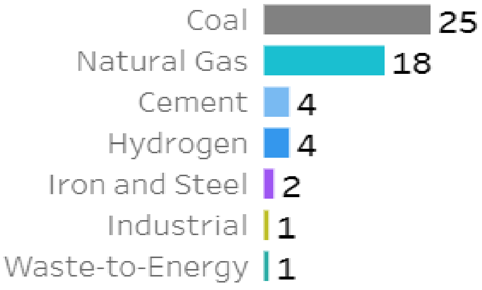
Ending Scale



Key Technology



Application Type



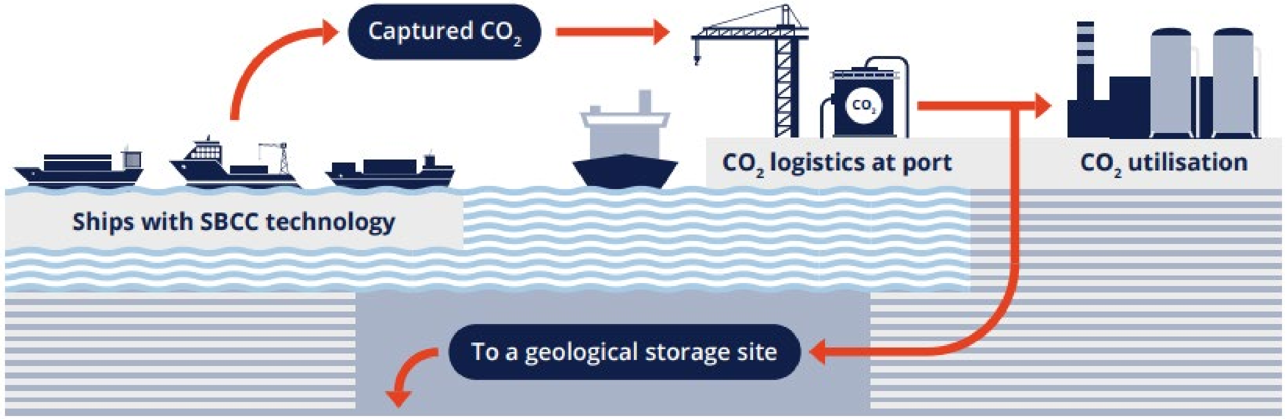
Challenges of Mobile Carbon Capture

- **Designing carbon capture solutions for mobile systems presents specific design constraints relative to stationary systems**
  1. Capture material selection
  2. Heat integration
  3. Vehicle motions
  4. Variable loads
  5. Space and weight constraints

What point source capture technologies can best meet these requirements?

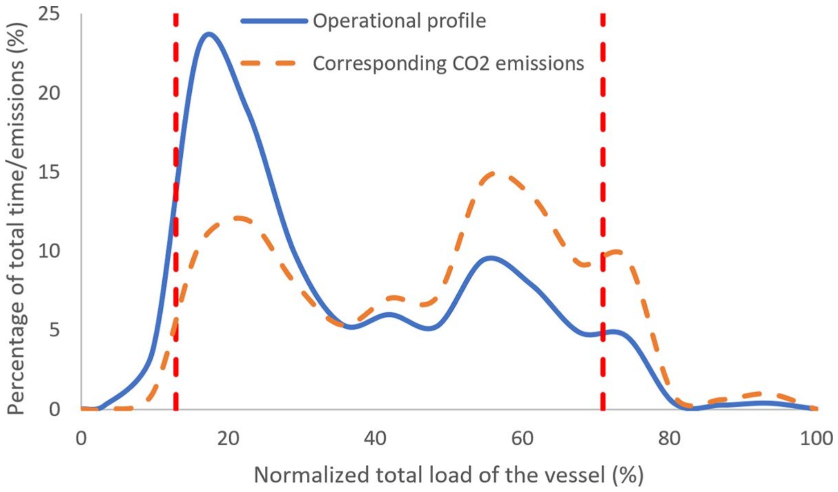
State-of-the-art MCC: EverLoNG

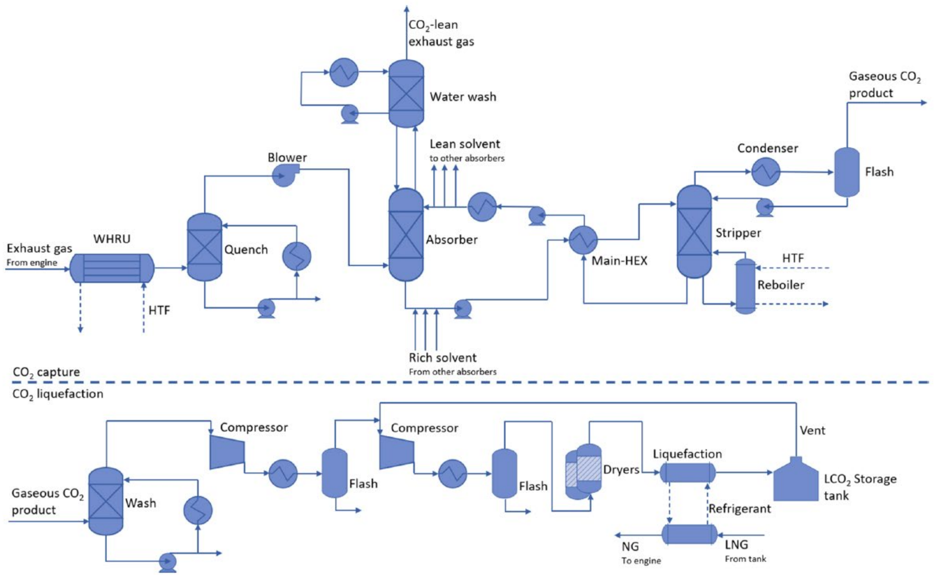
- Aim to demonstrate **ship-based carbon capture on LNG ships**
- **2500 h test campaign onboard a TotalEnergies LNG tanker completed**, next demonstration on Sleipner Ship
  - Achieved **80% CO_2 capture rates, stable operation**
  - **Solvent degradation** due to NO_2 concern



