Onboard Carbon Capture

Experience from Clipper Eris

IMO Technical Seminar

11. September 2025

The marine industry’s three pathways for decarbonisation

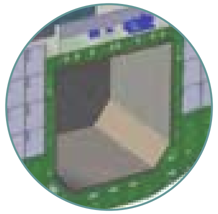
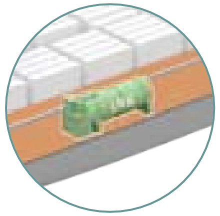
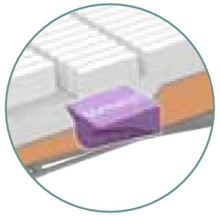
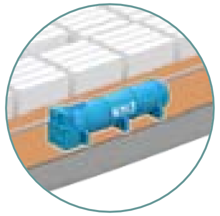
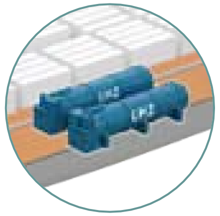
Burn less fuel
More efficient operations and solutions

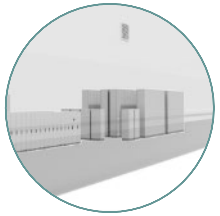
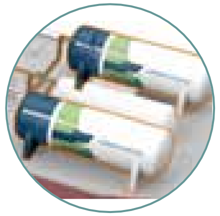
Clean up emissions
Carbon capture, exhaust treatment

Use alternative energy sources
Sustainable fuels, hybridisation and electrification

A 100% reduction in greenhouse gas emissions will require the adoption of sustainable fuels

COST OF EMISSIONS WILL INCREASE THE FUEL- AND EMISSION- RELATED PRICE, AND IMPROVE THE BUSINESS CASE FOR CARBON CAPTURE

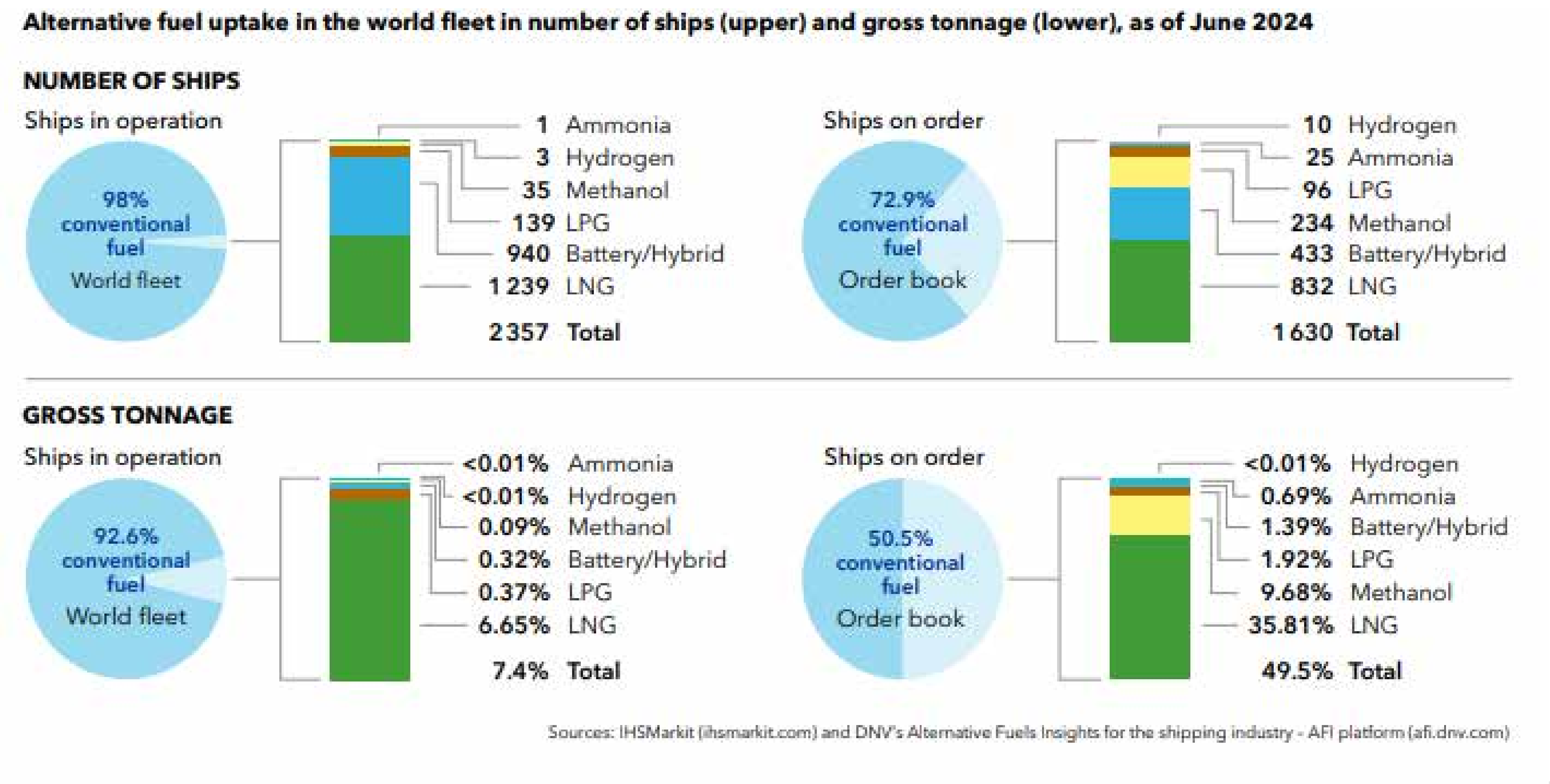



Fuel type	**Low Sulphur Fuel Oil** @ 20°C	**Liquified Natural Gas** @ -162°C	**Methanol** @ 20°C	**Ammonia** @ -33°C	**Liquid Hydrogen** @ -253°C	**Compressed Hydrogen** @ 350bar	**Marine Battery Rack**	**Carbon Capture** @ -26°C
Fuel price factor (per GJ)[1]	1x	1.1x - 4.6x[2]	2.6x - 5.5x[3]	2.4x - 4.3x[4]	3.6x - 4.6x[4]	2.1x - 3.1x[4]	2.0x - 5.3x[8]	1.3x - 1.5x[9]
Gross tank size factor[6]	1x	1.7x - 2.4x[7]	1.7x	3.9x	7.3x	19.5x	~40x (~20x potential)	2x - 3x

