EPFL

# Energy-efficient CCUS for Sustainable and Circular Economy

SusEcoCCUS

**Team**:
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Sascha Nick

## Project Update

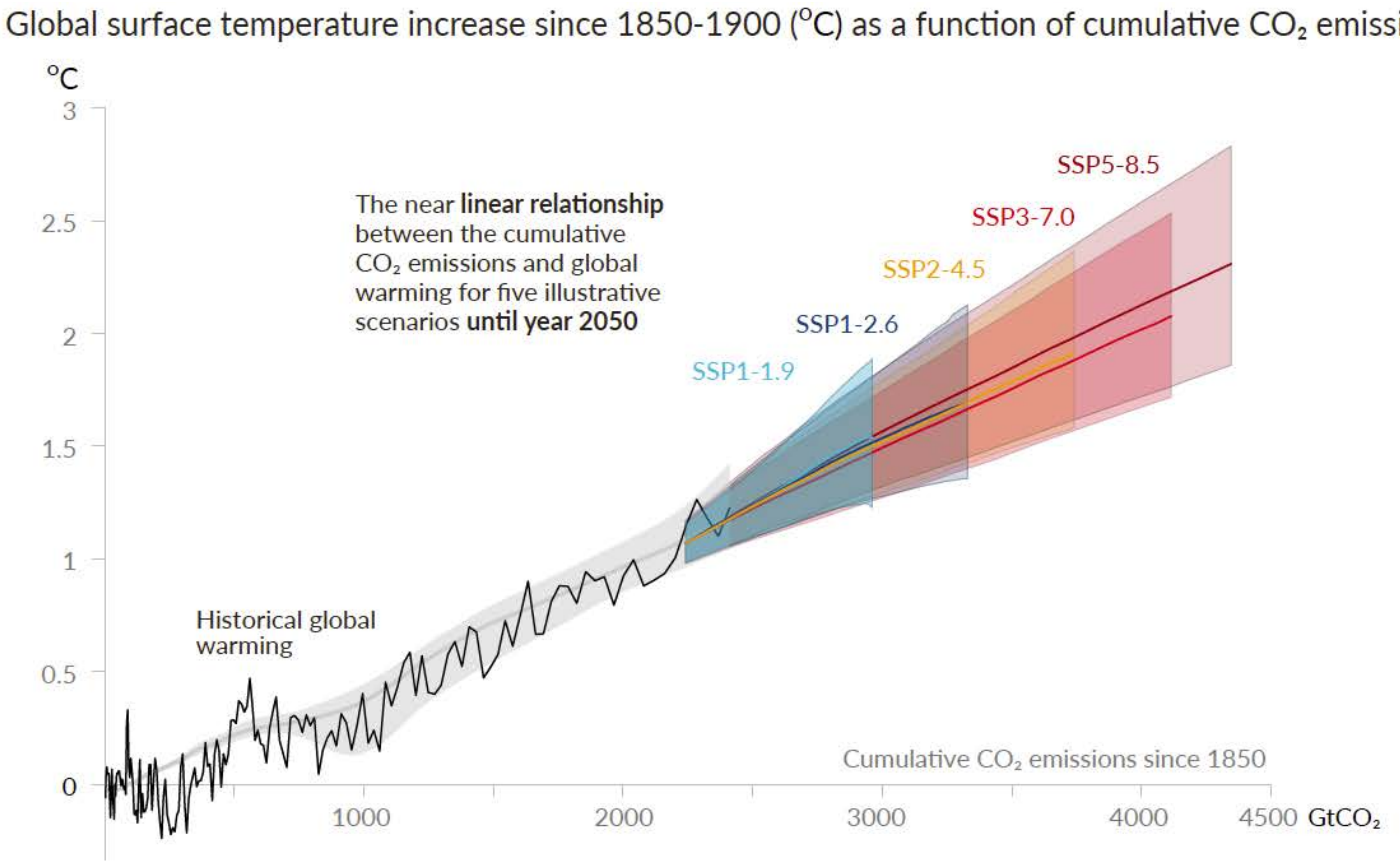
Kumar Varoon Agrawal

May 16, 2024

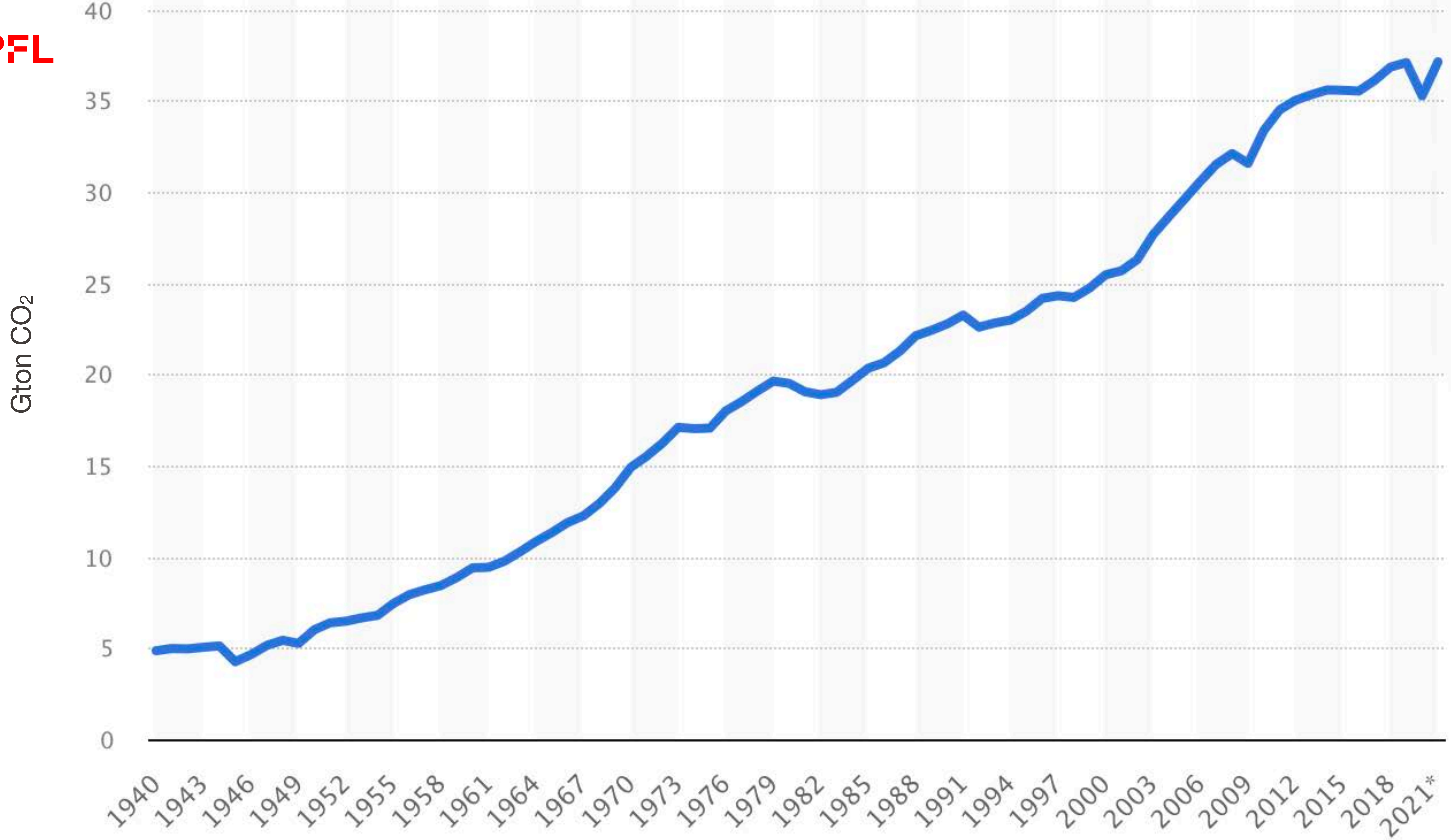
EPFL Symposium Research and Sustainability

**Contributing Faculties:** FSB, STI, ENAC
**Contributing Campuses:** Lausanne, Valais, Neuchâtel
**Demonstration site**: Enevi waste incineration plant (near EPFL Valais)

# Every ton of $CO_2$ emission adds to global warming




IPCC Sixth Assessment Report


Gton $CO_2$
40
35
30
25
20
15
10
5
0
1940
1943
1946
1949
1952
1955
1958
1961
1964
1967
1970
1973
1976
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1985
1988
1991
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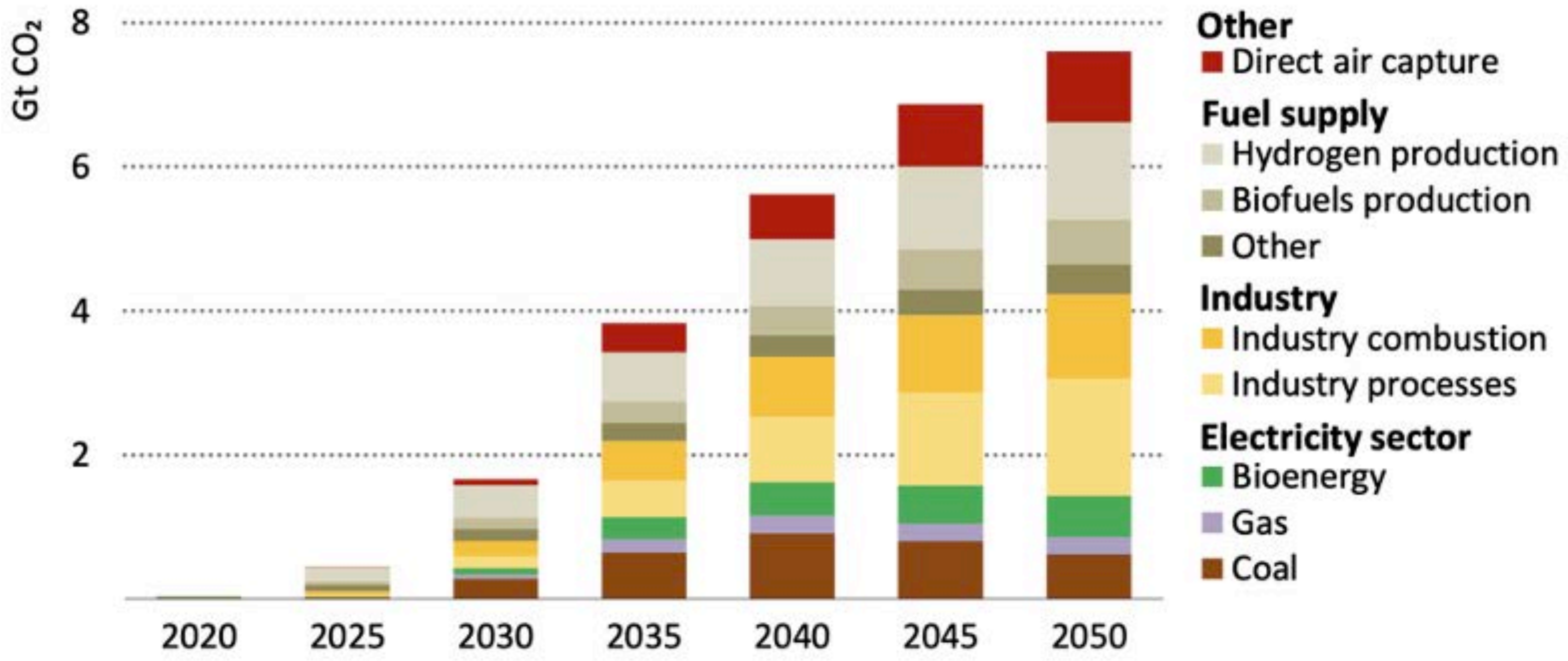
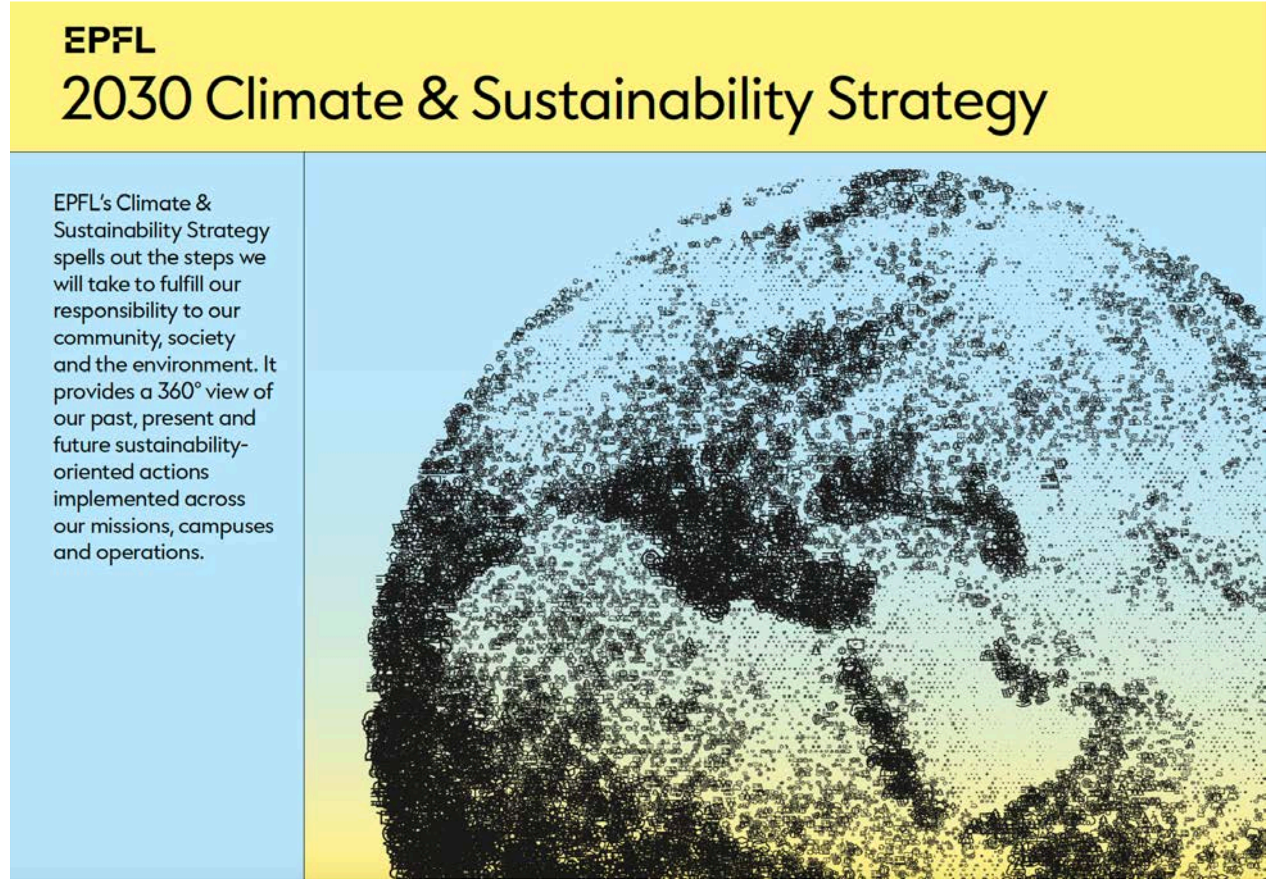
1997
2000
2003
2006
2009
2012
2015
2018
2021*

