Accelerating Industrial Carbon Capture: Innovations and Pathways to Impact

Overview of CCUS Innovations at TNO Petten (STIP)

Soraya Sluijter, December 2025, CATO Winter event

Sustainable Technologies for Industrial Processes

~4400
Employees

>1300
Public-private partnerships

>1000
Patents

CATO EVENT

Sustainable Technologies for Industrial Processes

Technology development and scale-up

We develop core technologies to enable industrial transformation and contributing to a reliable sustainable energy system

- In-process CO_2 capture and conversion
- Sustainable industrial heat systems
- Production of green hydrogen

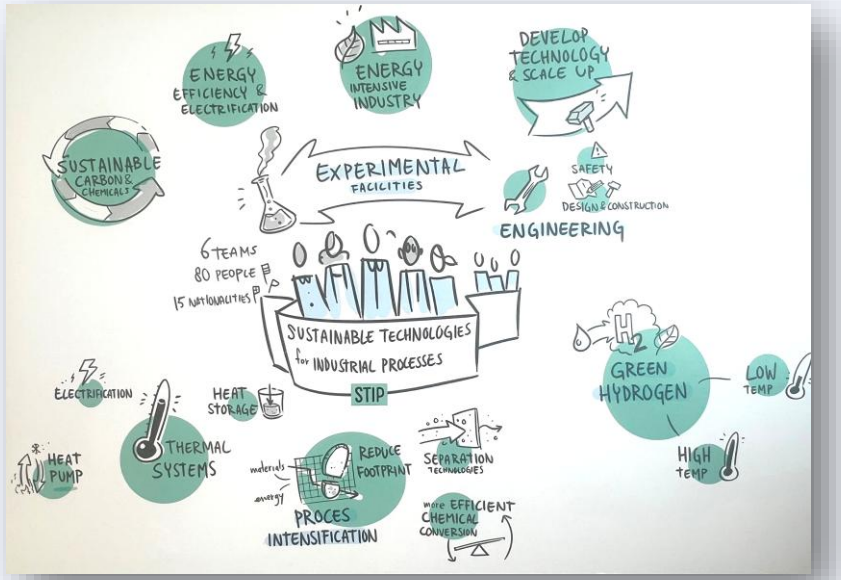
Key knowledge and expertise

Cutting edge knowledge and expertise enable us to innovate and scale-up technologies & have tangible impact on industrial transformation

- Separation enhanced synthesis
- Membrane technology
- Heat pumps & heat storage
- Process intensification
- Electrolysis
- Engineering for piloting & up scaling

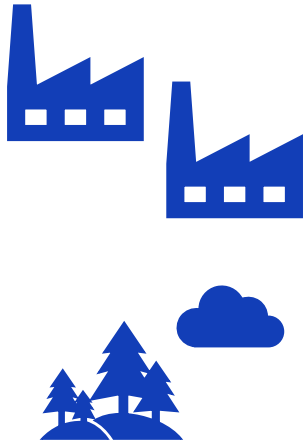
State of the art research facilities

Our research facilities open up new possibilities to fast- track innovations to a higher TRL level



Carbon Capture Utilisation and Storage at TNO

Value chain orchestration, system engineering approach, TEA, LCA



Capture

Capturing CO_2 from an industrial facility

Transport

The compressed CO_2 is moved by ship, truck or pipeline from the point of capture to the point of utilisation or storage.

Utilisation

Captured CO_2 is used as a resource or feedstock to create products and services.

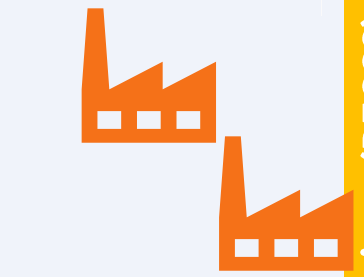
Storage

Storing CO_2 permanently in onshore and offshore geological formations.

- GHG measurements and (dispersion) modelling
- Technology development for efficient and electrified capture & purification from hard to abate Industry
- Simulations & experiments for safe and efficient transport
- Subsurface modelling & monitoring for safe and permanent CO_2 storage
- Process integration & electro- and thermochemical conversion to platform chemicals

https://climate.ec.europa.eu/eu-action/industrial-carbon-management/about-industrial-carbon-management_en

Overview Industrial Carbon Capture at TNO



Hard to abate industry

Negative emissions (BECCS)

Capture

In process capture

- TRL8 demo in the Iron & Steel industry
- SEWGS robust platform technology , TRL7 BECCS, increased efficiency

Post-combustion capture

- DORA and on-line monitoring standard in PCC
- Capture plants are equipped with mitigation technology
- *Electro-chemical regeneration at TRL8*
- *TNO established as knowledge partner for industry on electrified carbon capture*

DAC

Purify

CO_2 quality

- Processes and value chain to reach CO_2 specs
- Chemical looping at TRL5

Transport

The compressed CO_2 is moved by ship, truck or pipeline from the point of capture to the point of utilisation or storage.

Utilisation

Captured CO_2 is used as a resource or feedstock to create products and services.

Storage

Storing CO_2 permanently in onshore and offshore geological formations.

Reduce CO_2 in the atmosphere, with a focus on hard to Abate Industries.

- TNO is leading in development, upscaling and implementation of pre-combustion/separation enhanced CCS technologies
- Post-combustion technologies are applied in 20% of the amine-based CO_2 capture market, lowering costs and negative environmental impacts
- TNO enables high purity CO_2 to meet strict specifications for transport and storage

TNO Value proposition

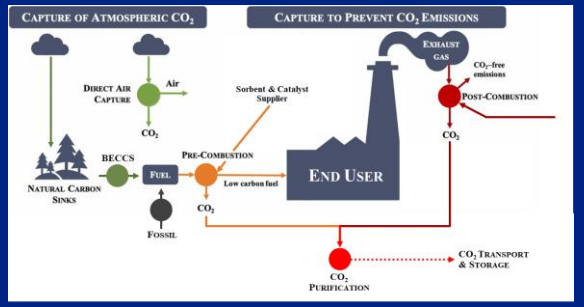
Problem & Opportunity

- Industrial sectors dependent on fossil carbon
- EU need for resource independence
- Hard-to-abate industrial sectors face urgent decarbonization challenges

Our unique Value

- Low to high-TRL technologies with robust IP portfolio
- Dedicated models & testing facilities
- Process design & engineering and sector-specific integration

Technical focus areas



- Solvent based post-combustion capture
- Separation enhanced in process capture & CO_2 conversion
- CO_2 quality: purification for transport, storage and reuse

Collaboration models

- Contract R&D and Consultancy
- Subsidized research collaboration
- Licensing and joint development

