MemCCSea

Innovative membrane systems for CO_2 capture and storage at sea

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Centre for Research & Technology Hellas

MemCCSea project is funded through the ACT programme (Accelerating CCS Technologies, Horizon2020 Project No 294766). Financial contributions made from GSRT (GR), BMWi (DE), RCN (NO) and DoE (USA) are gratefully acknowledged.

Greenhouse gas emissions from SHIPS are currently estimated at 3% of the total global emissions and are expected to rise by 2050 up to **17%**

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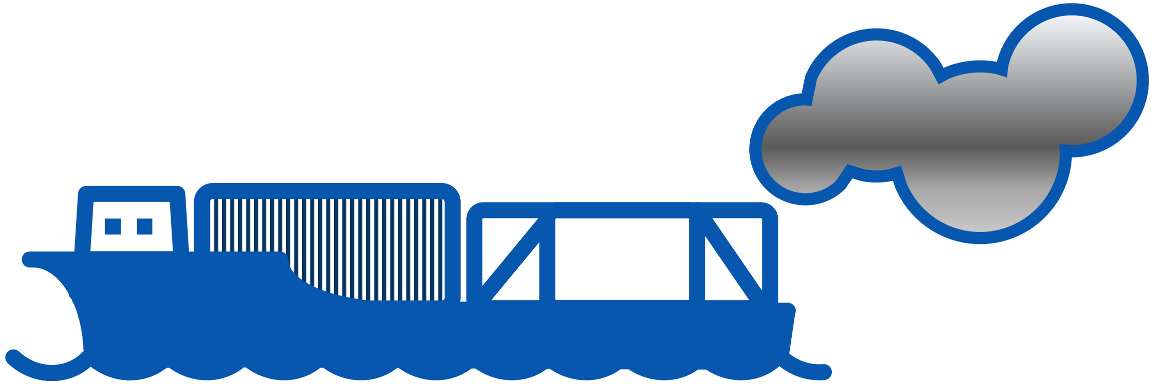

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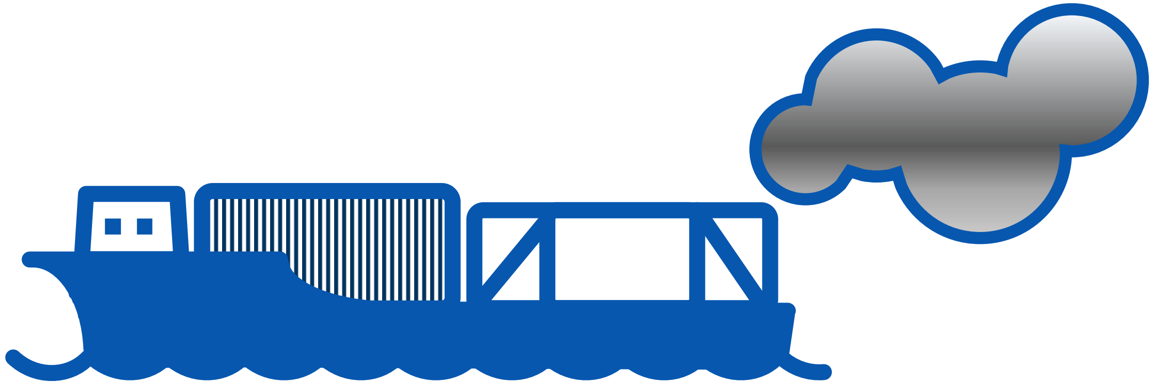
Innovative membrane systems for CO_2 capture and storage at sea

To address the Paris agreement,

IMO INTERNATIONAL MARITIME ORGANIZATION

has adopted an initial strategy for the reduction of GHG emissions from ships by 50%



Accelerating CCS Technologies

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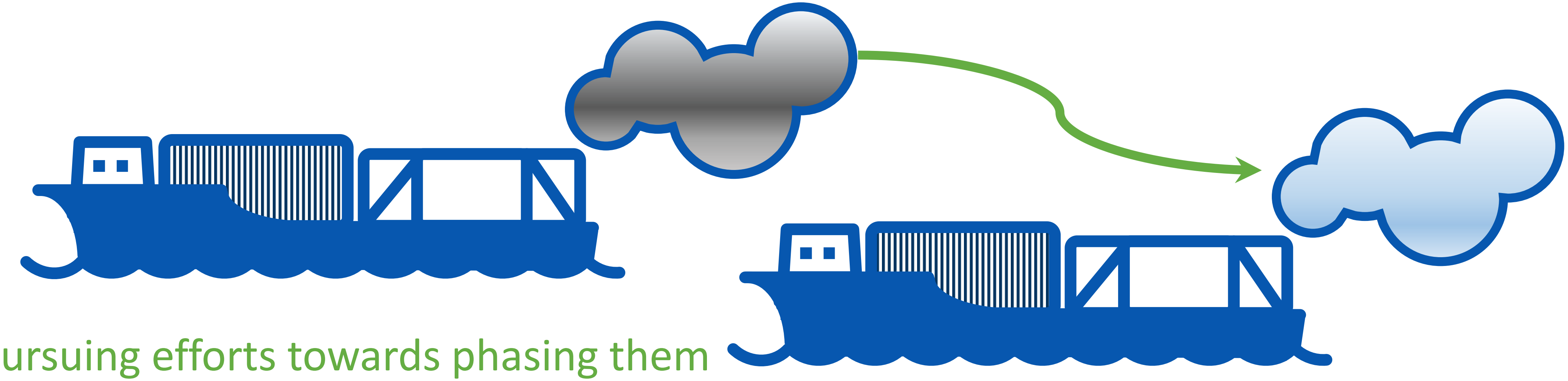

while pursuing efforts towards phasing them out <u>entirely</u>

In **MemCCSea**, we capture CO_2 from ships and floating vessels using

membrane technology

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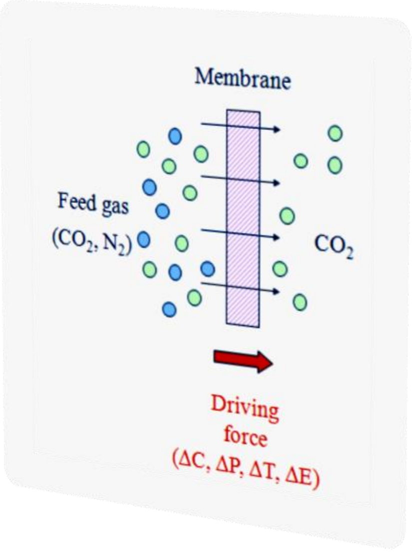

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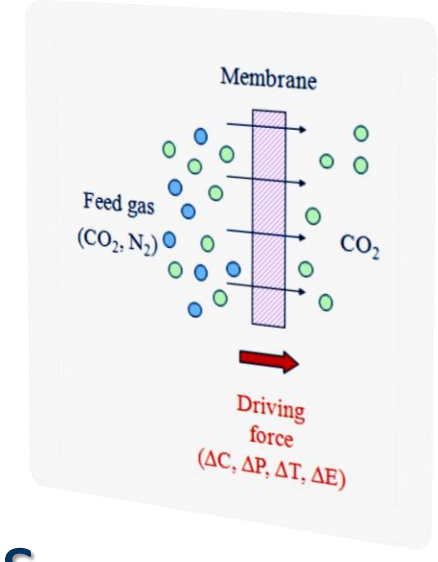
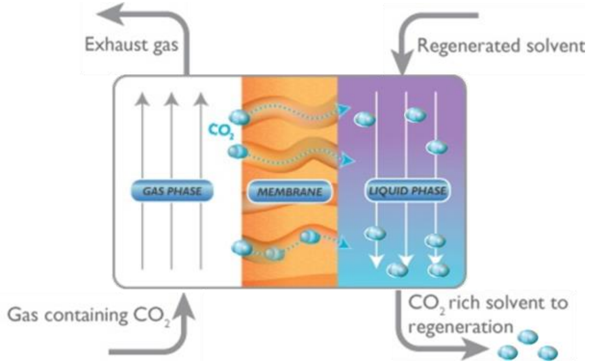
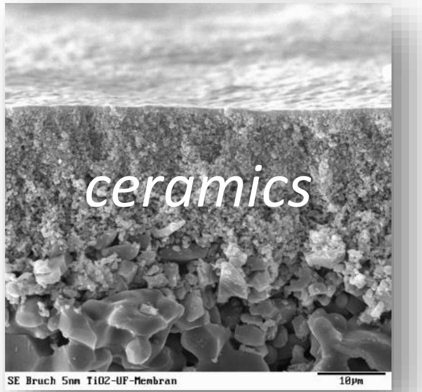