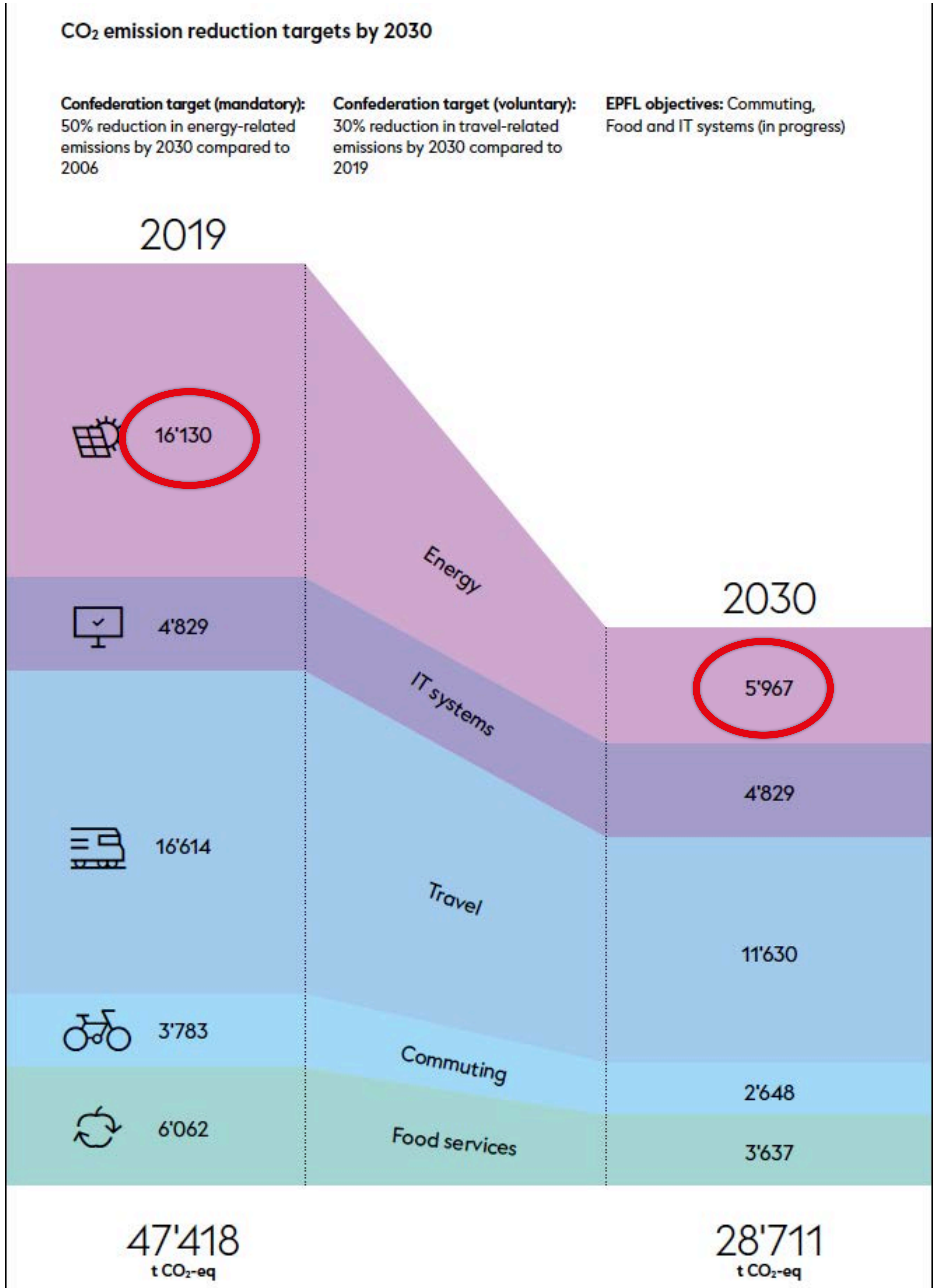
# International Energy Agency (IEA) projects large-scale deployment of CCUS for net zero by 2050




International Energy Agency, **2021**, https://www.iea.org.

# EPFL commitment: Solutions4Sustainability

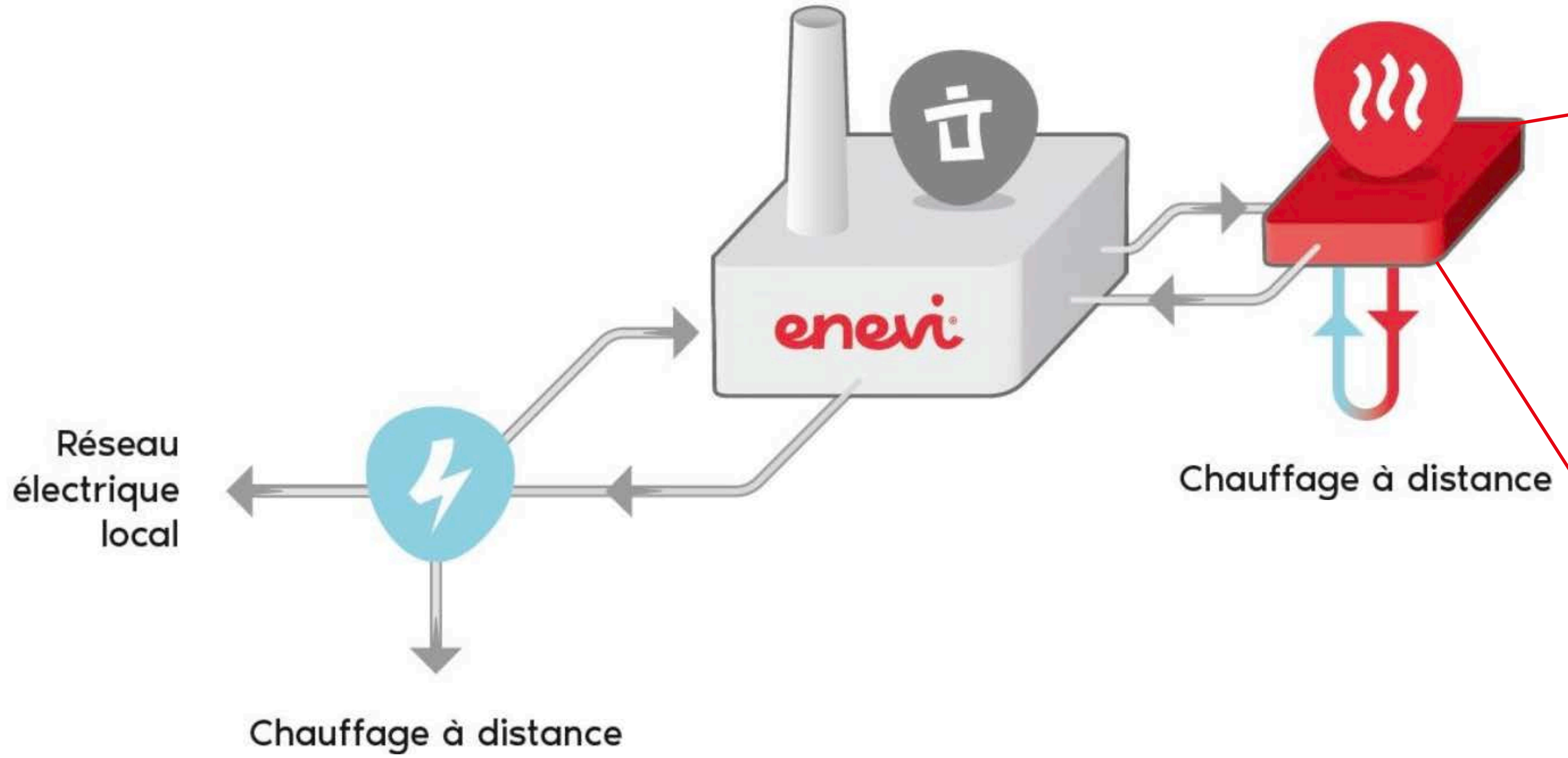



Cut our **energy-related carbon emissions by 50%** (from 2006 levels) by 2030.

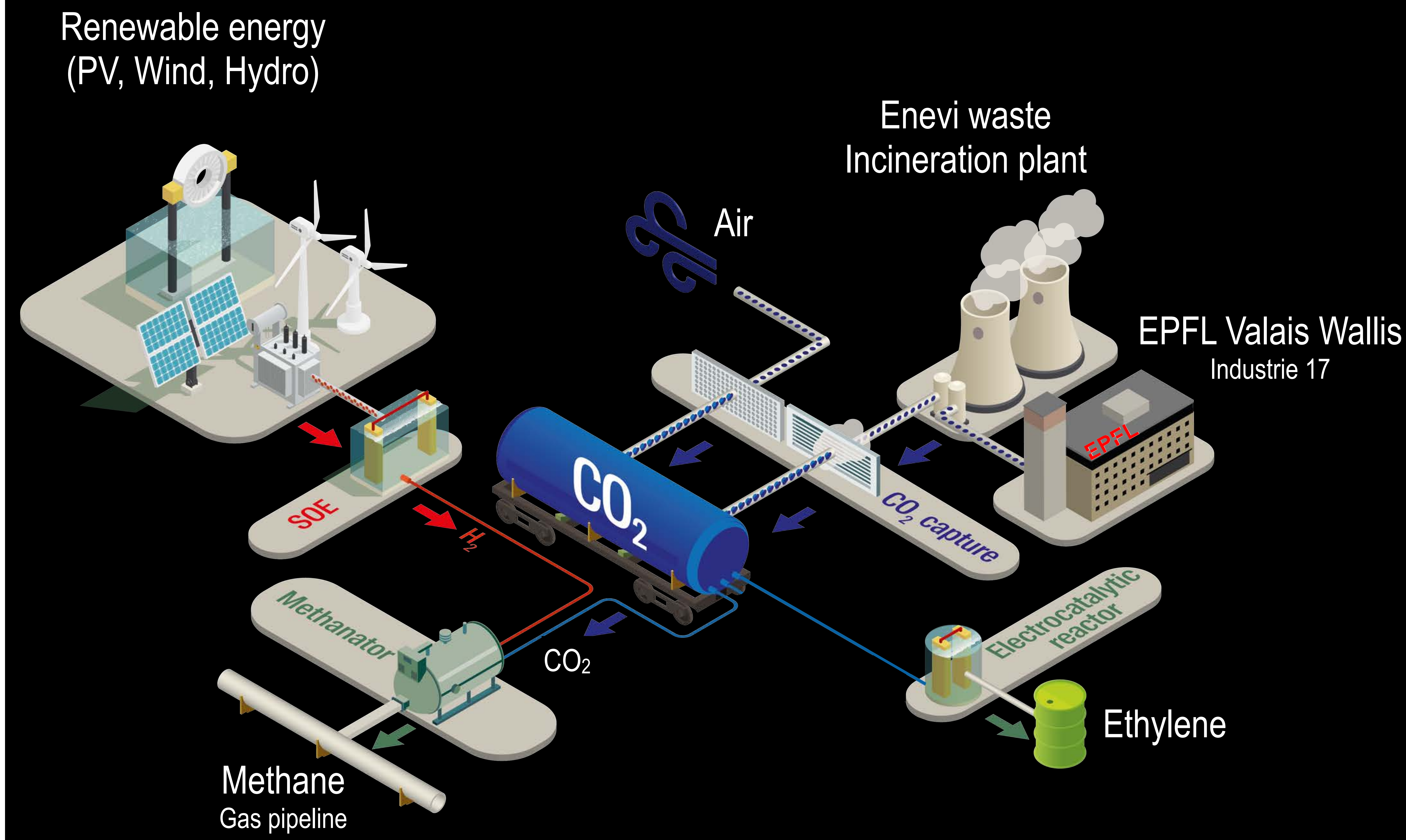
**Develop innovative, sustainable systems** for reducing our energy dependence and shrinking our carbon footprint, **by drawing on our know-how** in sustainability, clean energy, power storage, and **carbon capture, use and storage**.

# SusEcoCCUS at the site of Enevi


# Waste incineration plant as CCUS testbed


# SusEcoCCUS will reduce EPFL emission




- CCUS with flows up to 1 ton$_{CO_2}$/day to reduce EPFL emission footprint.
- Accelerate EPFL CCUS technologies 'well beyond state-of-the-art' to TRL 7.
- Position EPFL as a competence center in science, technology, and policy for CCUS.
- Generate of IP and expansion/creation startups in the area of sustainability.
- Promote strategic role of EPFL in Valais, especially in the context of energy transition.