EverLoNG: Case Study on Sleipner Ship

- 12 LNG-fuelled engines. Exhaust gas temperature 400 °C and exhaust 4.5 vol% CO_2
- Solvent: 30 wt. % MEA
- Capture unit runs 87% time
- Liquefaction capacity of the LNG limits the CO_2 capture rate





Ros et al. *Advancements in ship-based carbon capture technology on board of LNG-fuelled ships*. International Journal Greenhouse Gas Control (2022)

EverLoNG: Case Study on Sleipner Ship

- Costs dominated by Capital Expenses
- Capture Rate could be increased further by matching operating profiles more closely
- Findings from this study will be demonstrated onboard Sleipner Ship

	20 bar Case	7.2 bar Case
Capture Rate (%)	72	55
Cost (€/ton)*	119	133

*Costs in 2019 €

Ros et al. *Advancements in ship-based carbon capture technology on board of LNG-fuelled ships*. International Journal Greenhouse Gas Control (2022)

Open Questions and R&D Needs

1. In what scenarios does mobile carbon capture make sense? Detailed studies feasibility, TEA and LCA to understand when MCC can be cost and environmentally efficient decarbonization strategy

2. What are optimum technologies for MCC? Comprehensive analysis considering multiple criteria (space, weight, CO_2 capture rate, cost…) needed

3. Innovation in mobile carbon capture approaches needed:

- ***Capture materials***: membranes and sorbents could have advantages relative to solvents
    - Compact technology, reduced space and weight requirements
    - Lower energy requirement for regeneration
    - Lower or no emissions
- ***Reactor design***: Highly compact capture technology desirable e.g. Rotating packed beds and high-density packing materials
- ***CO_2 storage and offtake options:*** CO_2 regenerated on-board, off-board, converted?

FECM Mobile Carbon Capture Portfolio

Performer	Application	Capture Media	CO_2 Offtake	Regeneration Onboard/Offboard
ZENITH PURIFICATION	Marine	Membrane	Pure CO_2	Onboard
Susteon	Marine	Solvent in Rotating Packed Bed	Pure CO_2	Onboard
LUNALABS	Marine	Membrane	Pure CO_2	Onboard
PSI Physical Sciences Inc.	Marine	MOF Solid Sorbent	CO_2 conversion to methanol	Onboard
Carbon Ridge	Marine	Solvent	Pure CO_2	Onboard
TDA RESEARCH	Marine	Solid Sorbent	Pure CO_2	Off-board
MoleculeWorks Efficiency for a Sustainable World	Marine	Solid Sorbent	Pure CO_2 /electrochemical conversion	Onboard
ACT ADVANCED COOLING TECHNOLOGIES The Thermal Management Experts | www.1-ACT.com	Marine	Solid Sorbent	CO_2 conversion to bicarbonate	NA
OptimaBiome FACILITATING MOBILE CARBON CAPTURE	Marine + Heavy Duty Trucks	Hybrid (Solid Sorbent + Liquid Matrix)	Pure CO_2	Off-board

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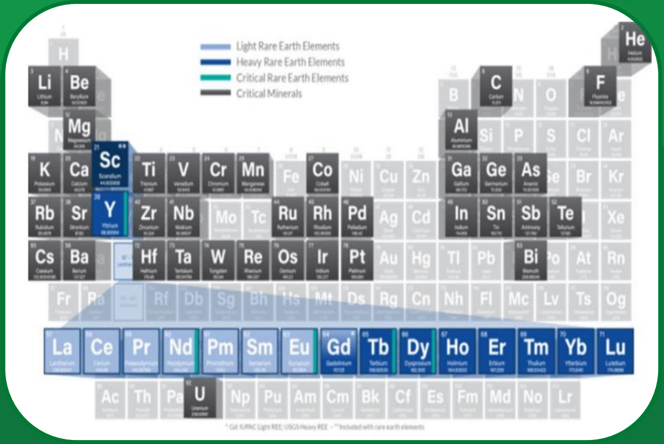
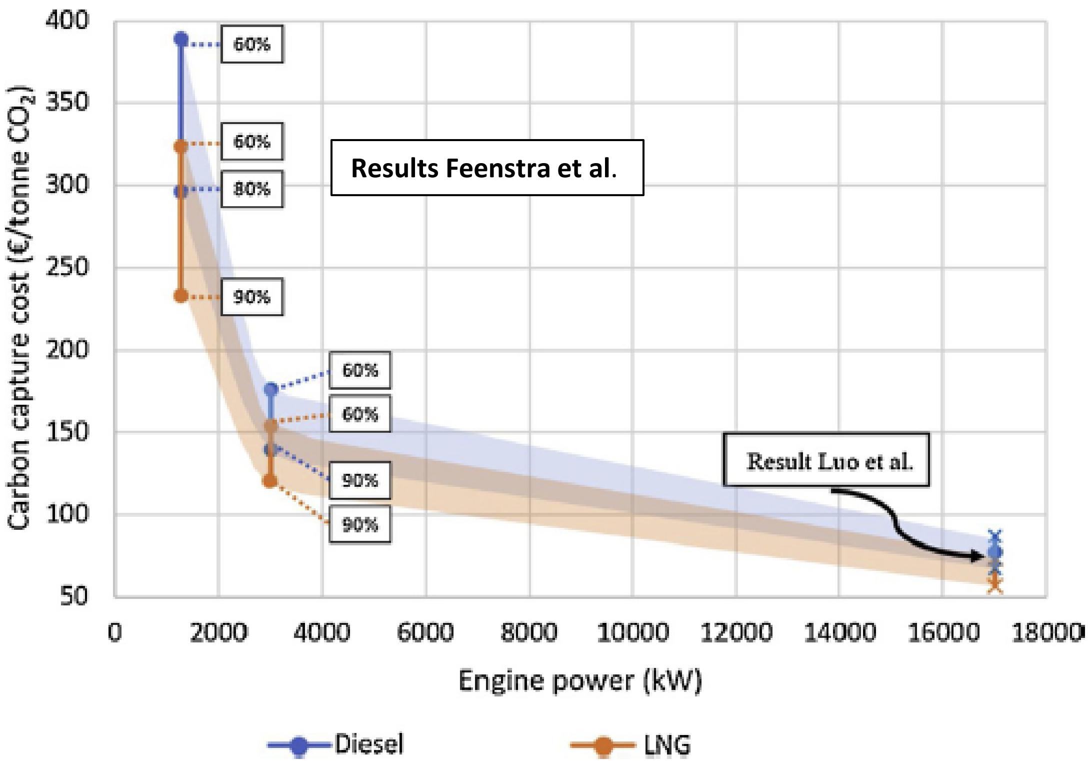
Questions?