Scaling up Separation Enhanced CCUS technologies

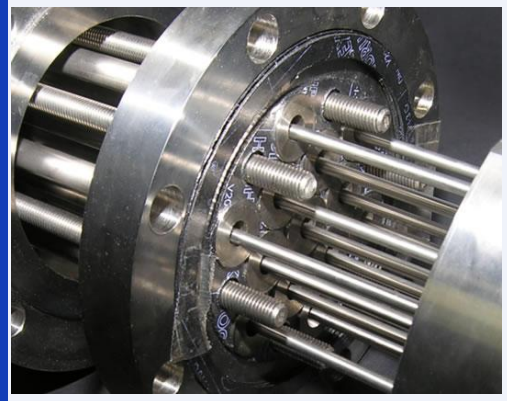
Examples of STIP CCUS innovations

Separation Enhanced processes How?

$$A + B \rightleftarrows C + D$$

$$A + B \longrightarrow C\downarrow + D$$

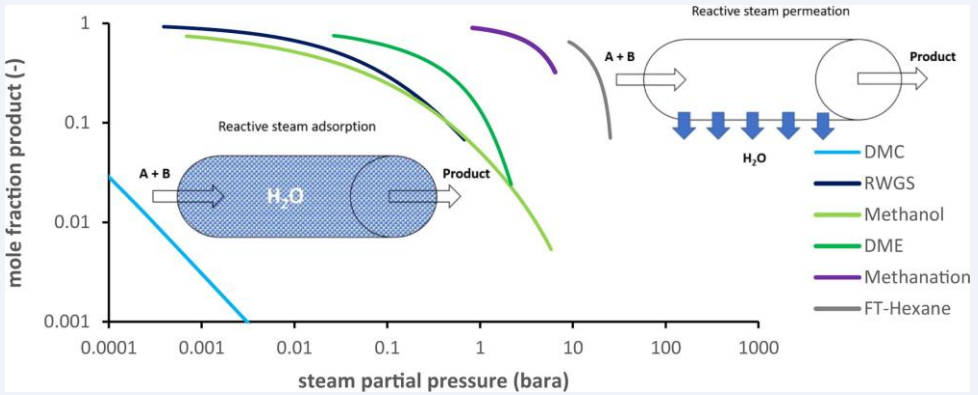
Henry Louis Le Chatelier
(1850 –1936)



$C = H_2$

$C = CO_2$

$C = H_2O$



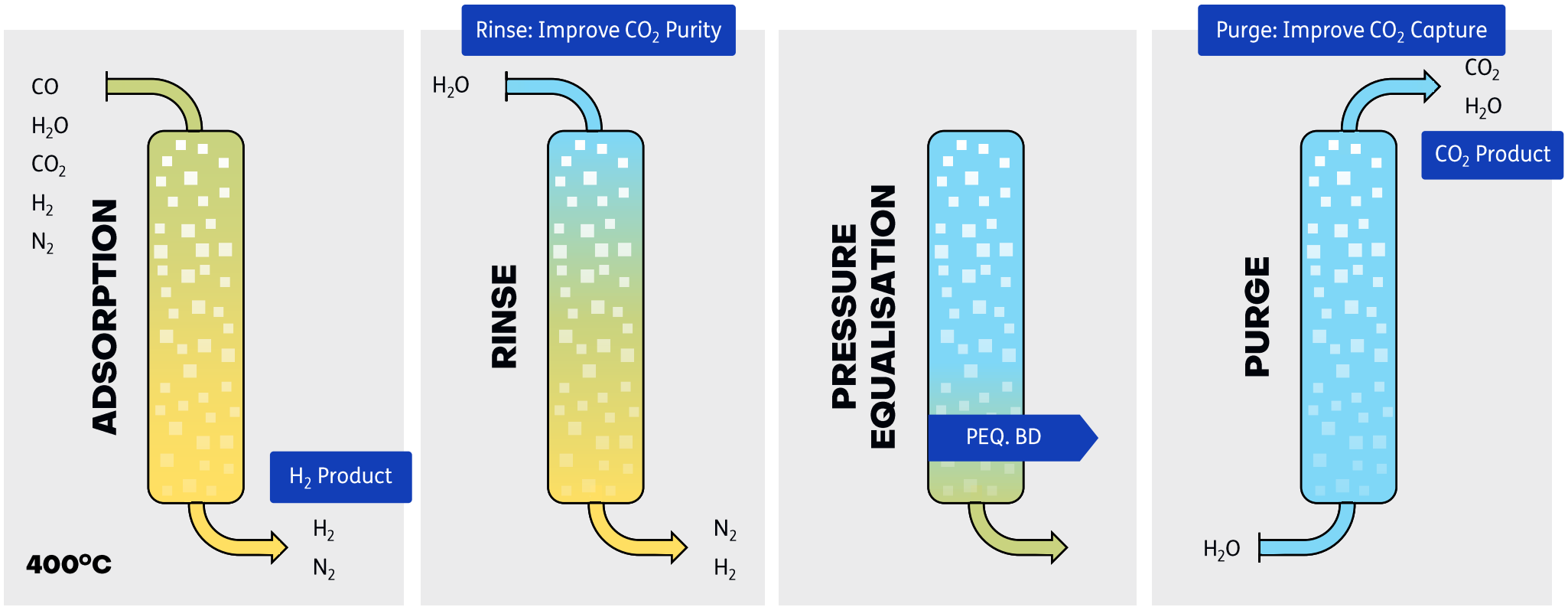
Steam separation enhanced reactions: Review and outlook - ScienceDirect

Sorption-Enhanced Water-Gas Shift (SEWGS)