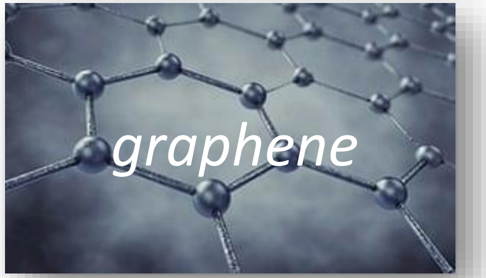
membrane technology

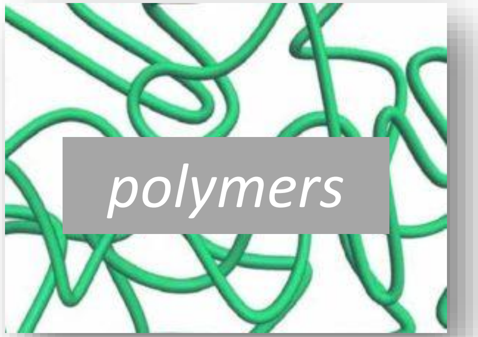
sea water + promoters



and advanced materials







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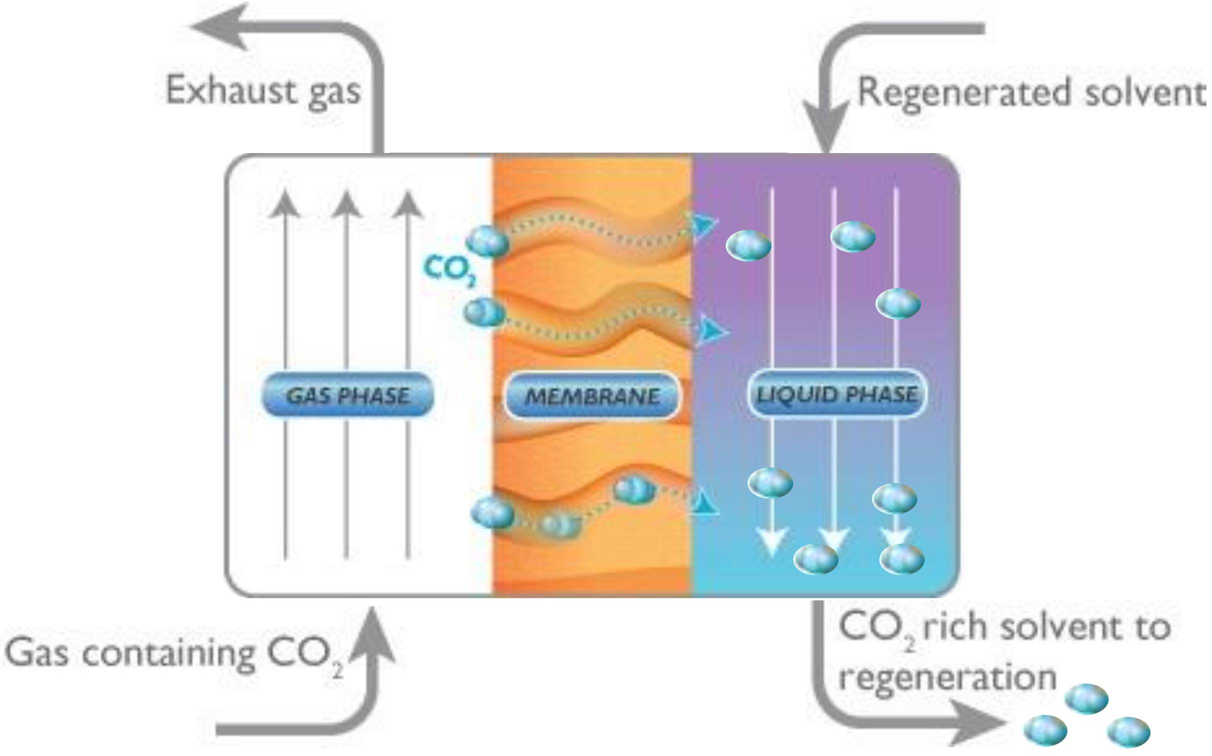
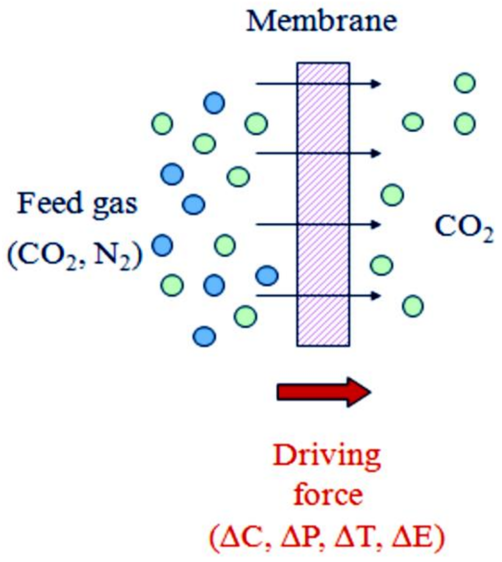
Membrane Technology | Gas-Liquid Contactors

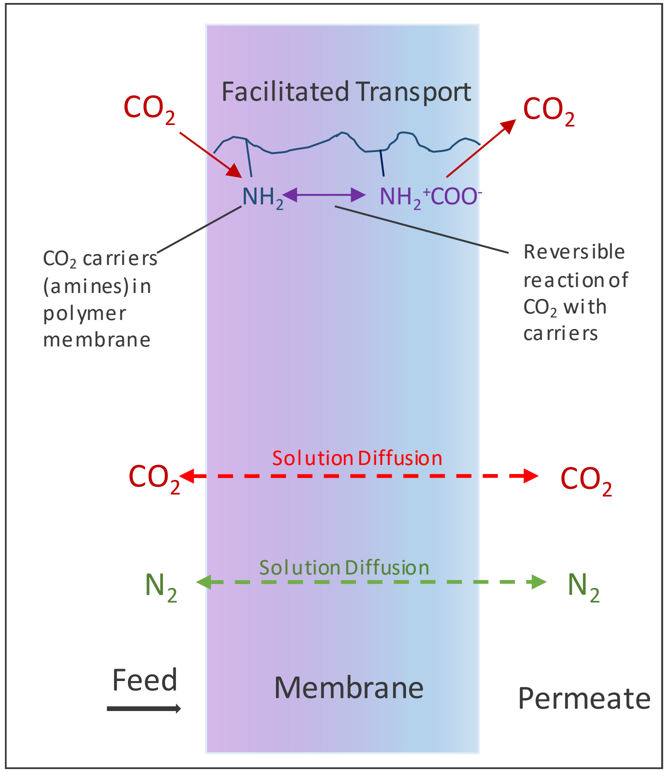


Cross section of a porous hollow fiber wall

Membrane Technology | Permeators



Cross section of a dense membrane wall during CO_2 separation

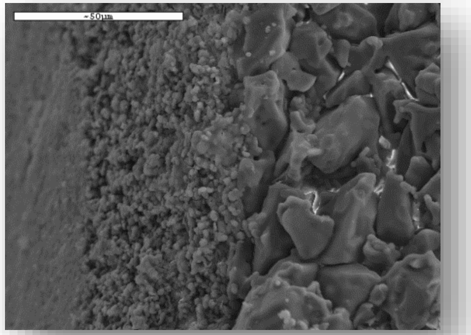


Aliphatic amine carrier for CO_2 - Reversible formation of carbamate

Ceramic membranes (e.g. TiO_2, Al_2O_3)

