Benchmarking Large-scale Hollow Fiber Hybrid Facilitated Transport Membranes for CO_2 Capture from Low CO_2 sources

Saravanan (Ram) Janakiram[a], Ricardo Wanderley[a] , Luca Ansaloni[b], Vilde Andreassen[b], Mahdi Ahmadi[a], Maura Di Giovambattista[a], Thijs A. Peters[b]

[a] Aqualung Carbon Capture, Oslo, Høvik, Norway
[b] SINTEF Industry, Oslo, Norway

PCCC-8, Marseille

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Aqualung at a glance

Unlocking cost-effective carbon capture across all industrial production

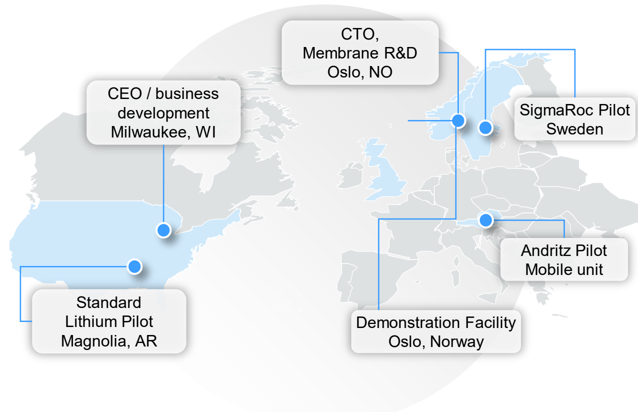
Company overview

- Aqualung is a provider of a cost-effective capture solution for a wide range of industrial emitters and fuel sources
- The Company's coated membranes utilize water vapor found within the flue gas to facilitate the movement of CO_2 across the membrane
- The membrane provides high CO_2 permeance and boosts CO_2 selectivity beyond standard solution diffusion membranes
- Aqualung will pursue multiple routes to market through CO_2 as a service
- Aqualung is backed by a strategic partnership with Denbury (ExxonMobil post acquisition close) the largest CO_2 pipeline operator in the world

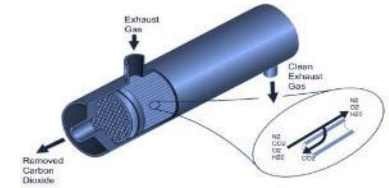
1st hollow-fiber membrane for flue gas

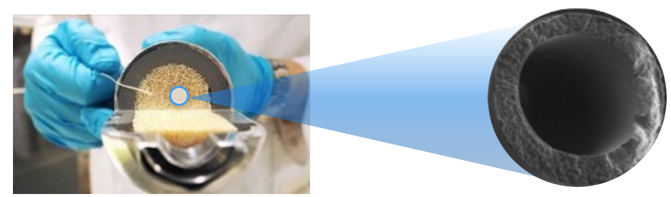
9 mtpa+ project backlog

Geographic footprint



Aqualung membrane technology





Customer value proposition

- ***Lower CapEx and OpEx***
- ***Compact & light***
- ***No absorbents***
- ***Modular & scalable***

Key partnerships to date

Nitto

ExxonMobil

ASH GROVE A CRH COMPANY

Standard Lithium

Delek US

Notes: (1) Based on 9mtpa commercialized project pipeline

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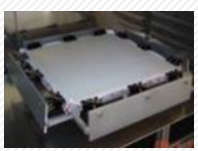
20+ years of R&D at NTNU to develop a breakthrough membrane CO_2 capture technology

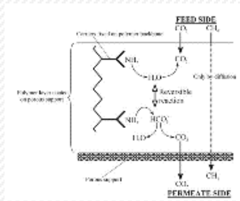
NTNU

2001
NTNU develops concept of fixed-site carriers

2004
NTNU files first set of patents on fixed site carrier with amine containing polymers



2006
NTNU files the patent on blend membranes using polyvinylamine and polyvinyl alcohol



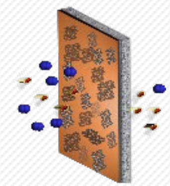
2009
NTNU files the patent on use of polyvinylamine and cross linked polyvinylamine for CO_2 separation applications

2010
NTNU files the patent on non crosslinked polyvinylamine and methods of purification of polyvinylamine for membrane applications

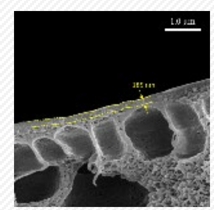
2013
Pilot deployment at Norcem alongside Air Products

NORCEM HEIDELBERGCEMENT Group

2017
NTNU expands research into mobile carriers and hydrophilic additives to increase performance



2018
New hybrid facilitated transport membranes developed both as flat sheet and hollow fibers



2019
NTNU deploys pilot at Colacem which sets the stage for patenting the Hybrid-Facilitated-Transport Membrane

COLACEM

2020
NTNU files patent for three phase hybrid facilitated transport membrane. Aqualung is established as the exclusive licensee