# SusEcoCCUS

## Large-scale Demonstrator
TRL 4/5 ⟶ TRL 7

### WP1: Postcombustion Capture
1 ton/day

**Accelerated manufacturing for rapid scale-up**
**Capture at Valais district heating site (Enevi)**
**Target capture penalty: 20-30 $/ton_{CO_2}$**

Kumar Varoon Agrawal, Vivek Subramanian, Jürg Schiffmann, Wendy Queen

Roll-to-roll production of graphene membrane,
High-efficiency capture process by energy harvesting using microturbines
Production of porous sorbents for hybrid membrane/sorbent process

### WP2: $CO_2$ to renewable $CH_4$ in gas grid
0.35 ton/day

**Large-scale valorization of $CO_2$**

Jan van Herle

$CO_2$ to renewable $CH_4$ with high-efficiency (>70%) by integration of SOE with methanator

### WP3: $CO_2$ Storage
5 ton $CO_2$

**Acceleration of geological $CO_2$ storage**

Lyesse Laloui, Eleni Stavropoulou

Short-term and long-term $CO_2$ storage demonstrator at EPFL

## Advancing Critical Technologies
TRL 2/3 ⟶ TRL 4/5

### WP4: Direct Air Capture (DAC)

**Accelerated material discovery for low-cost DAC**

Wendy Queen, Nicola Marzari, Philippe Schwaller, Kumar Varoon Agrawal

High-working capacity porous adsorbents with long lifespan combined with highly-selective membranes for dilute feed

### WP5: $CO_2$ Refinery

**$CO_2$ to value-added chemicals**

Xile Hu, Jan van Herle

Stable $CO_2$ electrolyzer to ethylene, scale-up to 1 kW

## CCUS Enablers

### WP6: Process Modeling and Integration

**Robust, energy-efficient and integrated process**

François Marechal, Marina Micari

Process modeling, technoeconomics and life-cycle assessment

### WP7: Economics, Financing, Governance, and Policy

**Accelerating Swiss net zero**

Sascha Nick

Financing model, Governance framework, public policy instruments

### WP8: Dissemination, Student Involvement, and Outreach

**Training next generation of scientists**

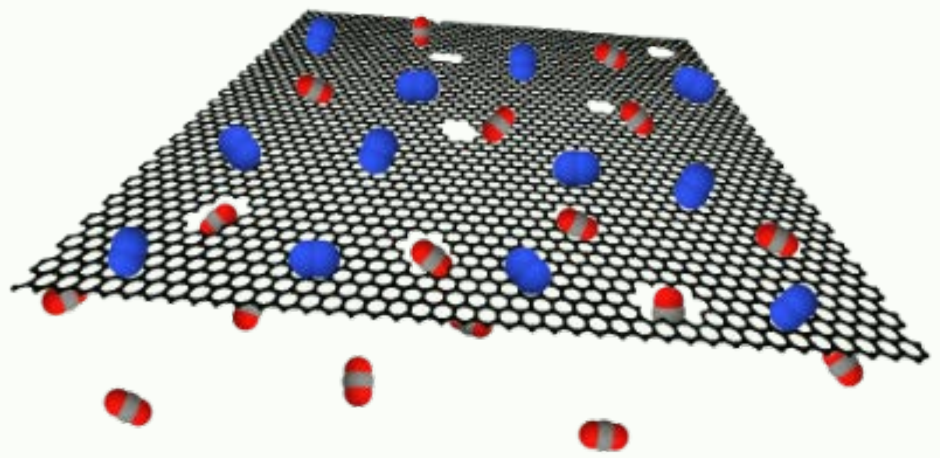
Marina Micari, Kumar Varoon Agrawal, François Marechal

EPFL student MAKE (carbon) team, Master's project

# Accelerating EPFL CCUS Tech by SusEcoCCUS

## Large-scale Demonstrator (TRL 4/5 →TRL 7)

### Roll-to-roll production of graphene membranes to capture 1 $ton_{CO_2}$/day from waste incineration

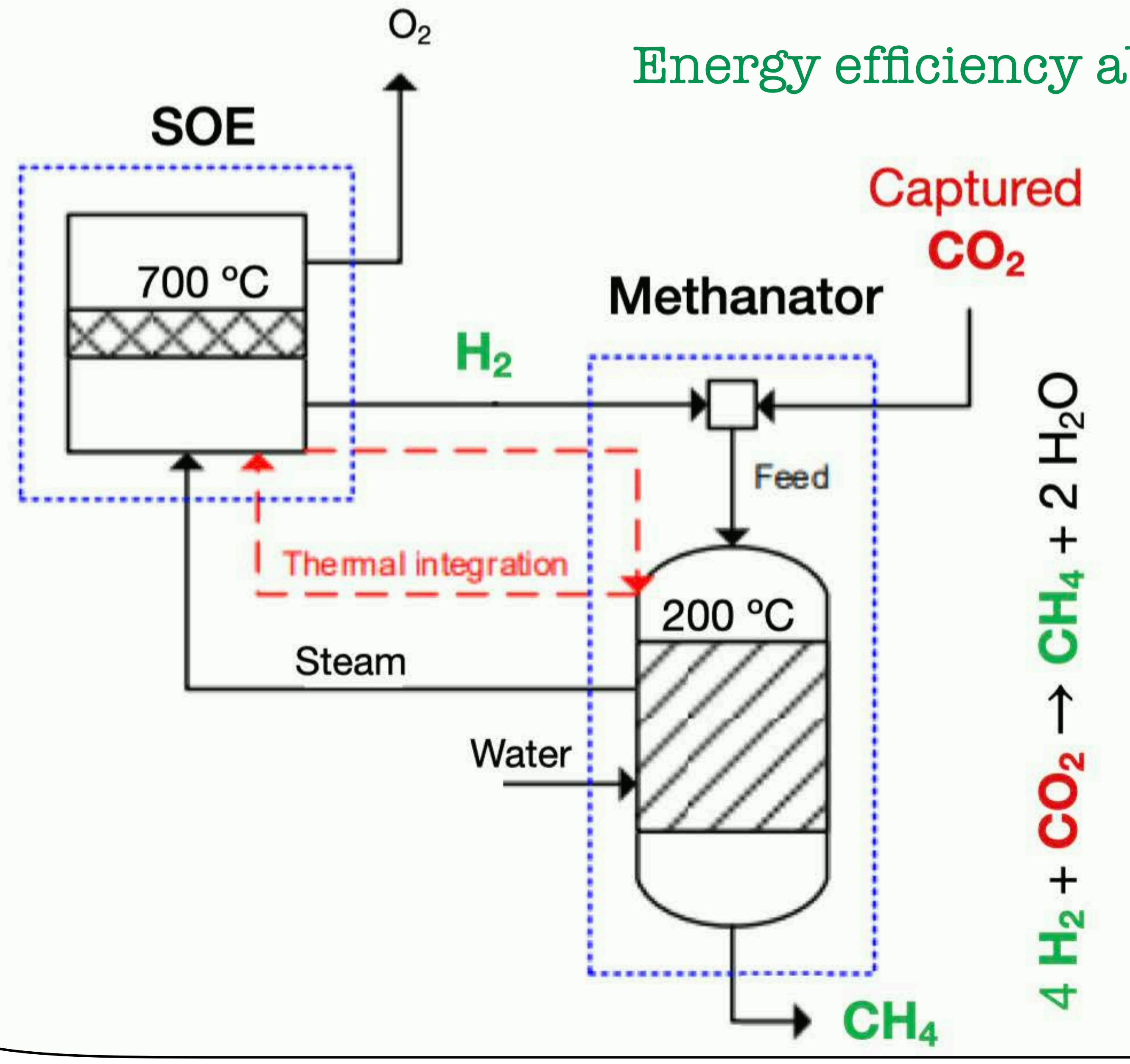


| | Specific energy consumption: | Capture penalty: |
|---|---|---|
| Commercial technology | 3-4 $GJ/ton_{CO_2}$ | 50-110 $\$/ton_{CO_2}$ |
| Graphene membrane | < 1 $GJ/ton_{CO_2}$ | 20-30 $\$/ton_{CO_2}$ |

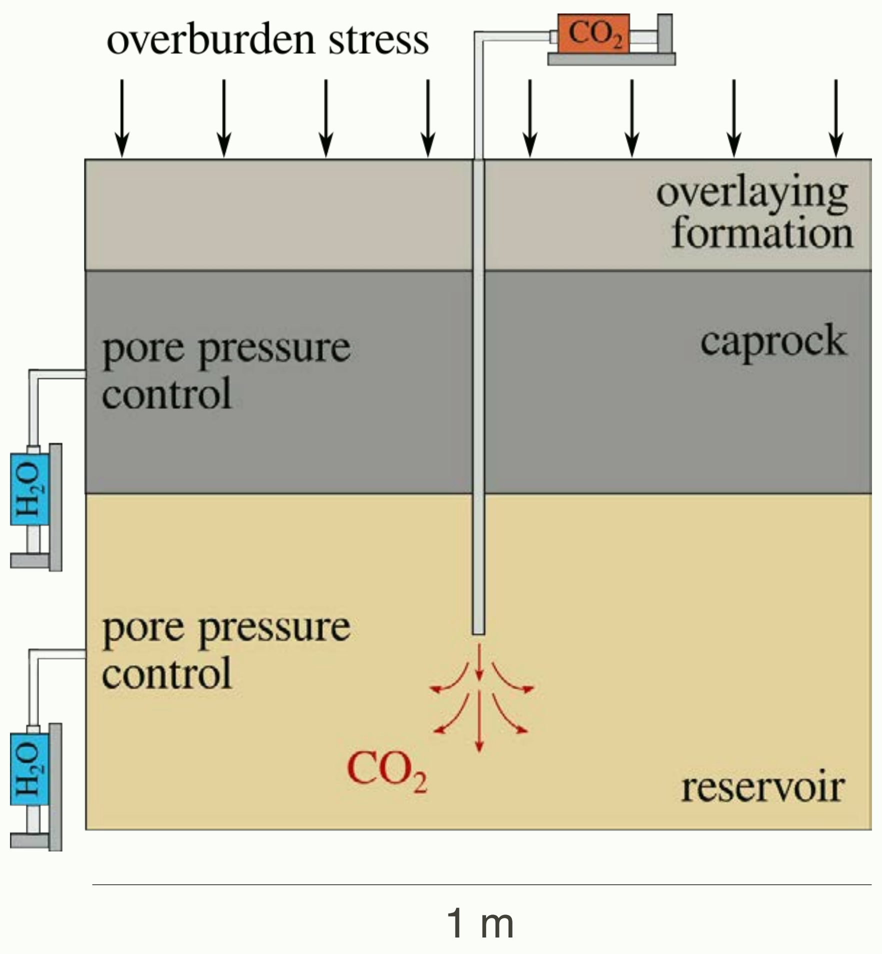
### Short-term storage of captured $CO_2$ (5 ton)


