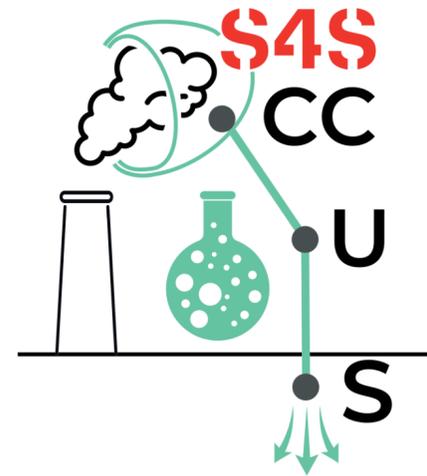


From Lab to Plant: Scaling Disruptive CCUS Technologies at EPFL



An EPFL Solutions4Sustainability CCUS project



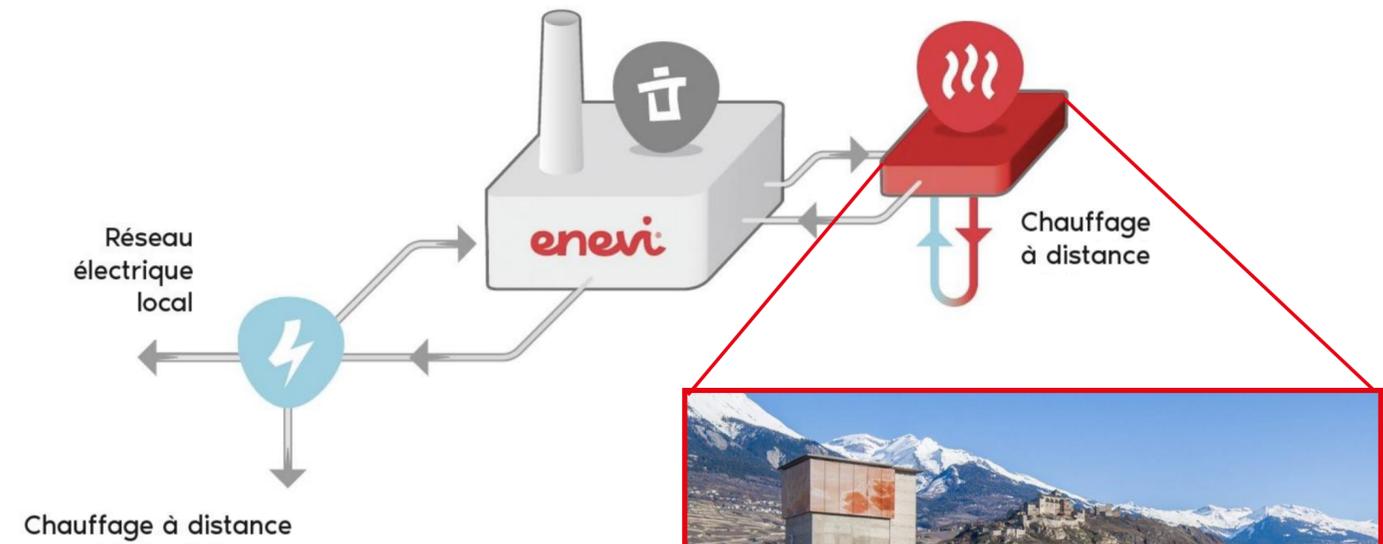
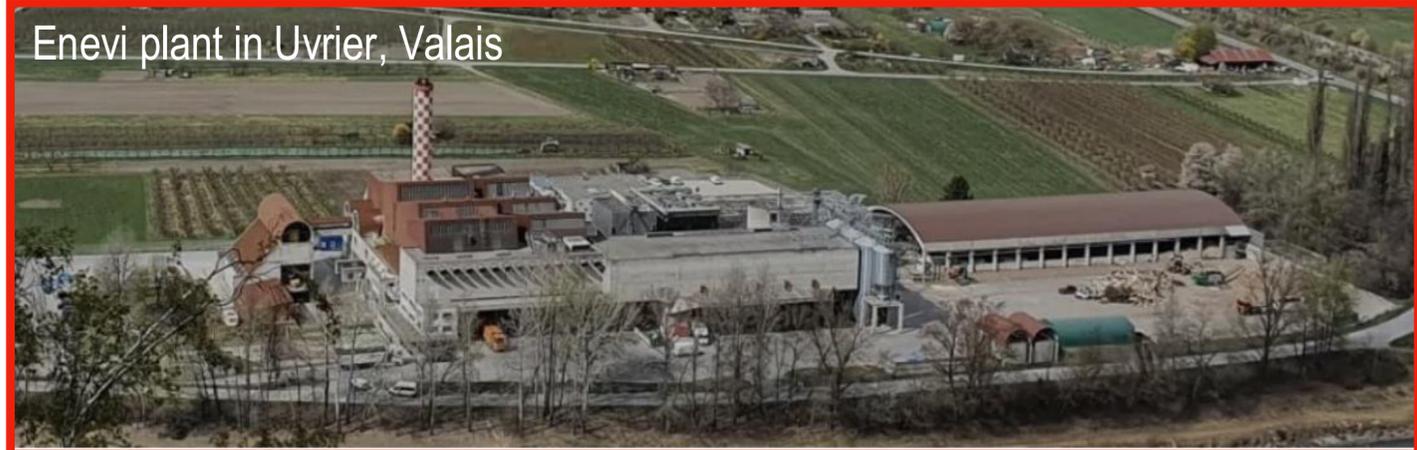
<https://s4s-ccus.epfl.ch>

Kumar Varoon Agrawal
Associate Professor, EPFL

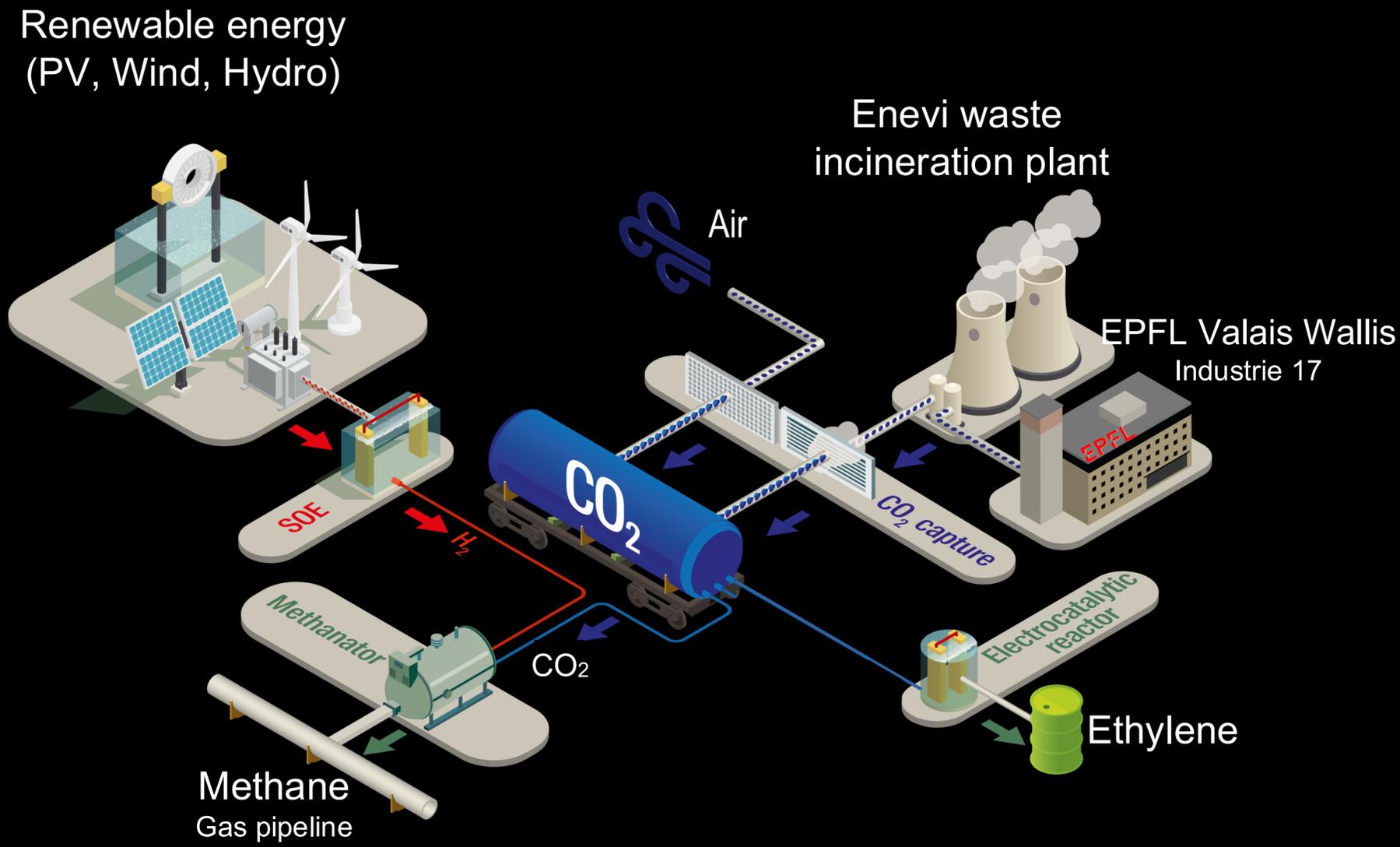
Science for Sustainability
March 6, 2026



Waste incineration plant as CCUS testbed



EPFL is building a full CCUS value chain at a large pilot scale



- ✓ Accelerate EPFL CCUS technologies 'well beyond state-of-the-art' to TRL 7.
- Capture:** 1 ton CO₂/day capture using graphene membrane with cost ~ \$ 30/tonCO₂.
- Geological sequestration:** meter-scale simulator for sequestration.
- Utilization:** 100 kW electrolyzer/methanation with energy efficiency above 70%.