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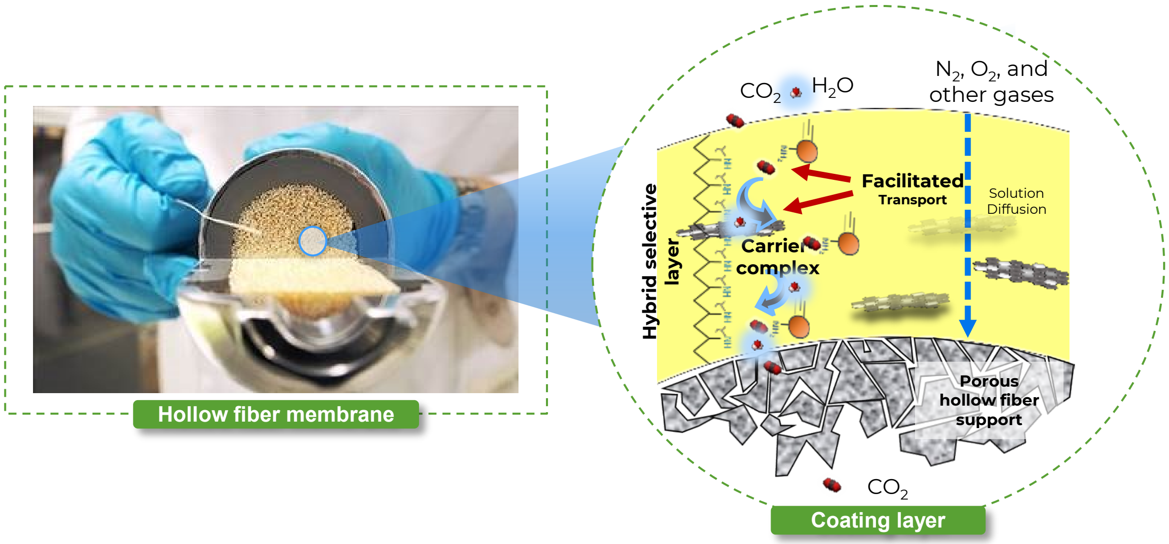
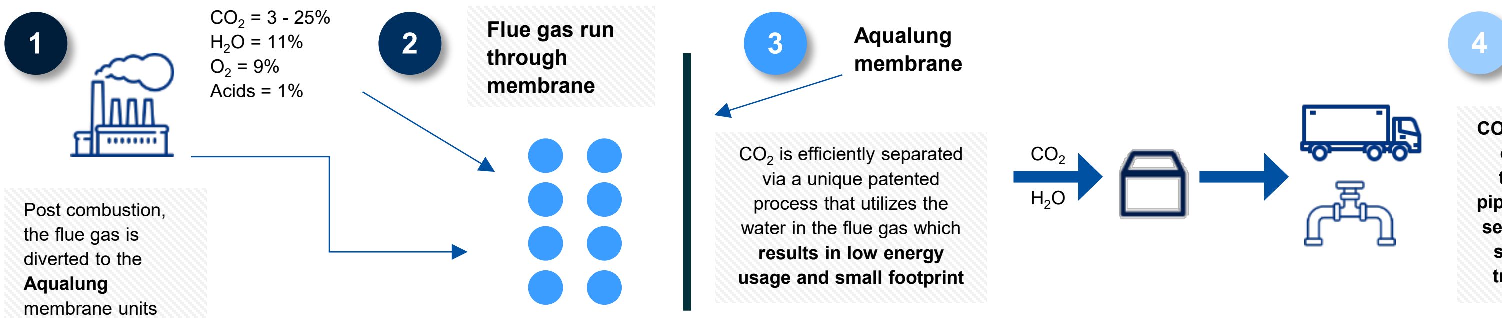
Aqualung technical solution – overview

The Aqualung solution visualized in detail



Hybrid facilitated transport membrane

- **Base polymer -** Facilitated transport membrane material enables thin coatings
- **Mobile carriers** – boosters for flux, fine-tuning amines
- **Graphene oxide –** stability, durability and water management



1 Post combustion, the flue gas is diverted to the **Aqualung** membrane units

2 **Flue gas run through membrane**

3 **Aqualung membrane**

CO_2 is efficiently separated via a unique patented process that utilizes the water in the flue gas which **results in low energy usage and small footprint**

4 **CO_2 purity can be optimized to transport via pipeline for EOR / sequestration or sent for liquid transportation**

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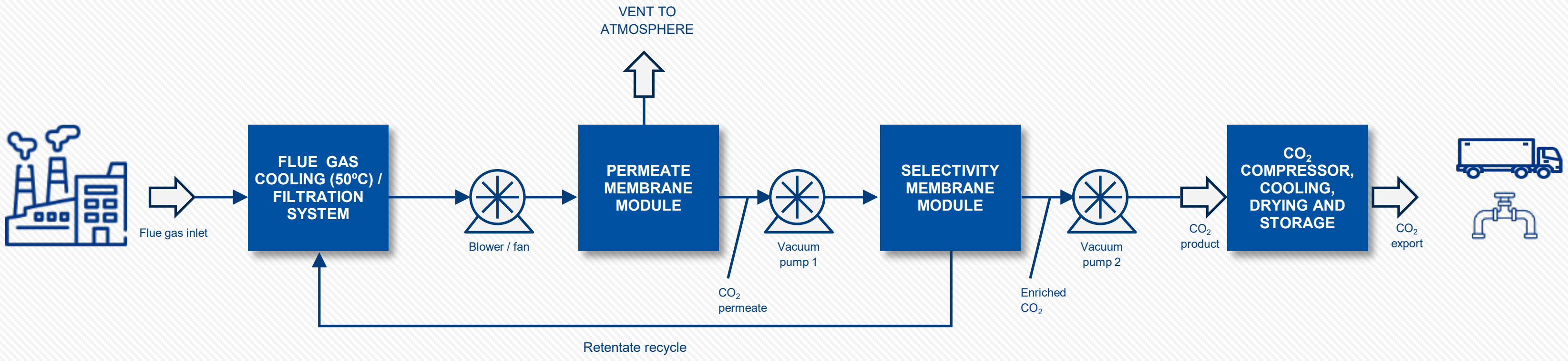
Aqualung stand-alone process flow at a glance

2-stage process flow diagram – simplicity drives down OpEx and CapEx



Key process highlights

- Low pre-treatment processes (cooling, filtering, no need for dehydration)
- The first stage is a permeance membrane used to set the overall capture rate (~90% capture rate)
- The second stage is a selectivity membrane used to set the CO_2 purity (~95%+ purity)
- Vacuum pumps facilitate low driving force across both membrane stages
- Process consists of multiple membrane modules operating in parallel stages
- CO_2 purity can be optimized for transport for EOR / sequestration / utilization

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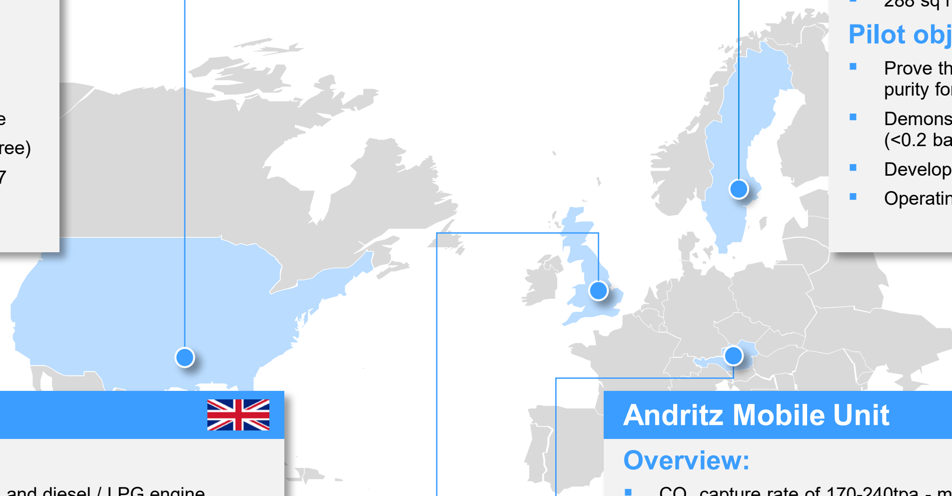
Unique technology proposition ready for industrial deployment