### Valorization of captured $CO_2$ as energy carrier ($CH_4$, 200 $m^3$/day) for injection in natural gas grid

Energy efficiency above 70%



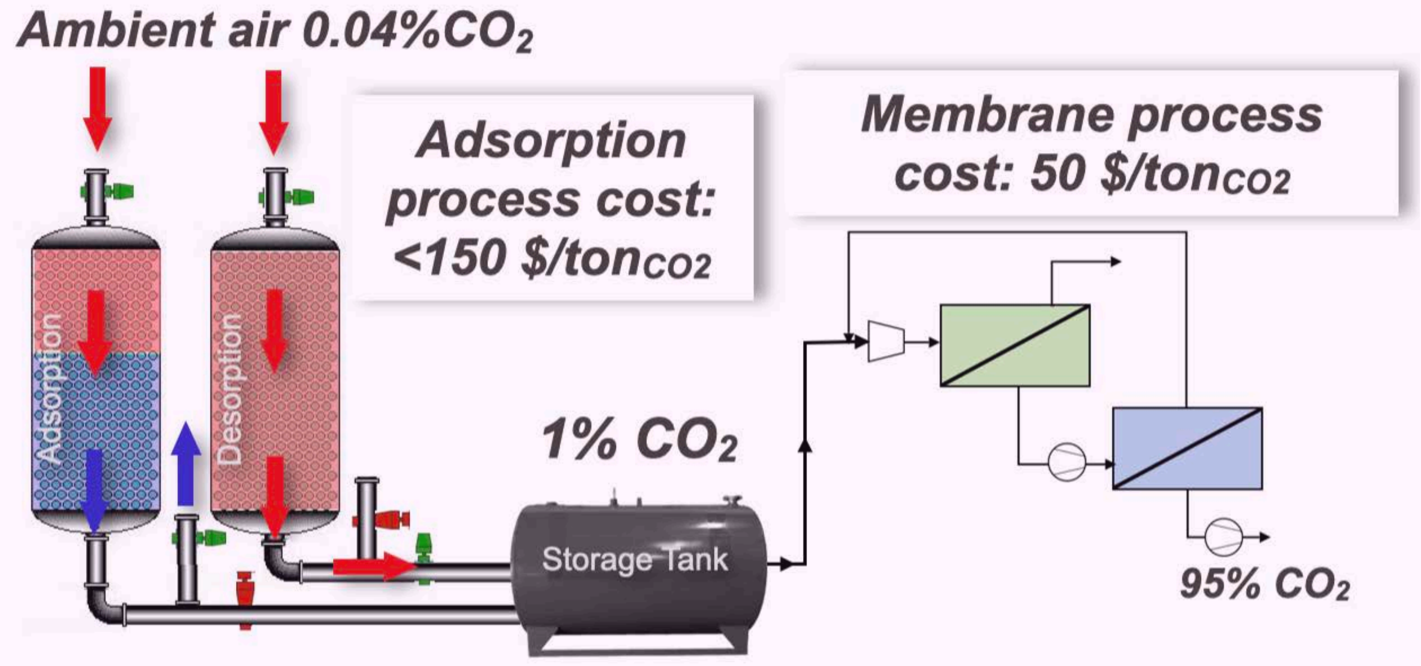

### Unique geological $CO_2$ storage simulator to predict real field



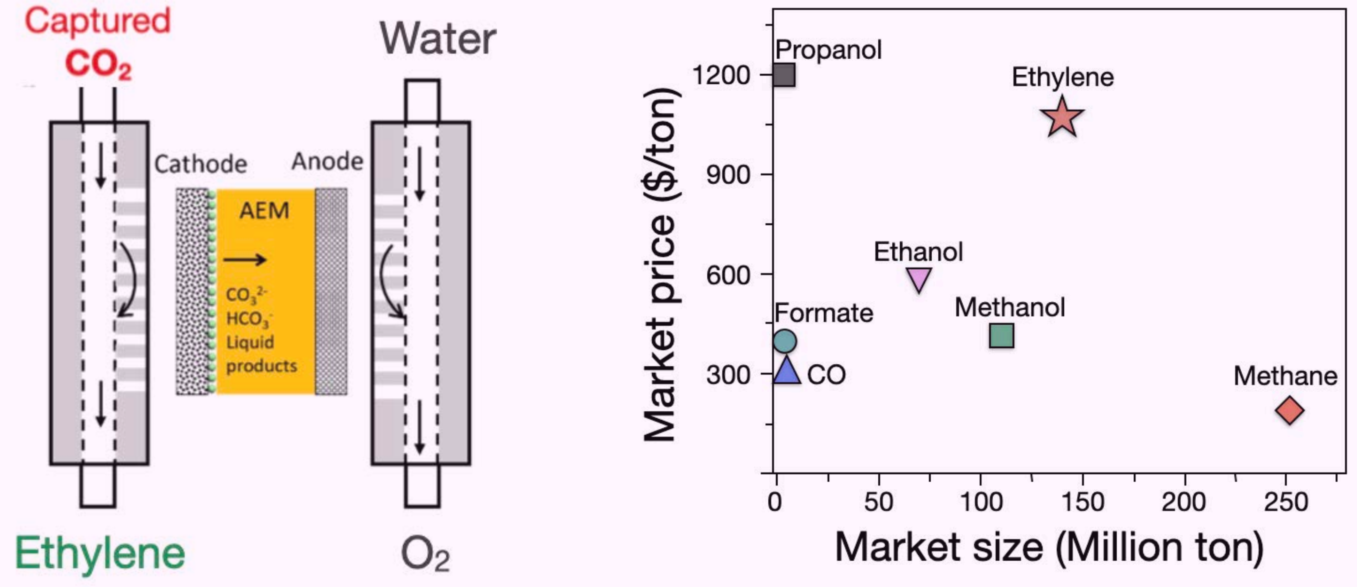

Meter-scale GCS simulator

## Advancing Critical Technologies (TRL 2/3 → TRL 4/5)

### Accelerated development of low-cost direct air capture (<200 $\$/ton_{CO_2}$)




### Valorization of captured $CO_2$ into highly value-added chemicals



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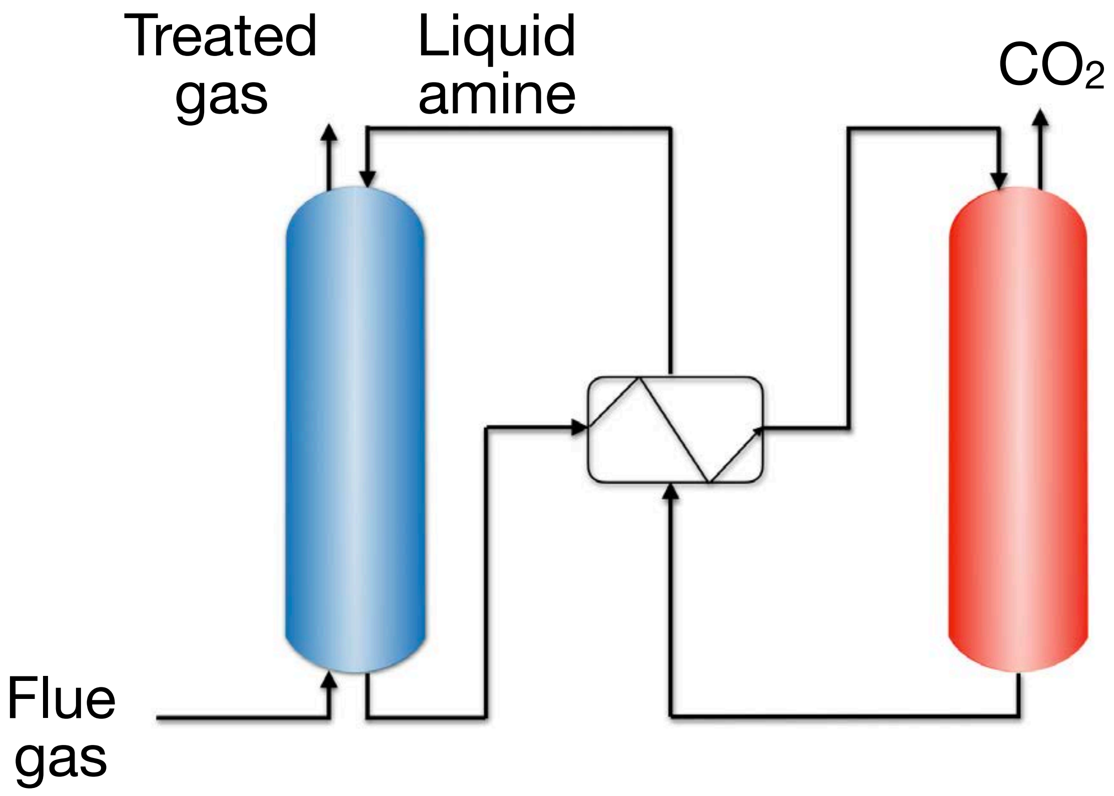
# WP1: Postcombustion Capture

Large-scale

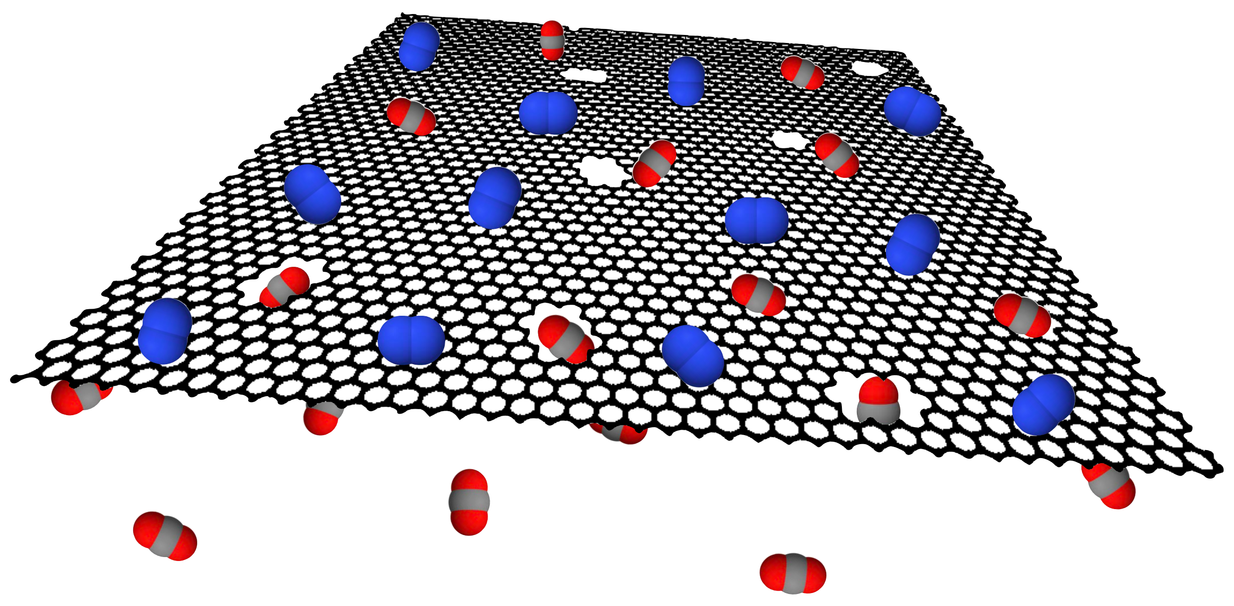
1 ton/day

## Commercial solution: Amine-based $CO_2$ absorption




- Complex operation and high capture penalty.
- Degradation and loss of amine during regeneration.

## EPFL capture technology using atom-thick graphene membrane



| | Specific energy consumption: | Capture penalty: |
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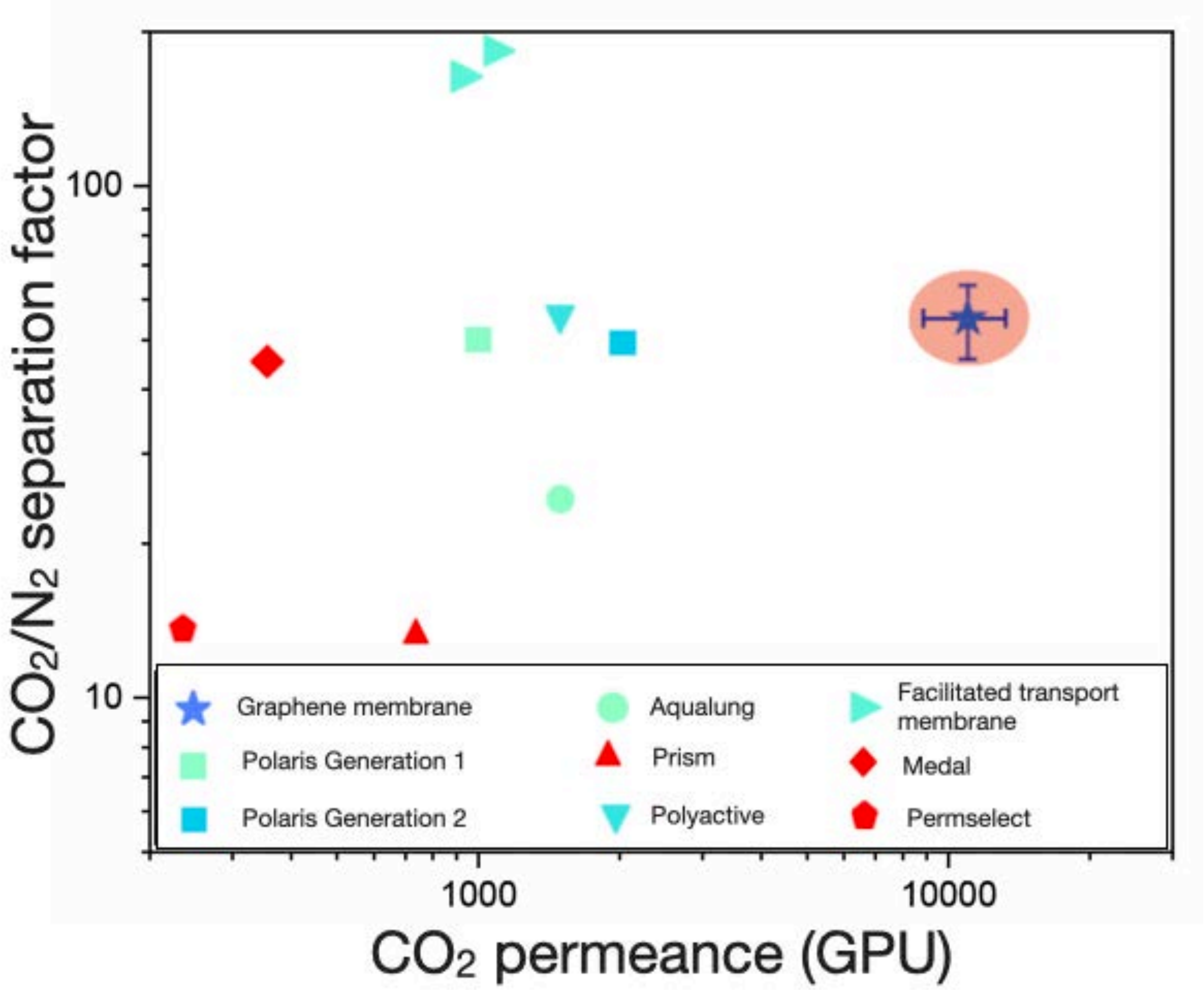



Nature Energy **2024**, In Press

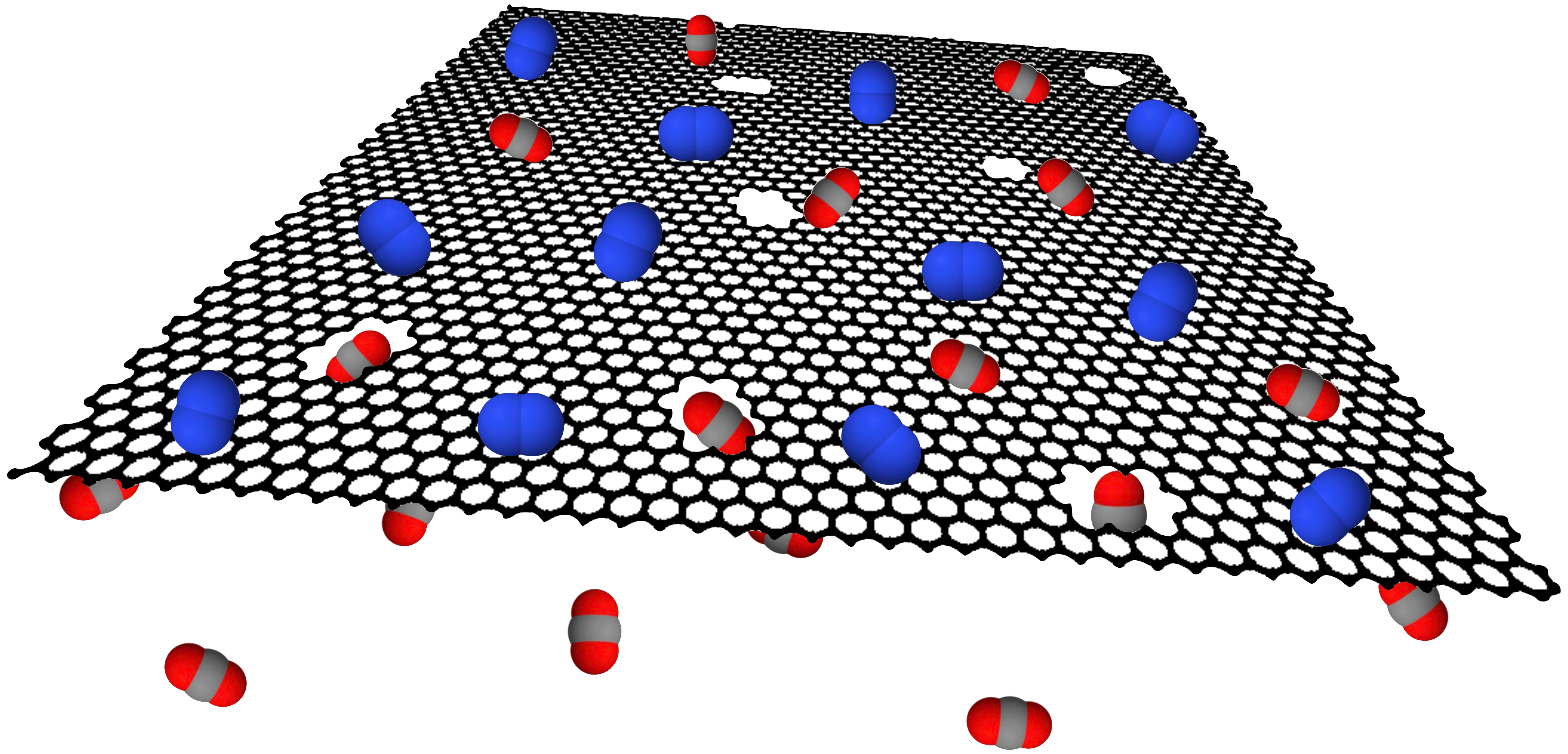

Nature Communications **2018**, 9, 2632
Science Advances **2019**, 5, eaav1851
Advanced Functional Materials **2020**, 30, 2003979
Science Advances **2021**, 7, eabf0116
JACS Au, **2022**, 2, 723
Advanced Materials, **2022**, 34, 2206627
Accounts of Materials Research **2022**, 3, 1073
JACS Au **2023**, 3, 2844-2854
Physical Review Letters **2023**, 131, 168001
Journal of Physical Chemistry C **2023**, 127, 22015-2202