Findings from other SBCC Studies

- Cost of CO_2 capture varies between **98 to 389 €/tonne**
- **Costs and capture rates achievable vary** depending on ship (engine) size, fuel used, and capture technology (choice of solvent)
- **Increasing capture rate decreases the specific cost of CO_2 capture**
  - Design capture rate should be as high as feasible given the heat available in the exhaust gas

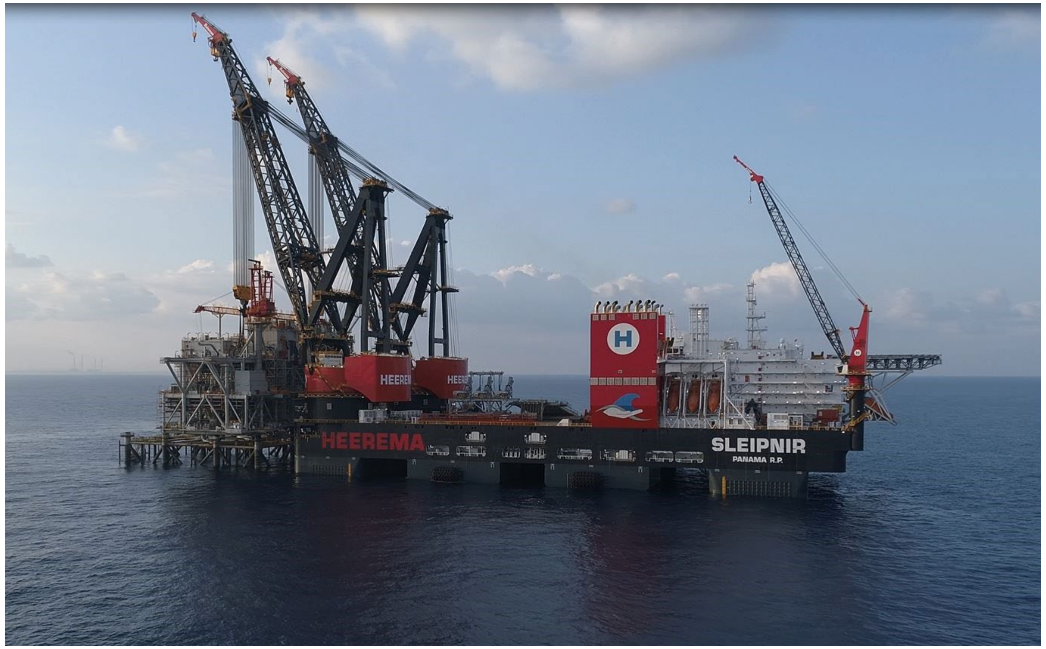


Adapted from Feenstra et al. (1) and Luo and Wang (2)

Journal Greenhouse Gas Control (2019)
(2) Luo and Wang. *Study of solvent-based carbon capture for cargo ships through process modelling and simulation*. Applied Energy (2017)

Ship-based Mobile Carbon Capture (SBCC)

- Most MCCC work targets **maritime industry** (3% global emissions)
- Ships currently **rely on fossil energy**: heavy fuel oils, marine diesel oil, LNG
- Optimizing SBCC involves consideration of general arrangement, power, energy and heat balance, fuel consumption, engine type, and machinery configuration



Conoship (2019)

Considerations SBCC: Solvent selection

- Mostly **liquid solvents** have been studied due to higher TRL. 30 wt. % MEA standard

- **Amine emissions** may pose a greater concern in marine environments. Some solvents (e.g. Piperazine (PZ) **issues of biodegradability and ecotoxicity**