Standard Lithium Pilot

Overview:

- Rated to 1,000tpa from gas fired boiler at 2%-4% CO_2 concentration
- 640 sq meters membrane capacity
- Operated in Arkansas with Standard Lithium on Mission Creek's NGL processing plant

Pilot objectives:

- Provide capture rate >50% from low CO_2 source
- Concentrate to >40% in two stages (>95% in three)
- Develop ready-for-market solution by 2026-2027
- Operating since March 2023

SigmaRoc Pilot

Overview:

- Rated to 1,400tpa from lime kiln emission in Sweden at ~16% CO_2 concentration
- 288 sq meters membrane capacity

Pilot objectives:

- Prove the two-stage system (90% capture and 95% purity for high CO_2 cases)
- Demonstrate 95% purity under low feed-pressures (<0.2 bar gage)
- Develop ready-for market lime solution by 2025
- Operating since June 2023

Demonstration Facility

Overview:

- Test membrane performance with synthetic gas and diesel / LPG engine
- Single stage multi variable testing
- 25 sq meters membrane capacity

Pilot objectives:

- Optimize membrane design for full range of cases
- Fully benchmark all operating parameters
- Intermediate step before pilot deployment
- Operating since February 2024

Andritz Mobile Unit

Overview:

- CO_2 capture rate of 170-240tpa - multiple cases defined such as pulp & paper, waste-to energy at 5%-15% CO_2 concentration
- 96 sq meters membrane capacity

Pilot objectives:

- Prove two-stage system (>90% capture rate and 95% purity) for intermediate CO_2 sources
- Develop ready-for-market waste-to-energy solution by 2025-2026
- Delivery slated for 3Q 2024

Key project deployment highlights:

- *Skid construction time less than 8 weeks*
- *Full installation CAPEX less than $1,000,000USD for each project*
- *Proof of concept for scale-independent design*
- *Fast commissioning – from delivery on-site to flue gas ops in <2 weeks*

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Journey to Large-scale modules production and relevant checklist

Both counter current flow and humidification is required

Material sourcing

Support
Selective layer
Other layers

Small scale Coating

- ❑ Scalability
- ❑ Use of toxic solvents
- ❑ Productivity/Automation possibility
- ❑ Simplicity (costs)

Lab scale modules

- ❑ Low stage-cut performances

Pre-pilot modules

- ❑ High packing density modules
- ❑ Module efficiency
- ❑ Flux and Purity trade-off tests @ varying stage-cut
- ❑ Performance across varying driving force
- ❑ Performance at operating conditions

Large scale module production

- ❑ Productivity
- ❑ Automation possibility
- ❑ Coating efficiency
- ❑ Costs

Feasibility and plant design team
Remember the end user needs!

Pilot testing

- ❑ Process parameters
- ❑ Operational flexibility

CHECKLIST

- ❑ Cost of supports
- ❑ Support fiber production capacity
- ❑ Selective layer content availability (CRMs)
- ❑ Selective layer content reproducibility (QA)
- ❑ Stability (shelf-life) of layer coating solutions

Product roll out!

Testing platform and benchmarking criteria are NOT the same!

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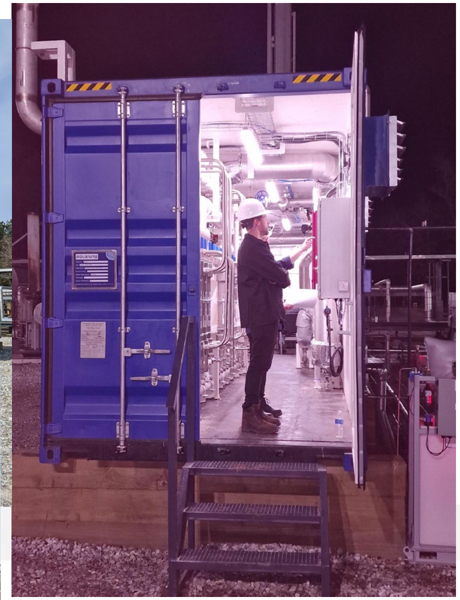
Current pilots in US and Sweden

Commissioned
March 2023
1900 kg/h
3-5% CO_2
Requirement >60%



Standard LITHIUM

Commissioned
June 2023
800 kg/h
15-25% CO_2
Requirement
>90%

Nordkalk

Our journey at the pilots

Membranes

- Parker modules – Air separation (high pressure applications)
- PPO hollow fibers
- Coated insitu with techniques developed inhouse

Plant

- 2-stage system with recycle
- Minimal pretreatment changes

Highlights

- 2 stage operation with membranes under 1.2 bar feed pressure on the flue gas
- Facilitated transport at industrial scale with humidity control
- High purity in Nordkalk (98 vol% from 14 vol%)
- High up concentration in SLI (32 vol% from 2-3 vol%)
- Membrane stability despite significant process disturbances

Issues and takeaways

- Process uptime – site specific disruptions
- Low capture rate (10-20% at each stage) – low membrane throughput
- Membrane limitations
  - Flux
  - Operational temperature
- Results have fed back into the membrane development
- Process upgrades implemented on site and fed into nextgen-design

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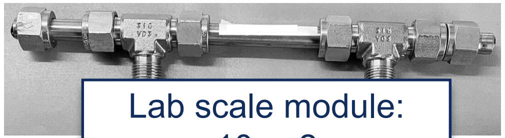
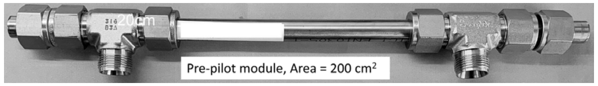
Technology Scale Up various module designs

The combination of commercial and bespoke modules (developed specifically for CO_2 separation by Aqualung and their technical partners) is key to optimising and scaling up the technology; unlocking deployment onto larger emission sources.