CO_2 purity up to 95%

Carbon Capture rate up to 100%

Cost reduction compared to SotA 28%

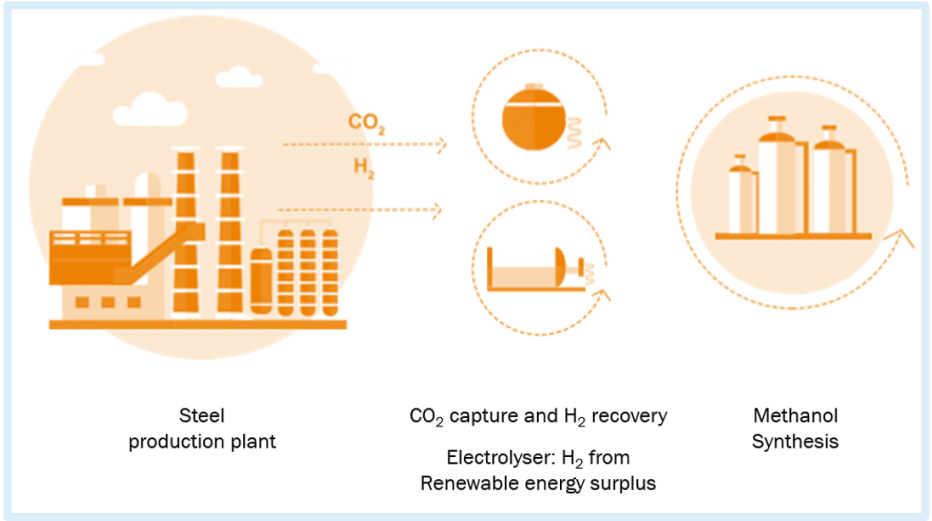


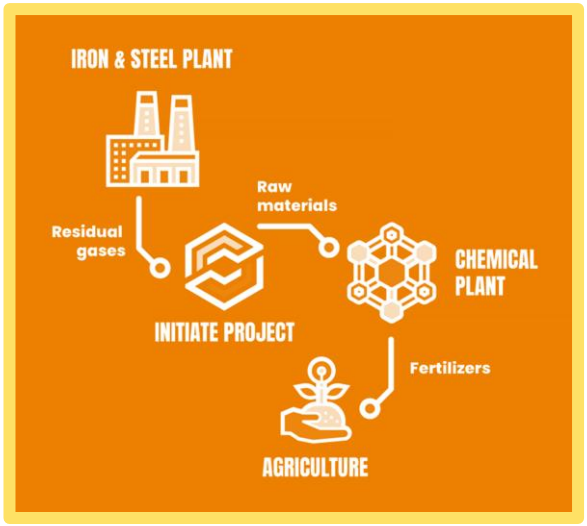
$CO + H_2O \rightarrow CO_2 + H_2$

$CO_2 + ads \rightarrow CO_2\text{-ads}$

Functional material: K-promoted Mg/Al hydrotalcite | Active for both CO_2 capture and Water Gas Shift

SEWGS applications: CO_2 from Steel Industry to use





Successful campaign in Lulea Nov. 2025: >150 ton CO_2 captured!

CCUS ready CO_2

CO_2

Steel gas (BOFG/BFG)

SEWGS

H_2/N_2

H_2/N_2 separation

H_2

Methanol synthesis

FReSM

H_2/N_2

H_2/N_2 purification

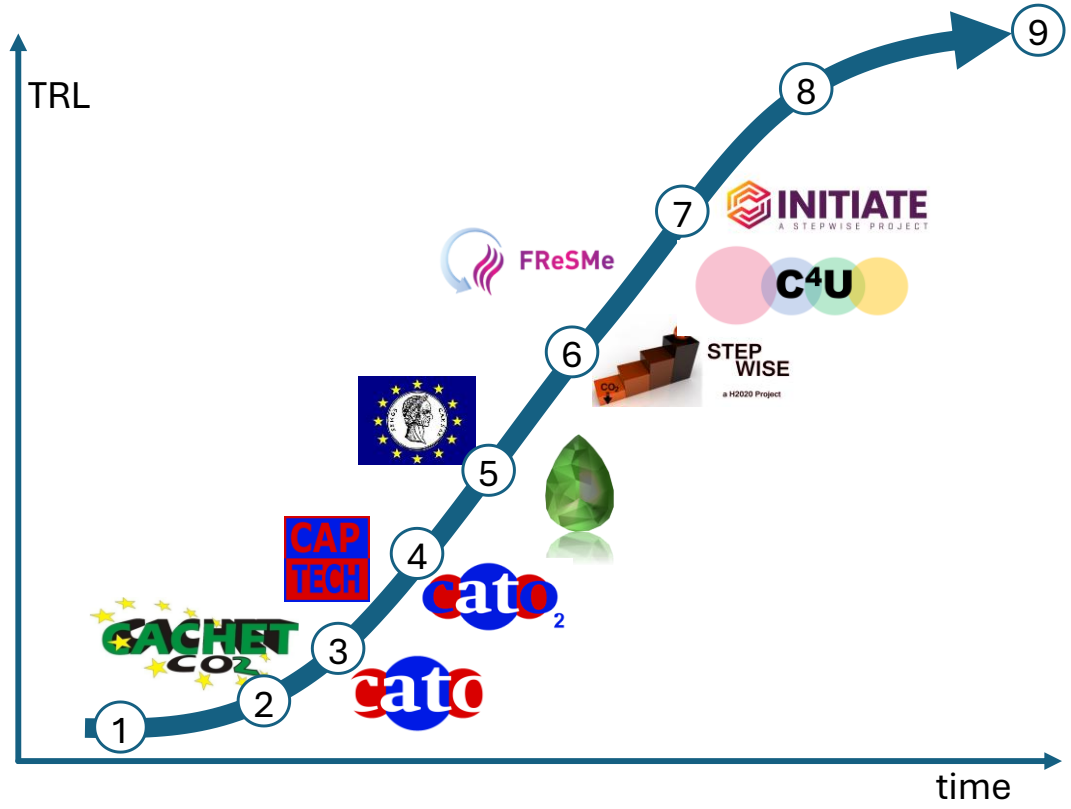
H_2/N_2

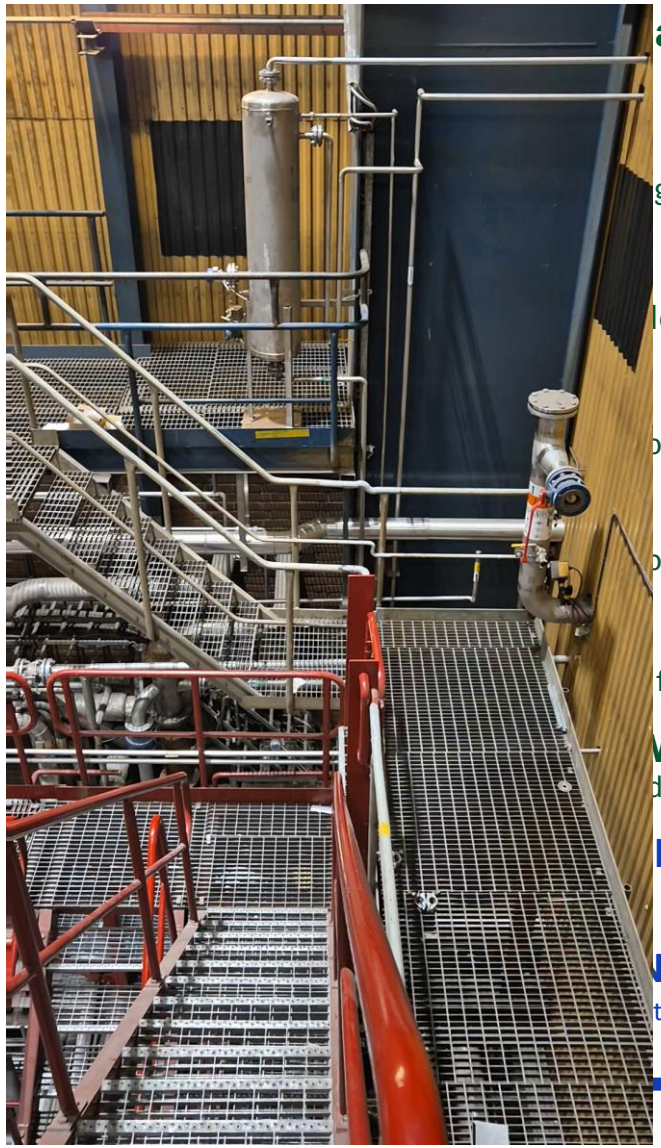
NH_3 synthesis

Urea synthesis

INITIATE
A STEPWISE PROJECT

SEWGS timeline: Scaling-up in projects





at lab scale

gle column.