1) Fuel production cost estimate for 2025; source: Maersk Mc-Kinney Møller Center for Zero Carbon Shipping - NavigaTE 2023; 2) Price range spans between fossil & electro- methane; 3) Price range spans between bio- & electro- methanol; 4) Price range spans between blue- & electro- ammonia/hydrogen; 5) Assuming 100% consumption subject to EU Fit-for-55, EU allowances at EUR 159/ton (source: Transport & Environment NGO); 6) Gross tank estimations based on Wärtsilä data; 7) 1.7x membrane tanks, 2.4x type C tanks; 8) Shore energy price EUR 0.1-0.27/kWh; 9) HFO consumption, 10% additional energy demand, carbon capture rate at 70% and cost of sequestration EUR 40-60/tonCO2, excluding CapEx

SHIPPING INDUSTRY IS A HARD TO ABATE SECTOR

Existing fleet and OB is almost exclusively operating on fossil fuels, and it is not expected to be easy to convert existing fleet to alternative fuels when they become widely available



CARBON CAPTURE

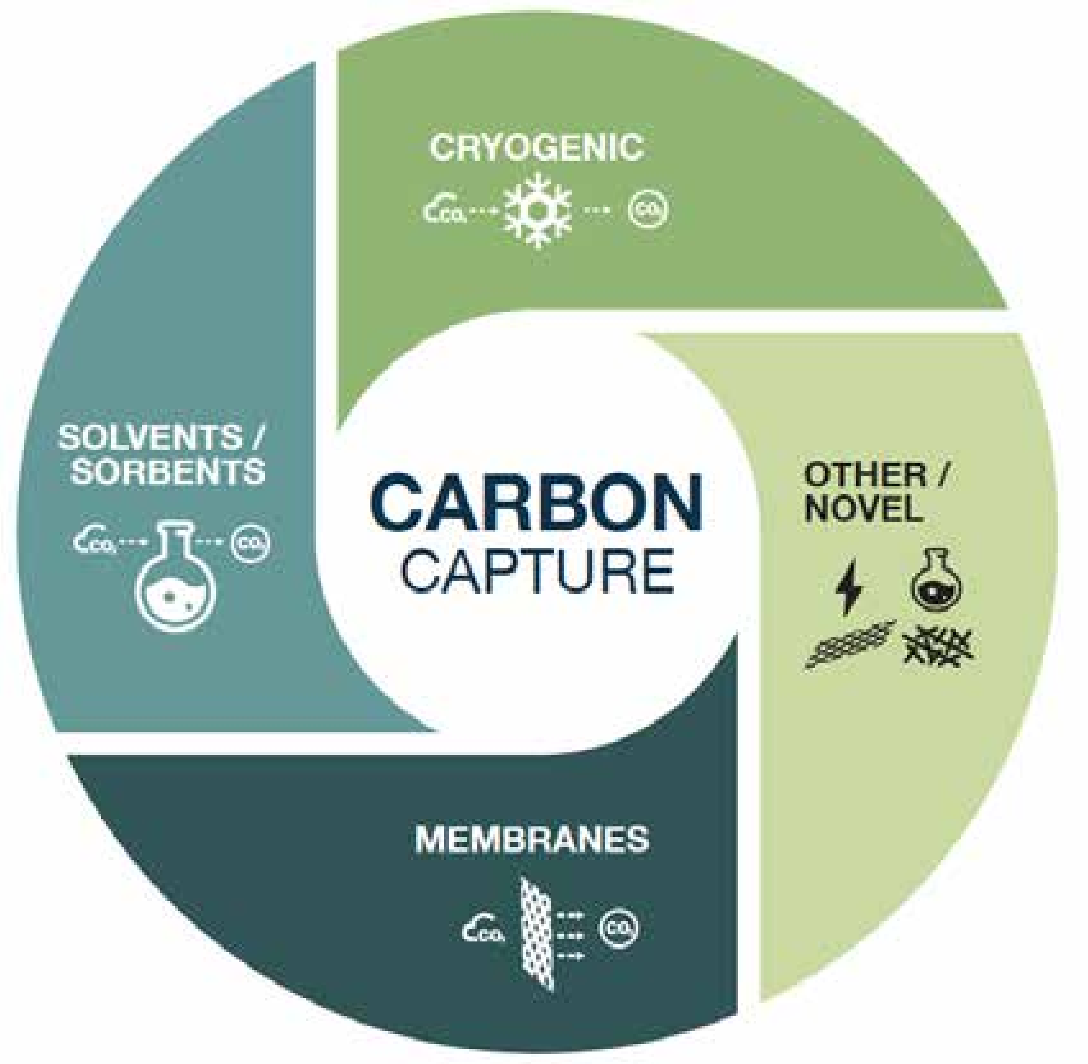
The basic methods

There are three basic methods for post-combustion carbon capture, considered for ships:

- Absorbtion with a solvent or sorbent
- Membrane separation
- Cryogenic separation

Solvent-based absorbtion is the most technically mature solution

CO_2 is absorbed from the flue gas into a liquid carrier, and pressure and/or temperature is used to release the CO_2 from the solvent



WÄRTSILÄ CCS INVESTMENT

Wärtsilä has launched a multi-million investment program for developing CCS technology for the maritime industry.