KPI	MEA	PZ	NH_3
TRL	9 (Rochelle, 2009)	7 (Chen et al., 2019)	8 (Augustsson et al., 2017)
Ease of operation	Easy	Okay	Hard (Augustsson et al., 2017)
Absorption rate (relative to MEA)	1	2 (Rochelle et al., 2011)	0.05-0.33 (Jayaweera et al., 2016)
Heat demand (MJ/kg CO_2)	3.5 (Moser et al., 2020)	2.6 (Rochelle et al., 2011)	2.2-2.6 (Augustsson et al., 2017), (Li et al., 2015)
Maximum desorption temperature (°C)	110-120 (Davis and Rochelle, 2009)	150 (Rochelle et al., 2011)	At least 150[1]
Maximum desorption pressure (bar)	2 (Li et al., 2016)	13 (Lin and Rochelle, 2014)	20 (Li et al., 2015)
Lean solvent volatility (relative to MEA)	1	0.25 (Rochelle et al., 2011)	250 (Yang et al., 2014)
Oxidative degradation (relative to MEA)	1	<1[2]	0 (Augustsson et al., 2017)
Biodegradability	Acceptable[3] (Eide-Haugmo et al., 2012)	Not acceptable (Eide-Haugmo et al., 2012)	Acceptable[3]
Ecotoxicity	Acceptable[3] (Eide-Haugmo et al., 2012)	Acceptable[3] (Eide-Haugmo et al., 2012)	Not acceptable[3]
Toxicity in humans	Acceptable[3]	Not acceptable[3]	Acceptable[3]

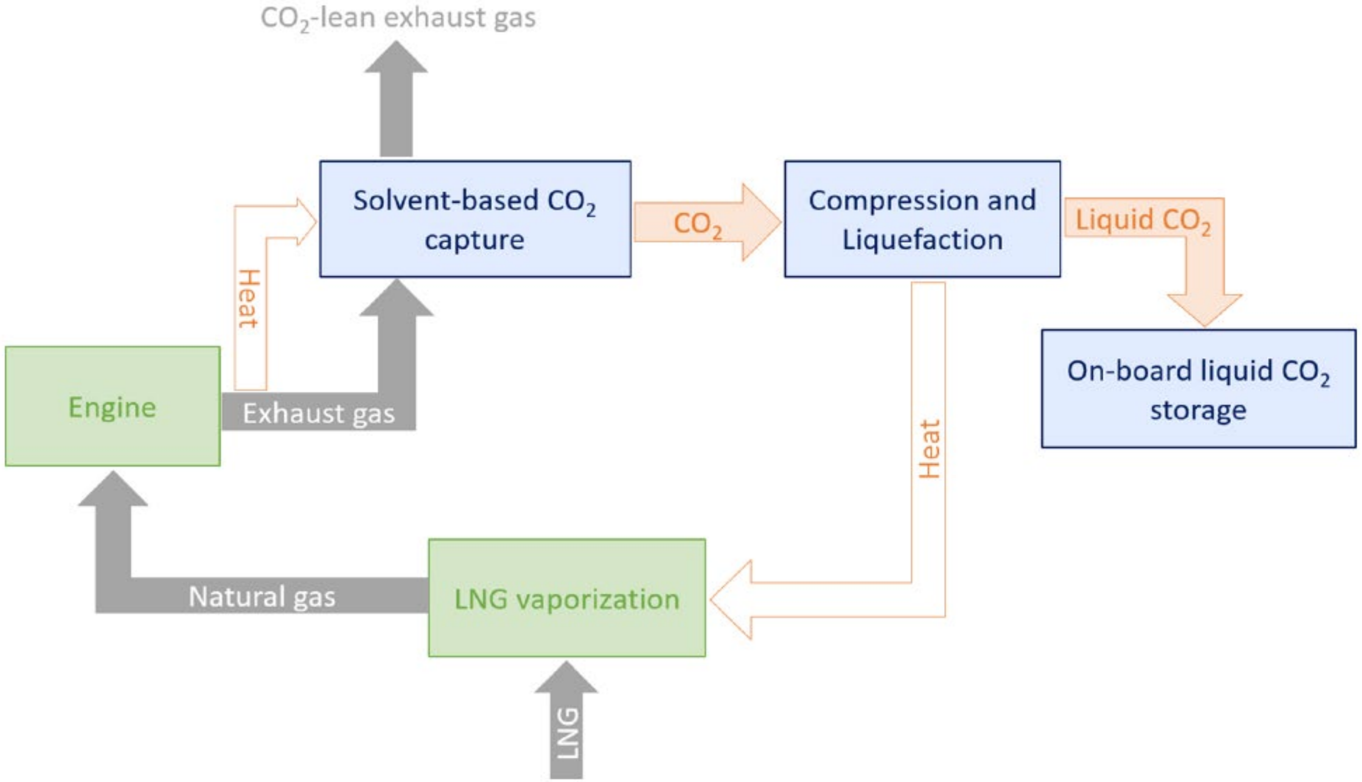
Ros et al. *Advancements in ship-based carbon capture technology on board of LNG-fuelled ships*. International Journal Greenhouse Gas Control (2022)