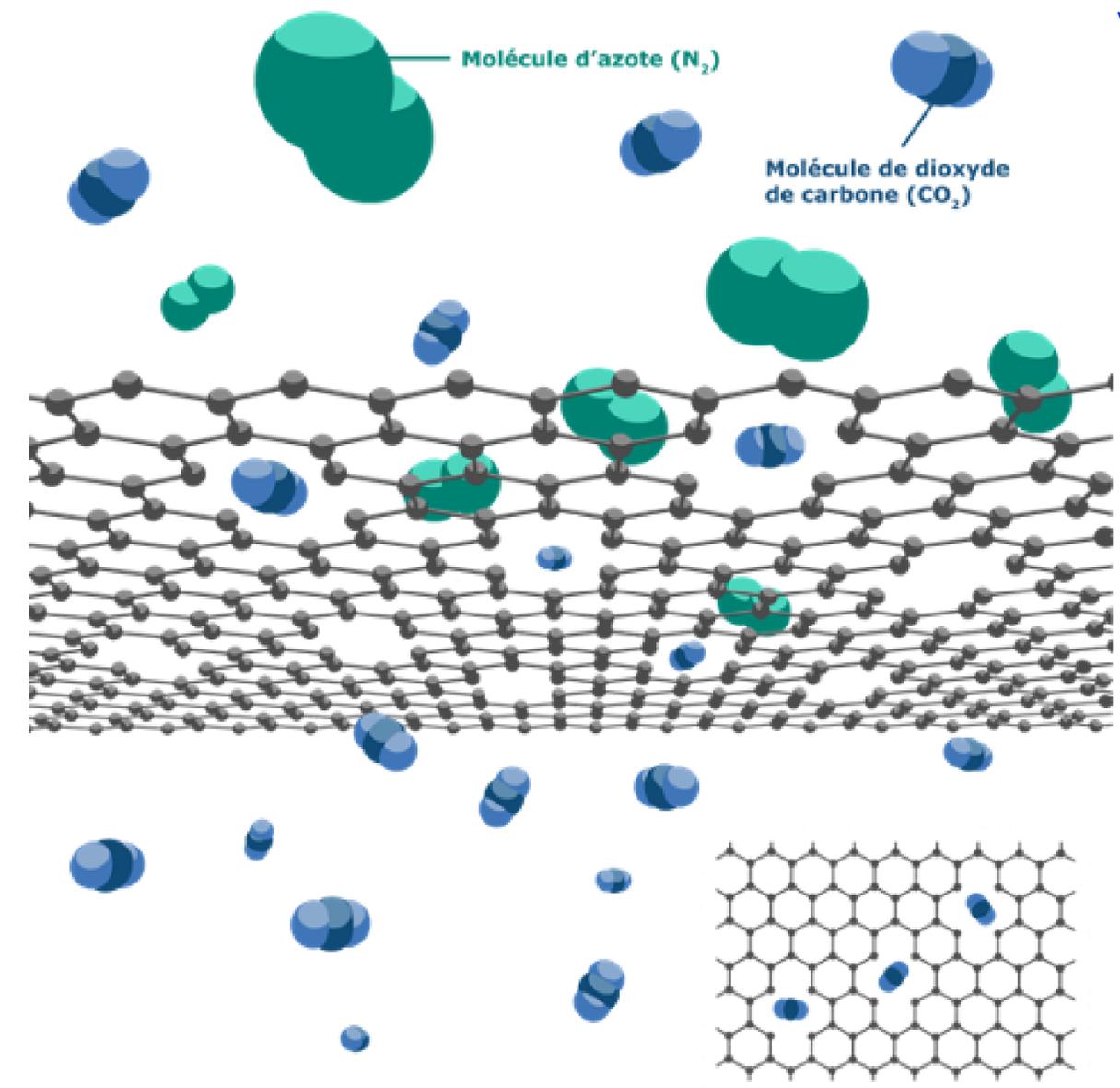


1 tonCO₂/day

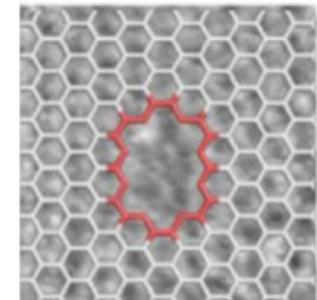
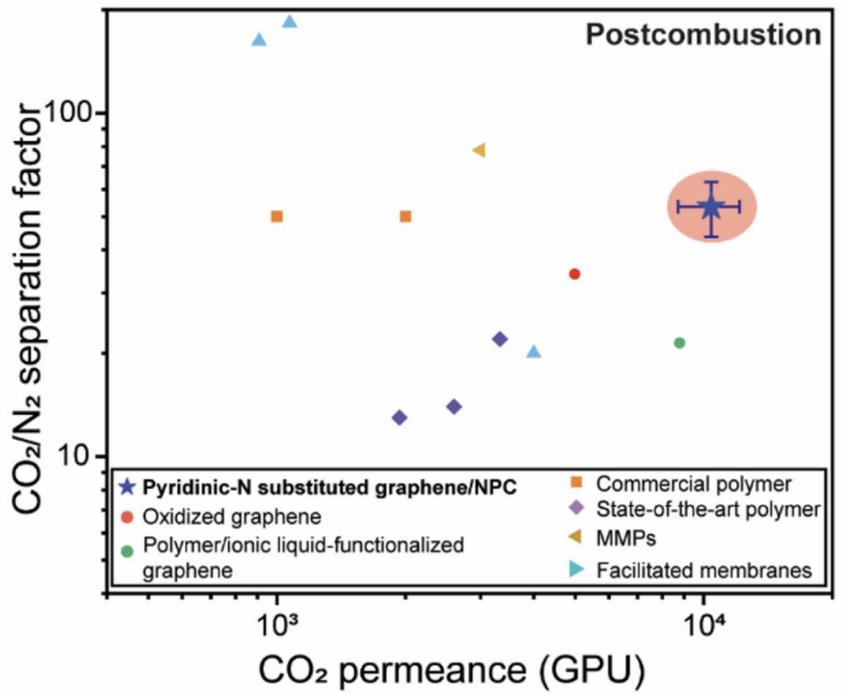
Kumar Varoon Agrawal
Vivek Subramanian

Flue gas capture by porous graphene membrane

- ☑ Graphene is a single layer of graphite (Nobel prize in Physics, 2010).
- ☑ EPFL developed technology for CO₂-selective porous graphene.
- ☑ Ultrafast CO₂ transport through atom-thin pores enables record capture performance



Record-high carbon capture performance



Huang,..., Agrawal*, **Advanced Materials**, 2022, 34, 2206627.

Villalobos,... Agrawal*, **Accounts of Materials Research** 2022, 3, 1073.

Hsu,..., Agrawal*, **Nature Energy** 2024, 9, 964 - 974.