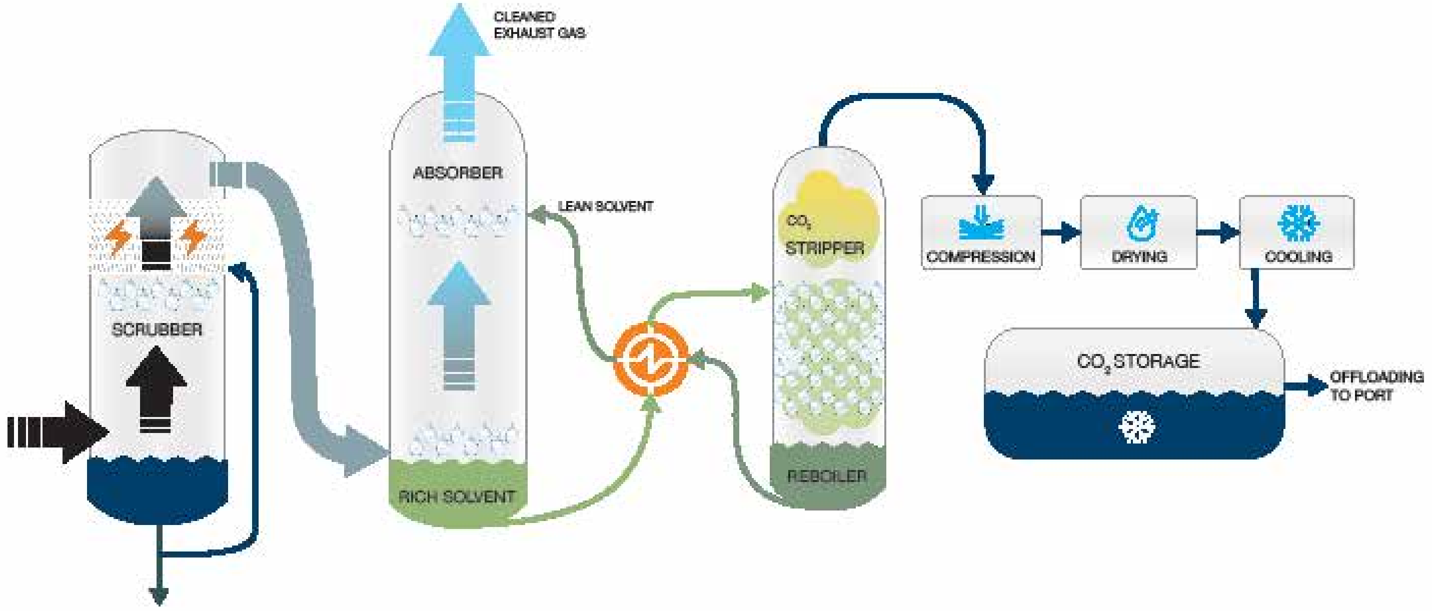
We have designed and installed a 1 MW pilot plant in our test facility in Moss, Norway in order to test our CCS technology in a range of scenarios and conditions.

We have been able to confirm the design assumptions and have been operating the system successfully since January 2022 achieving consistent CO_2 capture rates of 70%.

How to Capture CO_2?
Solvent-based absorption – simplified explanation

1. *Exhaust gas is treated to remove SOx and cool it down
2. *Through the WESP** the particulate matter is removed
3. Exhaust gas is then led to bottom of absorber
4. Lean solvent enters at the top of absorber
5. CO_2 is captured by the solvent when gas and solvent are mixed
6. Cleaned exhaust gas exits
7. Rich solvent is pumped via heat exchanger to the stripper
8. CO_2 is stripped from the rich solvent in the reboiler, becoming lean, and then recirculated to the absorber.
9. Water vapor content is condensed out of the gas stream
10. The CO_2 gas is then compressed, dried, and cooled
11. Finally the liquid CO_2 is stored in a tank, typically at 16 bar / -26°C

