Energy-efficient CCUS for Sustainable and Circular Economy

SusEcoCCUS

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)

Team:
Kumar Varoon Agrawal
Wendy Queen
Jürg Schiffmann
Vivek Subramanian
Jan van Herle
Lyesse Laloui
Eleni Stavropoulou
Nicola Marzari
Philippe Schwaller
Xile Hu
François Marechal
Marina Micari
Sascha Nick
Every ton of CO$_2$ emission adds to global warming
Every ton of CO₂ emission adds to global warming.
International Energy Agency (IEA) projects large-scale deployment of CCUS for net zero by 2050
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
Renewable energy
(PV, Wind, Hydro)

Enevi waste
Incineration plant

EPFL Valais Wallis
Industrie 17

Air

Methane
Gas pipeline

CO2

Methanator

SusEcoCCUS

will reduce EPFL emission

- CCUS with flows up to 1 ton CO2/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.

Waste incineration plant as CCUS testbed
SusEcoCCUS

**WP1: Postcombustion Capture**
- Large-scale Demonstrator
  - TRL 4/5 → TRL 7
  - Accelerated manufacturing for rapid scale-up
  - Capture at Valais district heating site (Enevi)
  - Target capture penalty: 20-30 $/ton CO₂
  - Kumar Varoon Agrawal, Vivek Subramanian, Jürg Schiffmann, Wendy Queen

**WP2: CO₂ to renewable CH₄ in gas grid**
- Large-scale valorization of CO₂
  - Jan van Herle
  - CO₂ to renewable CH₄ with high-efficiency (>70%) by integration of SOE with methanator

**WP3: CO₂ Storage**
- Acceleration of geological CO₂ storage
  - Lysses Laloui, Eleni Stavropoulou
  - Short-term and long-term CO₂ storage demonstrator at EPFL

**WP4: Direct Air Capture (DAC)**
- 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: CO₂ Refinery**
- CO₂ to value-added chemicals
  - Xile Hu, Jan van Herle
  - Stable CO₂ electrolyzer to ethylene, scale-up to 1 kW

**WP6: Process Modeling and Integration**
- Robust, energy-efficient and integrated process
  - François Marechal, Marina Micari
  - Process modeling, technoconomics 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

**Roll-to-roll production of graphene membranes to capture 1 ton\(\text{CO}_2/\text{day}\) from waste incineration**

<table>
<thead>
<tr>
<th>Commercially available</th>
<th>Specific energy consumption:</th>
<th>Capture penalty:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphene membrane</td>
<td>3-4 GJ/ton(\text{CO}_2)</td>
<td>50-110 $/ton(\text{CO}_2)</td>
</tr>
<tr>
<td></td>
<td>&lt; 1 GJ/ton(\text{CO}_2)</td>
<td>20-30 $/ton(\text{CO}_2)</td>
</tr>
</tbody>
</table>

**Short-term storage of captured \(\text{CO}_2\) (6 ton)**

**Valorization of captured \(\text{CO}_2\) as energy carrier (CH\(_4\), 200 m\(^3/\text{day}\)) for injection in natural gas grid**

**Energy efficiency above 70%**

**Unique geological \(\text{CO}_2\) storage simulator to predict real field**

**Accelerated development of low-cost direct air capture (<200 $/ton\(\text{CO}_2\))**

**Valorization of captured \(\text{CO}_2\) into highly value-added chemicals**

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

**Advancing Critical Technologies (TRL 2/3 → TRL 4/5)**
WP1: Postcombustion Capture

Commercial solution: Amine-based CO₂ absorption

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

EPFL capture technology using atom-thick graphene membrane

<table>
<thead>
<tr>
<th>Membrane type</th>
<th>Specific energy consumption: GJ/tonCO₂</th>
<th>Capture penalty: $/tonCO₂</th>
</tr>
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<tbody>
<tr>
<td>Commercial technology</td>
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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

Gas separation with atom-thick films

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

\[ \text{Flux} \propto H \exp \left( -\frac{E_{\text{barrier}}}{k_B T} \right) \]
Our contribution to the science of making holes in graphene

Cluster evolution as a function of extent of oxidation

Gasification

Energy

C-C  C-O-C  C=O

Science Advances 2021, 7, eabf0116
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We have simplified the way porous graphene is made

Pores are formed by flowing ozone over graphene + energy (heating) ...
That's it
**Greengas project with GAZNAT**

Capture of flue gas from CHP using graphene membrane

- Membrane skid capturing CO₂ from flue gas.
- Stable performance in flue gas achieved with parity performance with simulated gas mixture.

Agrawal, K. V.; Bautz, R. Capture Du Carbone. Aqua & Gas. 2022, pp 46–53.
WP1: Postcombustion Capture

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

- 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)

www.compressorworldcanada.ca

Prof. Jürg Schiffmann
WP2: CO₂ to renewable energy carrier (CH₄)

- Large-scale valorization of CO₂ at the scale of 0.35 ton/day to energy carrier.
- H₂ 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.

- 100 kW SOE from SolydEra.
- Scale-up methanator 10-times to produce 80 kW CH₄ (200 m³/day).
- Target efficiency > 70%.
WP3: CO₂ Storage

Acceleration of geological CO₂ storage, the most efficient technology for permanent storage of large volumes of CO₂

Inland storage in deep porous geological formations

→ Storage potential in the Swiss Molasse Basin (theoretical capacity 2.7 Gt CO₂)

Storage in a unique meter-scale GCS simulator

- 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
WP4: Direct Air Capture (DAC)

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

Adsorption process cost: 150 $/ton CO₂

Membrane process cost: 100 $/ton CO₂

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.

Prof. Wendy Queen
Prof. Philippe Schwaller
Prof. Nicola Marzari
WP5: Refinery for Value-added Chemicals

Valorization of CO₂ into high value chemicals such as ethylene

Electrocatalytic reduction of CO₂ into ethylene

Outstanding Challenges:
1. Formation of carbonate causes system instability.
2. Catalyst instability.

Solutions:
1. Alternative operating conditions to resolve carbonate problem.
2. Alloying Cu to improve stability.
WP6: Process Modeling and Integration

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

Applications
- Postcombustion capture (WP1)
- CO₂ to energy carrier (WP2)
- Sequestration (WP3)
- Direct air capture (WP4)
- CO₂ to value-added chemicals (WP5)

Processes
- Process configurations
- Process integration

Technologies
- Membranes
- Adsorbents
- CO₂ Conversion
- 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
WP7: Economics, Financing, Governance, and Policy

- 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

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

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

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