EPFL

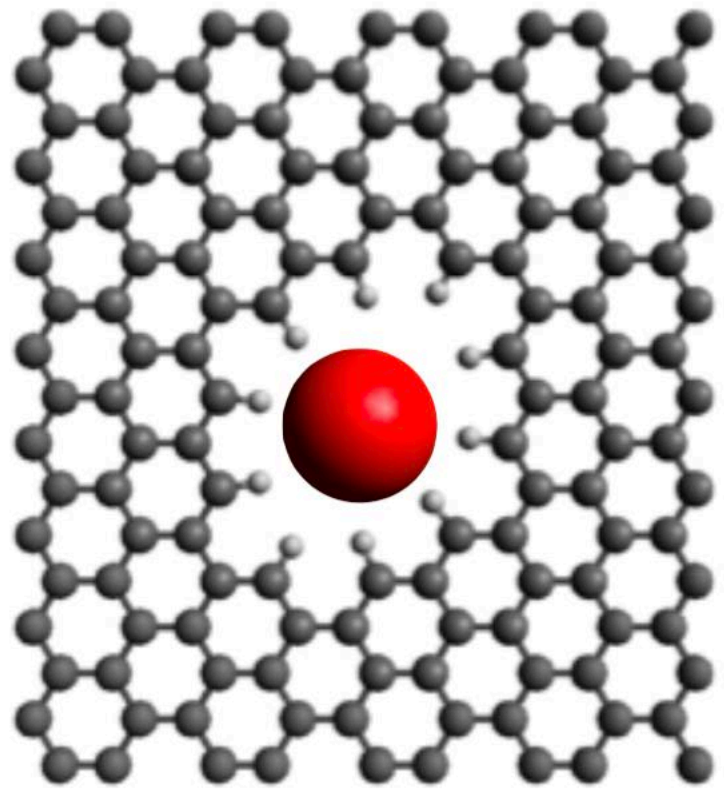
Laboratory of Advanced Separations

# Gas separation with atom-thick films

Graphene film is just one atom-thick: highest possible gas flux of all materials



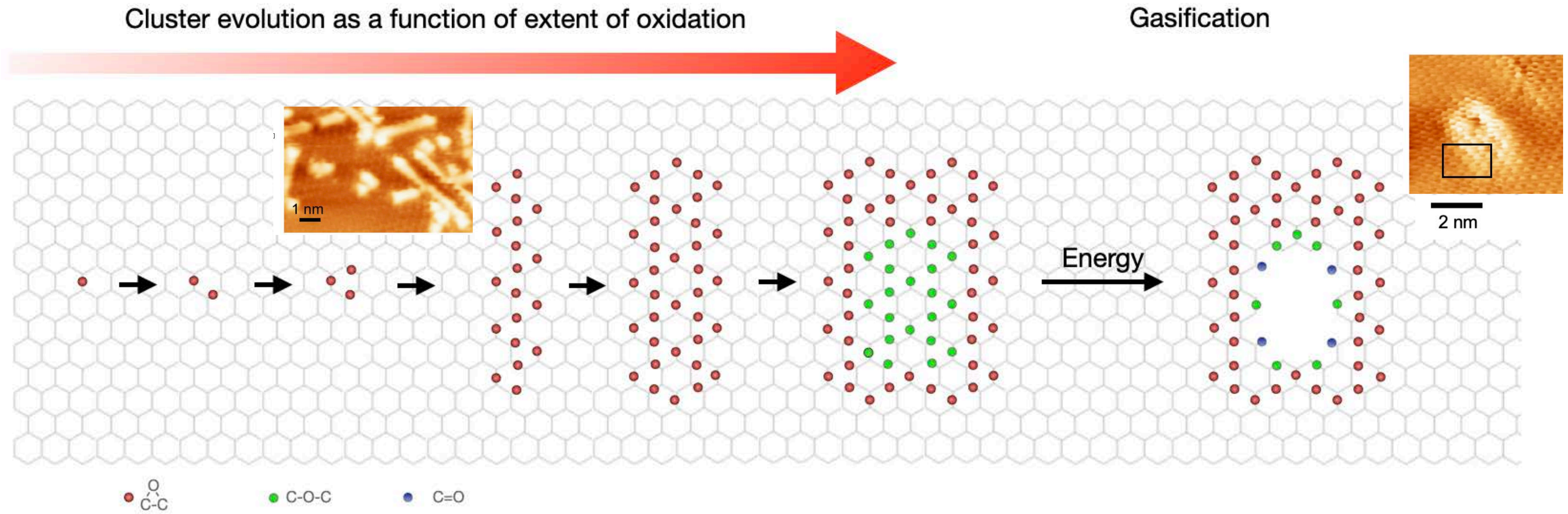
Molecular-sieving from Å-scale pores



$$\text{Flux} \propto H\, exp\left(\frac{-E_{barrier}}{k_B T}\right)$$


Nature Communications **2018**, 9, 2632
Science Advances **2019**, 5, eaav1851
Advanced Functional Materials **2020**, 30, 2003979
Science Advances **2021**, 7, eabf0116
PNAS **2021**, 118, e2022201118
ACS Nano **2021**, 15, 13230
JACS Au, **2022**, 2, 723
Advanced Materials, **2022**, 34, 2206627
Accounts of Materials Research **2022**, 3, 1073
ACS Nano **2022**, 16, 15382
Angewandte Chemie, **2022**, 61, e202200321
JACS Au **2023**, 3, 2844-2854
Physical Review Letters **2023**, 131, 168001
Journal of Physical Chemistry C **2023**, 127, 22015-2202
Carbon, **2024**, 118897
Carbon, **2024**, 221, 118866
ACS Nano, **2024**, doi:10.1021/acsnano.3c11068.
ACS Nano **2024**, doi:10.1021/acsnano.3c11885.
Nature Communication **2024**, In press
Nature Energy **2024**, In press

# Our contribution to the science of making holes in graphene




Science Advances **2021**, 7, eabf0116
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Advanced Materials, **2022**, 34, 2206627
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Laboratory of Advanced Separations

# We have simplified the way porous graphene is made

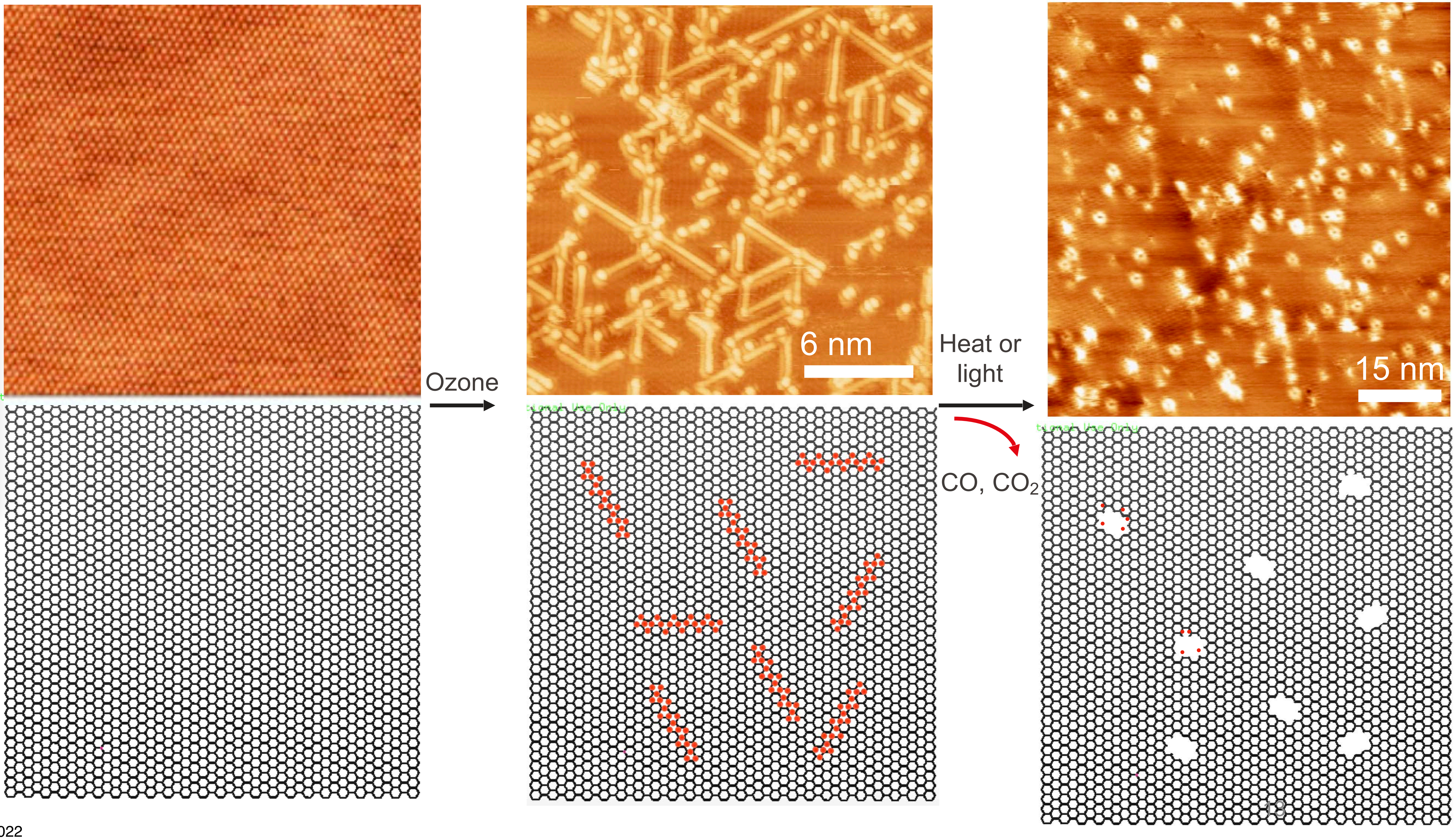
Pores are formed by

flowing ozone over graphene

+ energy (heating)

...

That's it




Science Advances **2021**, 7, eabf0116
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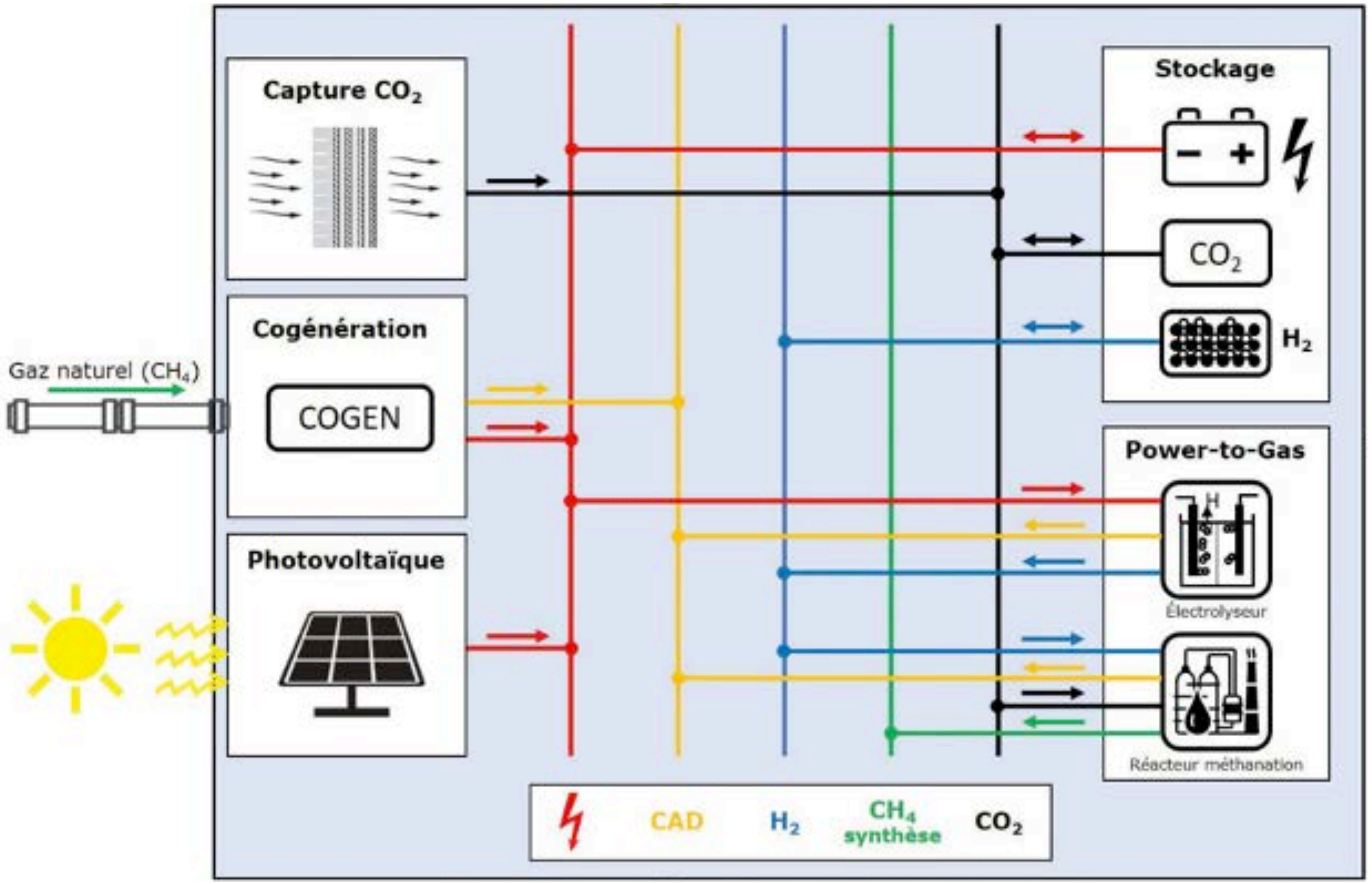
Journal of Physical Chemistry C **2023**, 127, 22015-22022

# Greengas project with GAZNAT

Capture of flue gas from CHP using graphene membrane




Agrawal, K. V.; Bautz, R. Capture Du Carbone. Aqua & Gas. **2022**, pp 46–53.

- Membrane skid capturing $CO_2$ from flue gas.
- Stable performance in flue gas achieved with parity performance with simulated gas mixture.