* In case of LNG, only cooling is needed
** Wet Electrostatic Precipitator

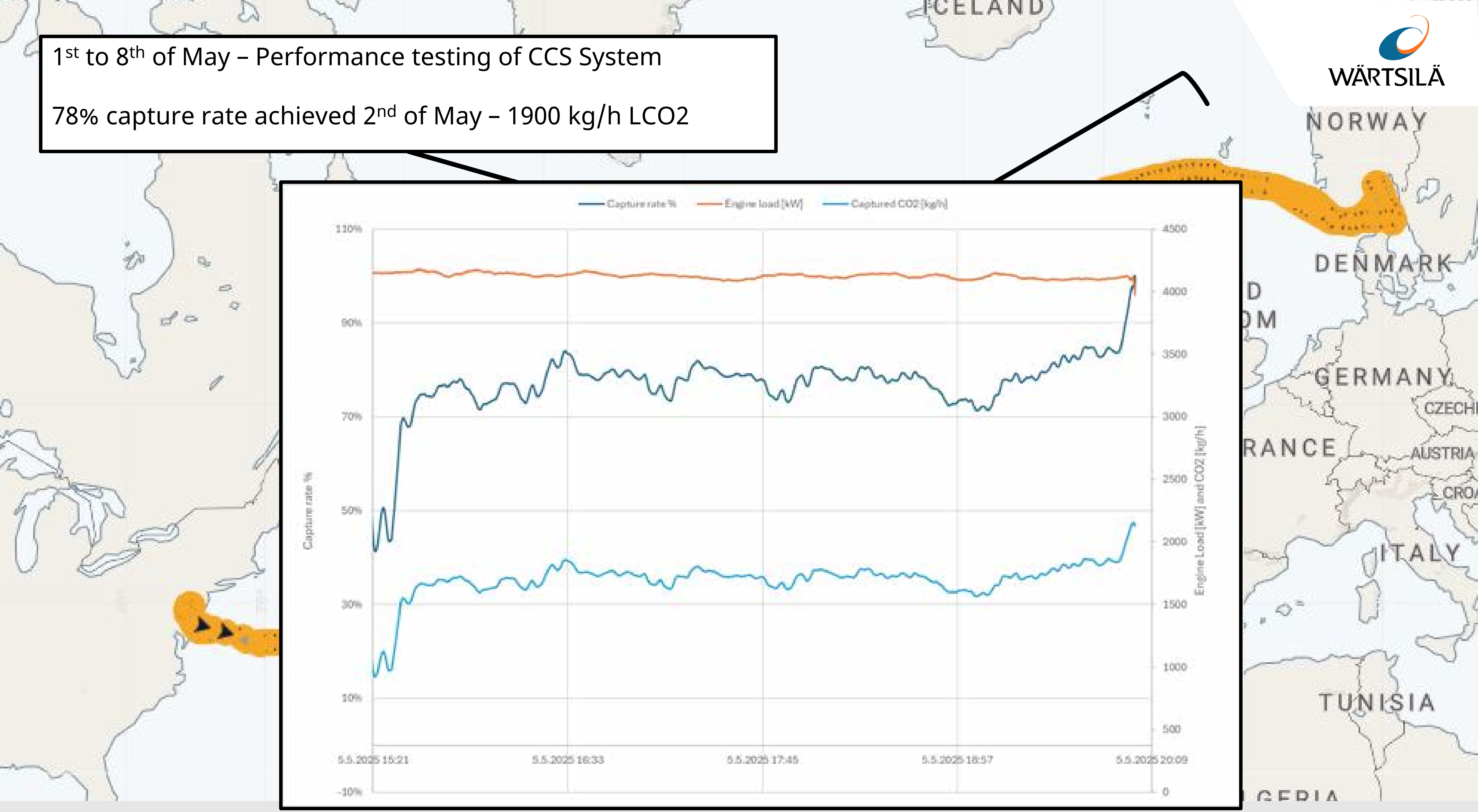


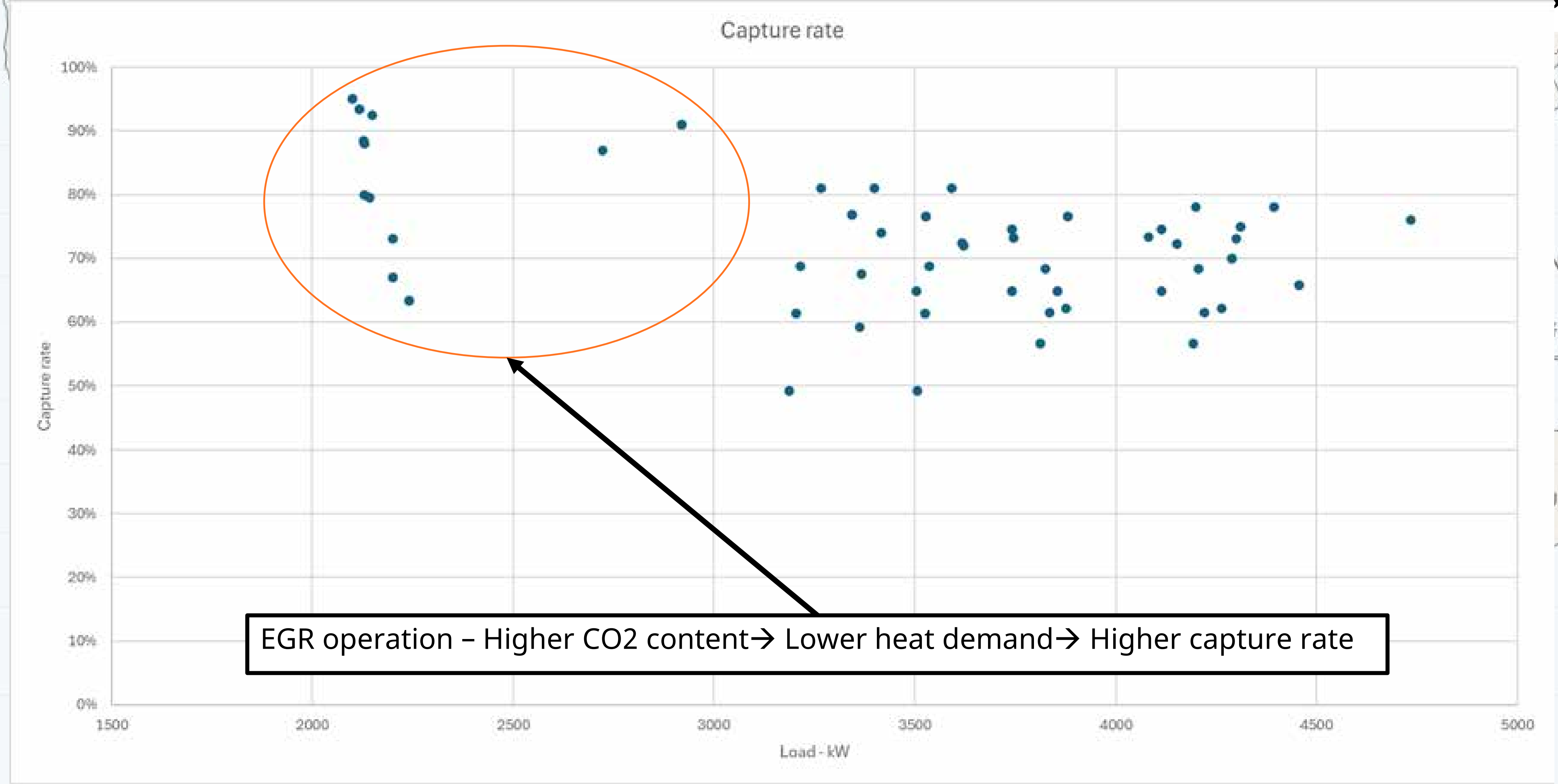
WORLD'S FIRST COMPREHENSIVE, FULL-SCALE SOLUTION ONBOARD SOLVANG ASA'S CLIPPER ERIS, WHERE THE TECHNOLOGY CAPTURES EMISSIONS FROM ALL EXHAUST GAS SOURCES

- Earlier this year, Wärtsilä installed its CCS technology onboard the 21,000 m3 ethylene carrier for full scale testing and optimisation.
- The solutions, which has been in operation since the Clipper Eris set sail from Singapore in February 2025, will support Solvang ASA's commitment to reducing carbon emissions and promoting sustainable maritime operations.
- Capture rates exceeding 70%

1st to 8th of May – Performance testing of CCS System

78% capture rate achieved 2nd of May – 1900 kg/h LCO2





Capture rate
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Capture rate
1500
2000
2500
3000
3500
4000
4500
5000
Load - kW
EGR operation – Higher CO2 content→ Lower heat demand→ Higher capture rate