levelopment, low steam use

o at Steel plant (Lulea, Sweden)

o for Methanol

for Ammmonia

MENT

d with Paul Würth Italy in Iron & Steel

D (IF) PROPOSAL

NDUSTRY OPERATIONAL

teel industry

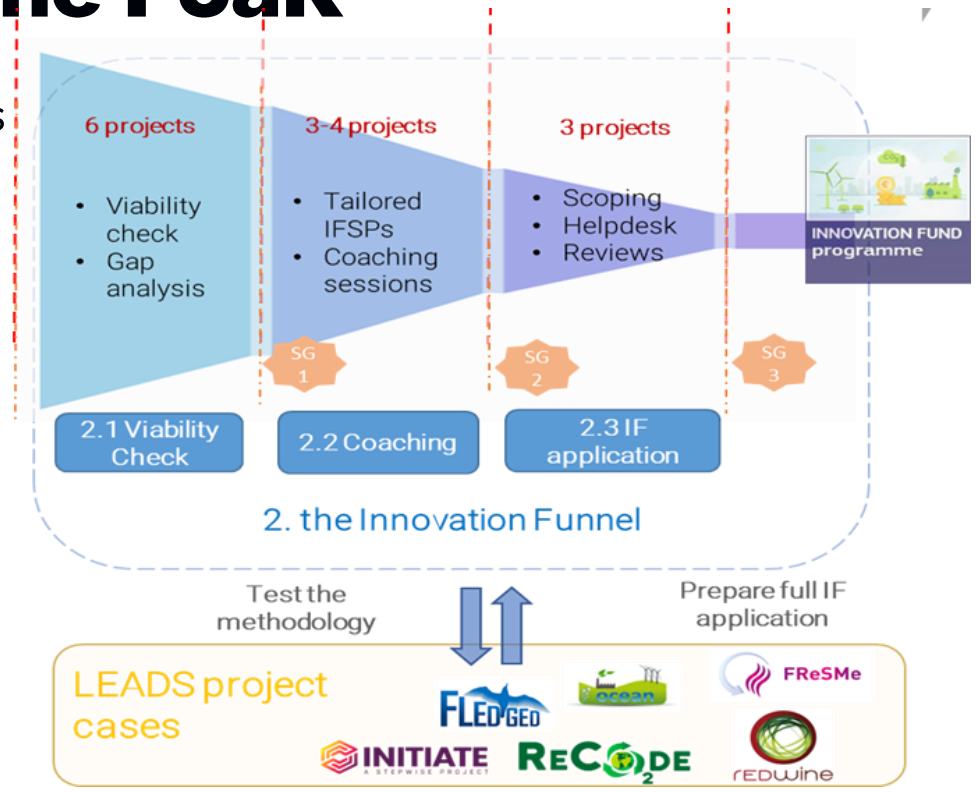
TNO innovation for life

LEADS

BRIDGING THE INNOVATION GAP

LEADS to support road towards the FoaK

- Bridge the gap between Horizon and Innovation Fund for CCUS projects



- Assess viability of TNO SE-CCUS technologies for IF
- Learnings so far:

1 IF: Determining product is key and depends on end-user

2 TNO will not be the party to apply for innovation fund, building consortium remains key!

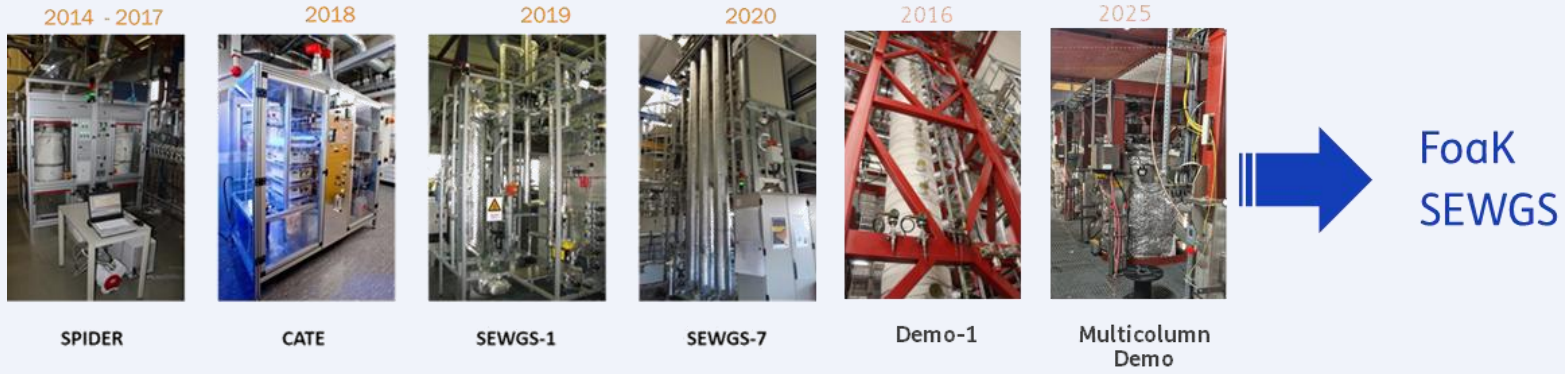
3 Keep involving relevant partners and study TEA & LCA as early as possible