Lab scale module: 10cm2



Pre-pilot module: 200cm2 – 0.2 m2

Test Rig/2nd stage module: 2m2

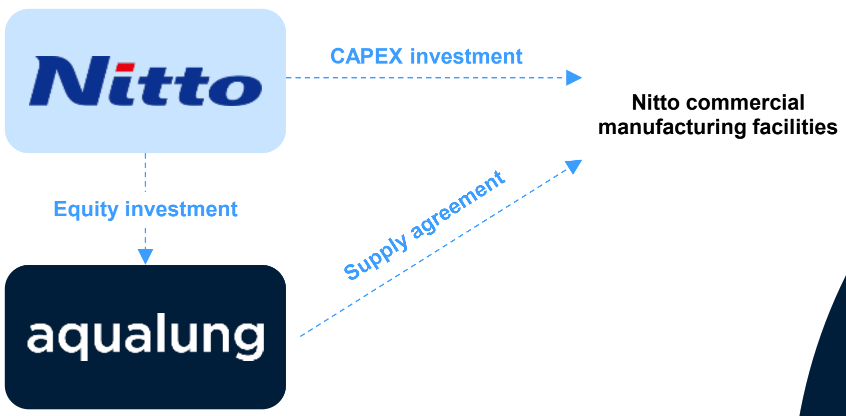
Bespoke Modules: 2-4m2

Pilot 1st stage module: 8 m2

Aqualung – Joint Development Agreement

JDA –custom-designed membranes with commercial production capacity

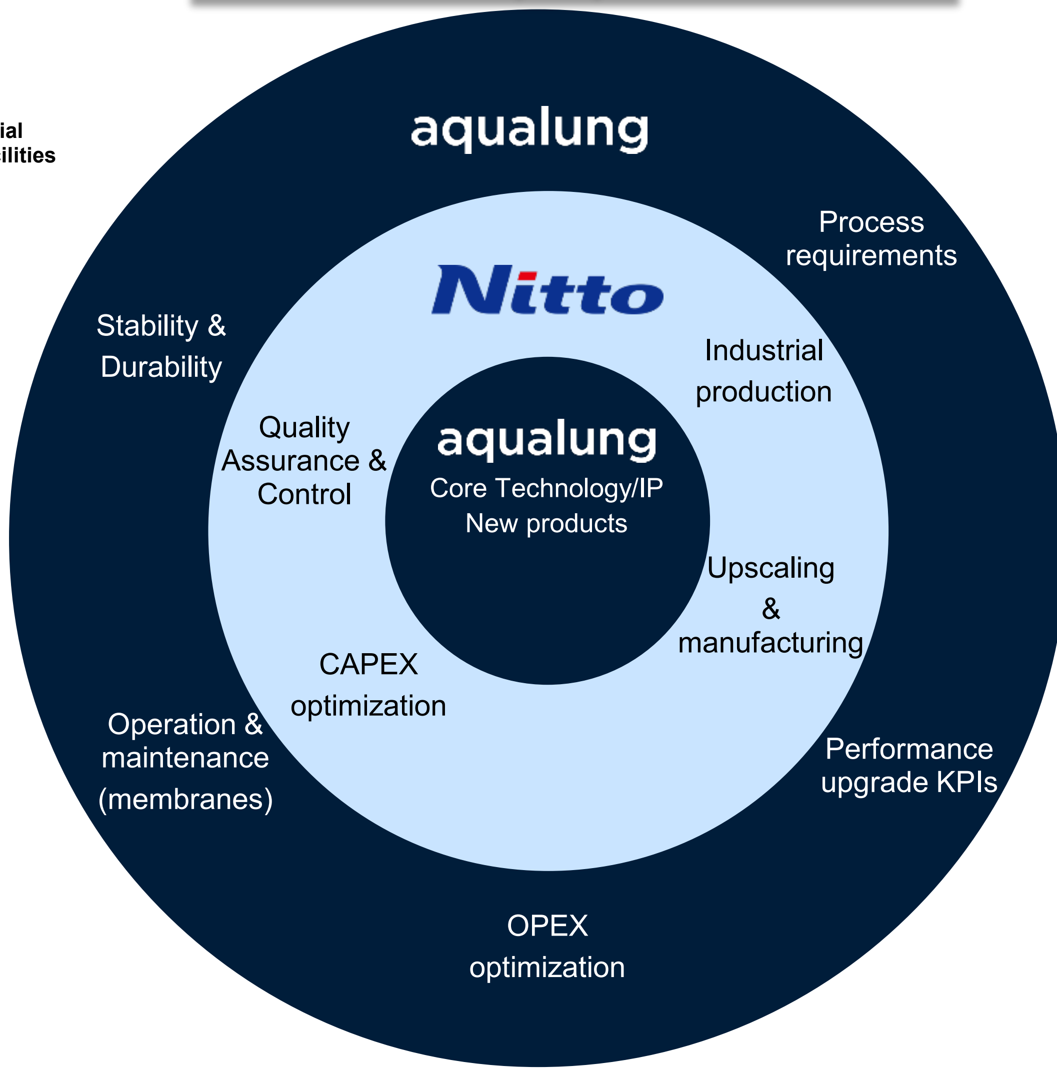
Transaction structure



Key highlights

Purpose	✓ Scale-up Aqualung's facilitated transport membrane coating to produce industrial scale products at Nitto's manufacturing facilities ✓ Agreement between Aqualung and Nitto sets the stage for unrivaled scale and continued technology advancement
Scope	✓ Nitto and Aqualung to jointly develop: 1. Bespoke hollow fiber 2. Upscaled module design 3. Large-scale integrated hollow fiber production, coating and module manufacturing facility
Outcome	✓ The successful deployment of the JDA will provide Aqualung with the capacity to deploy over 2mtpa of CO_2 capture units

Scope of parties



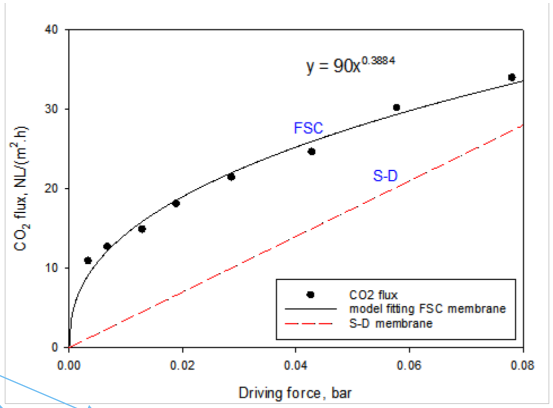
Notes: (1) Supply agreement in negotiation (2) Effective April 5th, 2024