# WP1: Postcombustion Capture

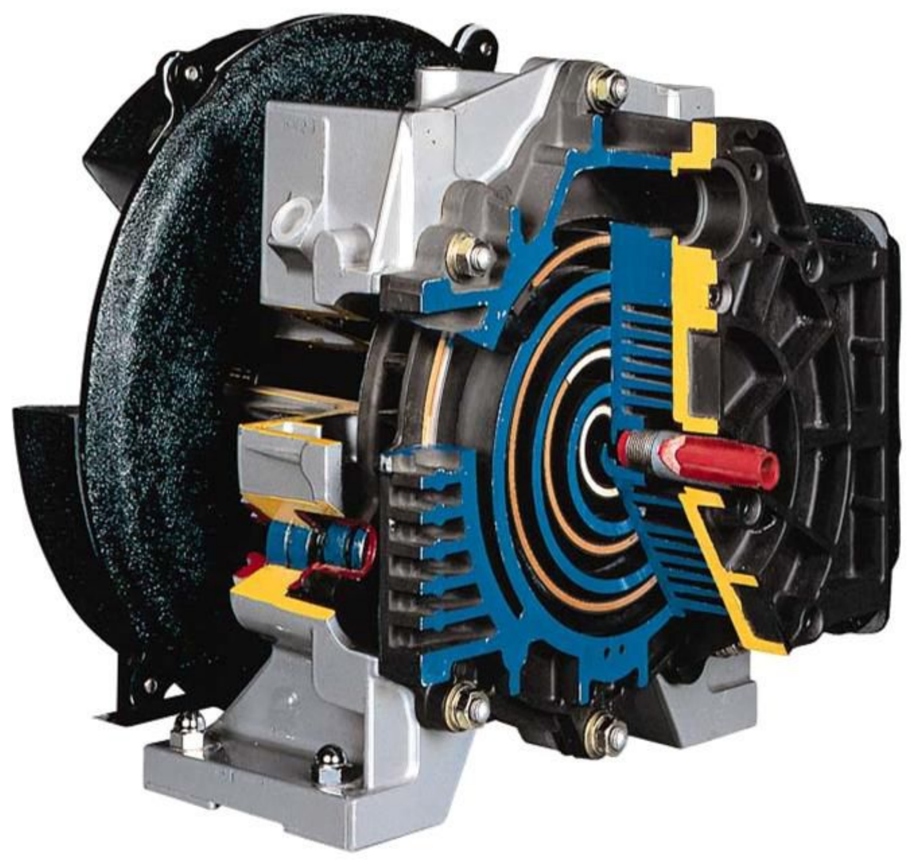
Large-scale

1 ton/day

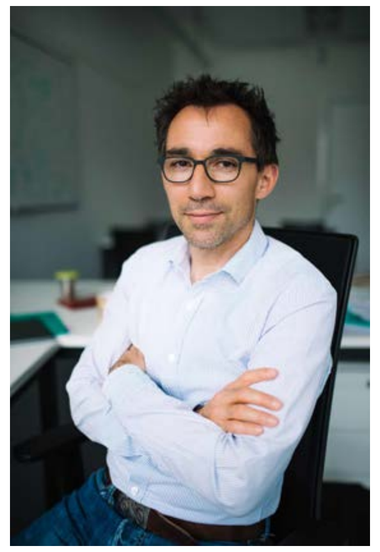
Kumar Varoon Agrawal, Vivek Subramanian, Jürg Schiffmann, Wendy Queen

**High-efficiency capture process by energy harvesting using microturbines**

- Current oil-free compressors based on scroll machines with abradable seals
  - Low efficiency
  - Maintenance interval 2’500h
  - Life-time 20’000h
  - Bulky



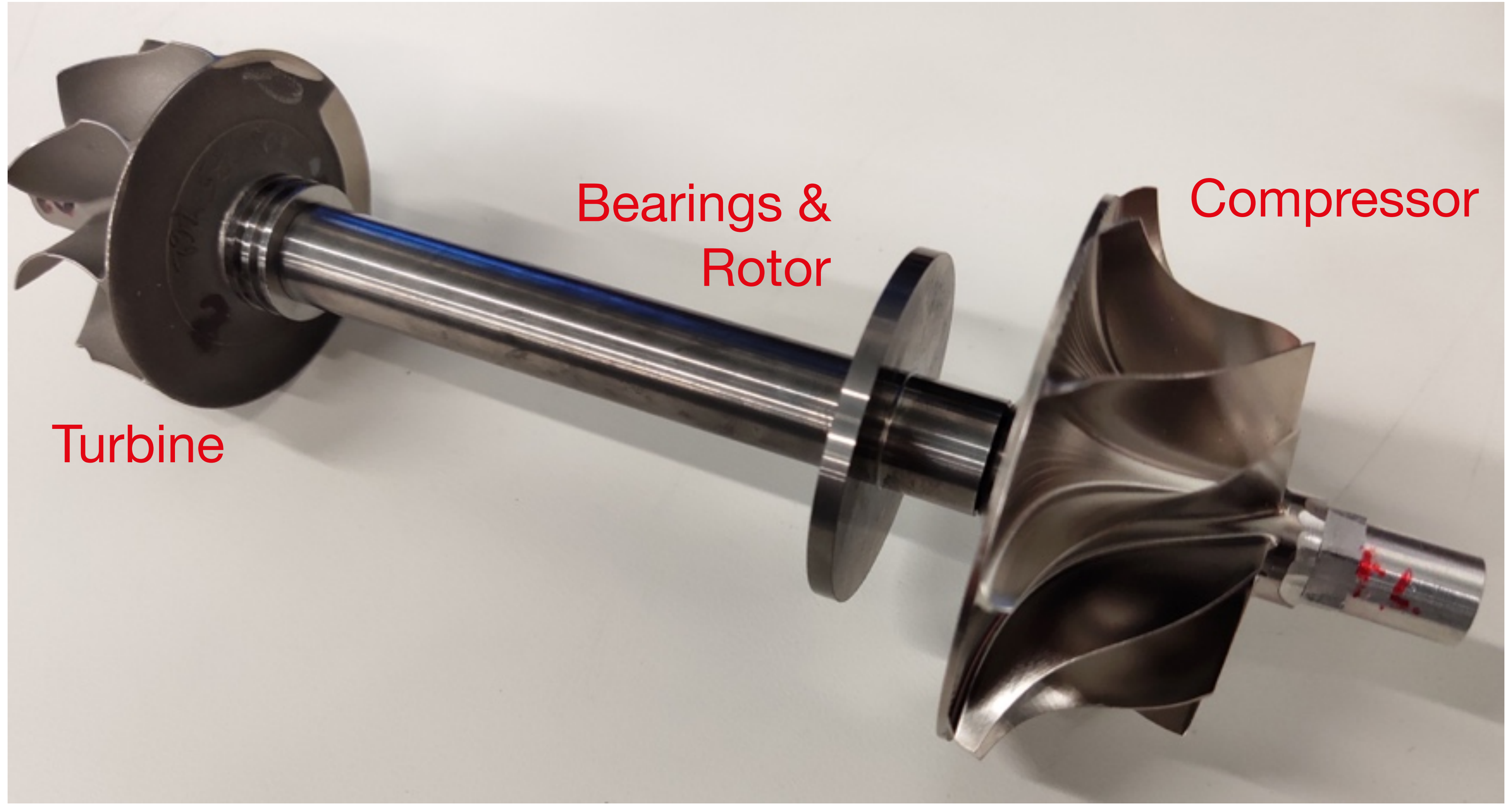
www.compressorworldcanada.ca



Prof. Jürg Schiffmann

SusEcoCCUS

- 2.8 kW gas bearing-supported turbocompressor coupled with turbine
  - 11% improvement in efficiency
  - Maintenance free
  - Longer lifetime (7.5-fold)
  - Smaller footprint (10-fold power density)



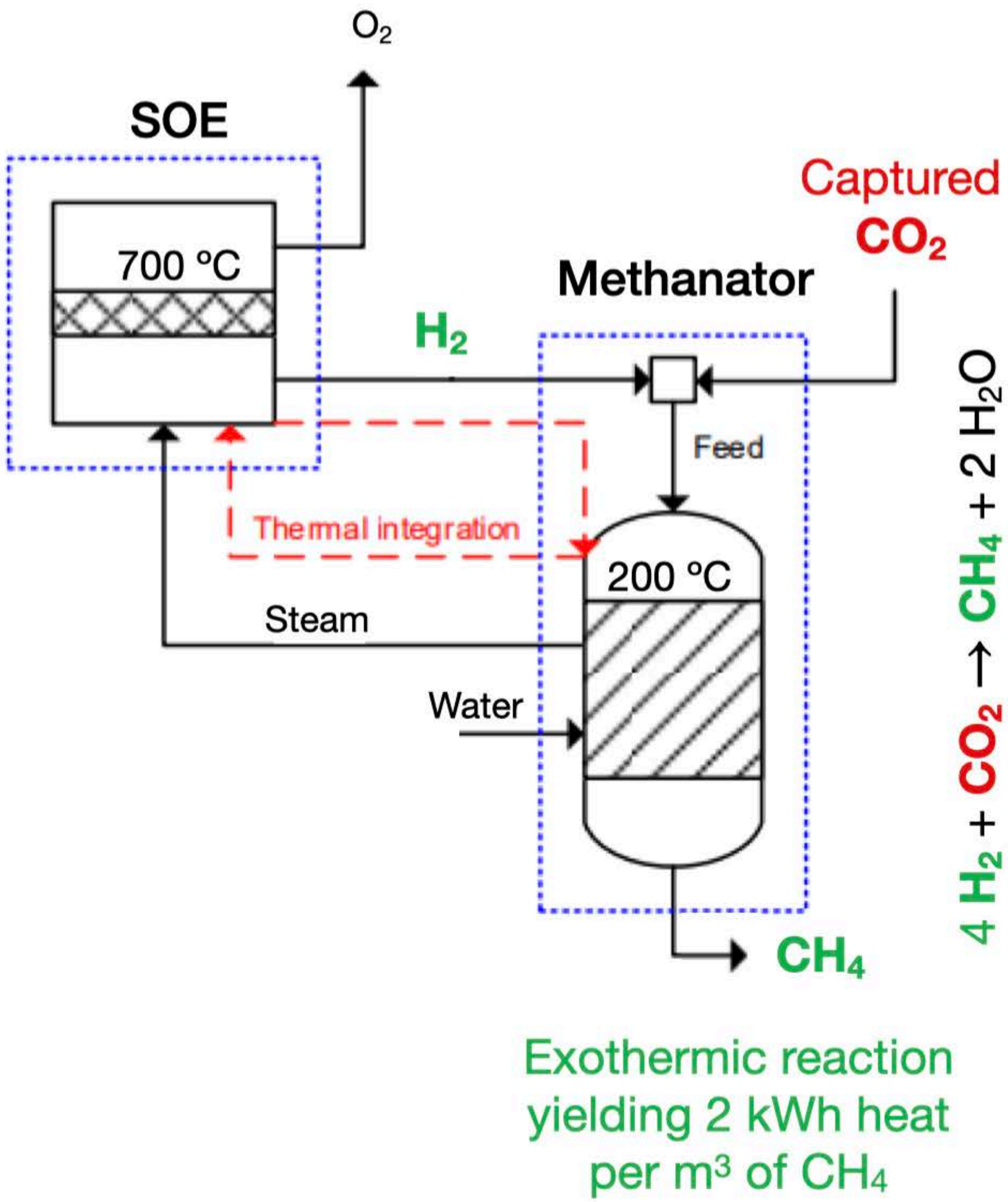
# WP2: $CO_2$ to renewable energy carrier ($CH_4$)

Large-scale

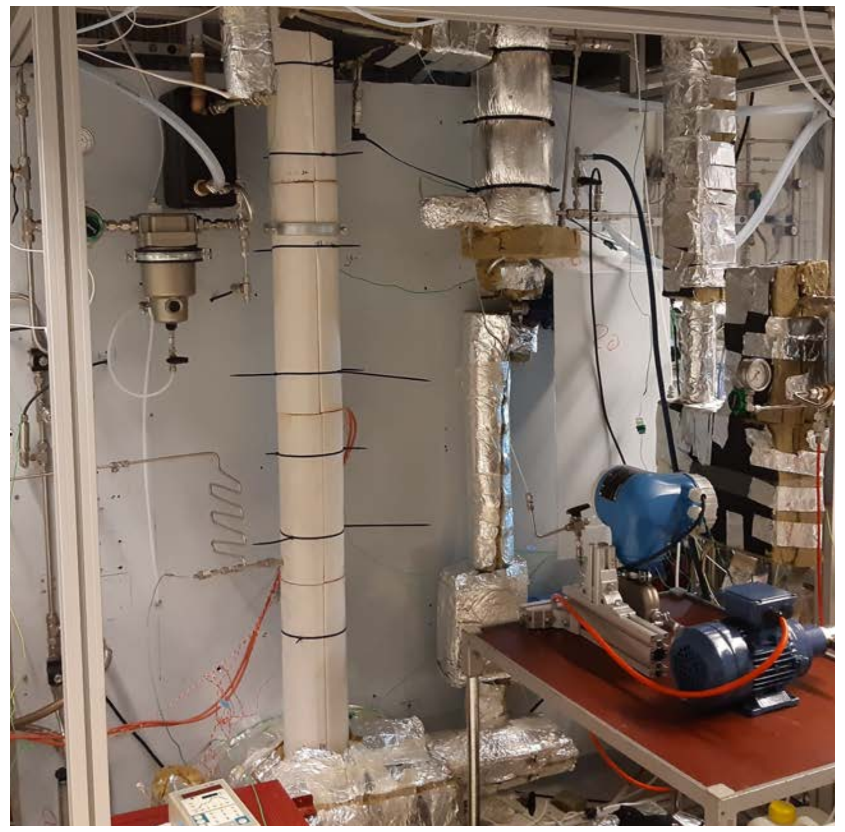
0.35 ton/day

Prof. Jan van Herle

- Large-scale valorization of $CO_2$ at the scale of 0.35 ton/day to energy carrier.
- $H_2$ by 100% efficient steam electrolysis in solid-oxide electrolyzer (SOE).
- SOE heat integrated with methanator with theoretical energy efficiency of 80%.




- 15000 hour successful operation of SOE.
- 10 kW methanator demonstrated.
- 5 kW SOE heat-integrated with methanator.



SusEcoCCUS

- 100 kW SOE from SolydEra.
- Scale-up methanator 10-times to produce 80 kW $CH_4$ (200 $m^3$/day).
- Target efficiency > 70%.