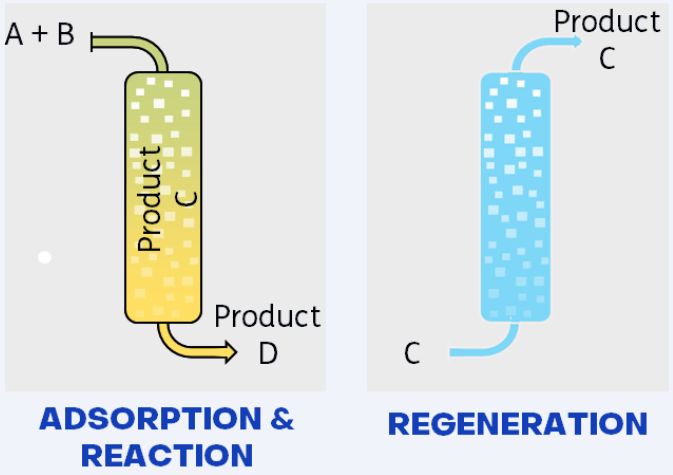
https://www.aspire2050.eu/leads

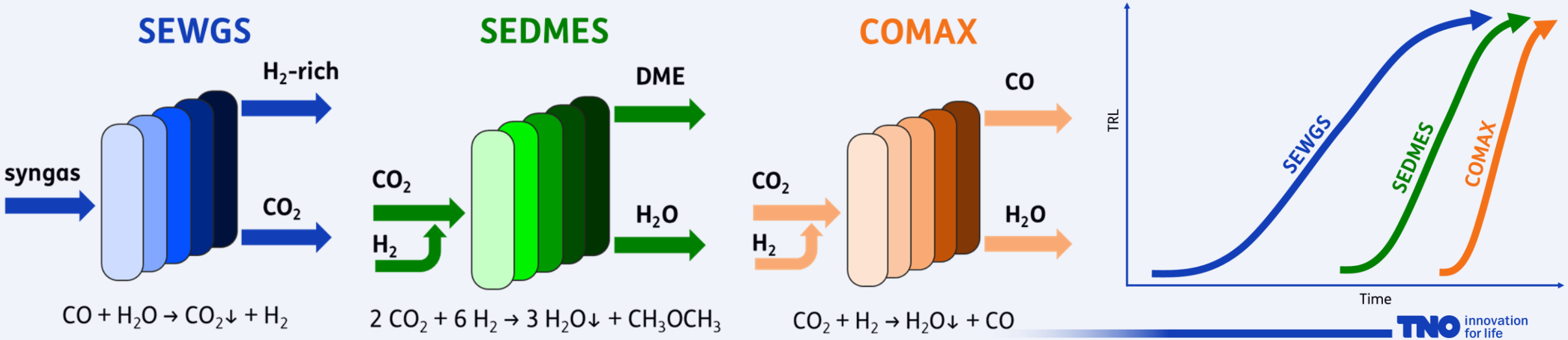
LEADS

Scaling up Sorption Enhanced CCUS

The development and scale-up of SEWGS (Sorption Enhanced Water Gas Shift) created a knowledge and infrastructure platform enabling a kickstart and accelerated development of Sorption Enhanced CCUS technologies