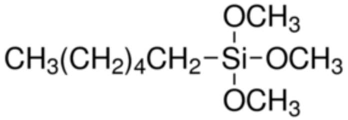
of various pore sizes

(1-1,000 nm)



are properly coated with hydrophobic precursors

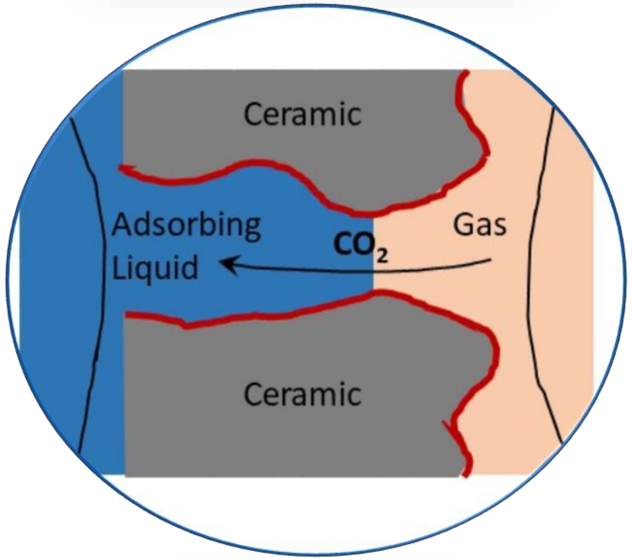
(e.g. carbon, organosilanes)



to prevent the entry of liquid into the gas phase for

efficient contactor mode of operation in gas-liquid

membrane process.



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So, **KER 2.1 – Hydrophobic coating on porous ceramic membranes** has already been achieved

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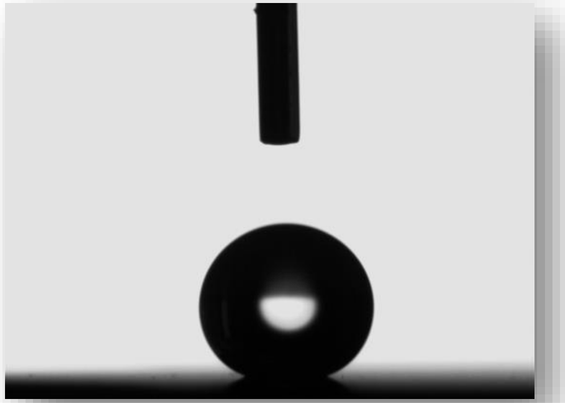
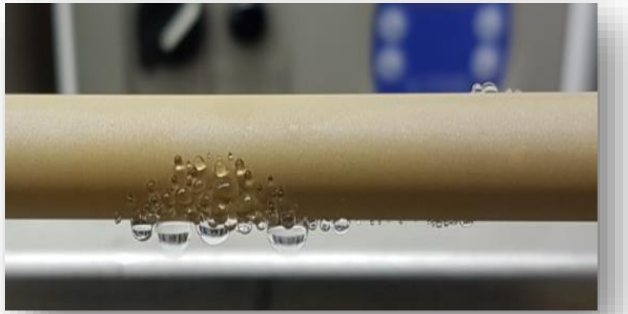
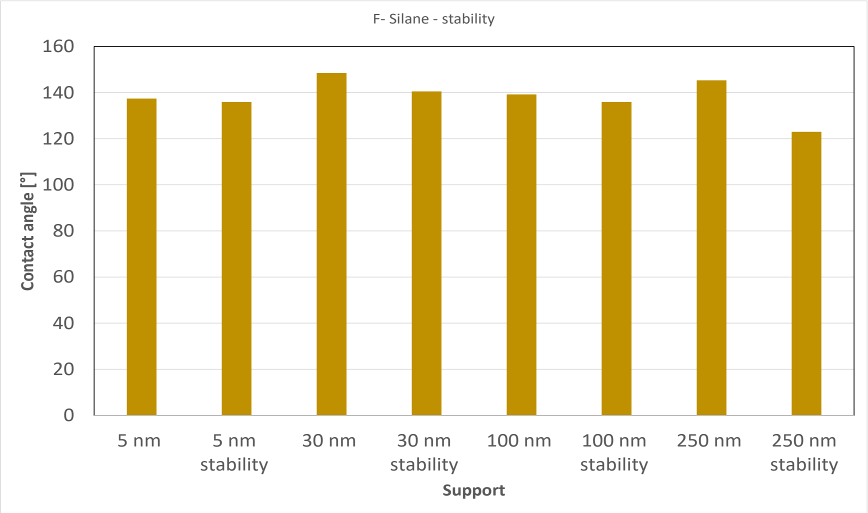
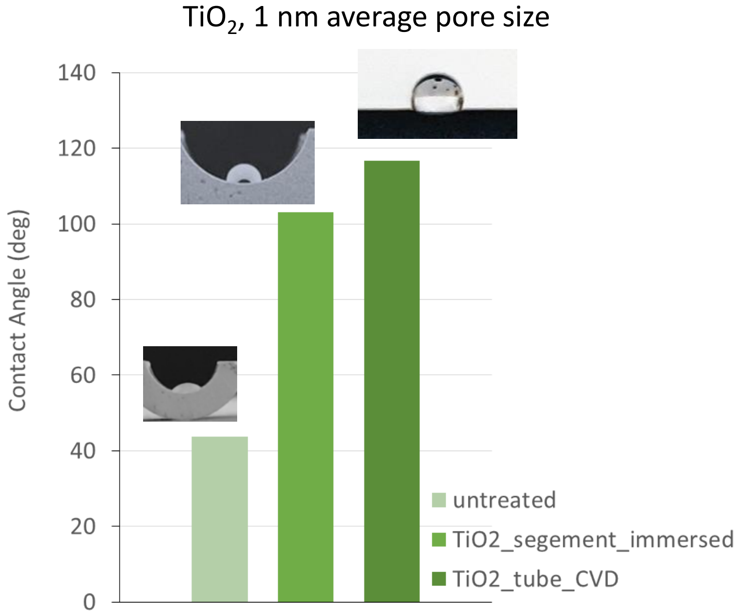


… and clear hydrophobic behavior is obtained even in initially really hydrophilic materials







Further optimization with decreasing pore size from 1000nm to 5nm, LEP becomes higher than 10bar