Evolution of membrane solutions

Work alongside Nitto for a competitive product

Most important metrics that define the membrane stage competitiveness

CO_2 flux **CO_2 purity** **Gas processing efficiency**



CO_2 flux = (Permeability / thickness) x driving force

CO_2 flux = (S x D/thickness) x driving force

CO_2 flux = (S x D/thickness) x driving force + FT component x driving force $^{x<1}$

Solution diffusion — Facilitated transport

Selective layer

- Polymer + amine chemistries
- Reactive Permeance and selectivity
- Temperature vs CO_2 flux effects

$FT = f(T, X_{NH2}, RH)$

Fiber + coating

- Quality at scale
- Minimum thickness (maximizing permeance)
- Fiber that is designed for purpose

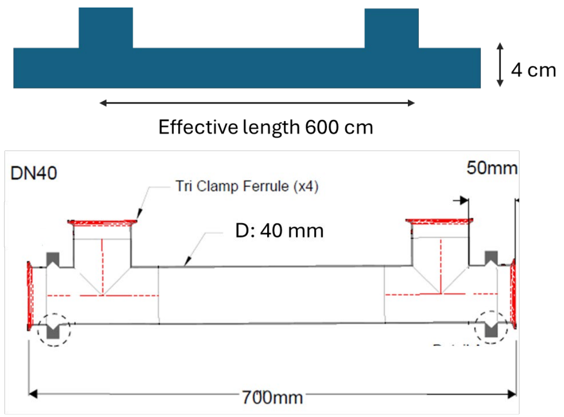
Module + Process

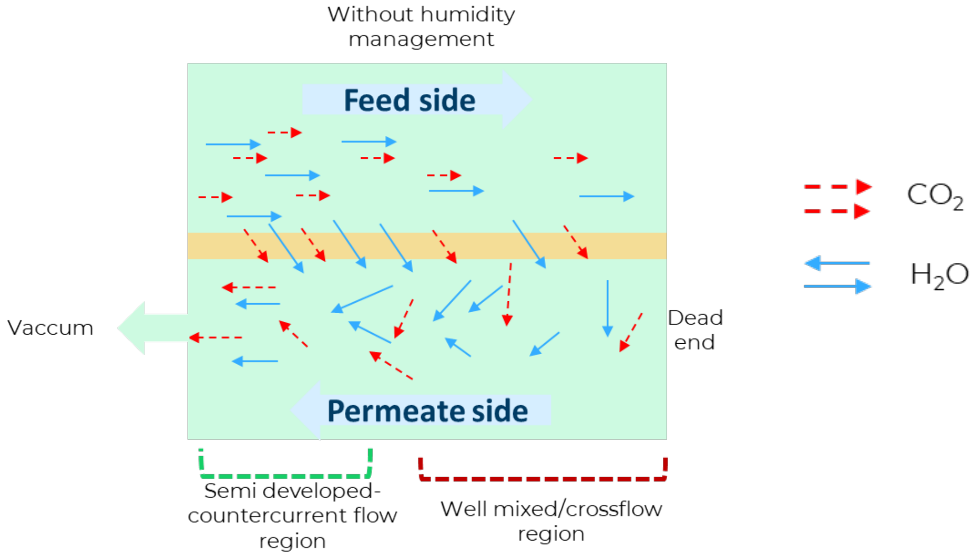
- Low pressure module design
- Maximizing facilitated transport effect – temperature control
- Water management

Favorable process conditions

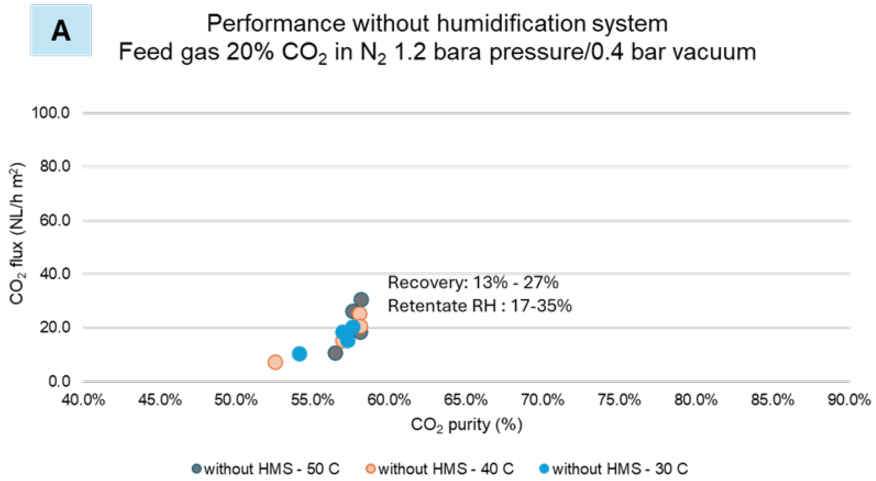
Module and flow limitations for humidity management and recovery