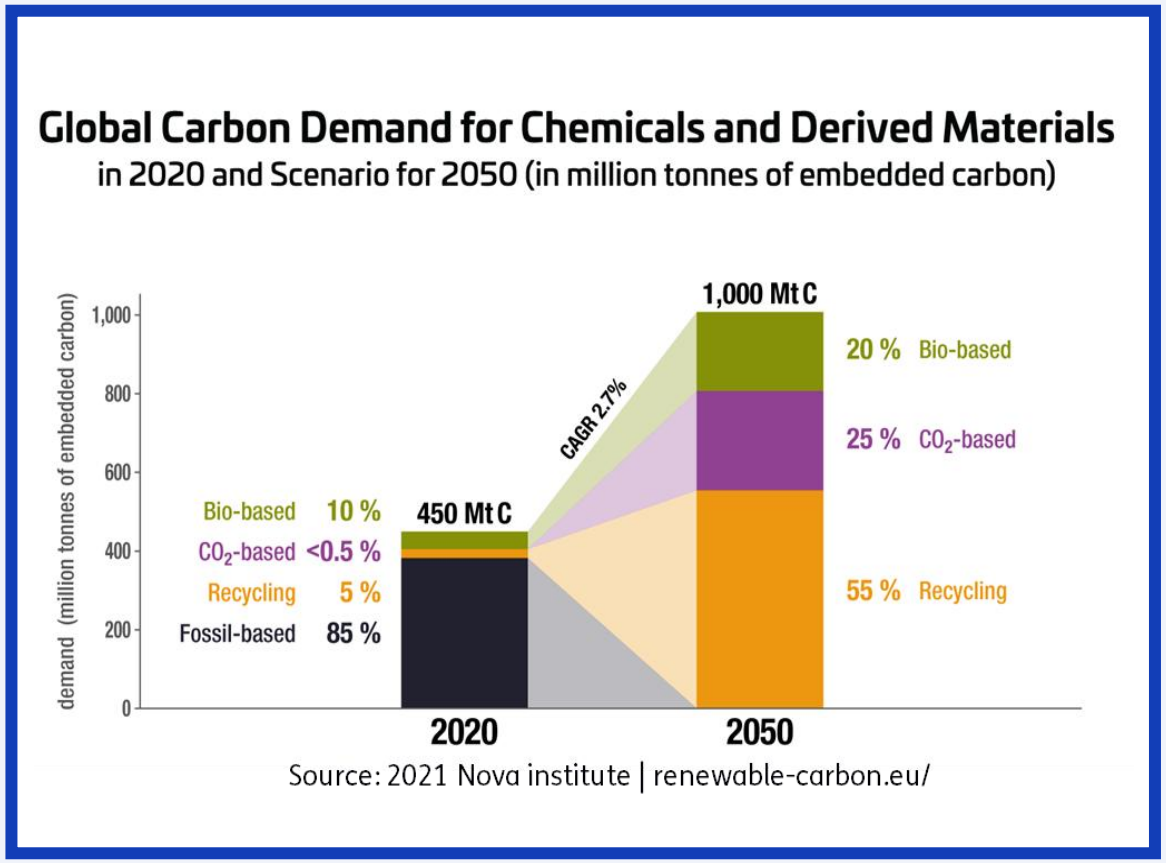


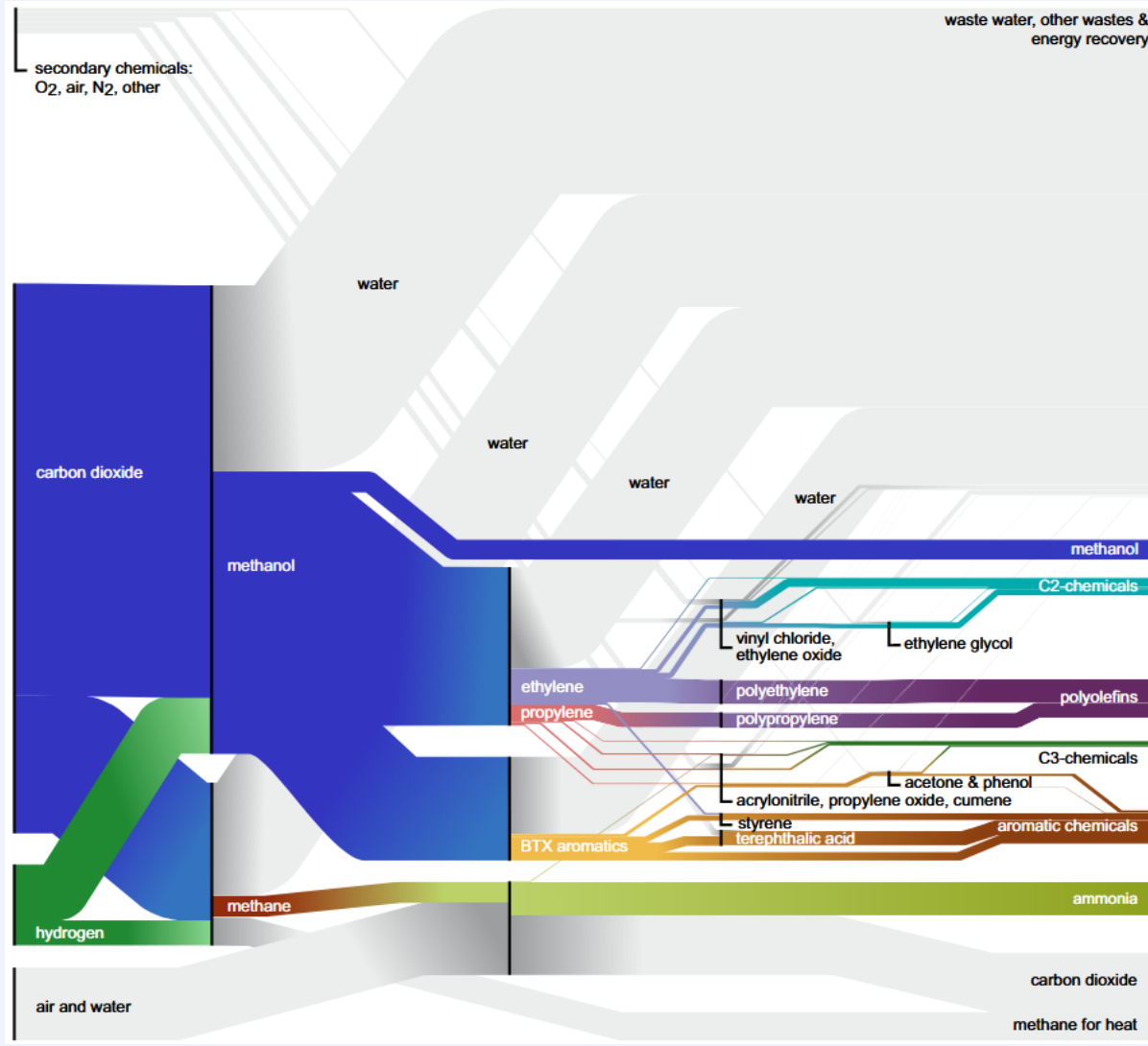




From fossils to CO_2 as feedstock: water management is key!

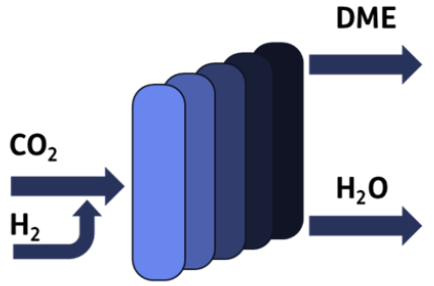
- Water management and process intensification by separation enhancement





Kätelhön, A., et al. (2019). *PNAS, 116*(23), 11187-11194.

SEDMES– scaling up

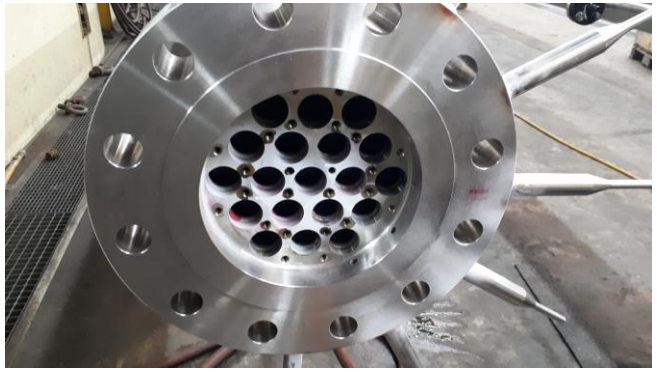


$2\ CO_2 + 6\ H_2 \rightarrow 3\ H_2O\downarrow + CH_3OCH_3$

Why Dimethyl Ether (DME)?

DME is a friendly gas, with potential to grow to large platform chemical:

- Aerosol propellant hairspray (current)
- Replacement of diesel
- Replacement of LPG
- H_2 H_2 carrier
- Chemical building block for circular carbon economy



SEDMES pilot

0.2 L bed

SPIDER

0.5 L bed

CATE

2 L bed

SEWGS-1

40 L
6 * 6m columns

SEWGS-7

Objectives POWERED

- Advance development of SEDMES, complete pilot with DME purification, unconverted gas recycle & DME storage
- Realisation of energy management system (EMS) and dynamic operation SEDMES
- Long duration testing
- Techno-economic evaluation & sustainability study
- Design & preparation demonstration scale

Subsidy Scheme: MOOI, theme Industry, mission C, MMIP6 & MMIP8

Start Date: June 2023

End Date: May 2027

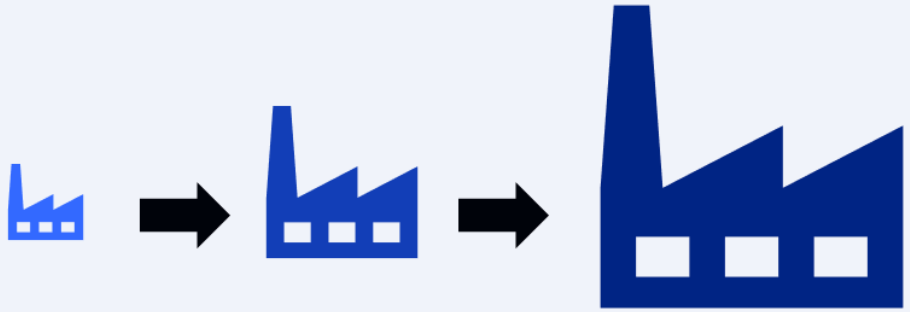
VDL Nouryon Shell TNO PHASE TO PHASE Technolution SHV ENERGY TATA STEEL T.EN TECHNIP ENERGIES Aramco Overseas Company B.V.