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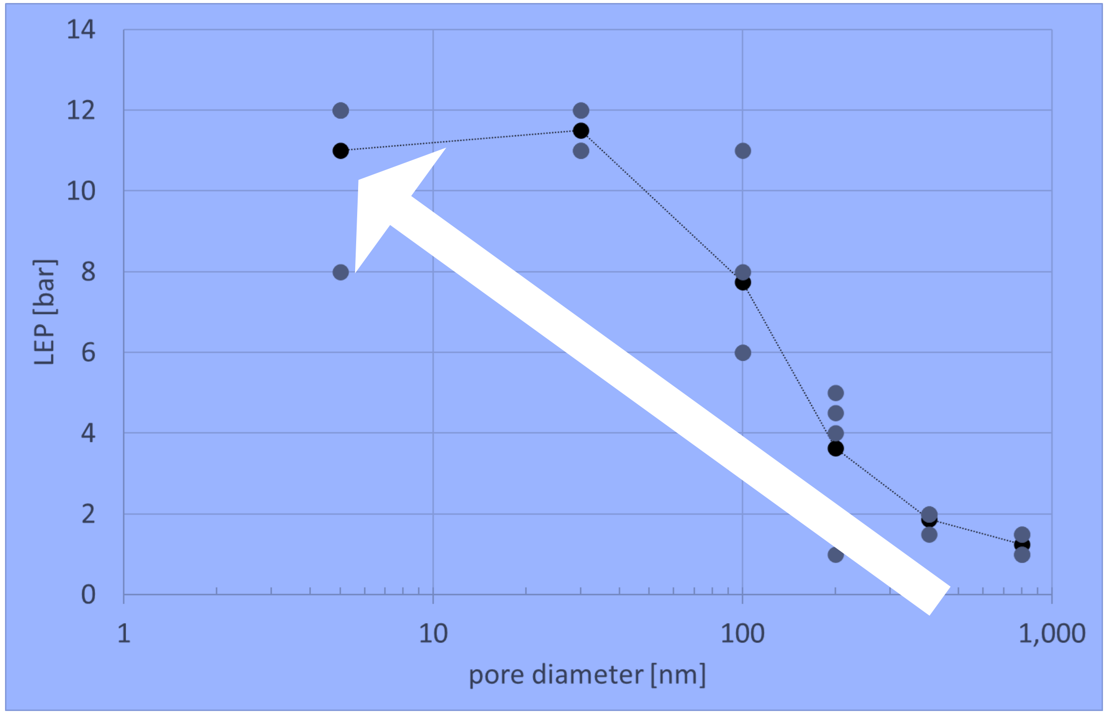
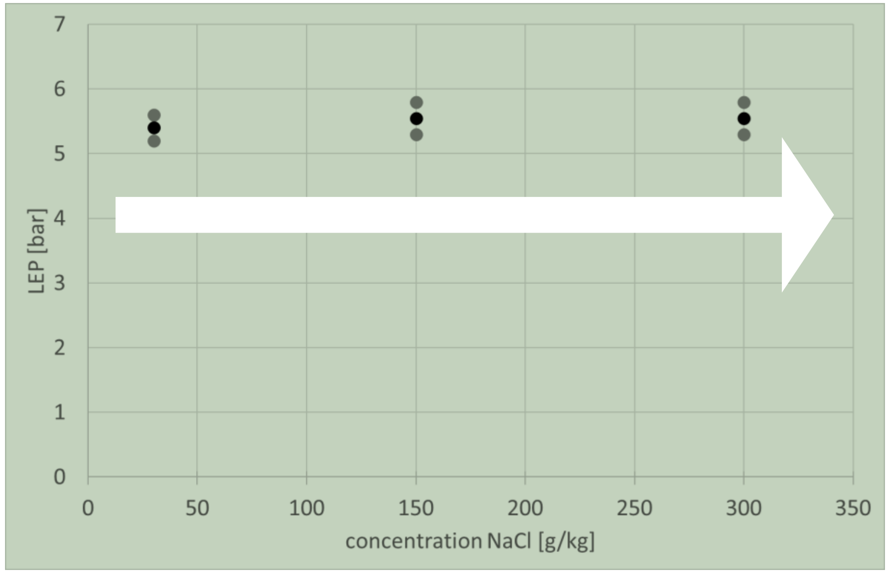


Sodium chloride is added in the absorption solvent to simulate sea-water based solvents (~35g/kg). Further increase of LEP is achieved!



Polymeric & Mixed Matrix Membranes through the synthesis of novel functionalized graphene

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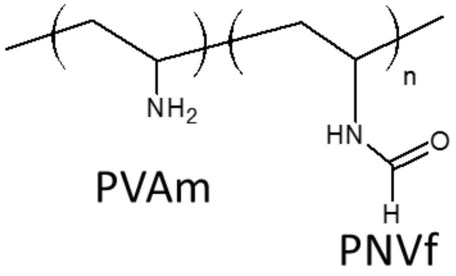
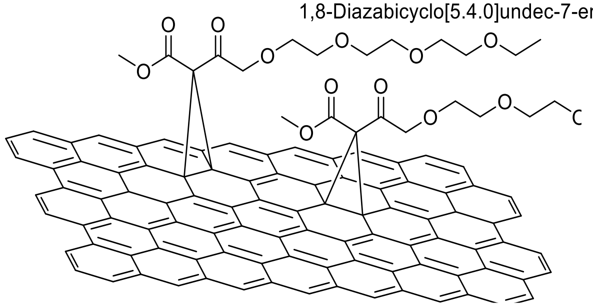
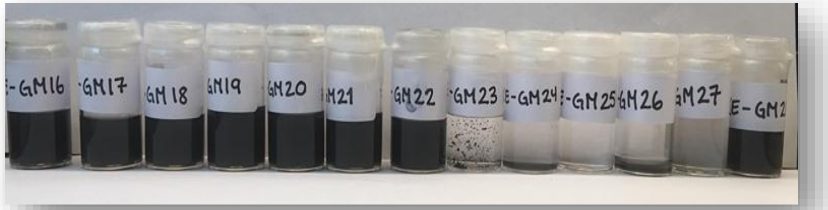
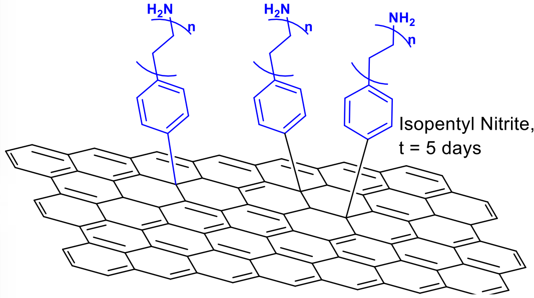
Polyvinylamine

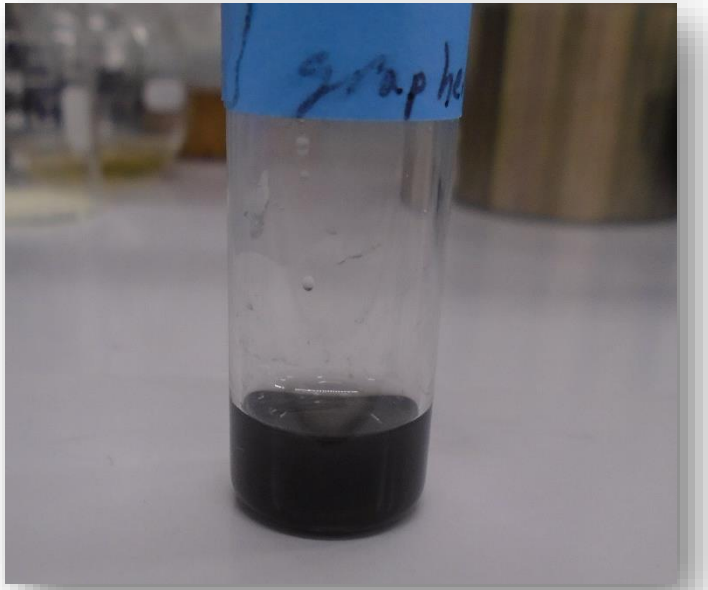


Graphene









Graphene in benzyl alcohol
Suspension stable upon standing overnight

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Polymeric & Mixed Matrix Membranes

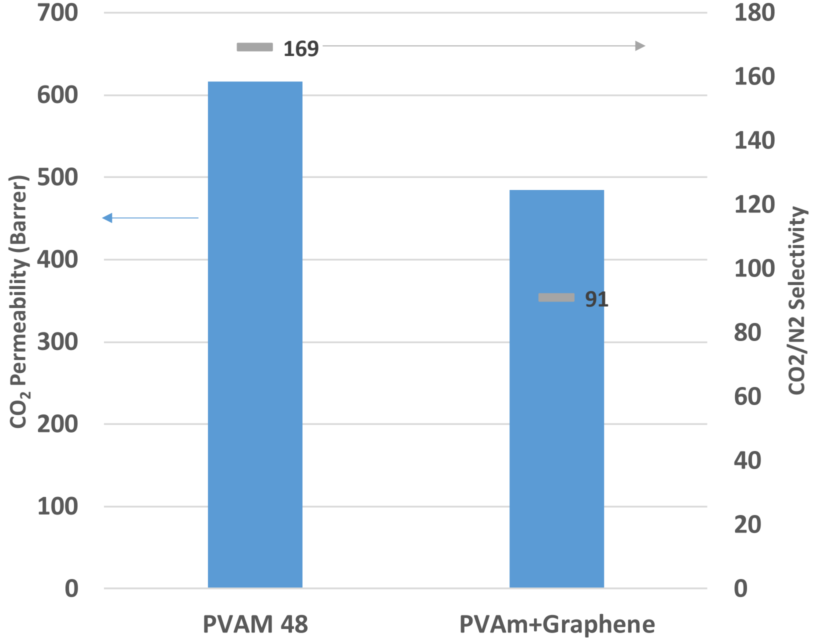
PVAm/graphene solution

Cast membrane film

PVAm/graphene solution (2 wt% graphene) is cast in mold and dried in vacuum oven.