Both counter current flow and humidification is required



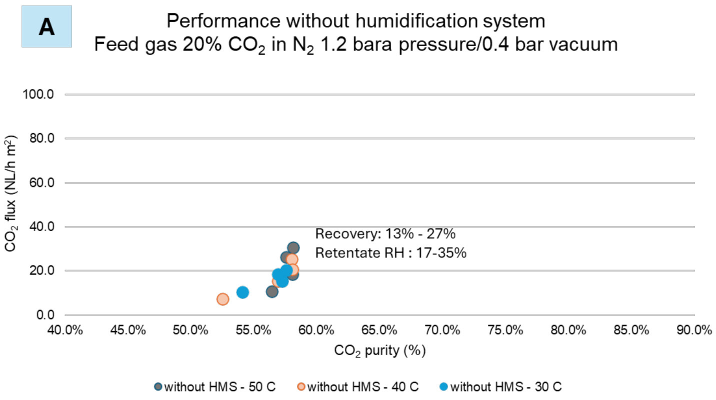


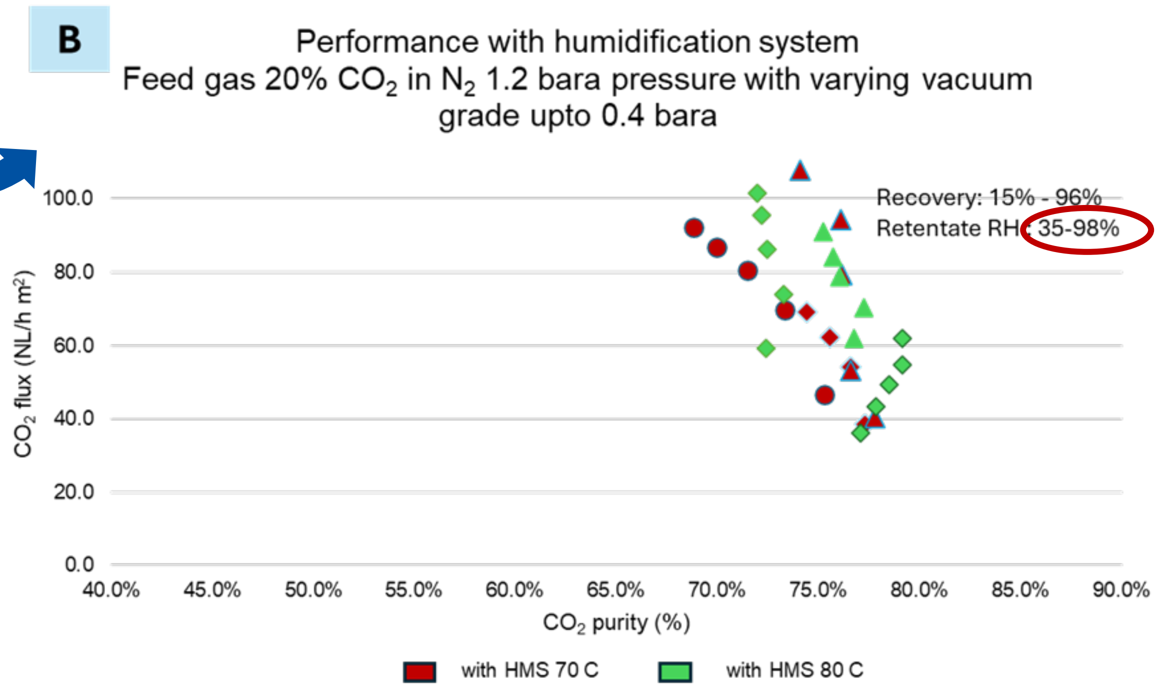
- Gen 2 modules designed for high T operation
- Higher temperatures preferred for FT effects
- RH management challenging at high T



Performance of Gen2 modules for high CO_2 concentration (single stage)

Increasing temperature - effects of RH





- Water permeation hindrance contributes to flux and purity improvements
- Facilitated transport effect at higher temperatures

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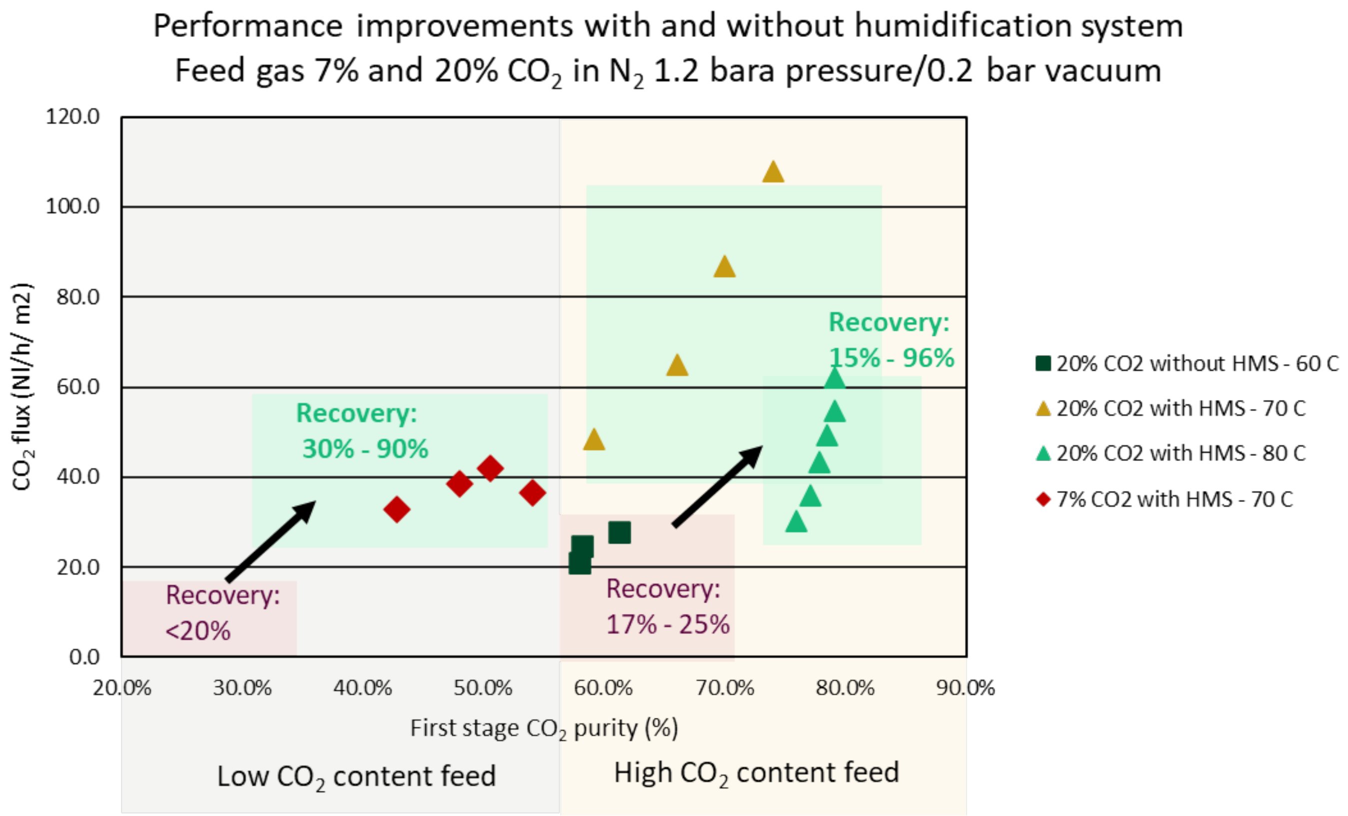
Performance of Gen2 modules for low & high CO_2 concentration