Follow-up: Scaling up SEDMES further

- Full chain long-duration testing at Petten → demonstration at industrial biomass gasification plant
- Engineering for next scale (>3 columns), TEA and LCA:

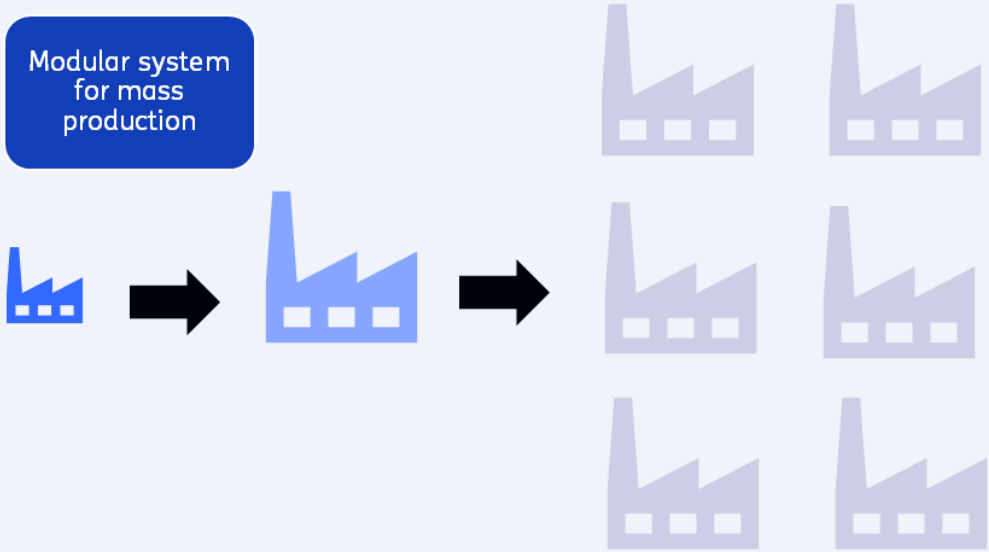
BUTTERFLY

Industrial DME production at scale



DME as seasonal storage of renewable energy

Modular system for mass production



And e.g. SE-MTO to higher carbons

groen vermogen nl

Shaping to drive cost reduction in SE-CCUS

- PSA systems are capital-intensive: process optimization & cost reduction key for industrial deployment.
- Optimized particle morphology and structured reactors improve heat/mass transfer and reduce pressure drop. → Higher productivity per reactor volume.
- Lower CAPEX/OPEX through enhanced performance and durability. Reduced energy consumption and improved regeneration efficiency.

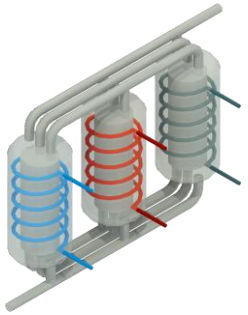
- Projects:
  - Green Smith: Sorbent shaping for SEWGS process in electrified steel making.
  - SENSATION: structured sorbents for intensified DAC.
  - MOF4BIO: Shaped metal-organic frameworks adsorbents for selective CO_2 capture from biogas streams.

https://greensmith-cetp.eu/

Adsorbent shaping as enabler for intensified pressure swing adsorption (PSA): A critical review

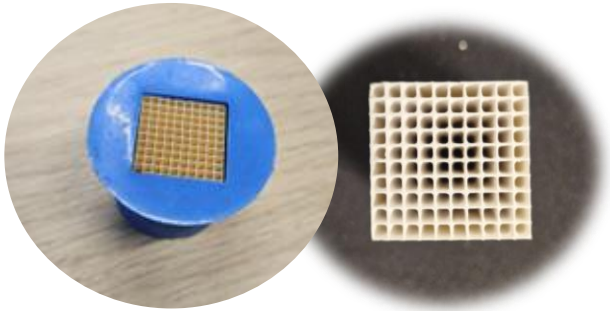
Example project shaping: SENSATION

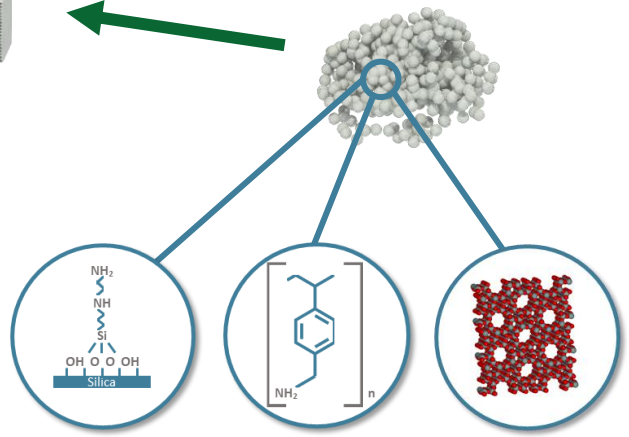
The overall objective of SENSATION is to develop a sorbent-based carbon capture technology tailored for low CO_2 concentrations varying from 400 ppm in air (DAC application) to 1-3 vol% for industrial sources.



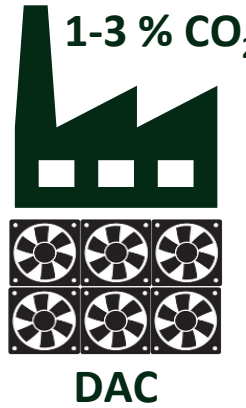
Design a compact system with optimized TSA/VTSA processes to reduce energy and capital costs.

Structure sorbents by coating the sorbent material onto a substrate monolith.





Design & construct TRL6 pilot



TRL6 demonstration at two locations to test the capture technology for:

1) Industrial sources with low CO_2 conc.
2) DAC

Validate scalable, commercially available sorbent materials.

Managing CO_2 Quality across Value Chain

CO_2 purity is key

- The control of impurities in CO_2 plays a vital role in the safe and effective design and operation of a CCUS chain.
- Impurities can significantly impact the cost of processing, transport, material and storage.
- Stringent specifications for Liquid CO_2