# WP3: $CO_2$ Storage



Prof. Lyesse Laloui


Dr. Eleni Stavropoulou

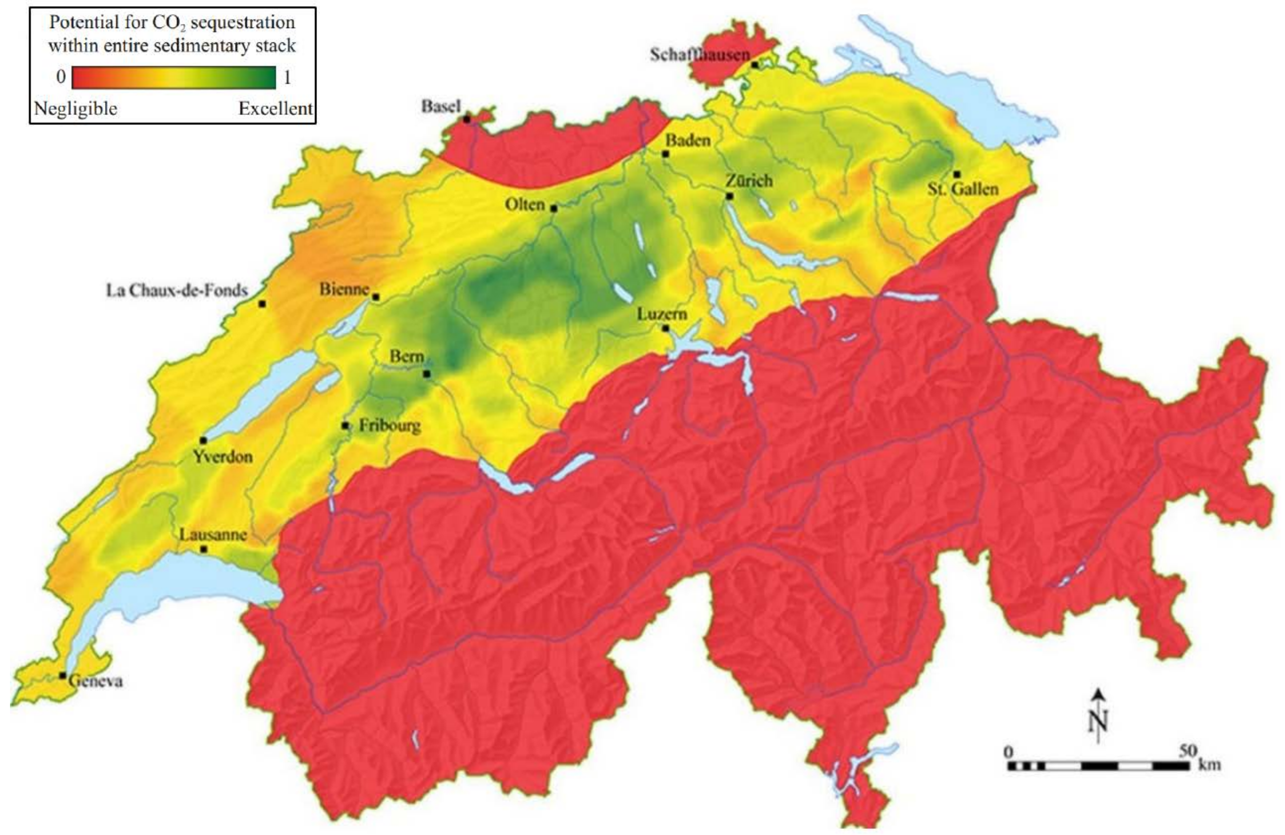

Large-scale

5 ton $CO_2$

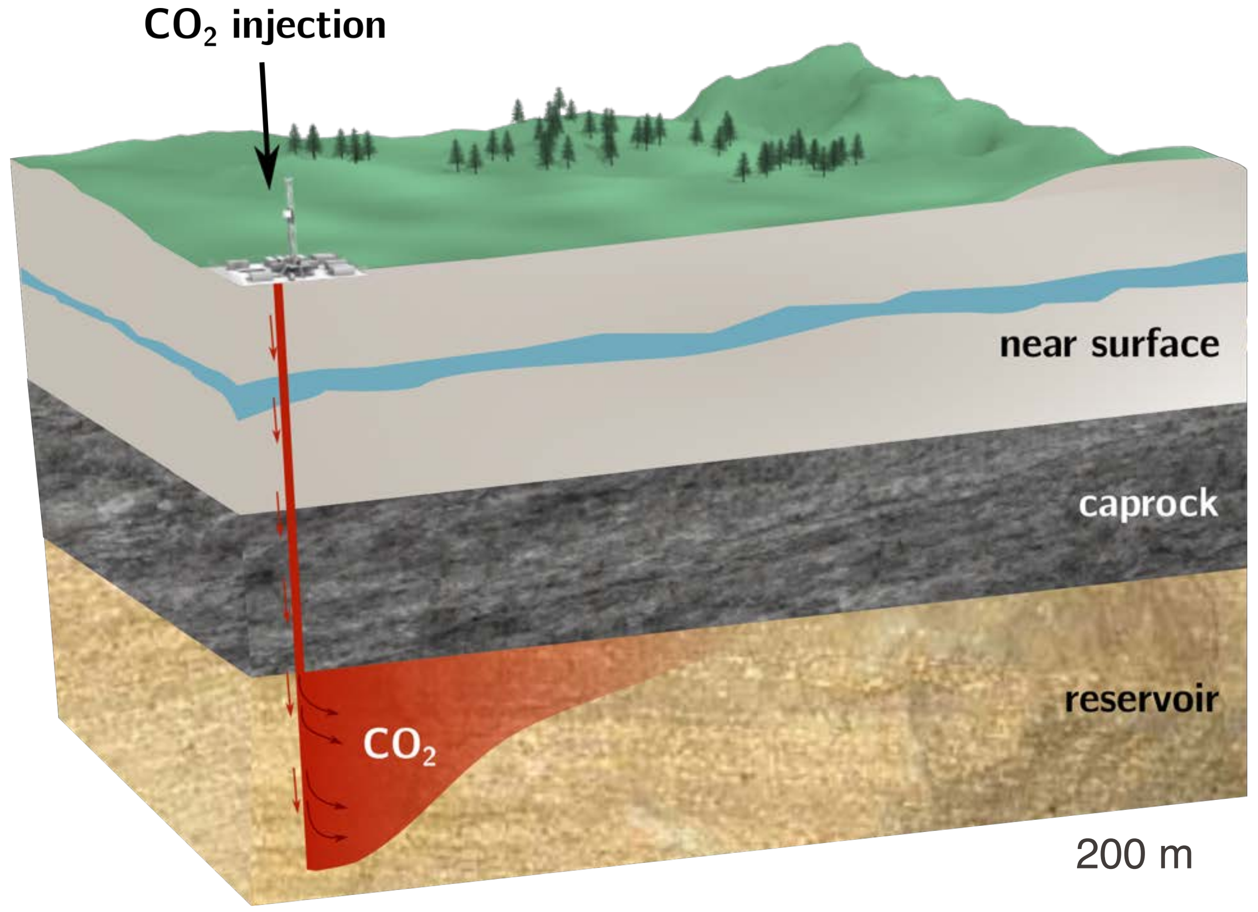
## Acceleration of geological $CO_2$ storage, the most efficient technology for permanent storage of large volumes of $CO_2$

**Inland storage** in deep porous geological formations

→ **Storage potential** in the Swiss Molasse Basin (theoretical capacity 2.7 Gt $CO_2$)




## Storage in a unique meter-scale GCS simulator




*GCS in the field*

High injection depth > 800 m

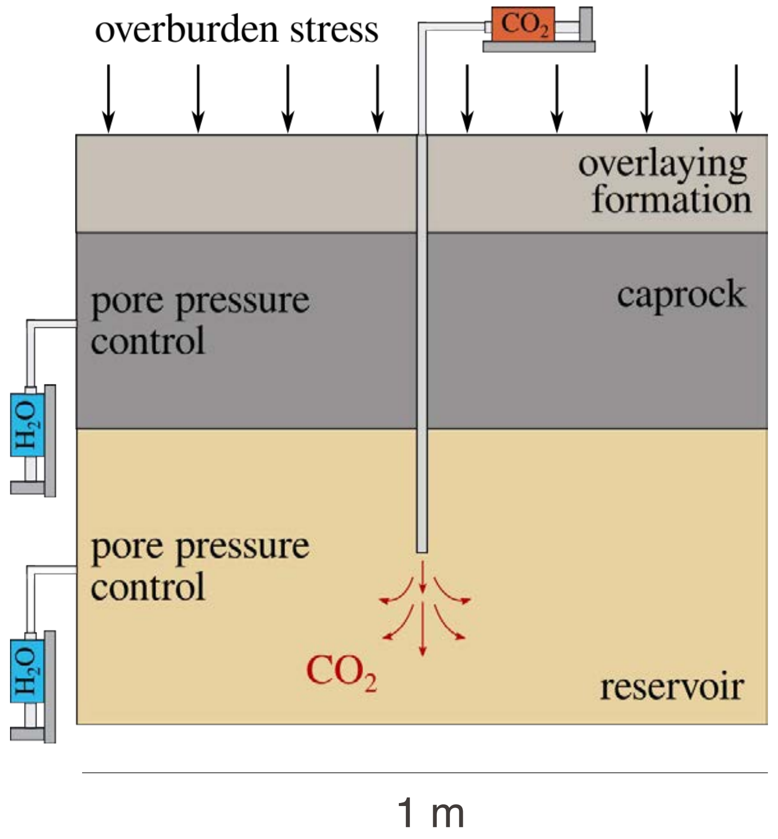
Overlaying caprock formation:
Hydro-mechanical barrier

Storage reservoir:
Highly permeable and porous rock formations

High overburden (200 bar) and pore (100 bar) pressures

Synthetic clayey caprock material

Reservoir reproduction with cemented sand




Meter-scale GCS simulator

0.1 ton $CO_2$

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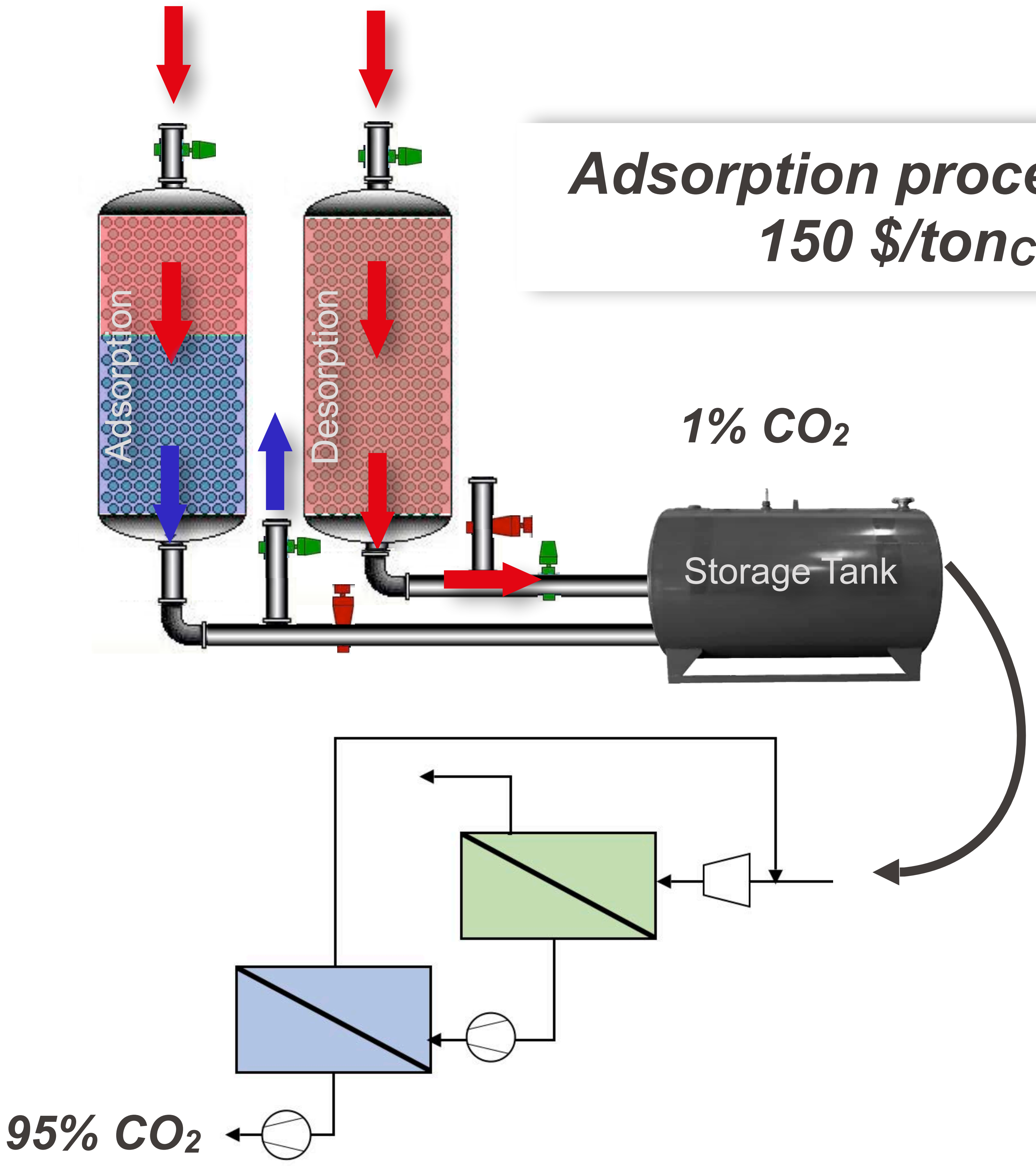
# WP4: Direct Air Capture (DAC)