Next steps: Test two more PVAm/graphene films Thin film composites (TFC) of sub-micron PVAm/graphene/graphene oxide on porous supports

Membrane gas permeability and selectivity



Permeation testing conditions:

60 °C, 95% relative humidity (feed and sweep), 14/86 CO_2/N_2 mixed feed gas at 1.36 atm, Air sweep gas at 1.22 atm, p_{CO2} 0.19 atm

Evaluation of the developed materials as permeators

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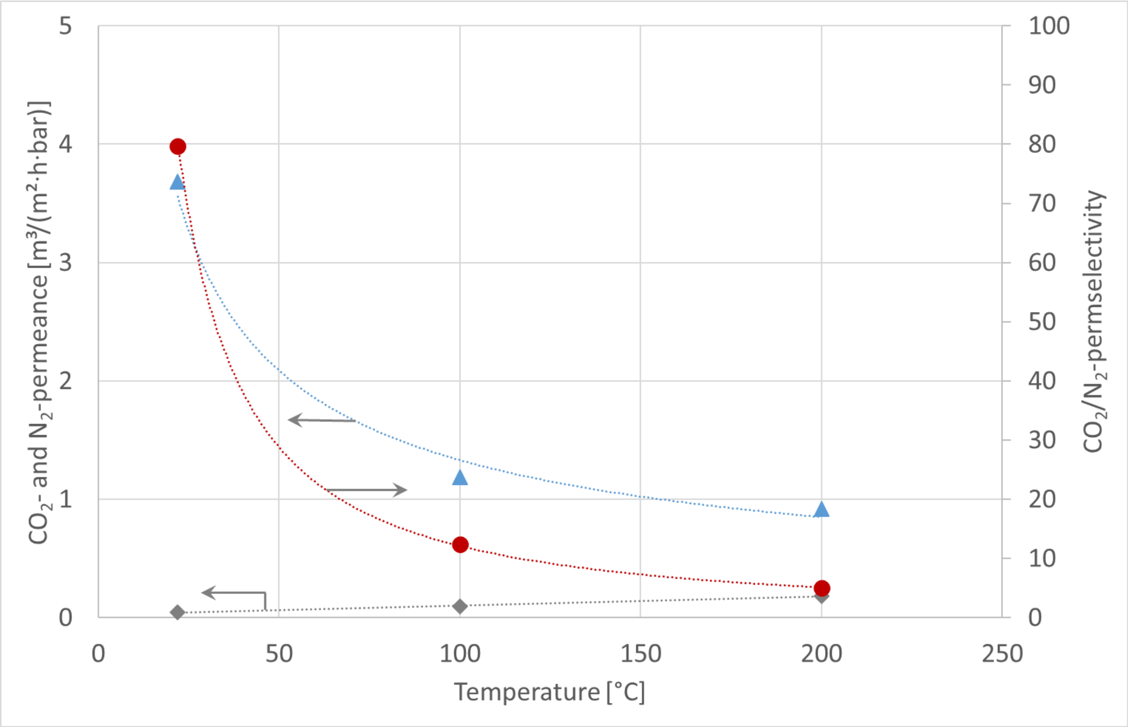
Carbon membranes for permeators



Highest CO_2/N_2-selectivity up to 80

Increasing of CO_2/N_2-selectivity with decreasing temperature

Evaluation of the developed materials as contactors

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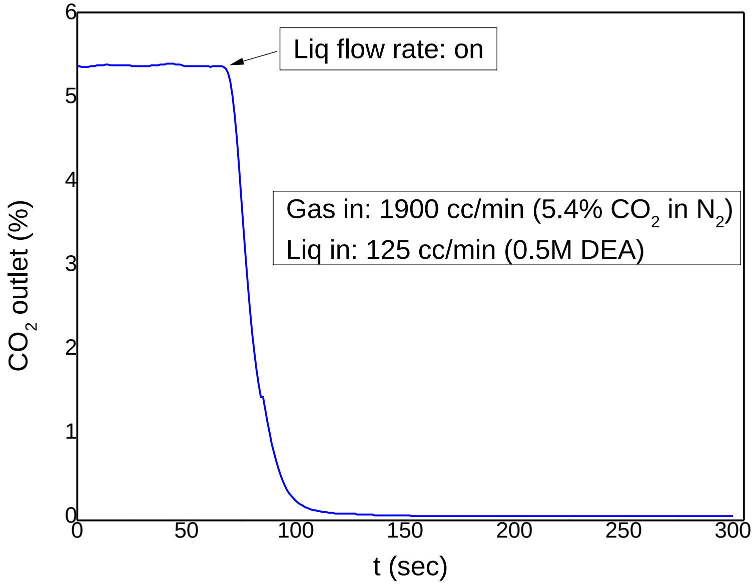
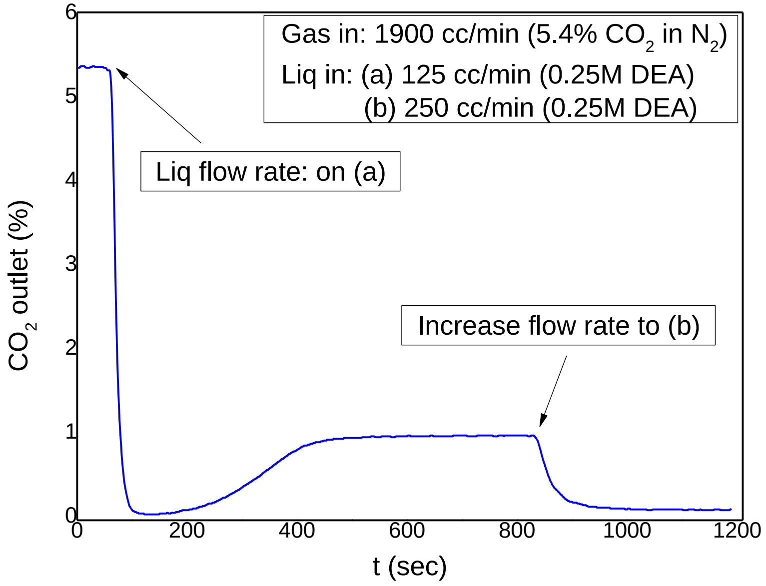
5.4% CO_2 in N_2 represents flue gas composition

Amine based solvent (DEA) | long-term working performance | no wetting | no efficiency loss





Even very low DEA concentrations are adequate for complete CO_2 capture at high G/L ratios

Online CO_2 analysis | Quick response | Quick steady-state development

We want to simulate the mass transfer phenomena and predict what happens in the lab….

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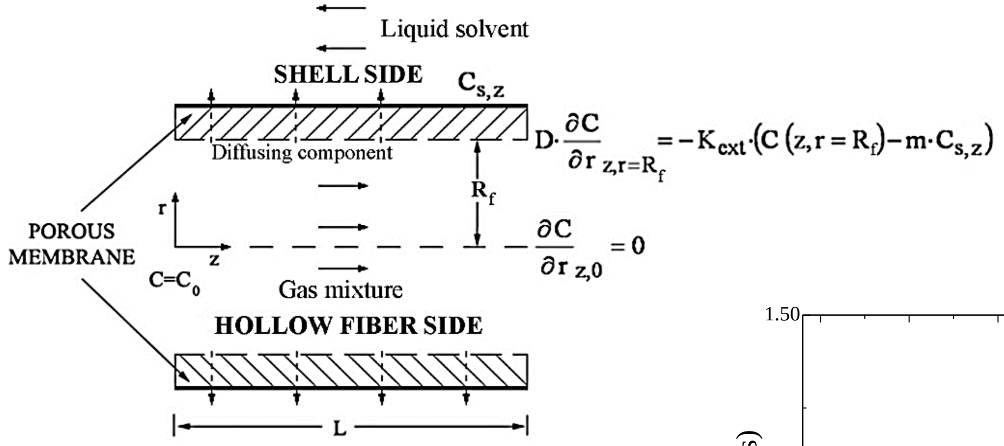
Gas-liquid membrane contactor model