From proof-of-concept membranes to pilot plant operation

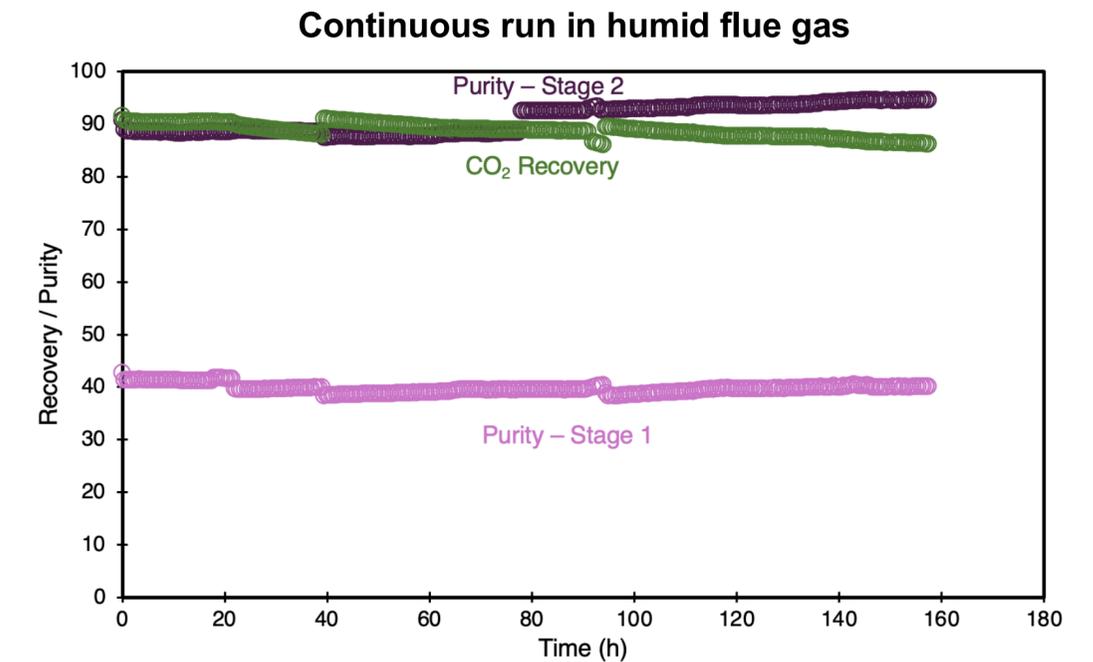
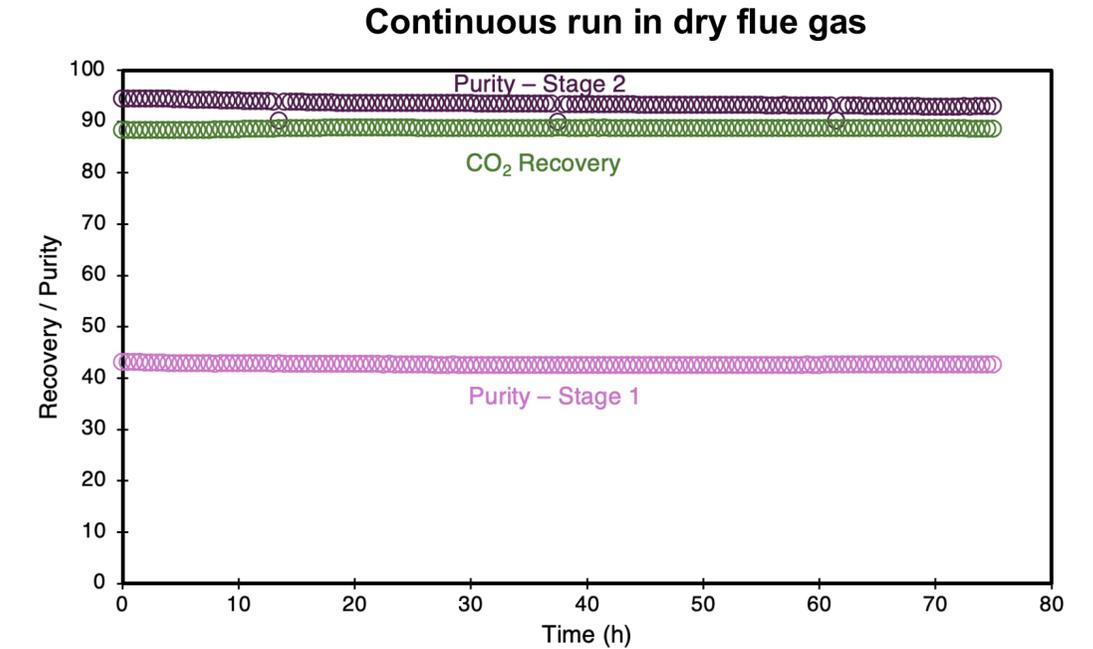
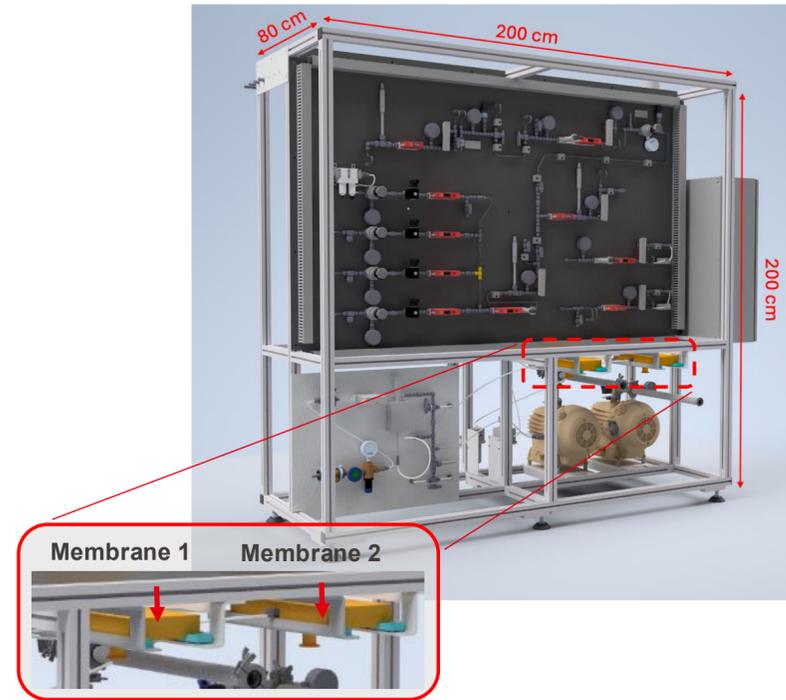
From lab discovery to continuous industrial operation under realistic flue gas conditions



1 tonCO₂/day



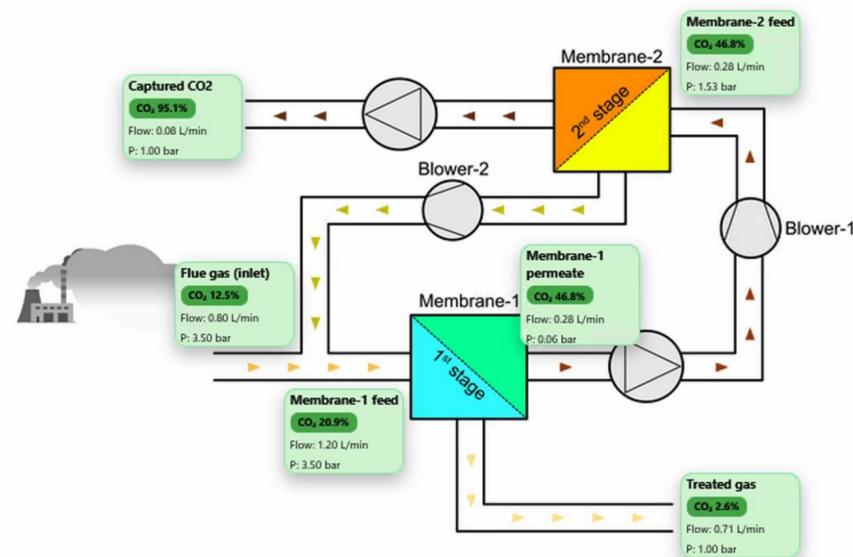
Hao, ..., Agrawal*, Nature Chemical Engineering, 2025, 2, 241-251