Considerations SBCC: Heat integration

- **2 possible sources of heat integration:**

  1. Hot exhaust gas and CO_2 capture (reboiler)
  2. CO_2 liquefaction and LNG vaporization

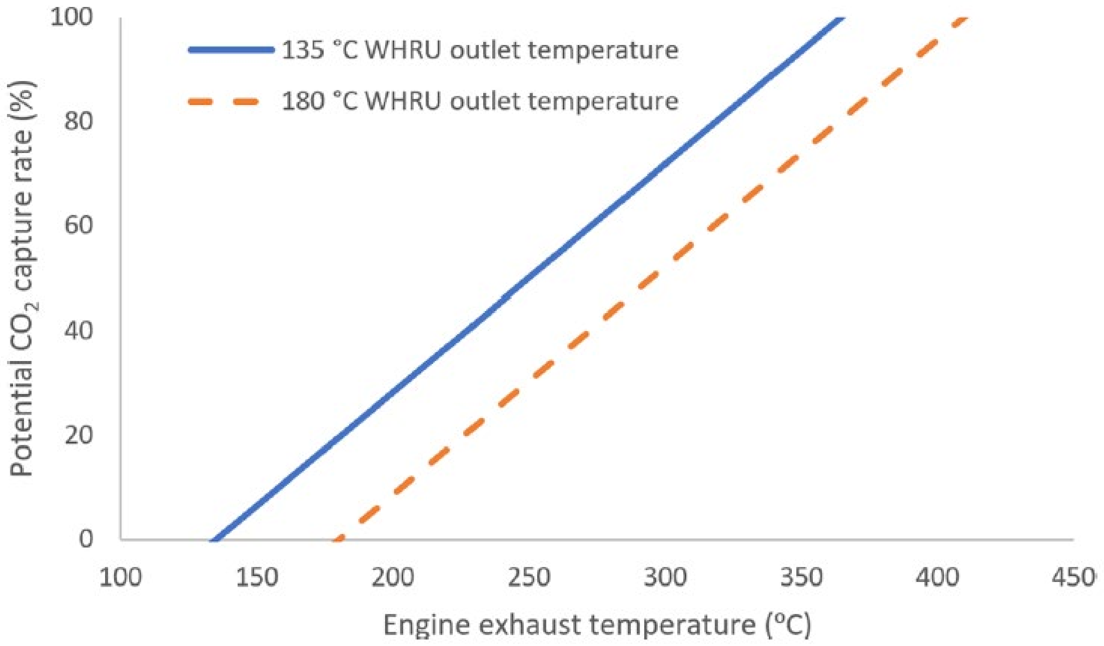
- **Heat integration will limit maximum capture rate onboard**



Ros et al. *Advancements in ship-based carbon capture technology on board of LNG-fuelled ships*. International Journal Greenhouse Gas Control (2022)

Considerations SBCC: Heat integration (exhaust gas and reboiler)

- Heat available for reboiler **varies based on specific engine type** (2 vs. 4 stroke, fuel type, engine rating)
- Exhaust temperature varies by engine and limits achievable capture rates
  - *4 stroke engine (exhaust T 350- 450 °C):* 90% Capture Rate
  - *2 stroke engine (exhaust T 220-250 °C)* : 45 % Capture Rate

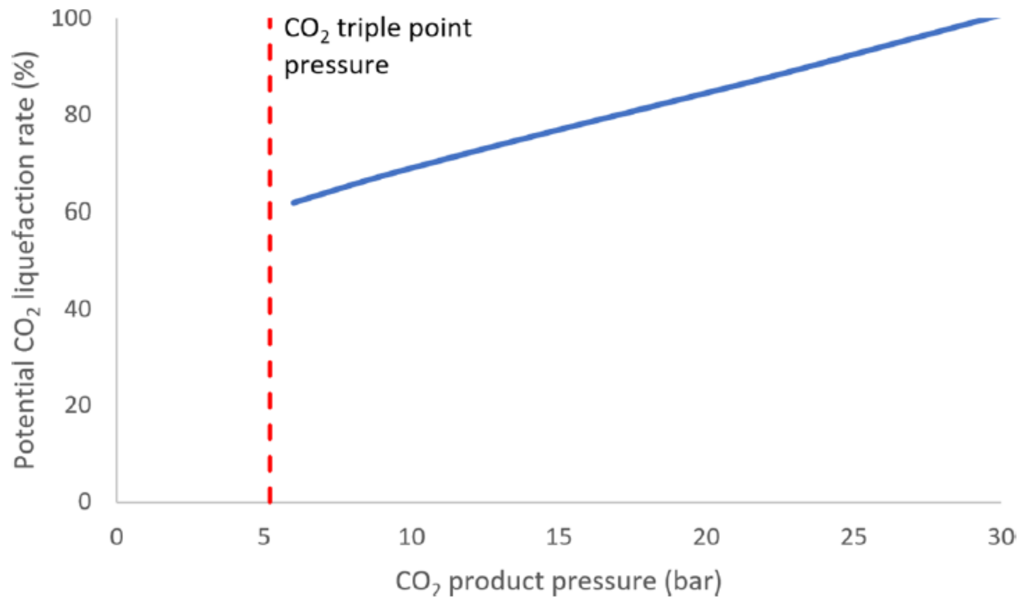


Ros et al. *Advancements in ship-based carbon capture technology on board of LNG-fuelled ships*. International Journal Greenhouse Gas Control (2022)

General considerations SBCC: heat integration dictates capture rate

Heat integration ***LNG vaporization and CO_2 liquefaction***:

- Amount of heat needed to liquefy CO_2 is a function of the product pressure
- Extra refrigeration equipment could be installed to increase capture rate (but would increase CAPEX)



Source: Ros et al. International Journal Greenhouse Gas Control. 2022.