Use of HMS enables high temperature operation – maximizing facilitated transport



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Update on pilot performance

Pilot overview

- ✓ Aqualung has proven the recovery, purity, and commercial viability of its technology through four operational test and pilot facilities
- ✓ The Company continues to apply operating learnings to optimize design for both low and high-concentration sources
- ✓ Results demonstrate clear progress towards commerciality with line of sight to significant scale

Achievements

99% maximum recovery

97% maximum 2nd stage purity

Test campaign summary, high CO_2 feed (20%)

Recovery	Dry feed CO_2 comp (%)	1st stage CO_2 dry purity (%)	TPA / m^2	kWh / t (2-stage system to >95% purity)
50%-60%	20	73	1.20	232
70%-80%	20	69	1.60	257
90%+	20	59	0.80	263

Test campaign summary, low CO_2 feed (7%)

Recovery	Dry feed CO_2 comp (%)	1st stage CO_2 dry purity (%)	TPA / m^2	kWh / t (2-stage system to >95% purity)
50%-60%	7	~55%	0.70	381
70%-80%	7	~43%	0.60	389
90%+	7	~33%	0.45	420

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- ➢ The pilots have shown purity and how proper gas distribution and inlet condition control can be achieved at scale
- ➢ Demo rig operations to date shows how the individual module, without much amendment, can be made to perform properly in a facilitated transport membrane
- ➢ These data points together provide a powerful proof of scale, and feeds further into the JDA upscaling work with Nitto Denko

High CO_2 concentration case capture solution - Current pilot demonstration and JDA targets

Highlights

High purity

- ✓ Our current demonstrations indicate high purity in single stage even at high recoveries upto 90%
- ✓ 60-75% dry vol% in one stage due Facilitated transport effect

KWh/tonne

- ✓ Current system operates at 30-40% higher KWh/tonne
- ✓ Main gaps come from pressure drop and module designs addressed in JDA

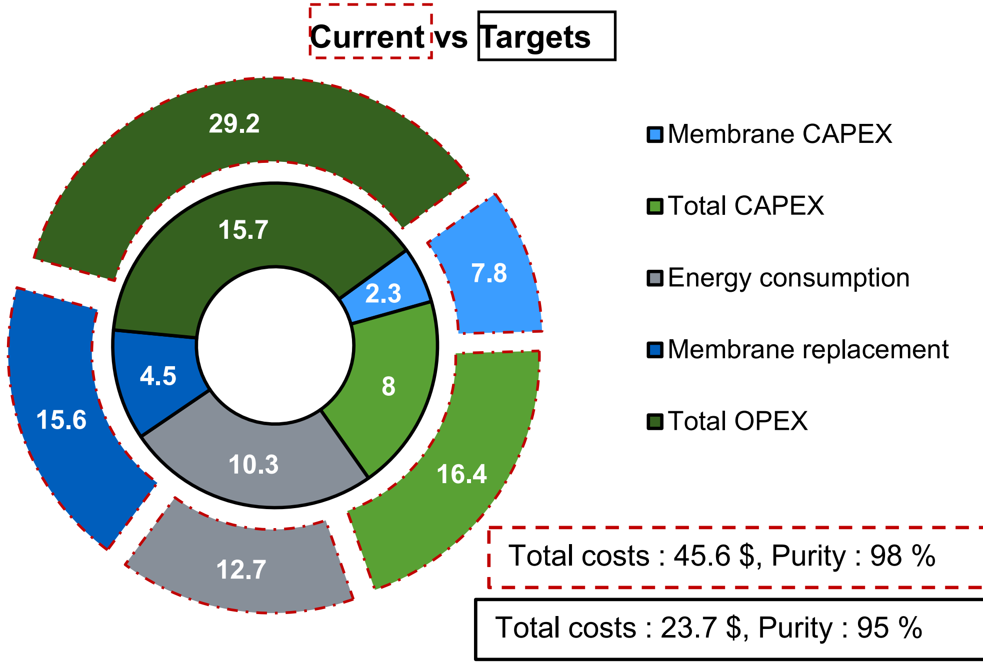
Membrane productivity

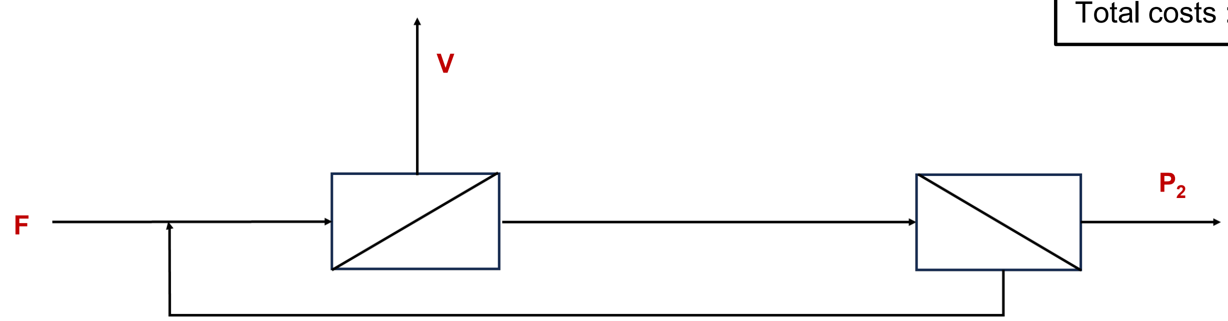
- ✓ Membrane productivity (TPA CO_2/m^2) is currently 40% of the targets
- ✓ Main gaps arise from fiber and the coating

Clear path to scale

- ✓ JDA membranes and module design target bridging largest gaps in the costs.
- ✓ FT effects will further outperform KWh/tonne CO2 if inherited

Capture cost distribution





Two-stage process operating at 1.2 bara/0.2 to 0.4 bara vacuum 15-20% CO_2 to 95% CO_2

Low CO_2 concentration cases – Status update - Current pilot demonstration and JDA targets

Key benefits

Bulk separation

- ✓ Current system processes low CO2 concentrations (4-10%) and upconcentrates in a single stage under non pressurized flue gas conditions
- ✓ Case presented 80% recovery. Upto 98% recovery in one stage

KWh/tonne

- ✓ Current system operates at 30-40% higher KWh/tonne
- ✓ Main gaps come from pressure drop and module designs addressed in JDA