CCS

- Size/Weight
- Energy consumption
  - Heat demand
  - Parasitic loads
- Solvent
  - Performance/efficacy
  - Lifetime
  - Treatment/Regeneration
  - Availability
  - HSE
- Capex
- Opex

- Purity


~~SOx~~
~~NOx~~
~~PM~~
~~CARBON DIOXIDES~~
THE GREEN FUTURE OF CONVENTIONAL FUELS

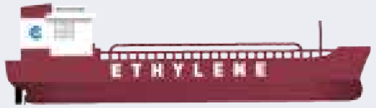
WÄRTSILÄ

Solvang ASA

Clipper Eris The world's first ship with full-scale carbon capture

Fleet director Tor Øyvind Ask

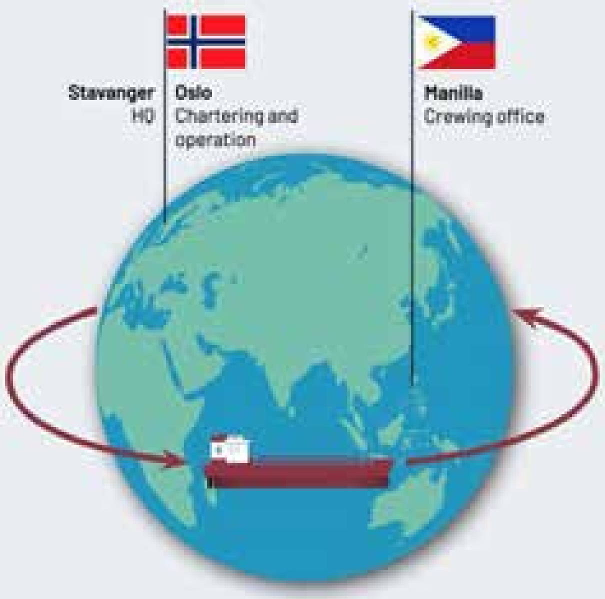
27 vessels (7)