DemoValais

Porous Graphene membrane CO₂ Capture Pilot

Scheme of the process

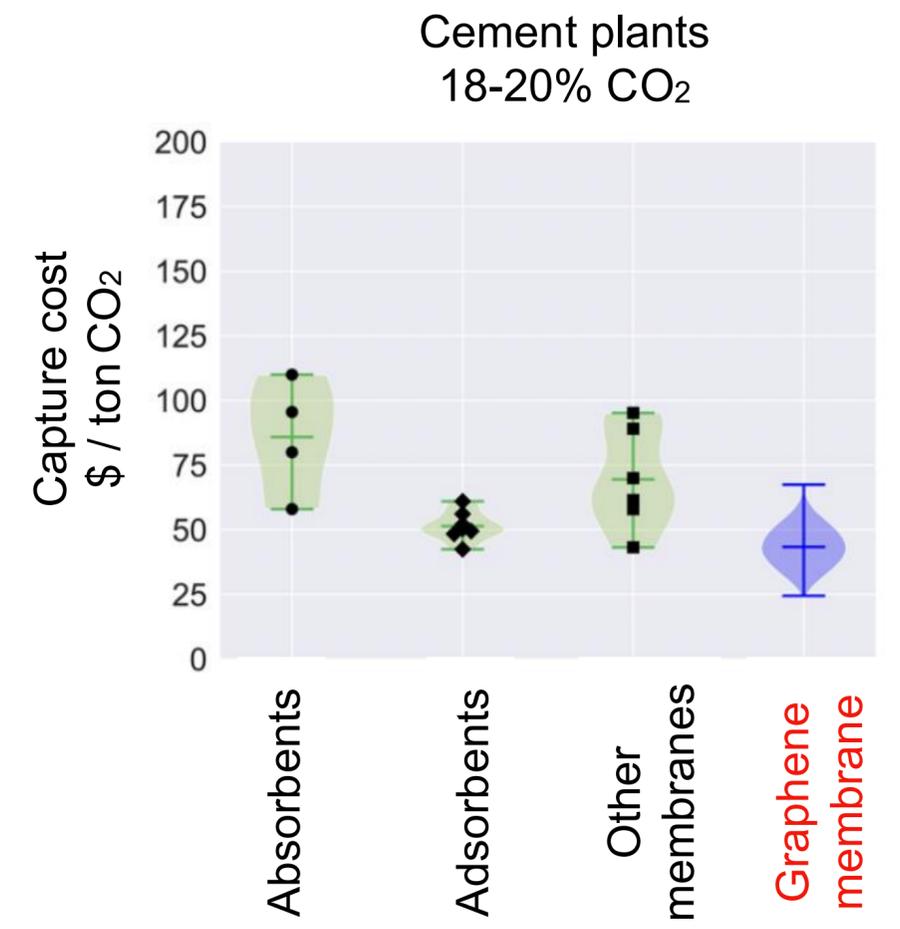
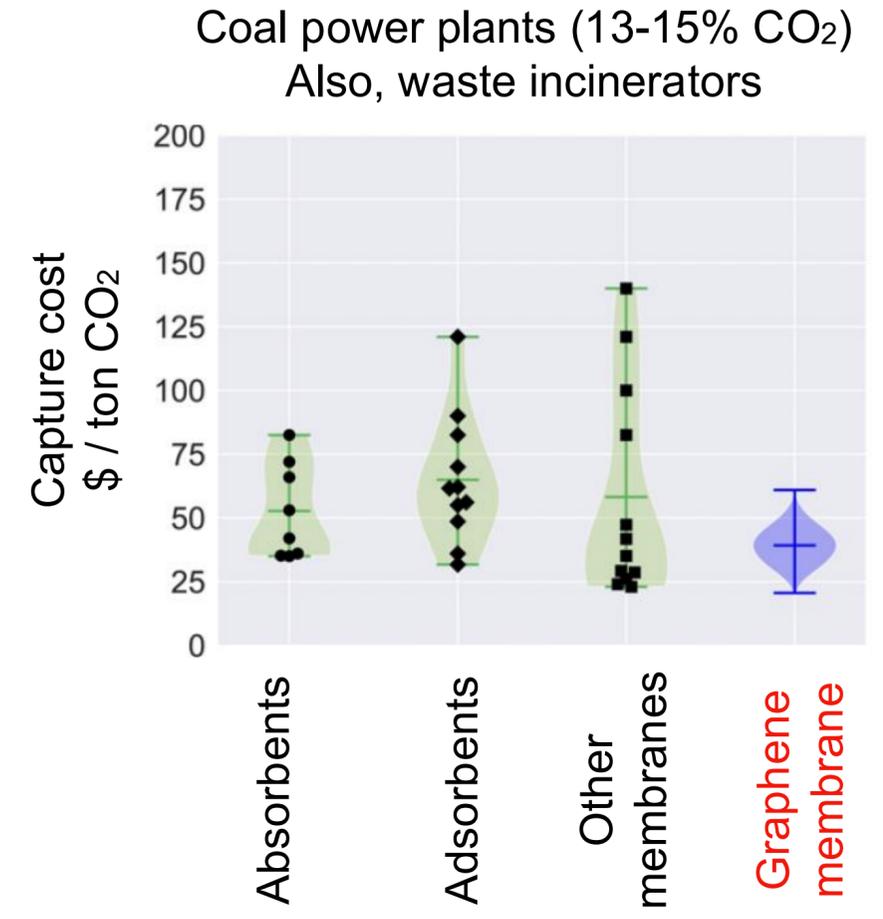
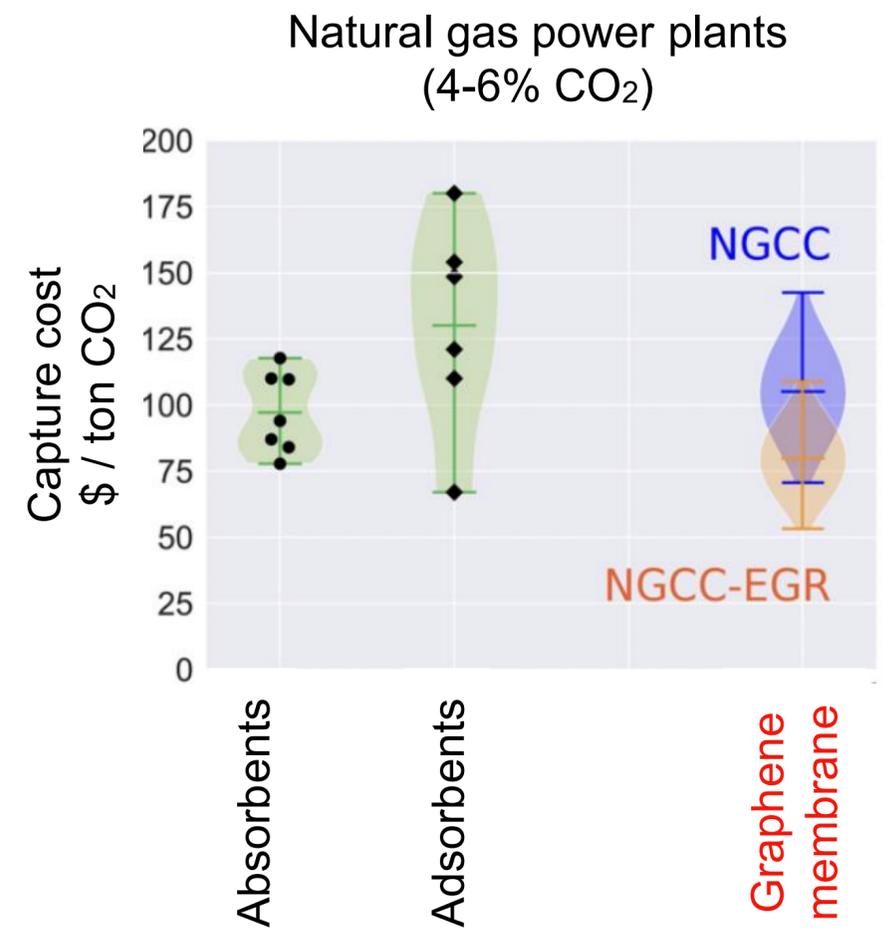


Cross-flow module for 50 cm² membrane

Graphene membranes cut capture costs across all emission sectors



1 tonCO₂/day



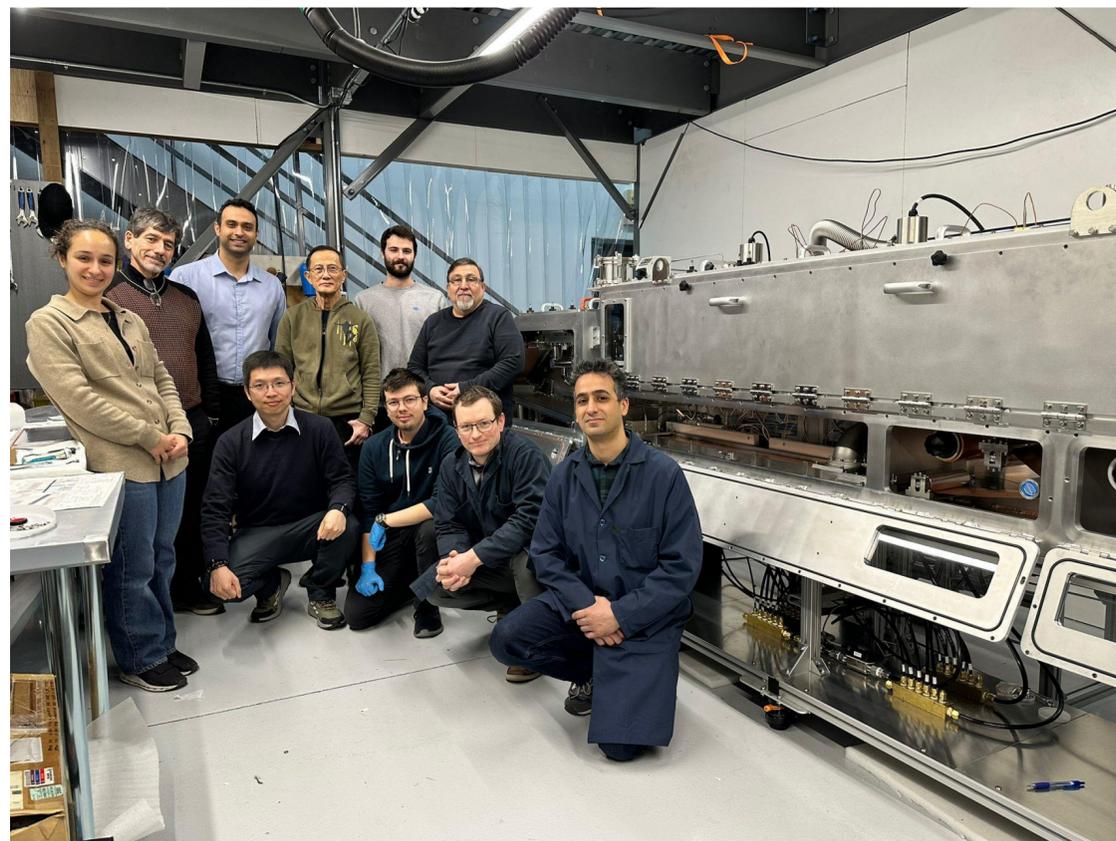
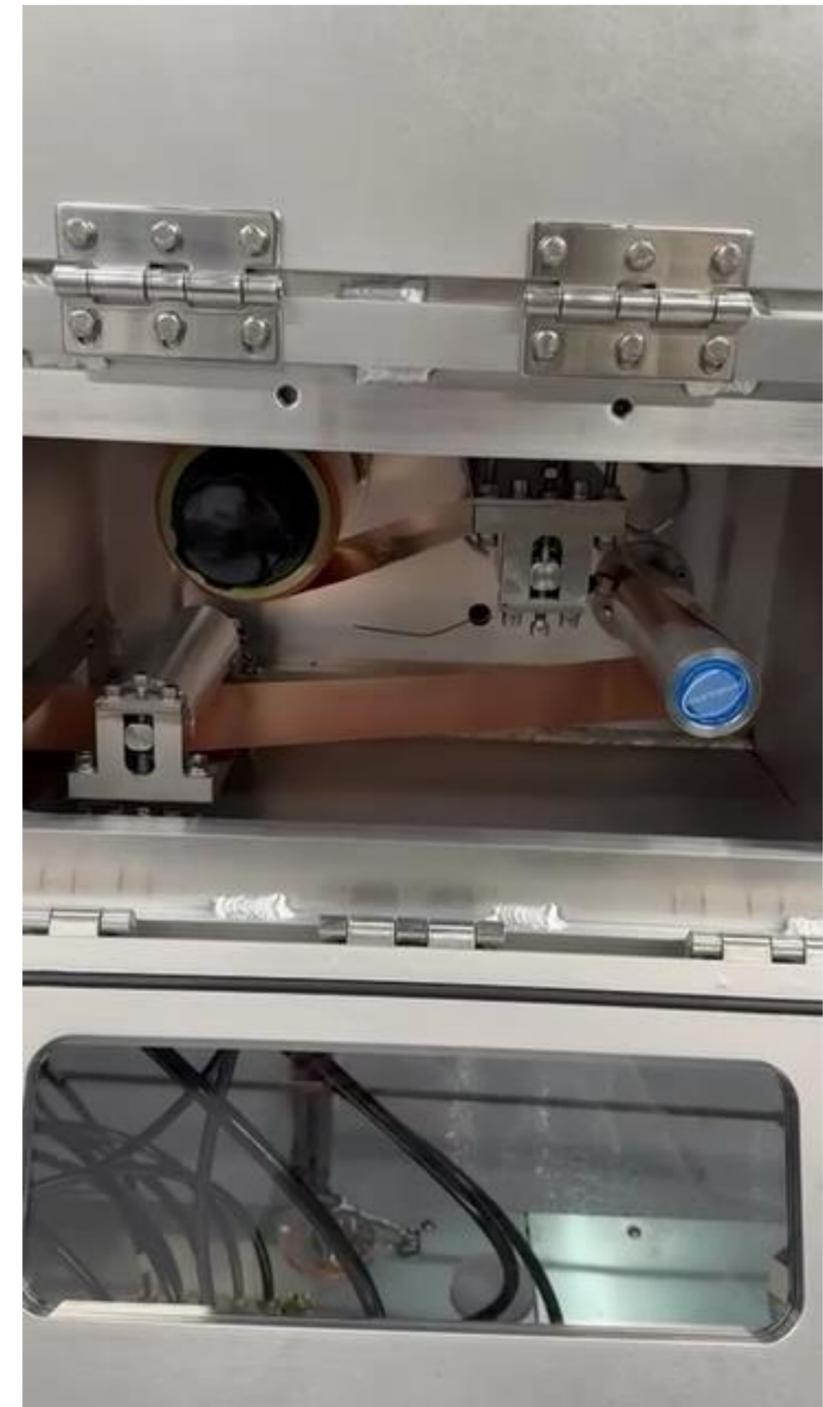
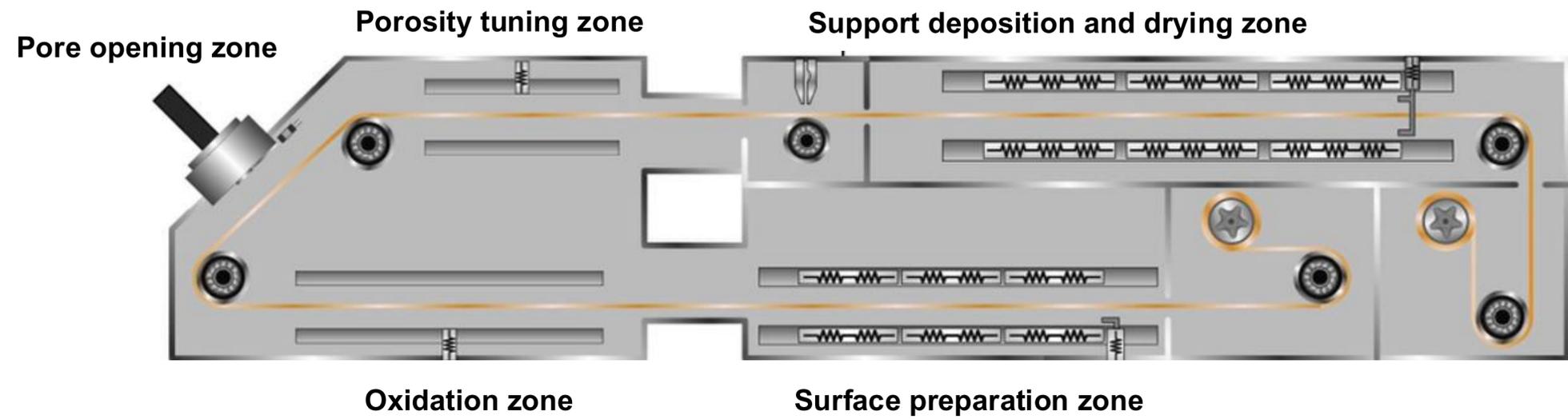
- ✓ High performance allows capture of dilute flue gas at low cost.
- ✓ The high stability of graphene makes it uniquely suitable for harsh flue gas (SO_x, NO_x).
- ✓ High flux of graphene significantly reduces capture footprint (capture unit for large scale plant in containers).