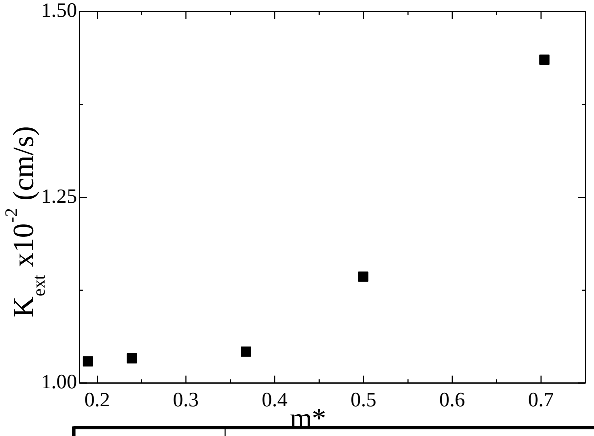
Coupled membrane process with solution thermodynamics

$CO_2 + 2RNH_2 + H_2O \rightarrow RNH_3^+ + RNHCOO^-$ ($R = HOCH_2CH_2$)

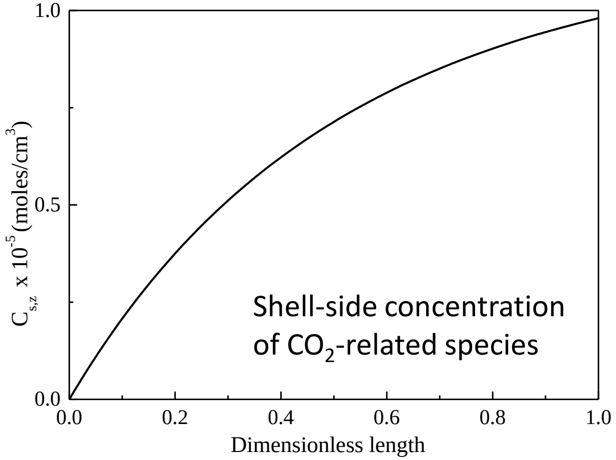
Steady-state, isothermal, 2D laminar flow (CO_2/N_2 mixture) in the fibre side (lumen)

Reaction in the shell side with the liquid solvent

Predict combined mass transfer resistance (K_{ext}) based on experiments



No.	E	K_{ext} (cm/s)	Sh_w	M	m*	H_{CO2} (mol/cm^3)*	z*
1	0.09788	0.01029	**1.600x10^{-3}**	0.12094	**0.18945**	3.582x10^{-5}	222.
2	0.19334	0.01033	**1.615x10^{-3}**	0.23519	**0.23922**	3.648x10^{-5}	544.
3	0.18207	0.01042	**1.620x10^{-3}**	0.22498	**0.36774**	3.582x10^{-5}	567.
4	0.09559	0.01143	**1.786x10^{-3}**	0.11628	**0.49979**	3.648x10^{-5}	214.
5	0.06827	0.01435	**2.242x10^{-3}**	0.08305	**0.70390**	3.648x10^{-5}	109.



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We want to simulate the mass transfer phenomena and predict what happens in the lab….

Membrane permeator model

Molecular Diffusion/Fick's Law Model (**FLM**)

$$\vec{J_i} = -\frac{D_i}{RT}\, c_i \frac{\partial \mu}{\partial x} \quad (i = 1, \dots, n)$$ Fick's First Law

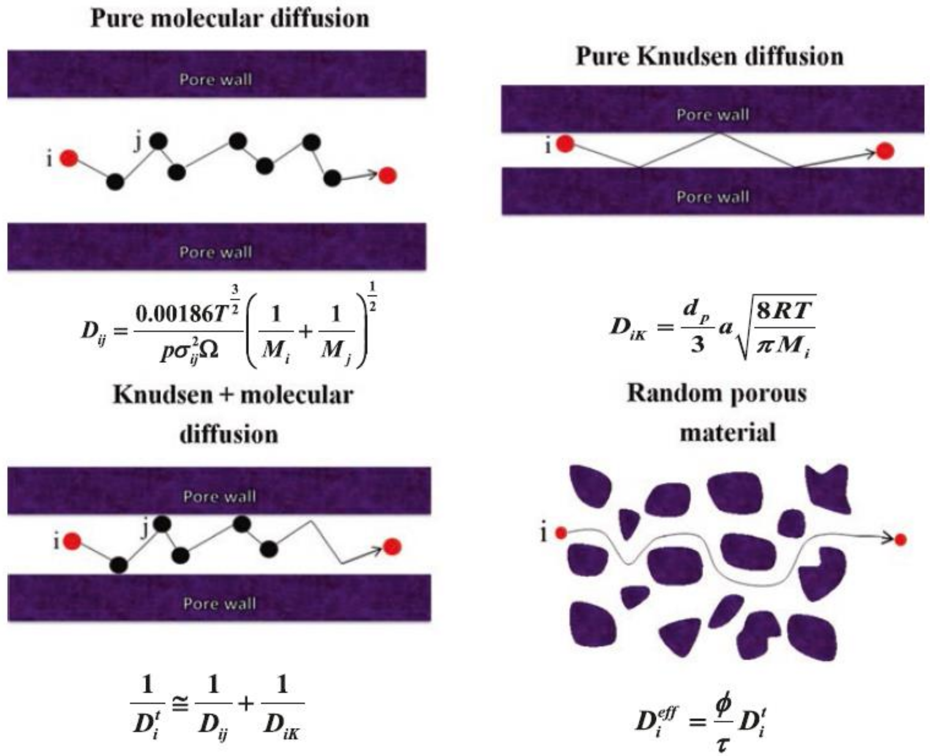
$$\mu = \mu_o + RT\, lnc_i$$ Chemical Potential

$$\frac{\partial c_i}{\partial t} = D_i \frac{\partial^2 c_i}{\partial x^2} (i = 1, \dots, n)$$ Fick's Second Law

FLM is (a) appropriate only for molecular diffusion of binary mixtures
(b) can accommodate Knudsen Diffusivity for binary mixtures

Mass Transfer Coefficient (MTC)

$$|\vec{J}| = MTC * \Delta c = \frac{1}{R_{MT}} \Delta c$$ Description of flux through MTC



...and optimize what happens on board!

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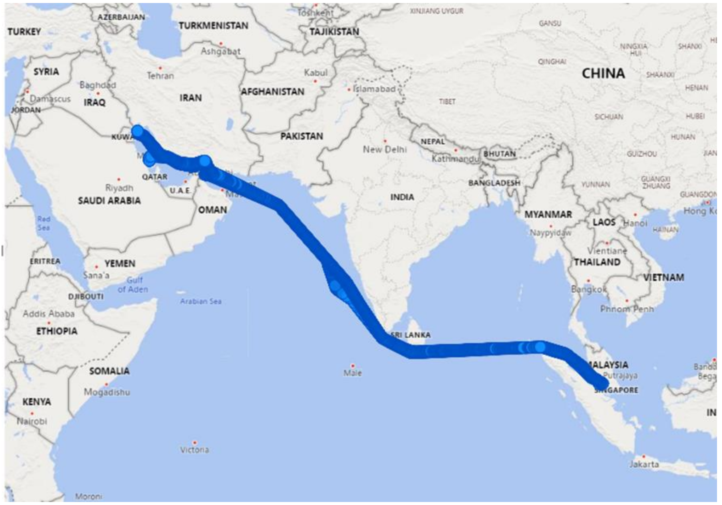
Specs that affect membrane system

Exhaust Gas					
Gas flow	kg/h	85471	67477	45858	27166
Gaseous Emission Data					
CO concentration (Dry)	ppm	119.0	58.5	55.5	48.0
CO2 concentration (Dry)	%	5.24	4.82	4.89	4.30
HC concentration (Wet)	ppmC	59.5	54.0	58.5	49.5
O2 concentration (Dry)	%	13.78	14.43	14.25	14.23
NOx concentration (Dry)	ppm	794.0	1038.0	1374.0	1404.0
NOx humidity/temp. correction factor	-	1.016	1.022	1.001	0.998
Dry / Wet correction factor	-	0.949	0.954	0.955	0.961
NOx mass flow	kg/h	103.84	108.30	95.53	58.02
NOx specific	g/kWh	8.64	12.01	15.90	19.31
Test Cycle (E3)	**g/kWh**	**11.85**			

* The IMO NOx value is based on reference scavenge air temperature, but not corrected reference Pmax.