Additional considerations SBCC

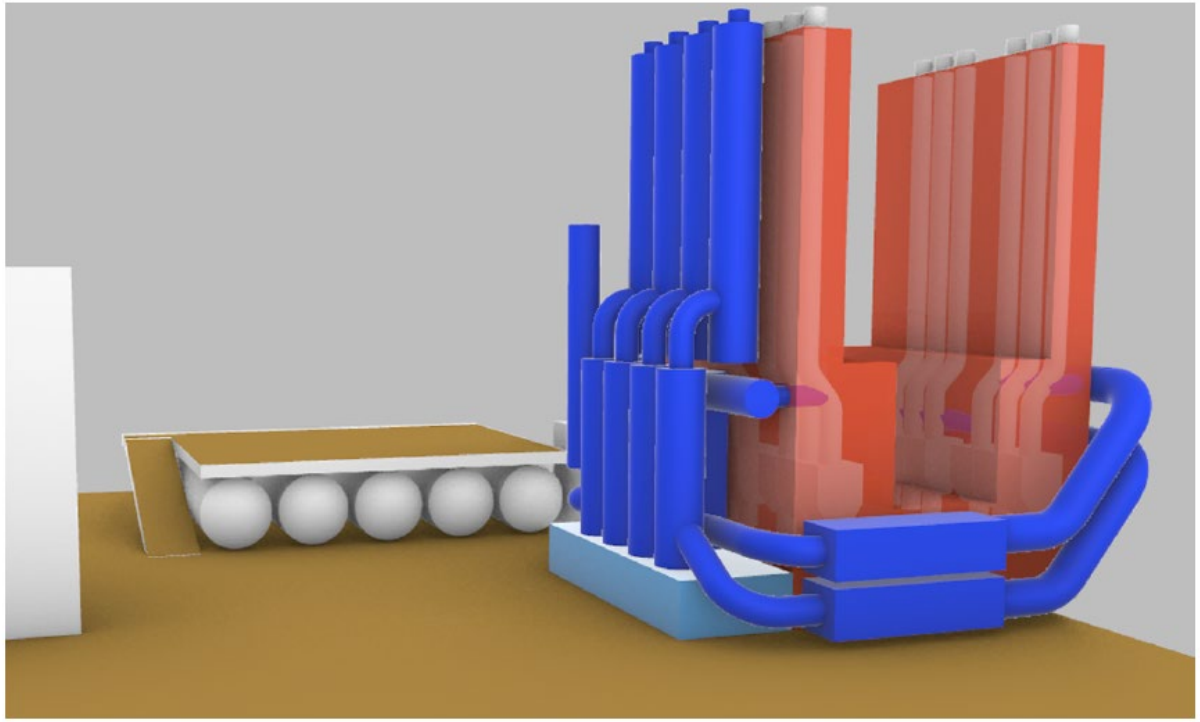
- **Variable engine loads**: highly dynamic exhaust gas
- **Ship motions**: CO_2 capture unit will be impacted
- **Space constraints:** more critical in retrofit cases, limited area available in the ship's machinery room and deckhouse
- **Impurities in the exhaust gas (SO_x and NO_x):** Challenge for solvent degradation
    - In LNG fuel TotalEnergies Ship, NO_2 level = 70 ppm

Other work on Mobile Carbon Capture

- MCC explored for **other transportation sectors** (e.g. heavy-duty trucks)
- Differences between Mobile Carbon Capture on-road applications vs. ships:
  - Relatively clean exhaust gas, free of particulates, NO_2 and SO_2
  - Higher concentration CO_2 (9 vol% for trucks)
  - Exhaust gas temperature differences
- Most studies have focused on **solvent-based systems** but some work on **solid sorbents**
- Conceptual study with amine solvents found capture rates of 40% achievable using waste heat from heavy duty trucks (1)

Specific design for SBCC on Sleipner Ship

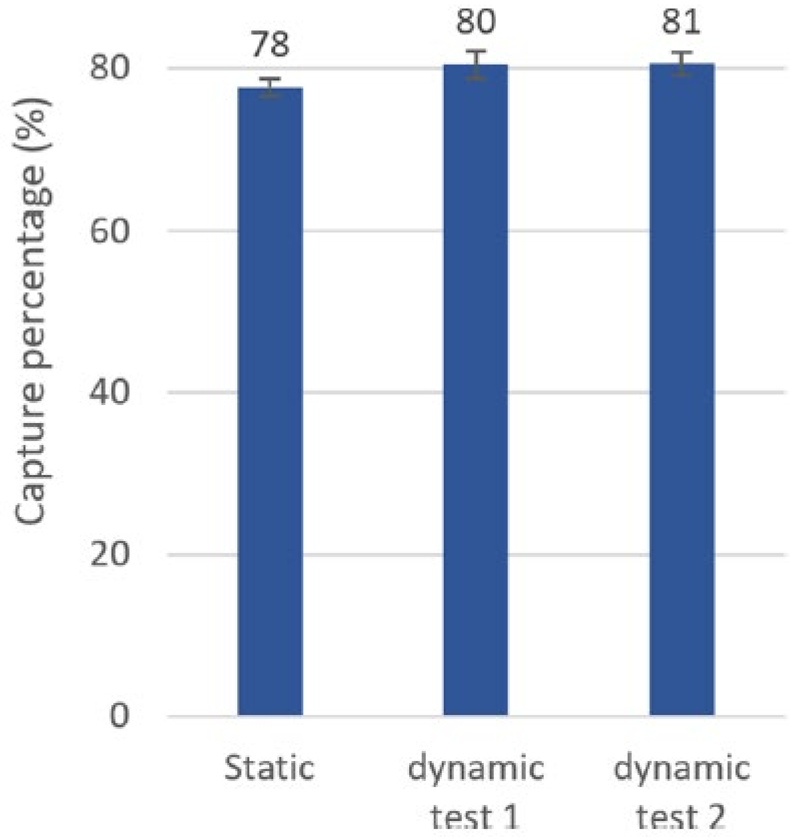
- Storage options considered:
  1. Repurposing of existing LNG tanks → discarded because only rated for 6 bar
  2. Installing CO_2 tanks below deck → would require conversion work
  3. Installing CO_2 tanks on the main deck



Conceptual Design from Ros et al. International Journal Greenhouse Gas Control. 2022.