First continuous manufacturing tool for graphene membrane



1 tonCO₂/day

Manufacturing scalability enabled by continuous roll-to-roll production



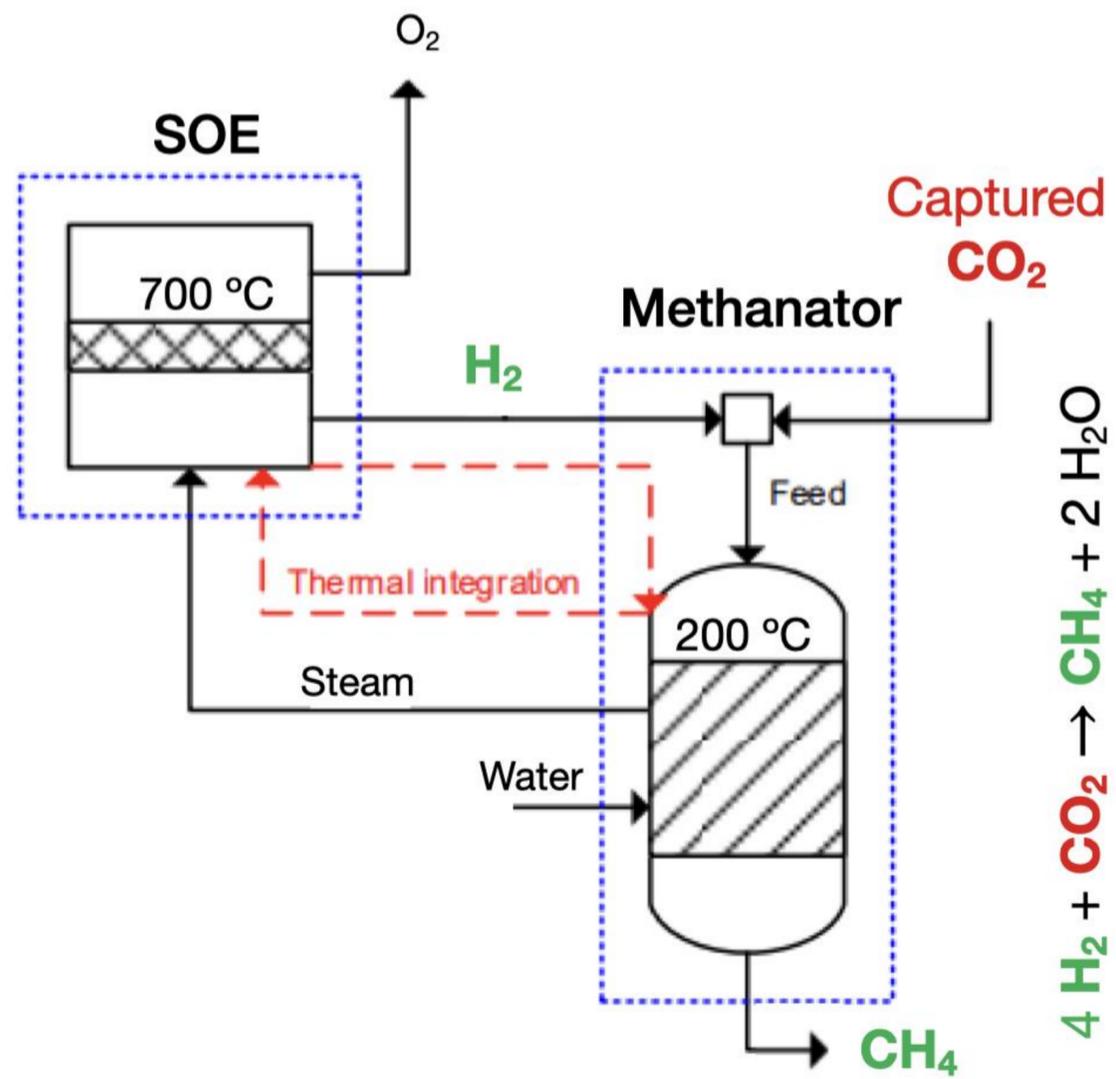


100 kW

Jan van Herle

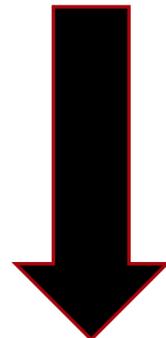
CO₂ to renewable energy carrier (CH₄)

- ✓ Converts captured CO₂ to renewable methane (energy carrier).
- ✓ H₂ production by near 100% efficient steam electrolysis in solid oxide electrolyzer (SOE).
- ✓ Integrated heat management leads to CO₂ to CH₄ energy efficiency of > 70%.



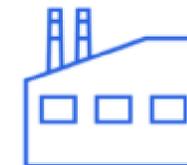
Exothermic reaction
yielding 2 kWh heat
per m³ of CH₄

- ✓ 15000 hour successful operation of SOE.
- ✓ 10 kW methanator demonstrated.



- ✓ 100 kW_e SOE in collaboration with SolydEra.
- ✓ 80 kW methanator (200 m³ CH₄ per day).





SOE/methanator system integrated at GAZNAT site for initial testing and validation



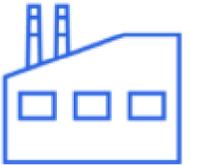
100 kW SOE

H₂ compressor

- ✓ The containers with SOE, dry H₂ delivery line (8 bar), ventilation and safety, have been commissioned.
- ✓ The system will be thoroughly tested in 2026, where EPFL team will be trained. It will then move to Enevi plant in 2027.