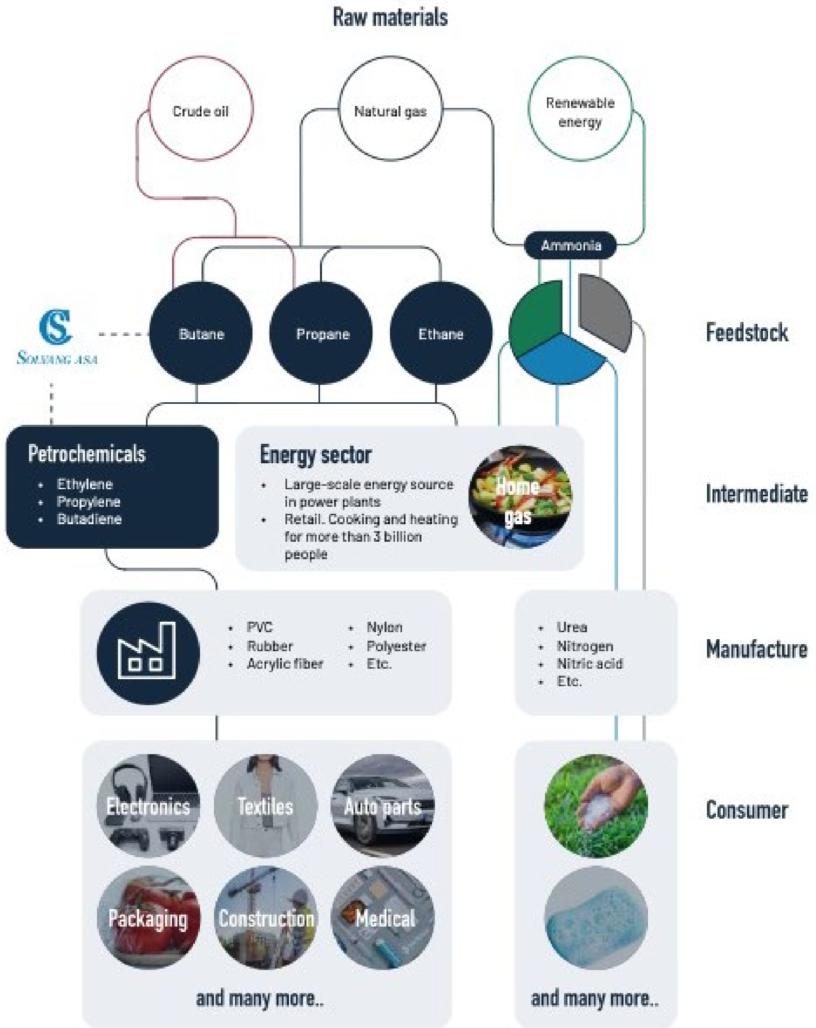
6 Semi-refrigerated Ethylene Carriers

8 Large Gas Carriers

6 + (7) Very Large Gas Carriers



Our Cargo



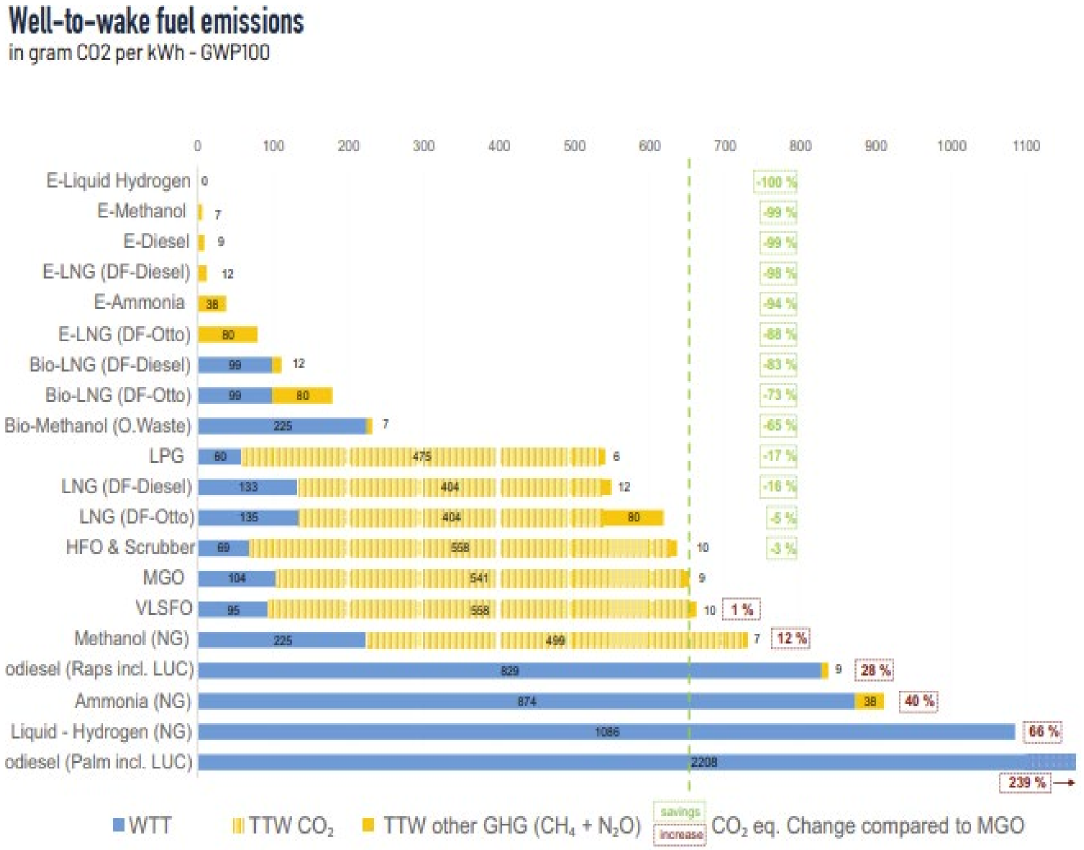
SOLVANG MISSION STATEMENT

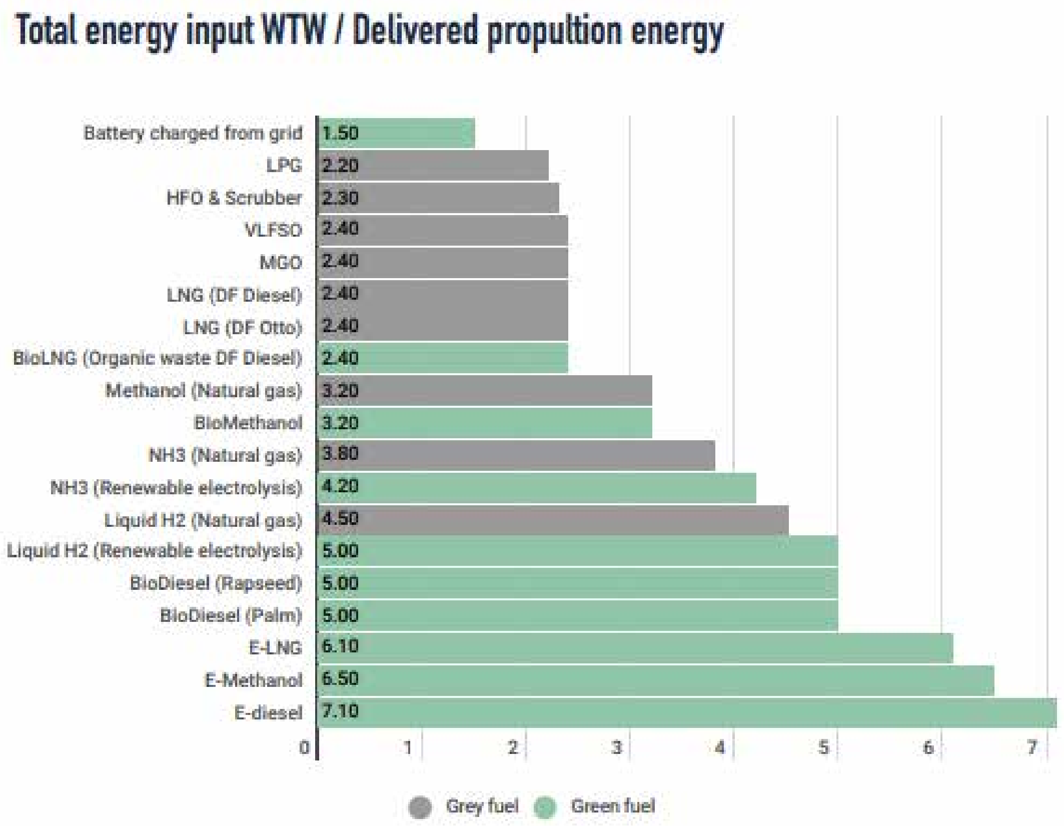
Solvang aims to be an industry leading provider of LPG and petrochemical tonnage to our clients in the safest, cleanest and most cost-effective manner.

Highligths of Solvang's ECO timeline and Emission control with exhaust gas cleaning (EGC)