Case study definition

Vessel type	• Tanker	
Trade route	• Modes of operation	Laden: Arab gulf → Singapore: 23 days Ballast: Singapore → Arab Gulf: 19 days
Trips per year	• Fuel and emissions per trip & year	Per trip: : ~1400 tons fuel → 4360 tons CO_2 Per year: ~15500 tons fuel → 48267 tons CO_2
Fuel type	• LSHFO • LNG	
Machinery in operation	• Main engine • Auxiliary engines • Auxiliary boiler	
Onboard space capacity	• Machinery • Deck	
Safety aspects	• Materials • Consumables	
Techno-economics	• CAPEX • CO_2 price	



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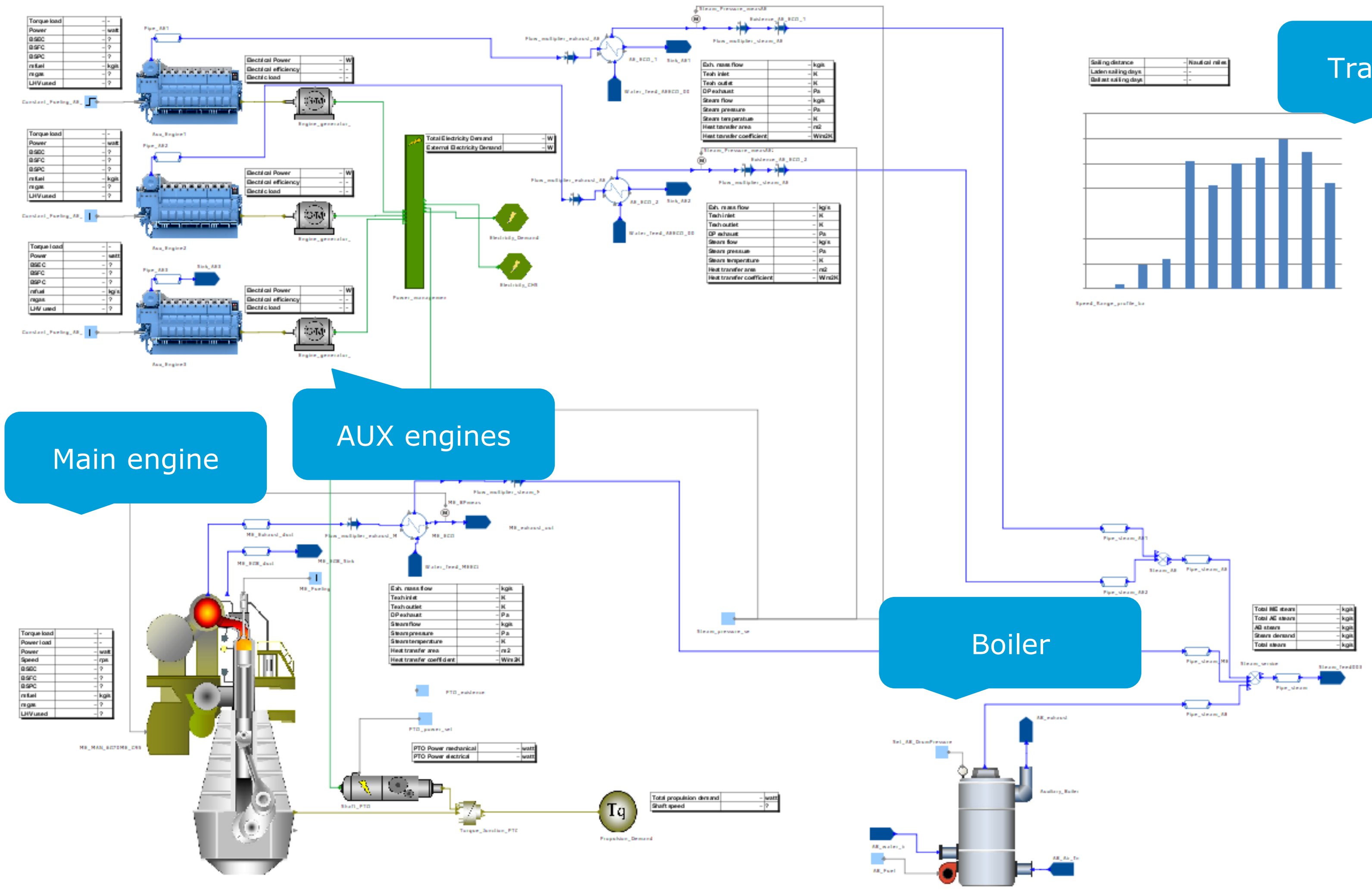

- **Specifications of the capture system:**
  - Flow rates – design for trade
  - Stream composition
  - Available power/heat sources to cover system loads
  - Location on board
- **Specifications of the storage system (if needed):**
  - Amount of CO_2 per trip
  - Location on board

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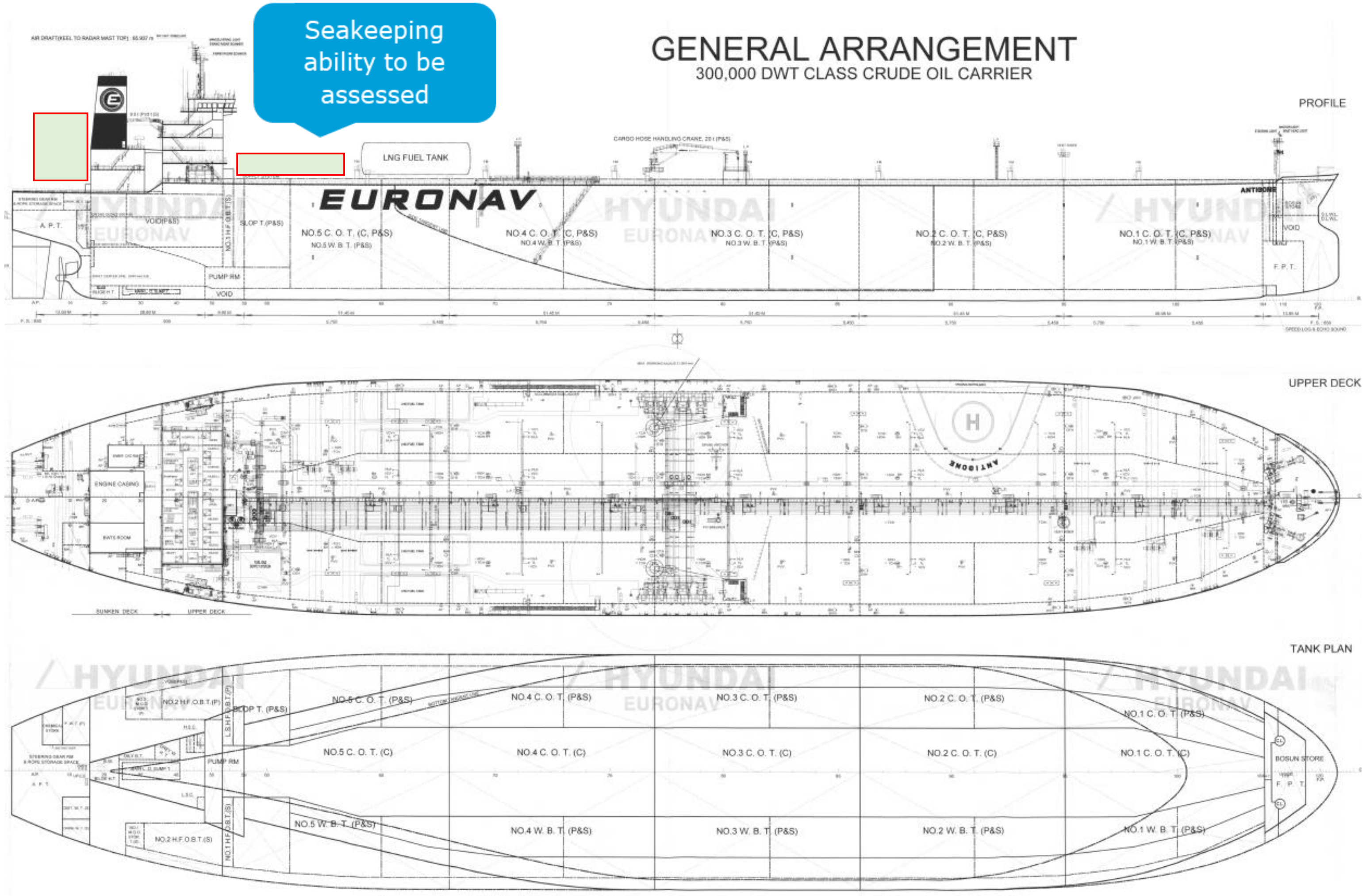