General considerations SBCC: ship motions

- ***Effect of ship motions*** on the CO_2 capture unit was explored
- Ros et al. found CR remains relatively constant (even small increase due to redistribution of solvent on packing walls)



Source: Ros et al. International Journal Greenhouse Gas Control. 2022.

EverLoNG Project

- **ACT funded project started in 2022**
- **Predecessor was DerisCO2 project (led by TNO in Netherlands)**
- **Project Goals**
  1. Develop strategies for reducing shipping's CO_2 emissions by at least 70%
  2. Demonstrate effectiveness SBCC on LNG-fuelled ships, comparing LCA results against operation without technology
  3. Evaluate impact of SBCC on ship infrastructure, stability and safety to guarantee technical feasibility SBCC technology
  4. Demonstrate emission reduction potential of SBCC according to energy efficiency and design guidelines
  5. Identify any major safety hazards associated with SBCC and highlight safeguards
  6. Cost SBCC with CO_2 capture and onboard storage below €100/t by 2025 and €50/t for follow-on developments
  7. Evaluate cost of offloading, transport, utilisation and/or storage in different CCUS chains
  8. Develop offloading strategies that guide onboard post-treatment of CO_2 and port infrastructure requirements.
  9. Establish a CO_2 Shipping Interoperability Industry Group (CSIIG) and develop a scale for evaluating port CCUS TRL
  10. Propose a Roadmap for a European offloading network

- More information: [Home | EverLoNG (everlongccus.eu)](everlongccus.eu)

EverLoNG Project Team

EverLoNG Project

- Organized in work packages to accomplish different project goals

WP1

Demonstrating ship-based carbon capture

Ship-based carbon capture (SBCC) will be demonstrated on board two types of LNG-fuelled ships provided by TotalEnergies and Heerema and using TNO's capture plant prototype. The onboard capture plant prototype is a key innovation.

WP2

Ship-based carbon capture in the full CCUS chain

We are taking a holistic view of SBCC as part of international CCUS networks. Our CO_2 Shipping Interoperability Industry Group will connect European ports with developing CCUS projects.

WP3

Impact of SBCC on shipping infrastructure

We are studying the flexibility of SBCC for large-scale use in different scenarios – for retrofitting or new build vessels – and on board any LNG-fuelled ships from bulk carriers and ferries to cruise ships.

WP4

Environmental impact, LCA & techno-economic aspects

Our Life Cycle Assessment (LCA) considers the full chain of SBCC, including the fate of captured CO_2 once offloaded – either transported to long-term geological storage or used in the manufacture of everyday products.

WP5

Regulatory frameworks

We will bring together technology developers and three major classification societies – Bureau Veritas Norway AS, Lloyds Register and DNV – to ensure SBCC technology complies with safety regulations supporting its uptake at large-scale.

WP6

Dissemination & knowledge sharing

Sharing our results is key to the uptake of SBCC R&D by stakeholders – including the international shipping community, workforces, policymakers and governments – and its acceptance by the wider public.

EverLoNG Project: Current Status

- ***3000 h test campaign*** started in July 2023 chartered by ***TotalEnergies***.
  - Campaign will run for 3,000 hours and capture up to 250 kg CO_2 per day

- After trial on TotalEnergies' LNG carrier, the SBCC unit will be removed and installed on a second vessel, the ***SSCV Sleipnir from Heerema Marine Contractors***, where a second campaign of around 500 hours will take place.

Details of EverLoNG testing

The Seapeak Arwa

Seapeak Arwa LNG tanker, chartered by TotalEnergies

Additional information:

- Main engines:
  - 3 x Wartsila 12V50DF (4-stroke)
  - 1 x Wartsila 6L50DF (4-stroke)
- Power 39.9 MW
- Year of build: 2008
- Length: 286 m
- Beam: 43.4 m
- Draught: 12.1 m
- LNG: 163.285 m^3

Carbon capture system was connected to AE2, LNG fuelled engine, running on boil-off gas

CO_2ASTS Project Technology

	Reference sea-river vessel	Reference dredger	Reference cruise ship
Specifications	LNG power, vessel design Conoship International Single Engine	Ecodelta ship designed by Conoship international 4 dual fuel engines (LNG + diesel)	LNG power, MEYER WERFT international 4 x 9 MW engines
Power (kW)	1050	7600	36,000
Capture Rate (%)	75	54	69
CO_2 storage capacity	38 m^3 (40.5 t of CO_2)	6 days (187 t CO_2)	7 days of sailing (585 t CO_2)
Cost (€/t)	301	115	154
Notes		Retrofit, CO_2 capture rate is limited by the cold available from LNG	

Notes: Capture cost includes the lost income associated with deadweight of the CC unit
The capture rate for these cases is mostly dependent on heat integration with LNG

Source: CO_2ASTS. 2020.