Critical Technology

Kg scale

***Development of novel hybrid adsorbent/membrane process to cut DAC cost***

*Ambient air 0.04%$CO_2$*




***Adsorption process cost: 150 \$/ton$_{CO2}$***

***Low-temperature desorption to improve stability***

***Membrane process cost: 100 \$/ton$_{CO2}$***


Prof. Wendy Queen


Prof. Philippe Schwaller


Prof. Nicola Marzari

Benefits

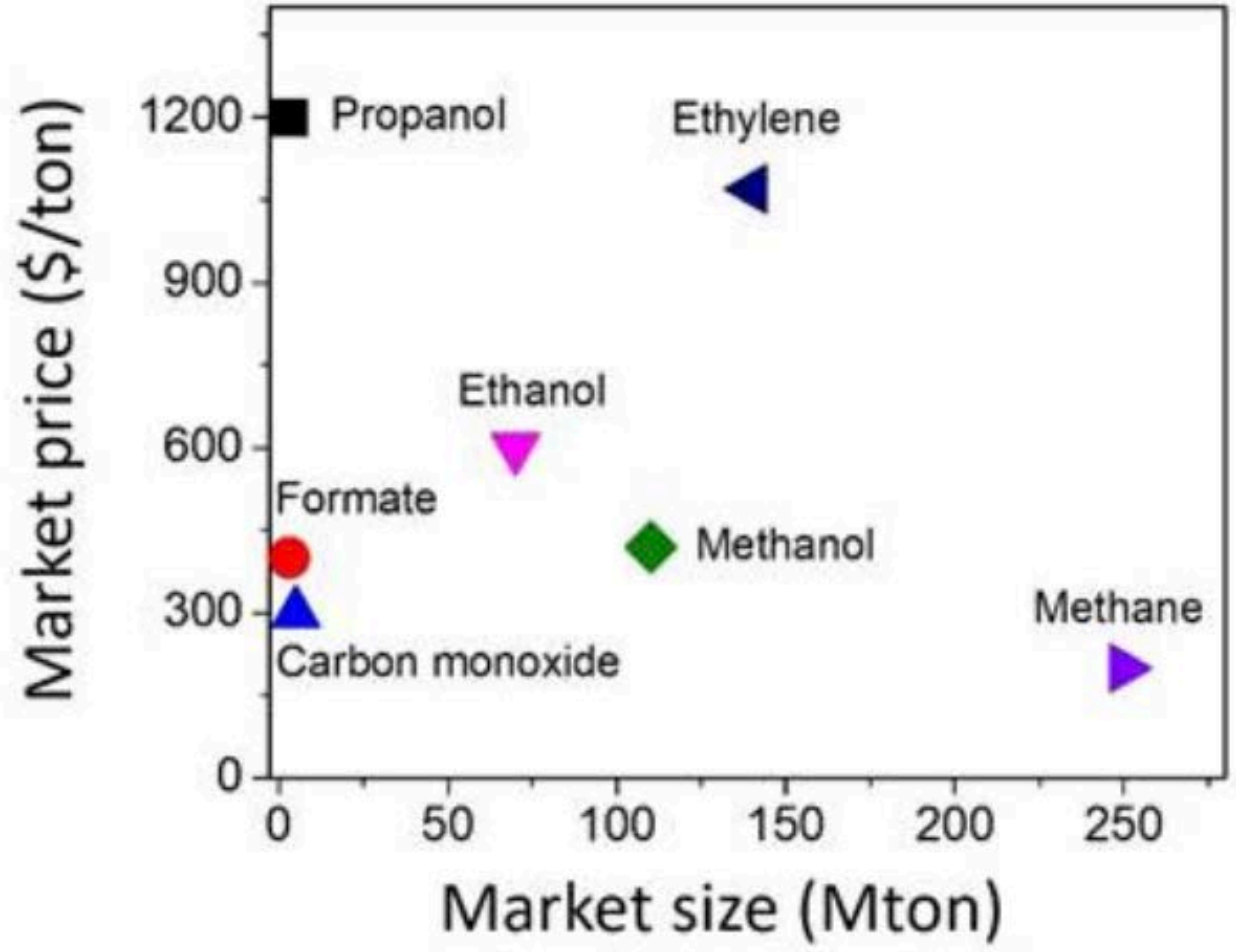
- Longer adsorbent lifetime will lead to significant cost reduction of adsorbent only process.
- Hybrid process will reduce cost by a factor of 2-3.

# WP5: Refinery for Value-added Chemicals

Critical Technology


Prof. Xile Hu

- Valorization of $CO_2$ into high value chemicals such as ethylene

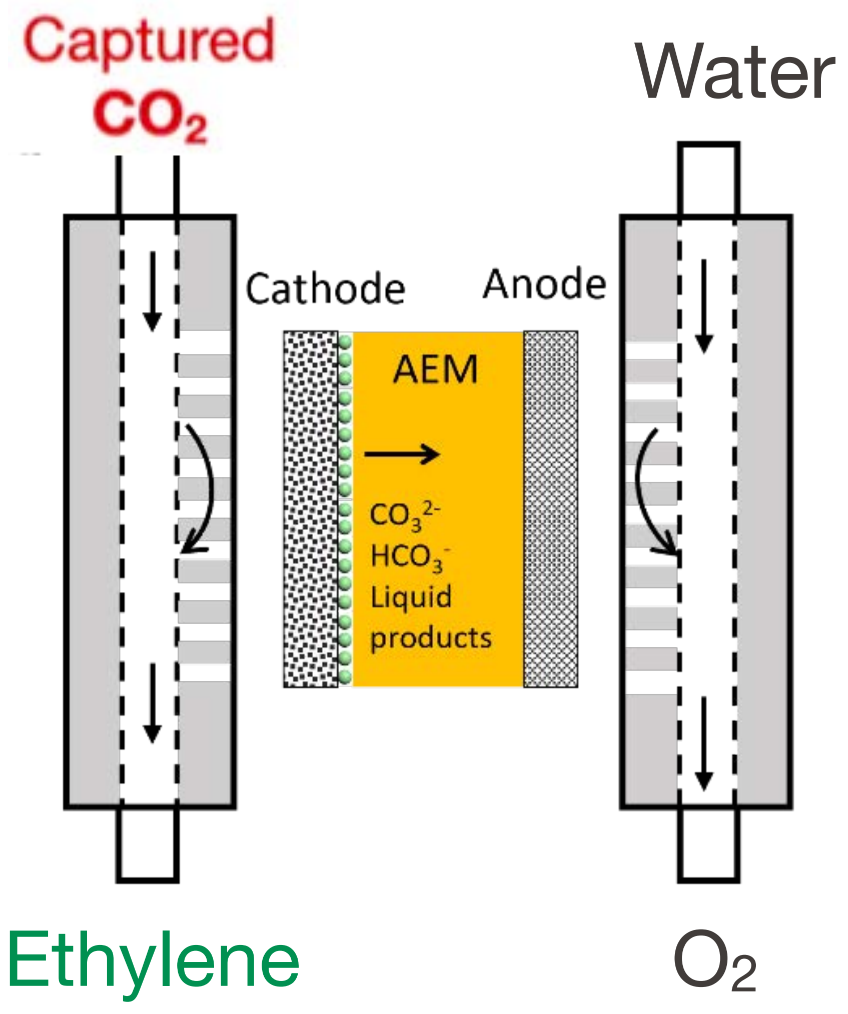



*Electrocatalytic reduction of $CO_2$ into ethylene*

Cathode $2CO_2 + 12H^+ + 12\,e^- \rightarrow C_2H_4 + 4H_2O$

Anode $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$

Total $2CO_2 + 2H_2O \rightarrow C_2H_4 + 3O_2$




**Outstanding Challenges:**

1. Formation of carbonate causes system instability.
2. Catalyst instablity.

**Solutions:**

1. Alternative operating conditions to resolve carbonate problem.
2. Alloying Cu to improve stablity.

# WP6: Process Modeling and Integration

CCUS Enabler

Prof. François Marechal

- Robust, energy-efficient and integrated CCUS
- Process modeling, technoeconomics and life-cycle assessment

**Applications**
Postcombustion capture (WP1)
$CO_2$ to energy carrier (WP2)
Sequestration (WP3)
Direct air capture (WP4)
$CO_2$ to value-added chemicals (WP5)

**Processes**
Process configurations
Process integration

**Technologies**
Membranes
Adsorbents
$CO_2$ Conversion

**Materials**
Graphene
Porous adsorbent
Electrocatalyst
Catalyst

**Assessment**
Technoeconomic
Life-cycle assessment

**Process design**
Process simulation
Process integration & optimization

**Sizing and Operating conditions**
Membrane systems
Adsorption cycles
Fuel cell systems
Reactor design

**Materials properties**
Process-inspired specification

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# WP7: Economics, Financing, Governance, and Policy

Dr. Sascha Nick

- Accelerating Swiss net zero which is not possible under current climate policy

## Swiss Climate Policy in 2023

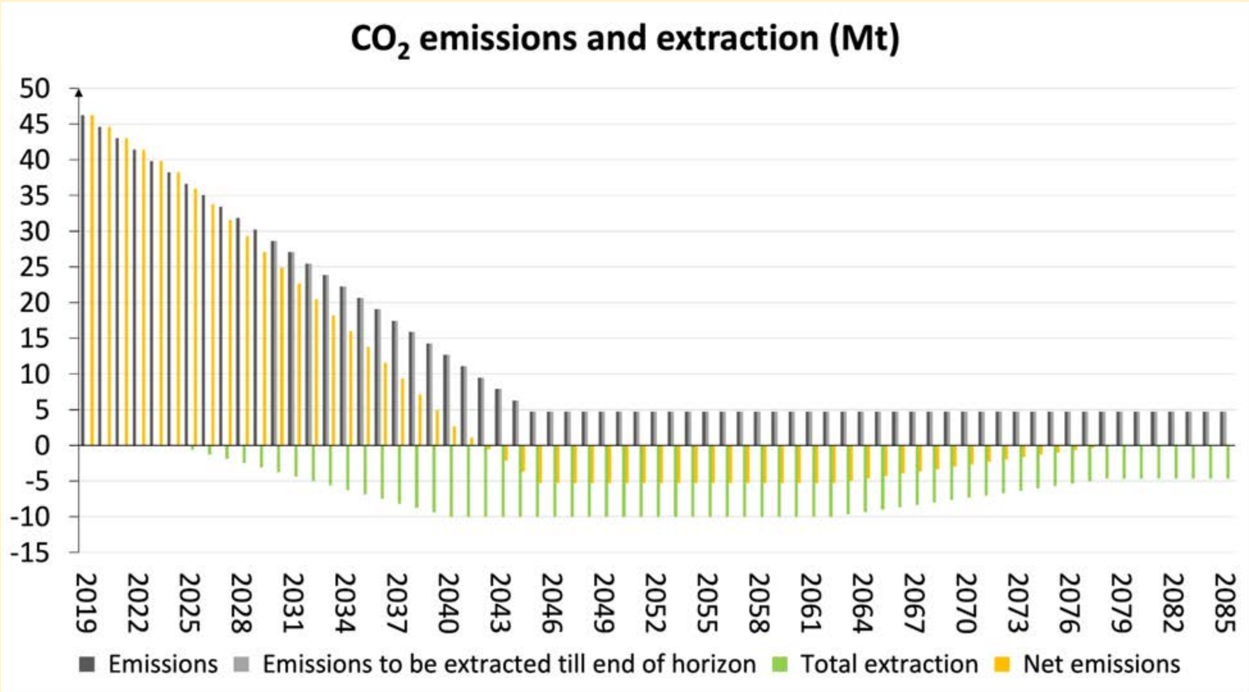
**CCUS** is seen as **expensive**, **unprofitable**, and **is poorly integrated**.

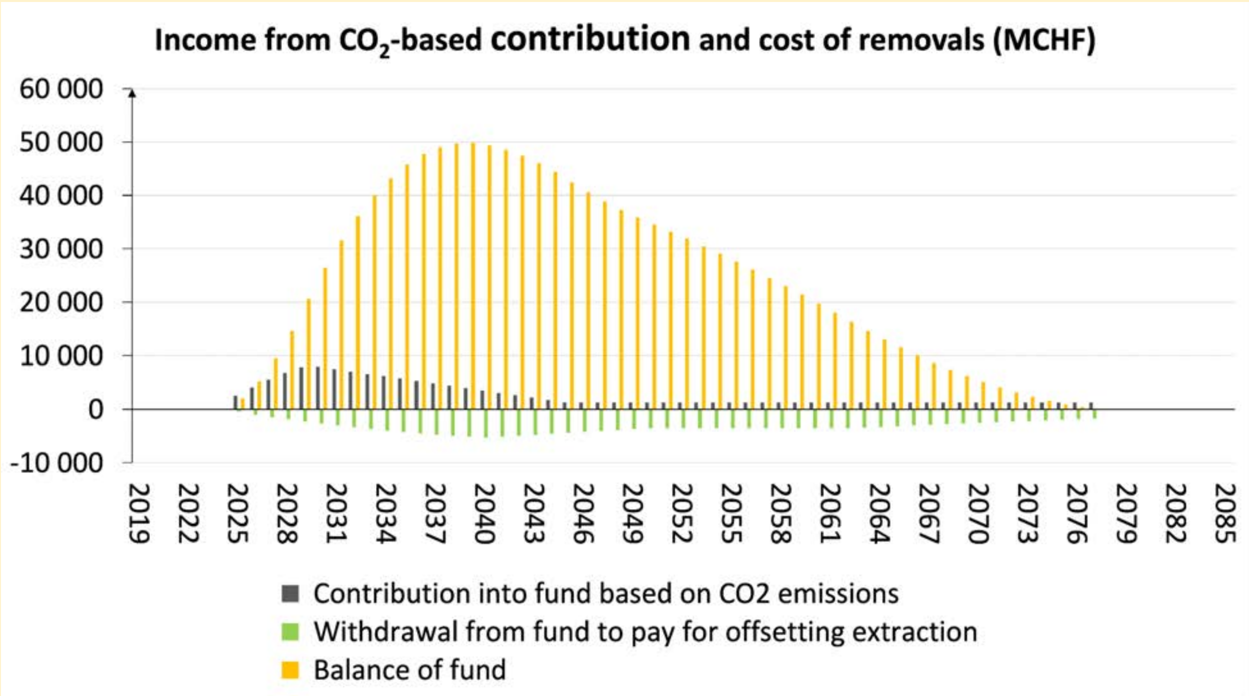
The current policy is does not deliver Swiss commitments under the Paris Agreement

## Goal of WP7

**Develop, model, and validate financing, governance, policy** proposals to scale improved CCUS technologies developed as part of SusEcoCCUS, and integrate in future climate policy.

Identify **implementation gaps** by stage: goals, targets, policy development, policy implementation.




Example of financing model

CCUS Enabler

# WP8: Dissemination, Student involvement & Outreach

- Training next generation of scientists.
- EPFL student MAKE (carbon) team (DAC demonstrator in Lausanne).
- Master's project within sustainable energy systems module, "decarbonizing the industry".
- CCUS stakeholder workshops (18M, 36M, 48M, 60M).
- Public outreach at *Portes Ouvertes* & *Scientastic.*

Make project on DAC: EPFL Carbon Team

# Impact of SusEcoCCUS

- Will accelerate 'a number of different technologies' related to CCUS, 'well beyond the state-of-the-art'.
- Will position EPFL as a competence center in science, technology, and policy for sustainable carbon management, significantly contributing to alleviating climate change.
- Generation of IP and expansion (creation) of existing (new) startups in the area of sustainability.

QAPTIS

$CO_2$ capture in trucks
(Francois Marechal)

NovaMea

Water electrolysis
(Xile Hu)

divea

Graphene membrane
(Kumar Varoon Agrawal)

- Promote strategic role of EPFL in Valais, especially in the context of energy transition.

# Thank you

kumar.agrawal@epfl.ch