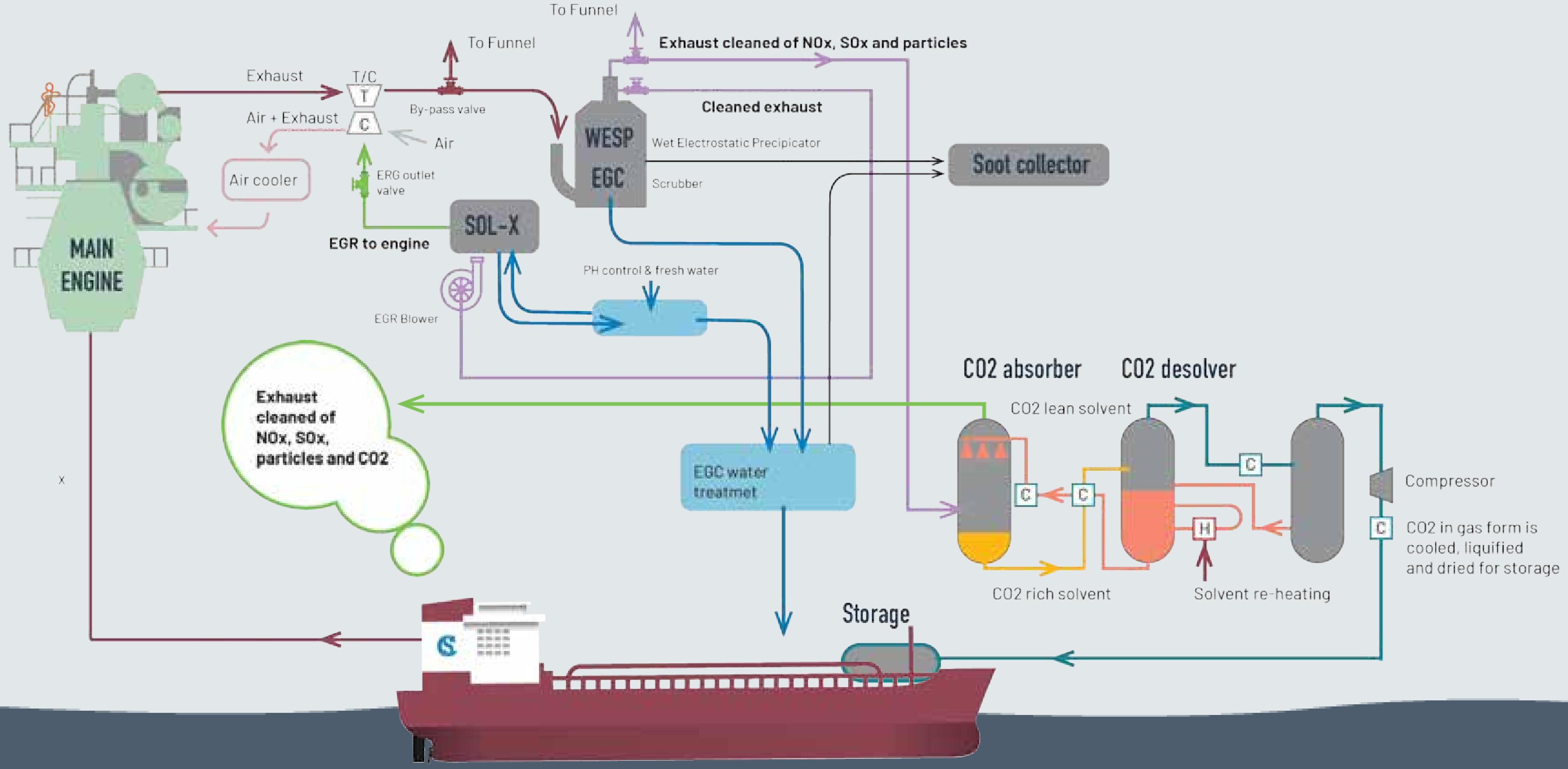
- 2010 "Make our Blue Logo Green" program.
- 2013 Delivery of the world's first ECO LPG Carrier with EGC with water treatment in open loop.
- 2015 Development of LP EGC + scrubber (NOx/SOx control) on an ethylene carrier.
- 2019 4 ECO Ethylene and 1 ECO Panamax VLGC newbuilds (EGC + LP EGR (NOx/SOx control)).
- 2021 Launches carbon capture project with Wärtsilä.
- 2023 Orders 7 VLGCs, OCCS-ready.
- 2024/2025 Installing and running the world's first full-scale OCCS system onboard the pilot vessel.

GHG emissions vs. energy needed for propulsion





All e-fuels have a large energy loss during production. The global lack of GHG-neutral electricity from renewable sources also make e-fuels unfit for deep sea shipping today.



To Funnel
To Funnel
Exhaust cleaned of NOx, SOx and particles
Exhaust
T/C
T
C
By-pass valve
Cleaned exhaust
Air + Exhaust
Air
WESP
Wet Electrostatic Precipicator
EGC
Scrubber
Soot collector
Air cooler
ERG outlet valve
SOL-X
EGR to engine
MAIN ENGINE
PH control & fresh water
EGR Blower
CO2 absorber
CO2 desolver
CO2 lean solvent
Exhaust cleaned of NOx, SOx, particles and CO2
EGC water treatmet
Compressor
CO2 in gas form is cooled, liquified and dried for storage
CO2 rich solvent
Solvent re-heating
Storage

CCS project goals and status

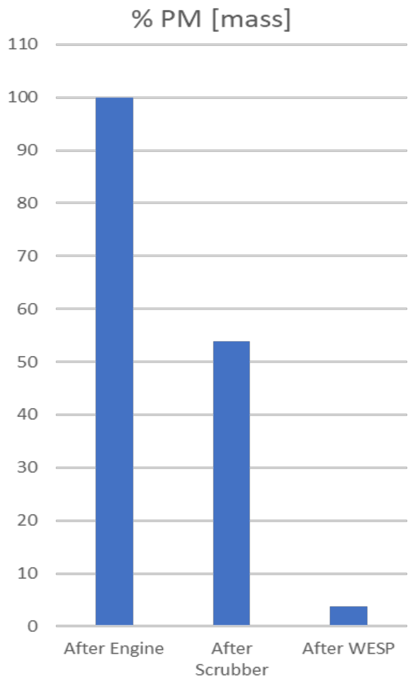
Project status & timeline;