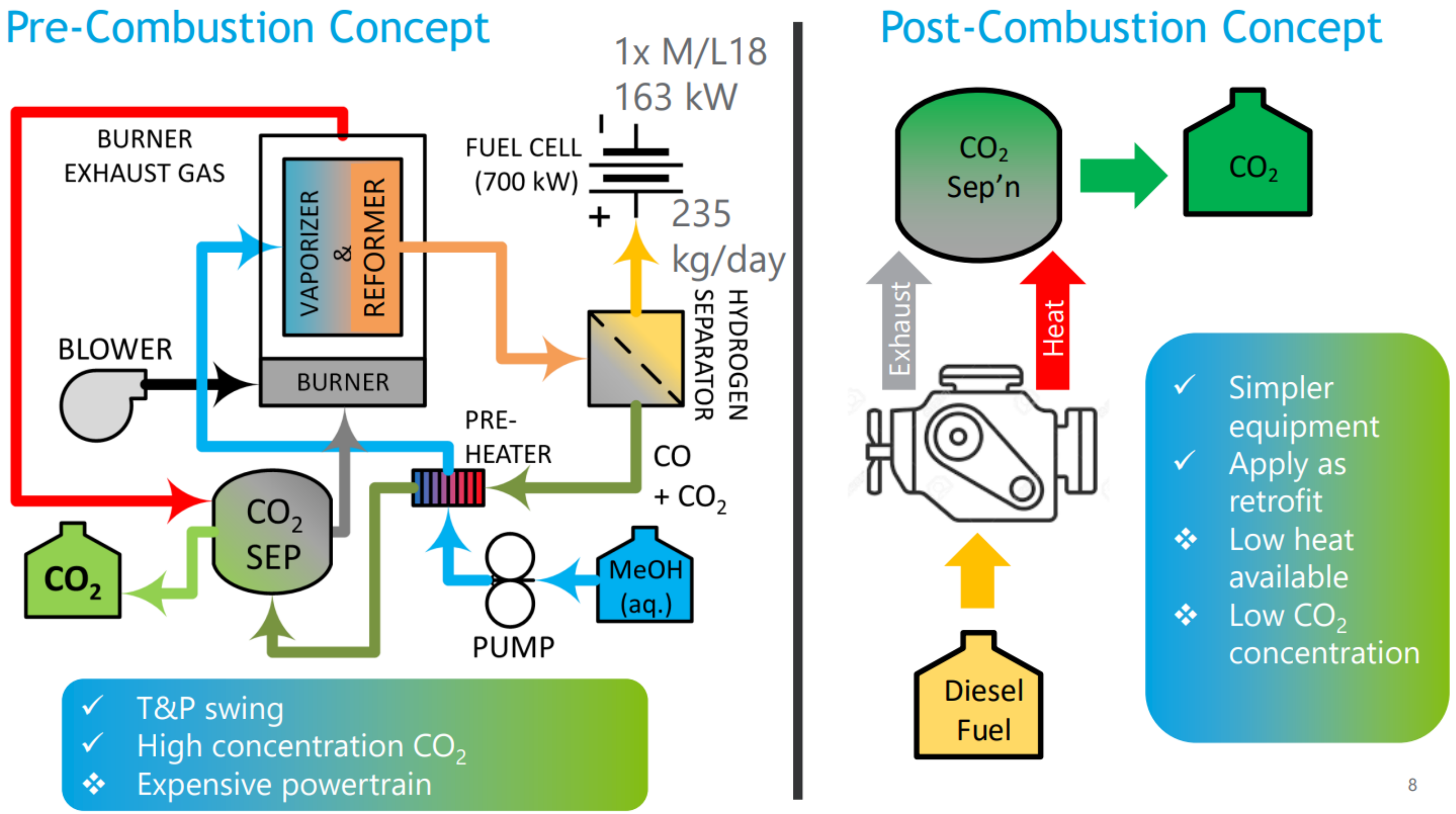
Other Literature on Ship Based Carbon Capture (SBCC)

- Einbu et al (2022). Energy assessments of onboard CO2 capture from ship engines by MEA-based post combustion capture system with flue gas heat integration – ScienceDirect
- Long et al. (2021). Improvement of marine carbon capture onboard diesel fueled ships – ScienceDirect
- Feenstra (2019). Ship-based carbon capture onboard of diesel or LNG-fuelled ships – ScienceDirect
- Luo (2017). Study of solvent-based carbon capture for cargo ships through process modelling and simulation – ScienceDirect

* Papers included on MCC Folder on Shared Drive

Other SBCC Projects: Aramco

- Exploring CO_2 capture from ships using waste heat
- Pre and post-combustion options
  - Max capture rate pre: 90%
  - Max capture post: 58%
- TEA analysis: higher cost pre than post-combustion capture



Work unpublished, presented at PCCC-7 Conference2023 by Alexander Voice

Table 4

Summary of nominal exhaust conditions and capture rates for various applications.

Application	Nominal Exhaust Temperature (°C)	Nominal CO_2 Concentration (mol.%)	Nominal exhaust gas flow rate (kg/min)	Max. Cap Rate – heat (%)	Max Cap. Rate - Heat & Work (%)
Car	450	12	1	49	28
Truck	310	9	15	38	22
Generator	465	7	120	78	47
Ship	220	4.5	700	24	15

Voice. Evaluating the thermodynamic potential for carbon capture from internal combustion engines. Transportation Engineering 10 (2022)

Table 1
Fuel and exhaust sulfur content.

Application	Fuel	Fuel Sulfur (ppm,w)	Air-fuel ratio	Exhaust SO2 (ppm)
Passenger Car	US spec gasoline	<10	~1	<0.29
Class VIII Truck	US spec onroad diesel	<15	~0.6	<0.27
Generator	US spec offroad diesel	<15	~0.6	<0.27
Ship	Global marine fuel	<5000	~0.6	<89
	US coastal fuel	<1000	~0.6	<18