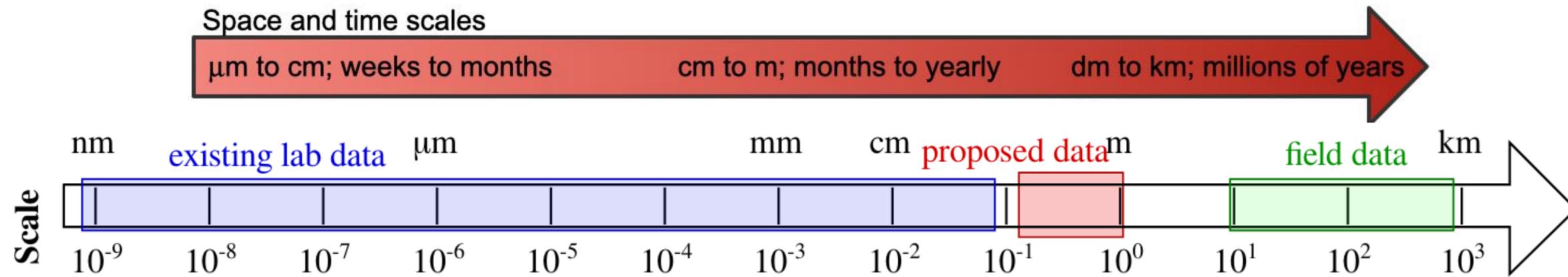
Geological CO₂ sequestration demonstrator

WP3



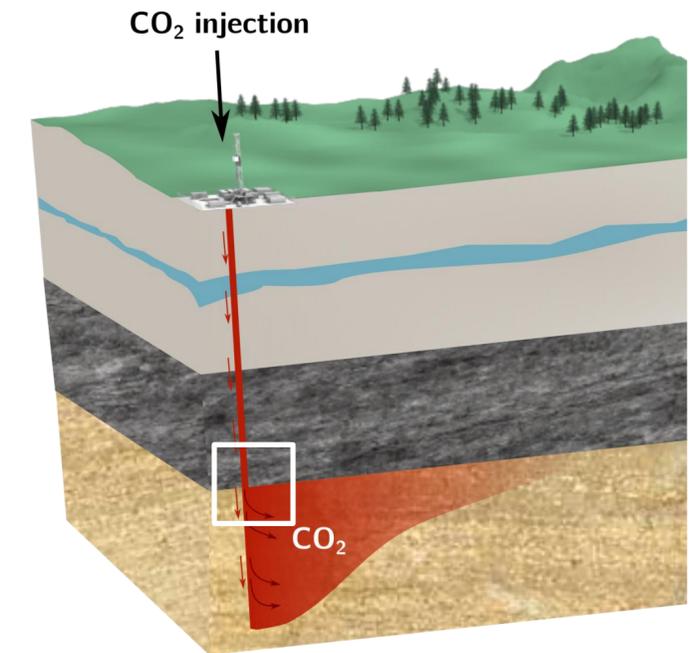
Meter-scale GCS

Eleni Stavropoulou
Lyese Laloui

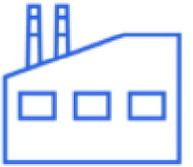


Lab-scale (µm) characterization of the structural properties of the synthetic caprock.

Lab-scale (cm) characterization & optimization of the synthetic caprock and reservoir (porosity, permeability, CO₂ breakthrough)



Field-scale (km) injection for geological storage at min. depth 700-800 m



Geological CO₂ sequestration demonstrator

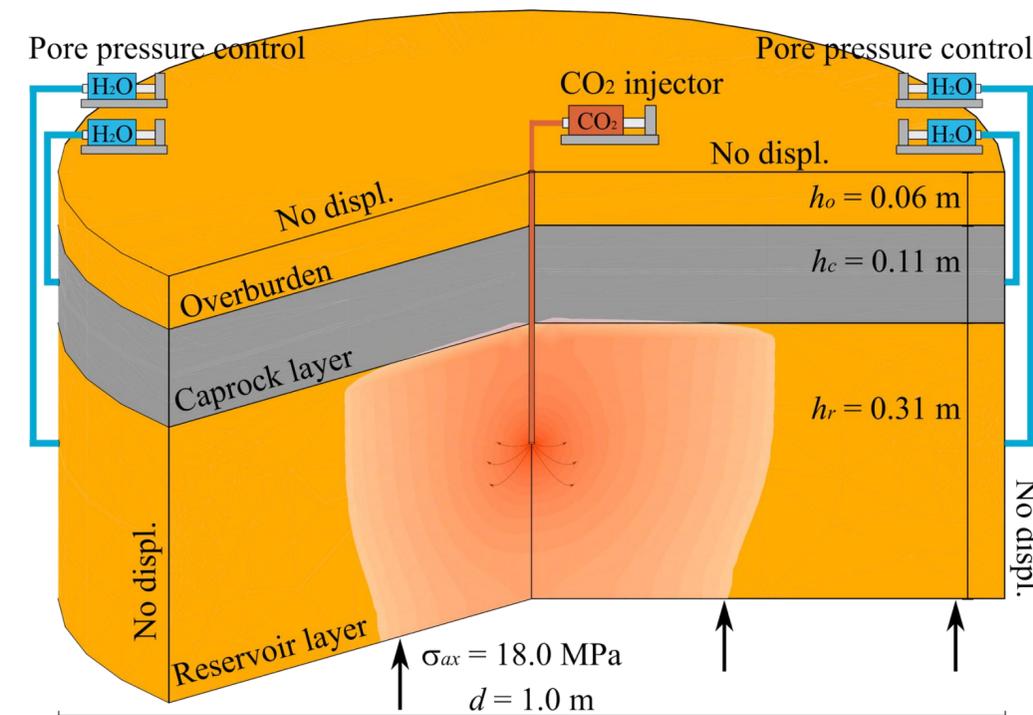
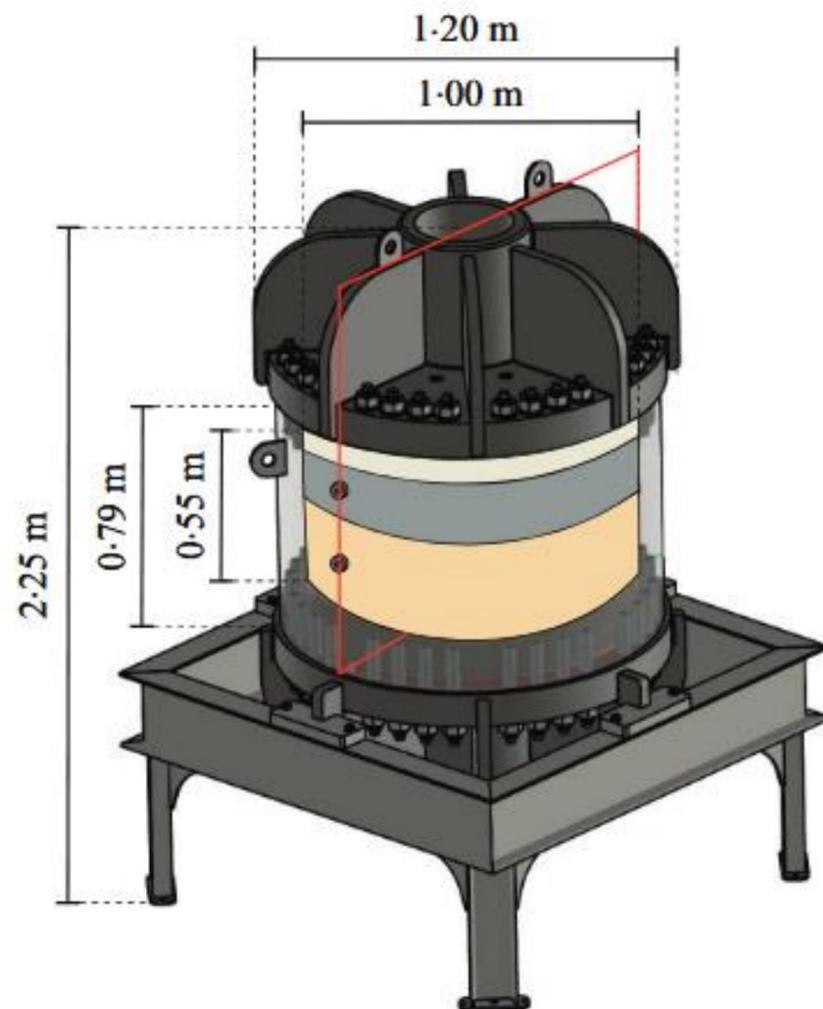
Meter-scale testbed for GCS will validate storage integrity under realistic geological stress conditions

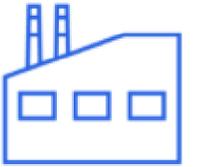
Materials:

- ☑ Cemented sand for reservoir.
- ☑ Crushed Opalinus clay for the caprock.

CO₂ Injection

- ☑ Constant rate over 15 days.
- ☑ Volume reaching 50% of the reservoir capacity.