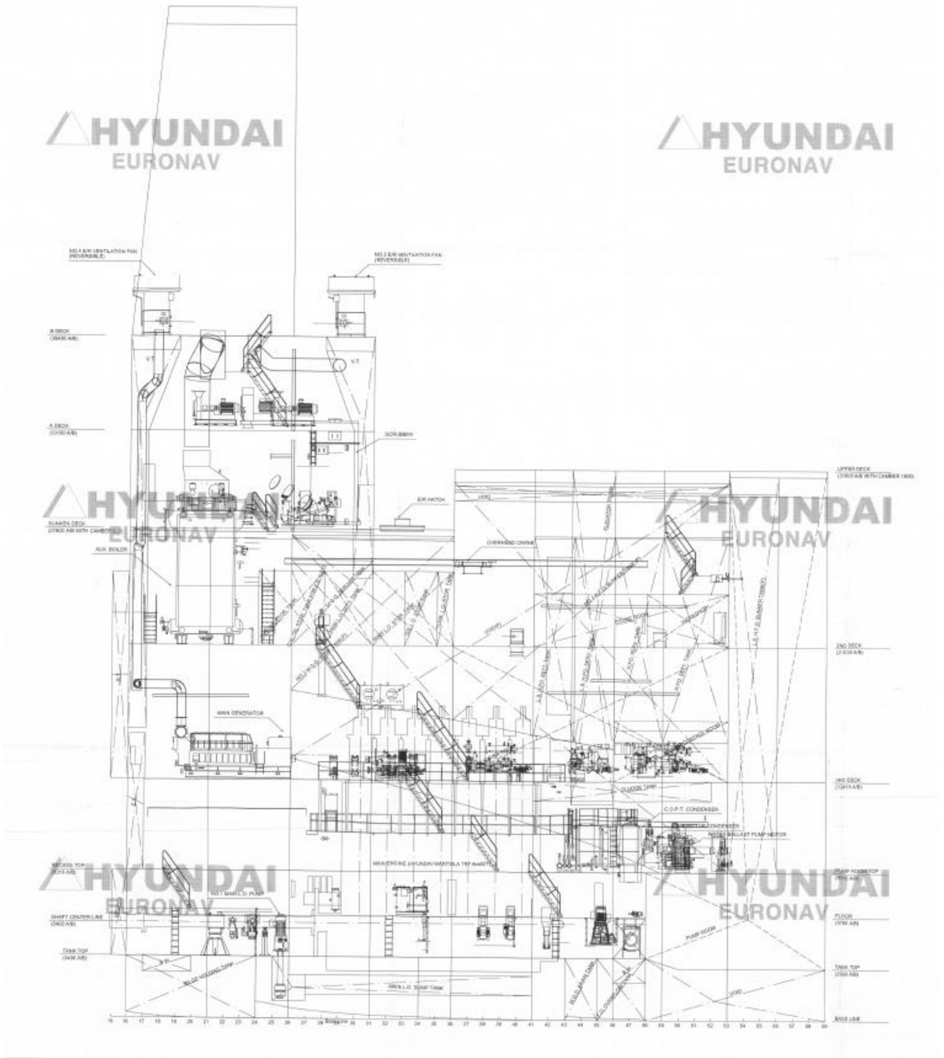

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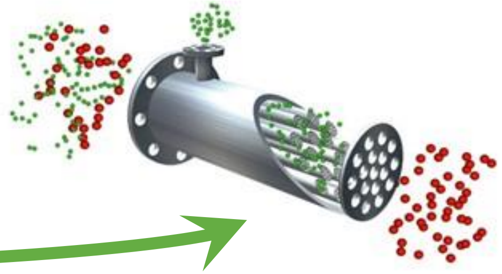
Our goal is to create a system



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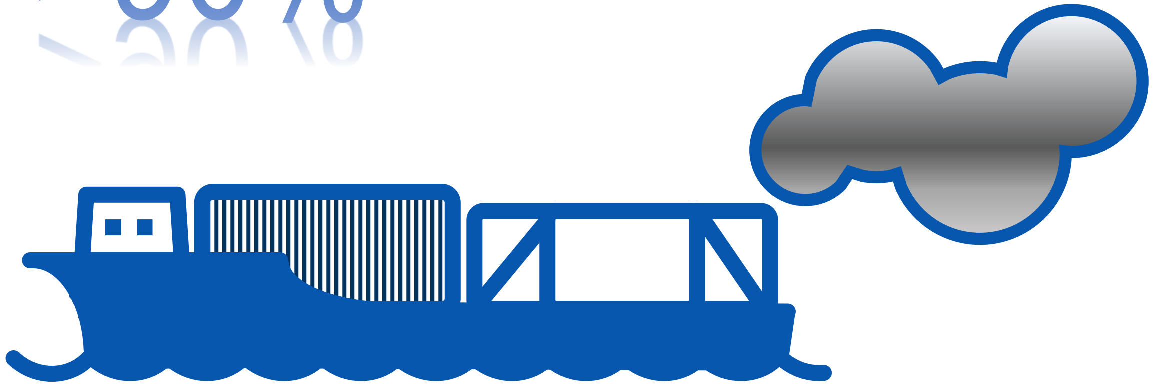
…and reduce the main ship engine CO_2 emissions by more than >90%



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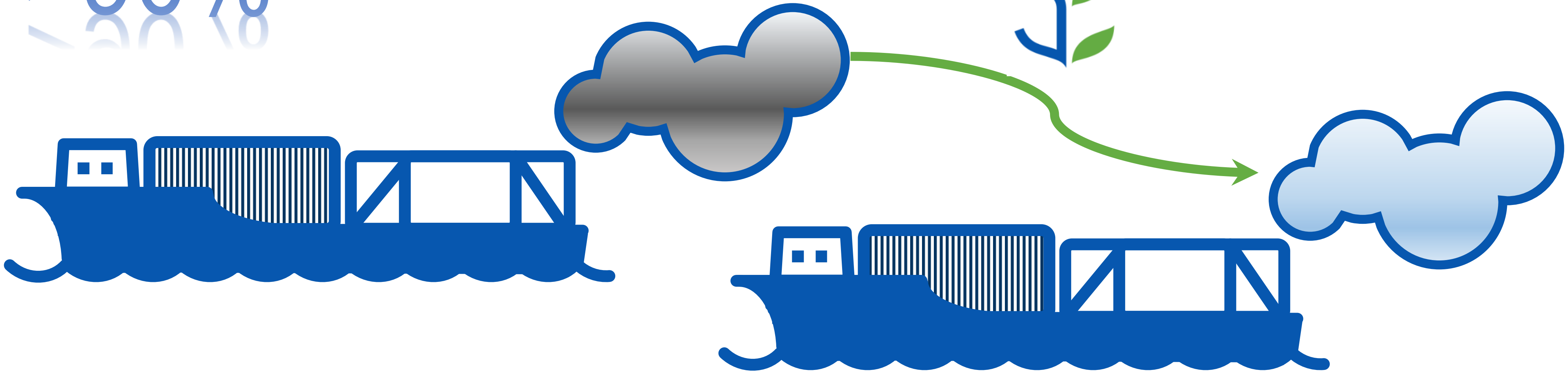
MemCCSea anchors for CLEANER SHIPS!



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Chemical Process and Energy Resources Institute

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EURONAV

GENERAL SECRETARIAT FOR RESEARCH AND TECHNOLOGY

ΕΣΠΑ 2014-2020
Partnership Agreement 2014 - 2020

European Union
European Structural and Investment Funds

Bundesministerium für Wirtschaft und Energie

The Research Council of Norway

Thank you!

http://memccsea.certh.gr


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