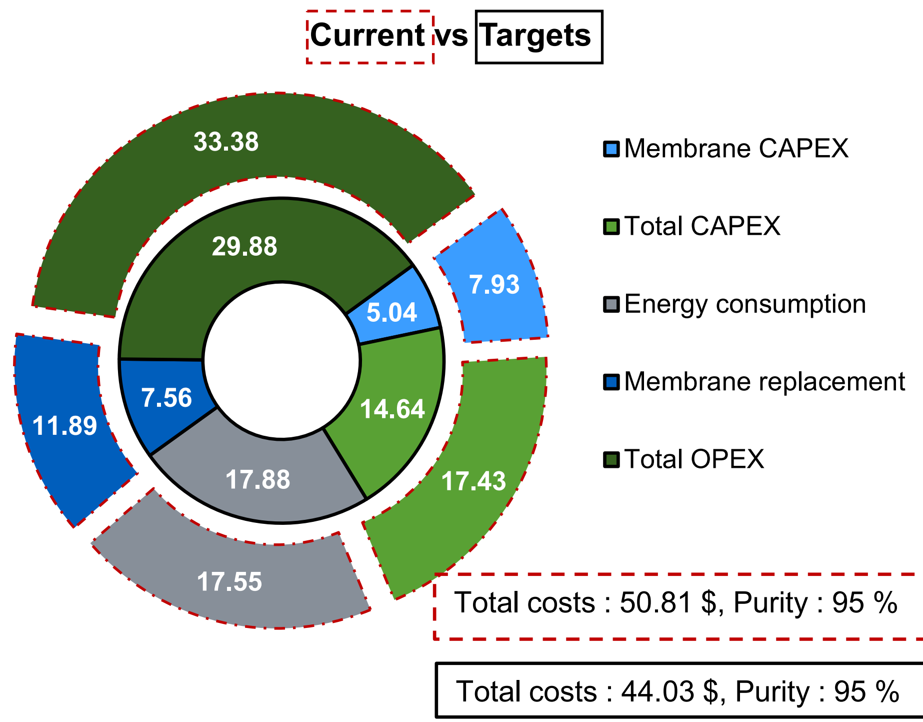
Membrane productivity

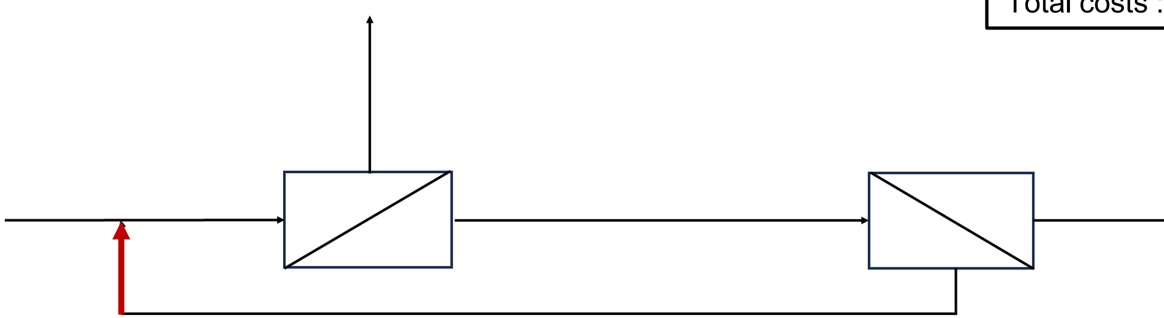
- ✓ Membrane productivity (TPA CO_2/m^2) is currently 65% of the targets
- ✓ Main gaps arise from fiber and the coating
- ✓ Low CO2 concentration also requires unique module design to increase the gas processing efficiency (lower OPEX)

Clear path to scale

- ✓ Aqualung membranes have proven stability towards degrading species in flue gas thus boosting performance lifetime

Capture cost distribution

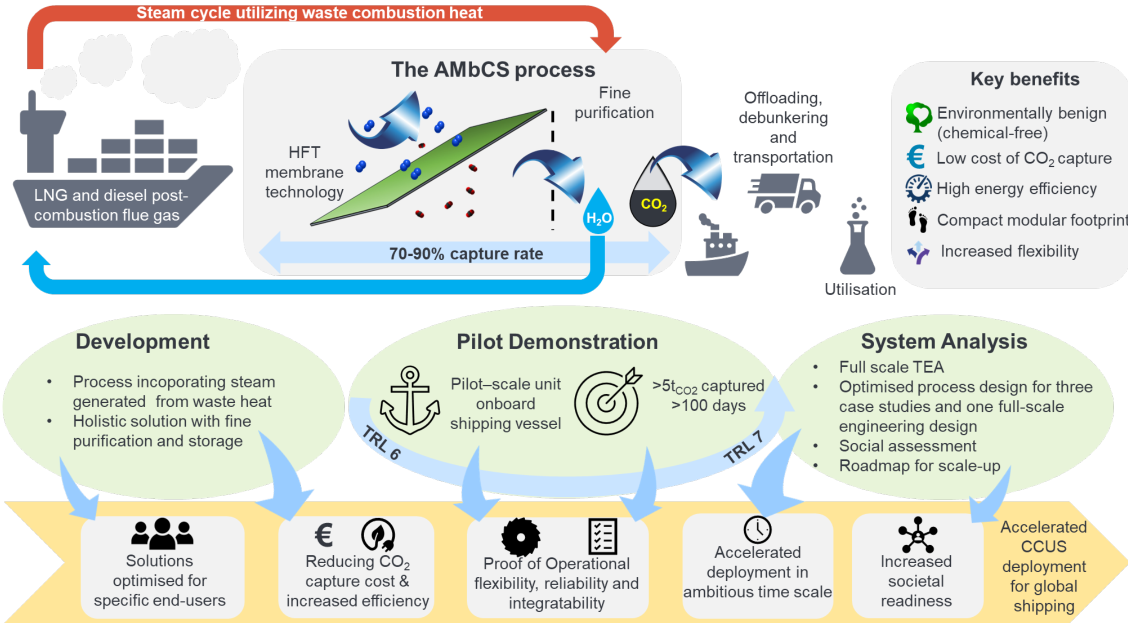




Two-stage process operating at 1.2 bara/0.2 to 0.4 bara vacuum 5-7% CO_2 to 95% CO_2

Upcoming pilots

CETP – AMbCS project



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AMbCS

Advanced Membrane-based solutions for CCUS in Shipping

aqualung ANDRITZ VICTROL NTNU SINTEF REDERI AB GOTLAND

Acknowledgements

CETP project, 348564

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