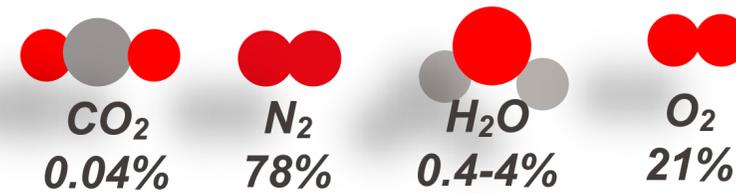


Direct air capture

Wendy Queen

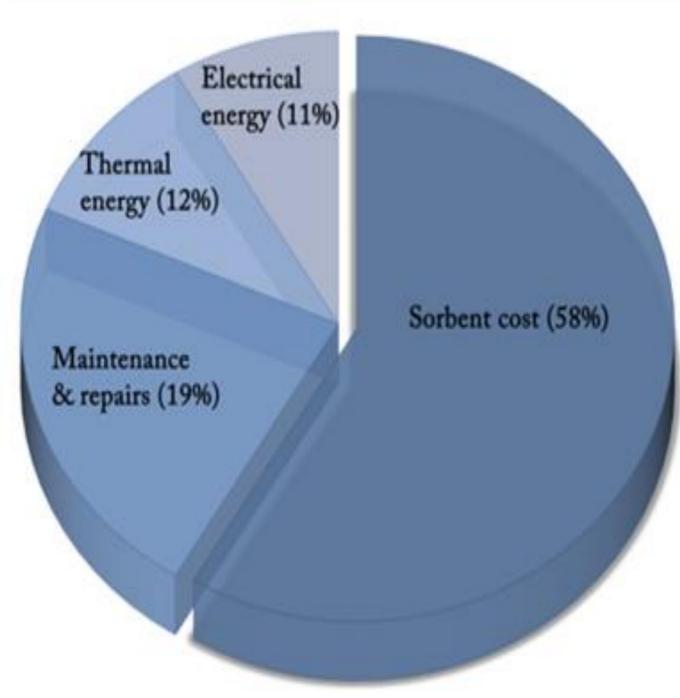
Marina Micari

Direct Air Capture



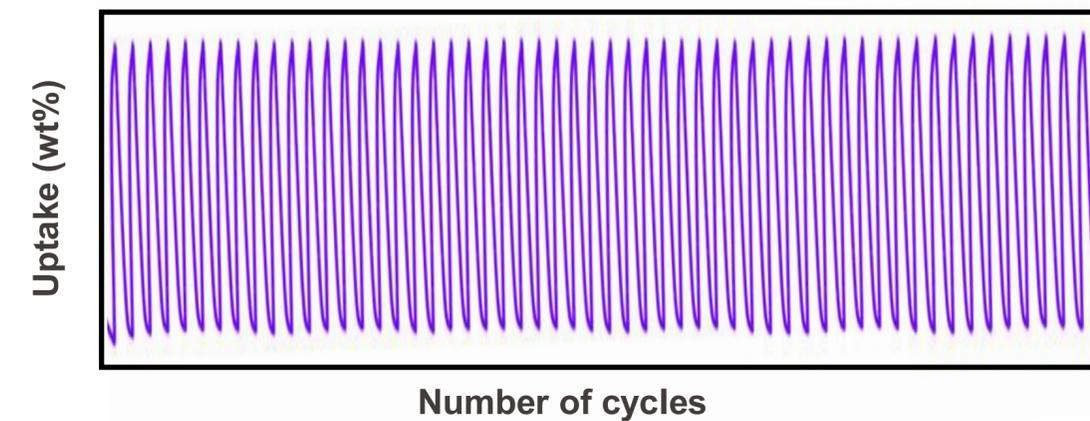
DAC not only offsets fossil-fuel emissions but also help to manage challenging emissions (food consumption, air travel)

Adsorbent is the biggest cost contributor to DAC



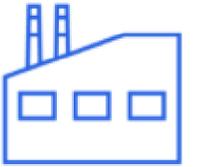
- ✦ Adsorbent lifespan ~ 3 – 6 months
- ✦ DAC cost > 600 \$/tonCO₂

Improving adsorbent lifetime and working capacity will significantly reduce costs.

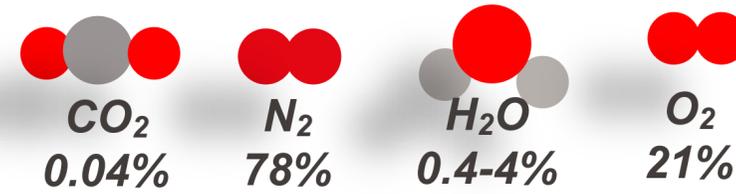


- ✦ Lifetime improved significantly.
- ✦ Working capacity improved by ~20 times

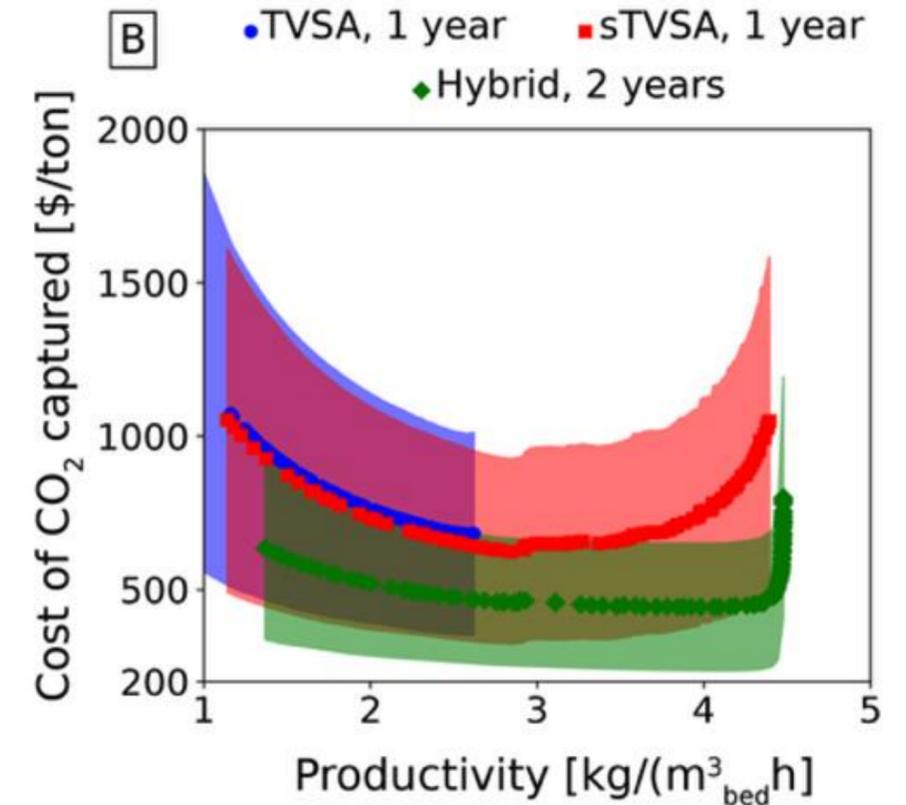
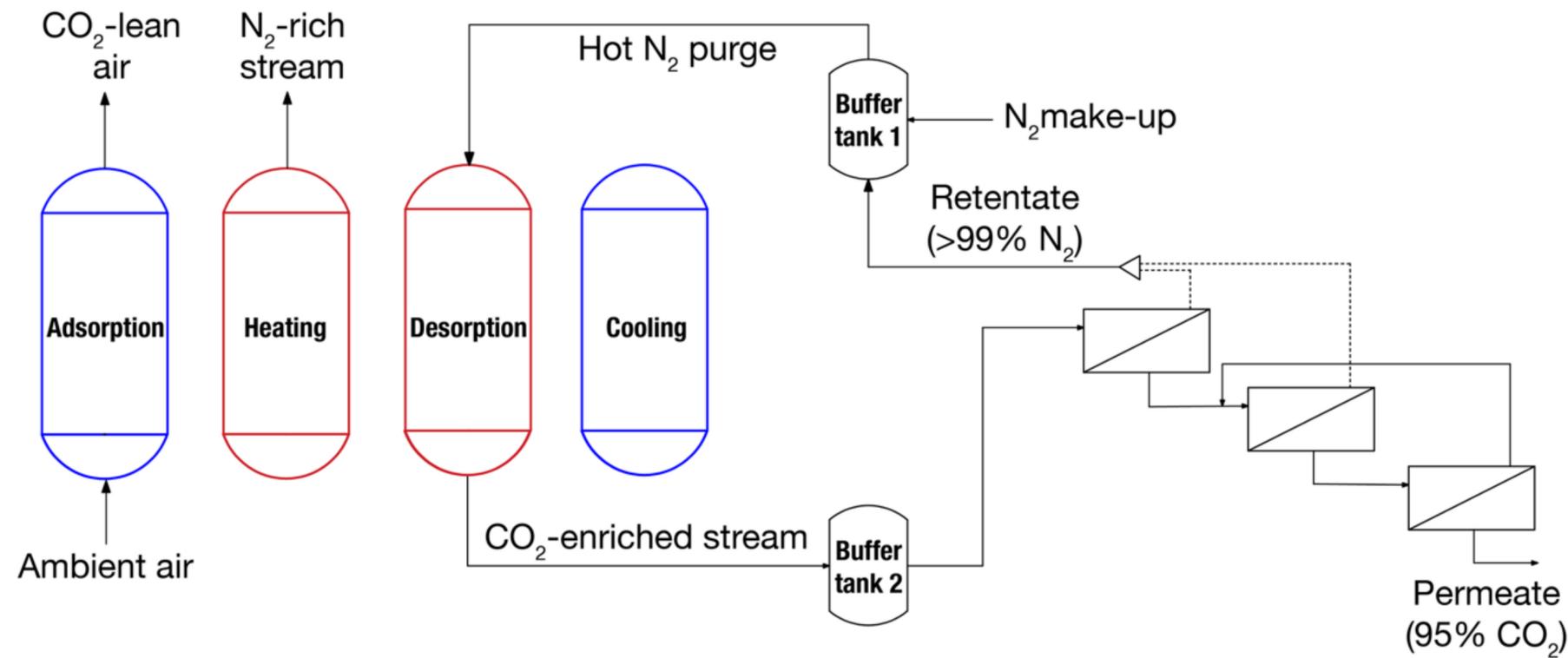
Direct Air Capture