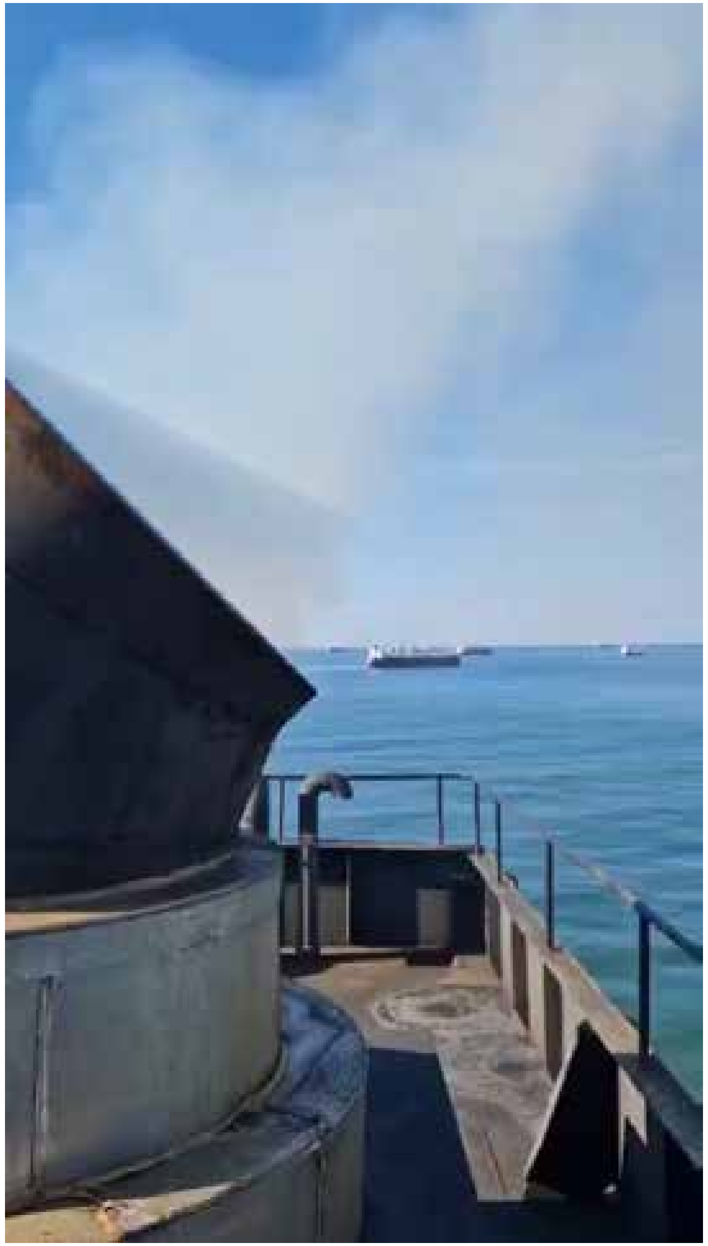
- LOI signed October 2021
- On-shore test started mid Feb2022
- Install WESP filter 2024 (5 vessels)
- Full CCS installation Q4 2024 (DD)

Deliverables;

- To demonstrate that CO_2 can be captured and stored as liquid CO_2 in the deck tank
- Gain real experience of operation of an onboard CCS plant;
- Energy consumption
- Cost (CAPEX and OPEX)
- Maintenance requirements
- Input to Flag state and IMO and
- Find possible receivers of the captured CO_2

WESP (wet electrostatic precipitator) installation





Soot collected from WESP/water threatment after 12 hours operation.

- Automat filter for soot handling.

- Previous SYSTEM, filter bags

OCCS installation on Clipper Eris

Design

- Combination of EGC with water treatment + WESP + LP EGR
- Conventional HFO
- Transatlantic with offloading in both end
- 75 % capture rate ~ 50 tons CO_2 pr day
- 2 x 350 m^3 CO_2 tanks ---> 14 days sailing
- Collecting CO_2 from ME, AE and boilers

Key Milestones

2023 | 2024 | 2025

Feasibility Studies
26 Oct 23

Contract Award
03 Feb 24

Basic & Detailed Engineering Commencement
06 Jan 24

Procurement Commencement
29 May 24

Prefabrication CCS Equipment Room & CO2 Handling Room
20 Jul 24

Vessel Arrival
21 Nov 24

60 days

Construction and Integration
21 Nov 24

Vessel Dock
16 Dec 24

17 days

Vessel Undock
02 Jan 25

Inclination Test
19 Jan 25

Start Commissioning
20 Jan 25

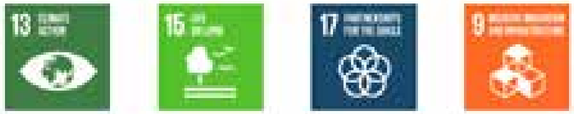
Sail for Gas Trials
06 Feb 25

10 Dec 24 – Block Installation

11 Dec 24 – LCO_2 Tanks Installed

02 Jan 25 – Undock

THE GREEN FUTURE OF CONVENTIONAL FUELS



After 12 years of experimentation, research and development, Solvang and partners present a game changing technology: The shipboard carbon capture system.

The abatement systems onboard will provide the following emission reductions:

- **SOx**: >97% reduction (EGC)
- **NOx**:>80% reduction (EGR)
- **PM**: ~90% reduction (EGC+WESP)
- **CO2**: >70% reduction (CCS)

Status today + further work

- Ready for first off-loading of CO_2 (300 tonn today).
- Tuning of engine and CCS plant finding optimum operation parameter with and withouth Solvang EGR.
- Tuning main engine and CCS plant together, total emission controll + waste heat.
- More testing of CO_2 purity (From lab 99.9? % CO_2)
- Measurement and verfication by third party (Sintef)
  - Energy consumption, particel emissions ++

OCCS: The Scalable, Fuel-Flexible Solution for Immediate Impact

- The main benefit with the onboard CCS is that this system can be implemented as a retrofit and newbuilding.
- It can handle all fossil fuels + biofuels; it would only be a cost issue.
- It can be done in massive scale if/when shore terminals are available and several are under construction.
- Compared to the other decarbonization solution this can be done very fast. Ref number of scrubber vessels.
- A combination of Exhaust gas cleaning, EGR and CCS reduce all harmful emissions to air.

Key parameter to consider for successful implementation of OCCS

- Technology neutrality:
  - Reducing GHG emissions require more energy, whether this come from fossil energy or renewable is irrelevant if the total GHG emissions is reduced.

- All part of the value chain must take care of their own GHG emissions.
  - As the regulation are today there is no reason for reducing up stream fuel emissions.
  - Well to tank emissions must be real values, not fixed factors based on worst case production path. I.e. Well to tank emission need to be handled of fuel producer with CCS or renewable and emission related to CO2 handling after discharging very small compared to the actual values (efficient and low emission value chain).

  - Regulation needs to simple and predictable.

SOLVANG ASA

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