Northern Lights

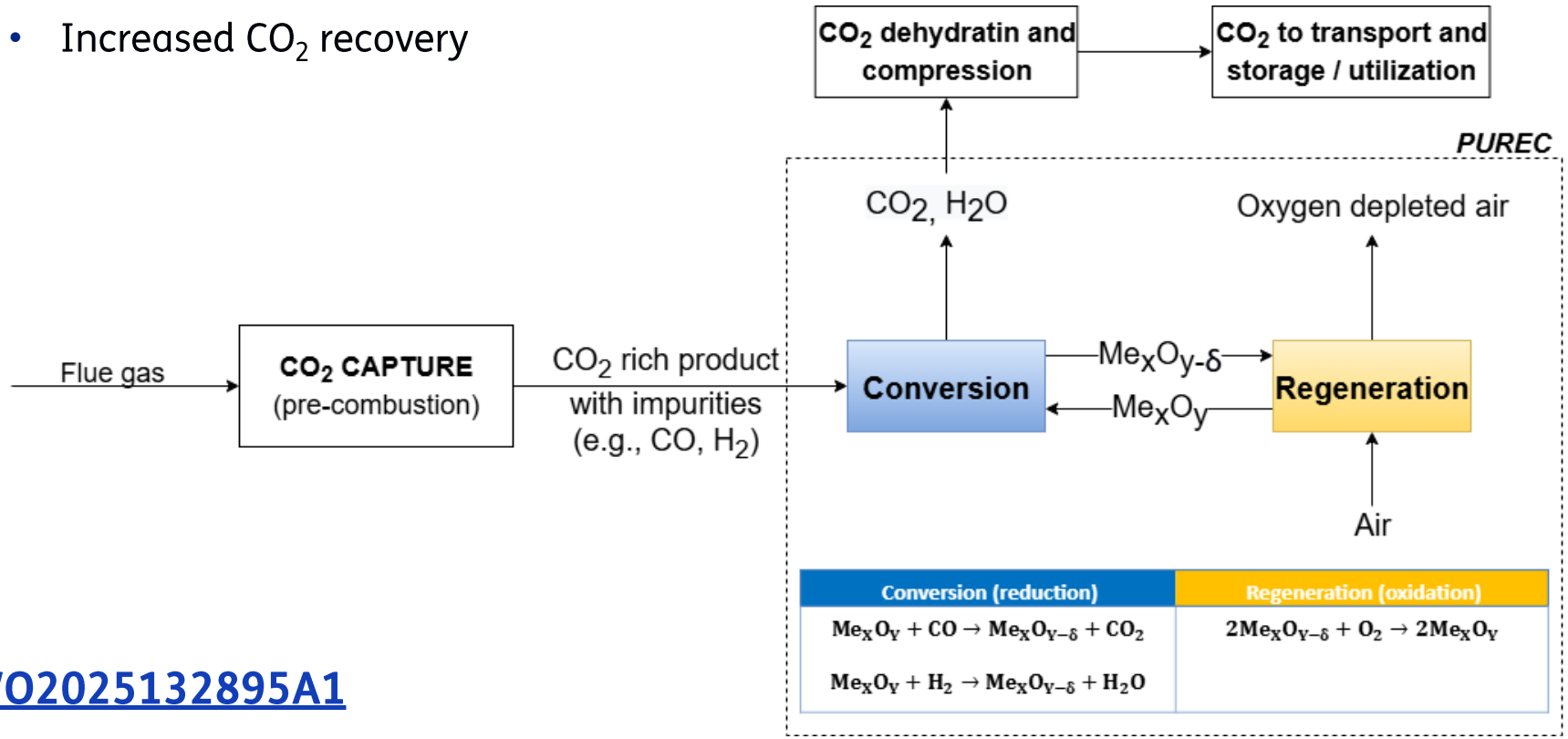
Liquid CO_2 (LCO2) Quality Specifications

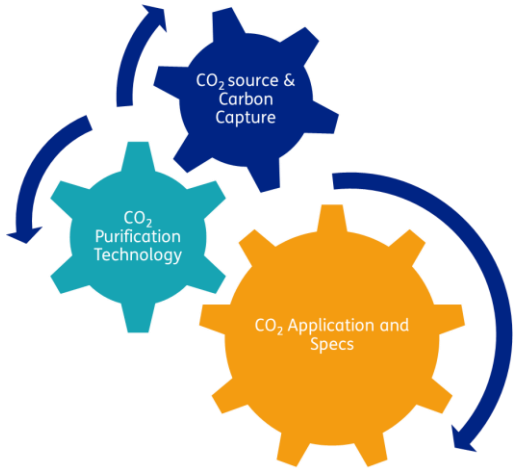
	Component	Unit	Limit for CO_2 Cargo within Reference Conditions[1]	
Original CO_2 spec	Carbon Dioxide (CO_2)	mol-%	Balance (Minimum 99.81%)	
	Water (H_2O)	ppm-mol	≤ 30	
	Oxygen (O_2)	ppm-mol	≤ 10	
	Sulphur Oxides (SO_x)	ppm-mol	≤ 10	
	Nitrogen Oxides (NOx)	ppm-mol	≤ 1.5	Updated component
	Hydrogen Sulfide (H_2S)	ppm-mol	≤ 9	
	Amine	ppm-mol	≤ 10	
	Ammonia (NH_3)	ppm-mol	≤ 10	
	Formaldehyde (CH_2O)	ppm-mol	≤ 20	
	Acetaldehyde (CH_3CHO)	ppm-mol	≤ 20	
	Mercury (Hg)	ppm-mol	≤ 0.0003	Updated component
	Carbon Monoxide (CO)	ppm-mol	≤ 100	
	Hydrogen (H_2)	ppm-mol	≤ 50	
	Cadmium (Cd), Thallium (Tl)	ppm-mol	Sum ≤ 0.03	Moved to solids
Clarification from original CO_2 spec	Methane (CH_4)	ppm-mol	≤ 100	
	Nitrogen (N_2)	ppm-mol	≤ 50	
	Argon (Ar)	ppm-mol	≤ 100	
	Methanol (CH_3OH)	ppm-mol	≤ 30	New component
	Ethanol (C_2H_5OH)	ppm-mol	≤ 1	
	Total Volatile Organic Compounds (VOC)[2]	ppm-mol	≤ 10	

https://safety4sea.com/wp-content/uploads/2024/03/Northern-Lights-GS-co2-2024_03.pdf

CO_2 conditioning for in-process capture purity

- **Purification & Recuperation of Energy Content** is a pre-combustion CO_2 purification technology for removal of CO, H_2
  - Avoids introduction of other impurities (e.g., O_2, N_2)
  - Possibility to extend to other impurities removal (e.g., CH_4, H_2S)
  - No energy input required (exothermic steps) → possibility for energy recovery
  - Increased CO_2 recovery





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TNO innovation for life

Summary and message

- **TNO's innovations in carbon capture are at the verge of making real impact in hard-to-abate sectors:**
  - Separation-enhanced and in-process capture technologies are transitioning from lab to industry, with proven pilots and scalable solutions.
- **Collaboration is essential:**
  - Partnerships, joint development, and knowledge sharing drive progress and bridge the gap from research to implementation.
- **Looking ahead:**
  - Continued scale-up, integration, and demonstration projects will be critical to realizing a sustainable, low-carbon future for industry.

Thank you for your attention!

- GreenSmith and SENSATION are funded by CETPartnership, the Clean Energy Transition Partnership under the 2022 CETPartnership joint call, co-funded by the European Commission (GA N° 101069750 & N°101069750) and with the funding organizations detailed on https://cetpartnership.eu/funding-agencies-and-call-modules.
- The INITIATE project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958318.
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- *The views expressed in this presentation do not necessarily reflect those of the funding agencies*

SENSATION

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GreenSmith

INITIATE
A STEPWISE PROJECT

LEADS

POWERED

TNO innovation for life