Direct air capture
Wendy Queen
Marina Micari

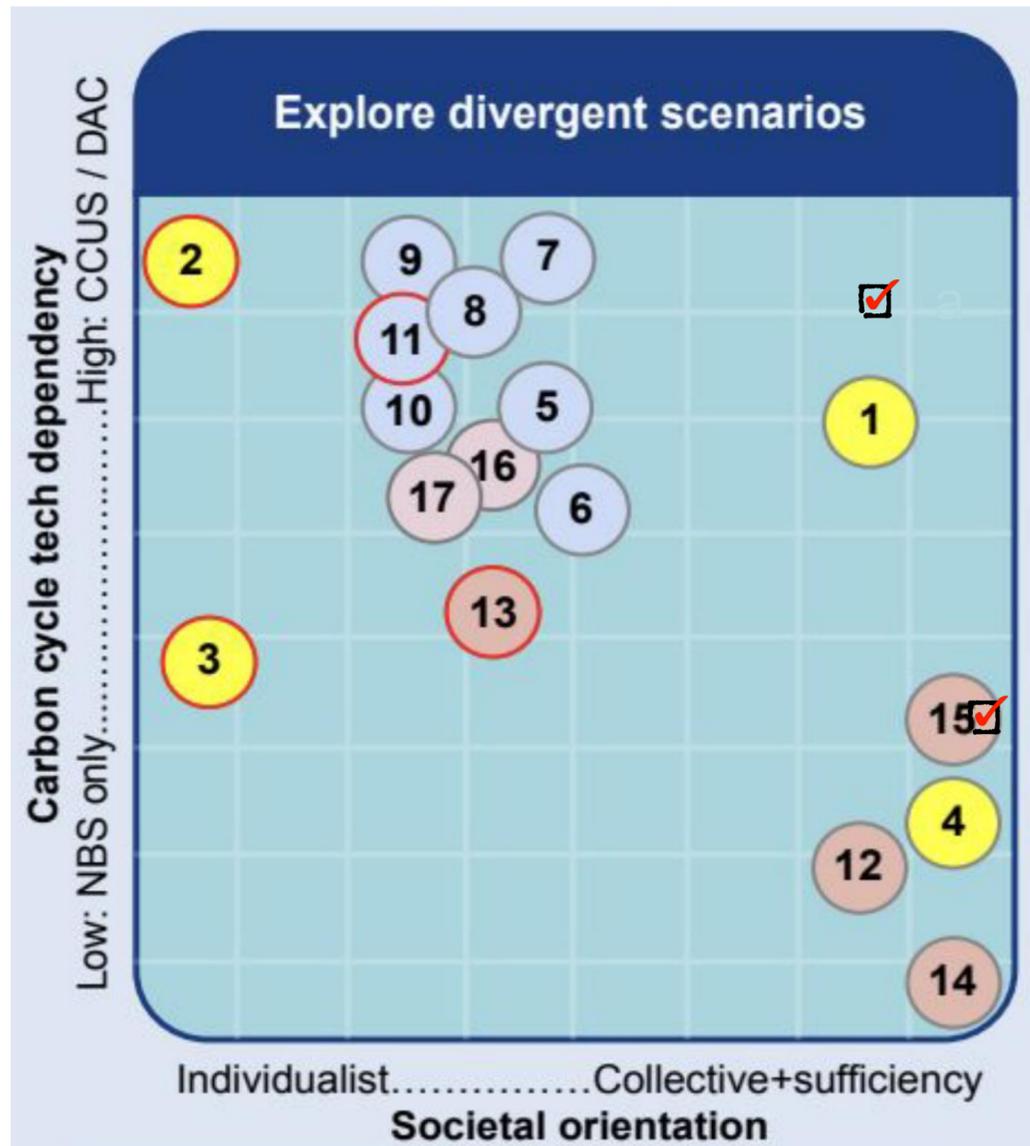


Significant cost savings by hybrid Adsorbent/Membrane process with capture cost as low as 250 \$/ton



Economics, financing, governance, and policy

- ☑ Divergent scenarios help prepare for uncertain futures.
- ☑ Identified Swiss specific divergent scenarios achieving Net-Zero by 2050.
- ☑ We are preparing tools and workshops for policymakers and broader society.



Proposed scenarios 1 - Full spectrum 2 - Tech-driven 3 - Fragmented futures 4 - Commons focus	Main Swiss scenarios 5 - EP2050+ Climate Strategy 6 - EP2050+ Zero A 7 - EP2050+ B&C 8 - DeCIRRA Octopus 9 - DeCIRRA Butterfly 10 - DeCIRRA Snail 11 - DeCIRRA Clam
IPCC 12 - IPCC SSP1 13 - IPCC SSP2 14 - IPCC SR15 P1 15 - IPCC SR15 P2	IEA 16 - Net Zero Roadmap 2021 17 - Net Zero Roadmap 2023 ○ Net zero 2050 missed

Implications for Swiss policy



Collaborate with us

What EPFL Delivers

- ✓ Low-cost CO₂ capture using graphene membranes.
- ✓ Pilot validation in real flue gas (Enevi, Valais).
- ✓ Integrated capture → utilization → storage platform.
- ✓ Manufacturing & scale-up readiness.

Collaboration Opportunities

- ✓ Pilot testing on industrial flue gas.
- ✓ Process & system integration.
- ✓ CO₂ utilization into renewable energy carriers.
- ✓ Investment & deployment partnerships.

Current Industrial Partners



Timeline & Locations

Pilot commissioning: 2027

Testbed: Enevi waste incineration plant

Contact & Next Steps

Kumar Varoon Agrawal

EPFL – Laboratory of Advanced Separations

kumar.agrawal@epfl.ch



<https://s4s-ccus.epfl.ch>

CCUS Stakeholder Dialogue

June 15, 2026

Venue: L'Aula, Industrie 23, Enegyptolis Campus, Sion

Hosted by: S4S CCUS project, EPFL VPS, EPFL Energy Center



When

June 15, 2026



Where

EPFL Valais Campus



Organizers and contact

S4S team, Energy Center, EPFL VPS

Key highlights:

Presentations by

- EPFL leadership,
- Policymakers,
- Swiss Federal Office of Environment,
- International Energy Agency,
- Swiss and international industries engaged in CCUS efforts (e.g., Shell, Holcim, KVA Linth, Airfix, etc.)
- CCUS projects at research institutes (EPFL S4S CCUS, SWEET, ETH JI, NCCR Separations)
- Student posters and poster awards (sponsored by Nature Sustainability)

<https://s4s-ccus.epfl.ch/stakeholders/workshop-june-2026/>

A center on energy and environmental sustainability— NCCR Separations

Focus area: Low-cost direct air capture, ammonia synthesis, critical metals from waste



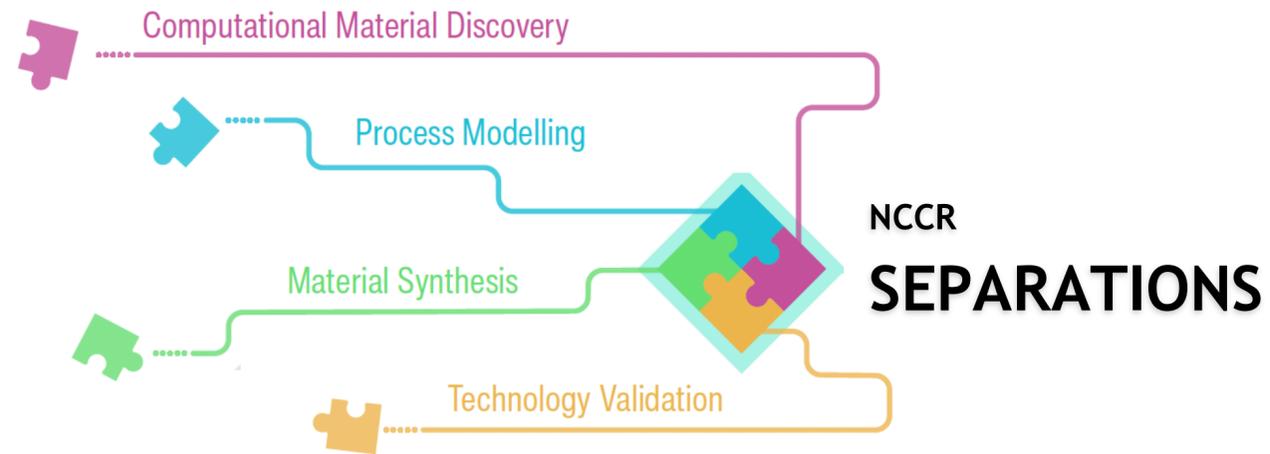
Wendy Queen
Director



Kumar Agrawal
Co-director



André Bardow
Deputy director



Arvind Rajendran



Randy Snurr



Ali Coskun



Wendy Queen
Kumar Varoon Agrawal
Michele Ceriotti
Nicola Marzari
Philippe Schwaller
Rachel Huang



Mathieu Soutrenon
Manuele Margini



Nathalie Casas
Andreas Borgshulte
Sandra Galmarini
Florian Kiefer



Andre Bardow
Christophe Müller
Paula Abdala



Thank you

enevi
producteur d'énergies positives

