Peter Westh DTU Bioengineering

CO_2 capture - challenges and opportunities from a research perspective.

Does life science have a role to play?

CORC

The Novo Nordisk Foundation CO_2 research center

https://corc.au.dk/

Key research areas

Chemistry
Life Science
Systems modeling

Goal:

Develop new fundamental understandings and early technology platforms for capturing and converting CO_2 for storage and utilization.

Research in CORC

Ten groups

Chemistry | Life Science | Systems modeling

- Lars Angenent, Eberhard Karls University of Tübingen
- Matteo Cargnello/Arun Majumdar, Stanford University
- Kim Daasbjerg, Aarhus University
- Andree Faaij, TNO Utrecht University
- Jiwoong Lee, University of Copenhagen
- Lars Ottosen, Aarhus University
- Alfred M. Spormann, CORC
- Troels Skrydstrup, Aarhus University
- Peter Westh , DTU - Technical University of Denmark
- Marta Victoria, Aarhus University

Major research themes

- Direct CO_2 **capture** from air
- Microbial/chemical **conversion** of CO_2 to C1-8 compounds
- Homogeneous, heterogeneous, and enzyme catalysis for CO_2 **capture and conversions**
- Electrochemical **reductions** of CO_2 and CO_2-derived multi-carbon compounds
- Novel carbonate (bio)chemistries for CO_2 **capture and conversion**

Fundamental research and technology - with potential for upscaling

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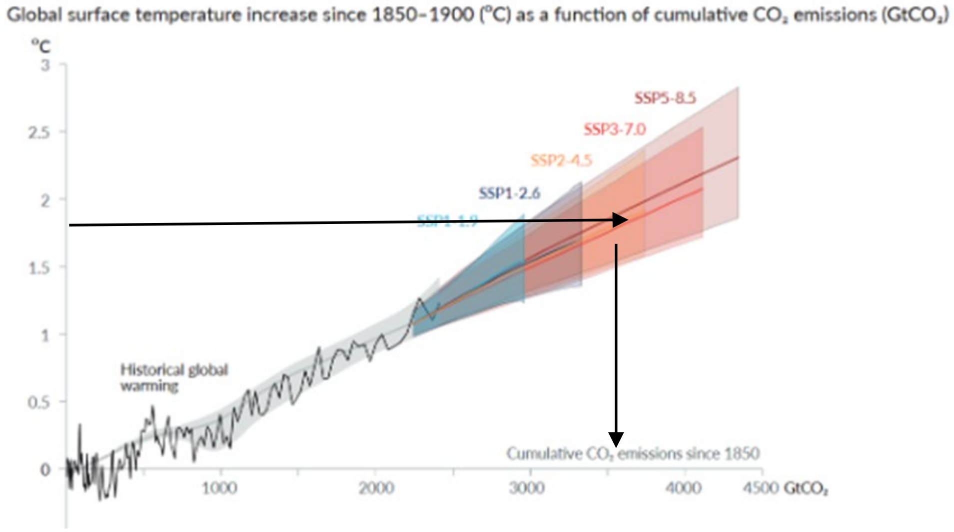
Current emissions are around 40 Gt/y



The average temperature increases by 1°C per 2000 Gt CO_2

Carbon utilization: CO_2 reduction with H_2

Sabatier reaction: $CO_2 + 3H_2 \rightarrow CH_4 + 2H_2O$

But: $H_2O \rightarrow H_2 + ½O_2$ 40 kWh/kg H_2

- Reduction of 3 Gt CO_2 requires 0.15 Gt H_2
- Current annual H_2 production is 0.07 Gt.
- 0.15 Gt H_2 requires 7500 TWh
- Current green production in the US 1500 TWh.
- Global production of plastics 0.4 Gt.

Rojas et al., Technoeconomics and carbon footprint of hydrogenproduction

Scaling challenges: energy and area problems

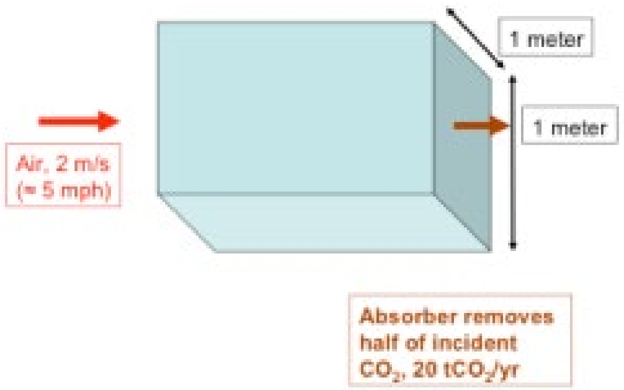
Direct air capture

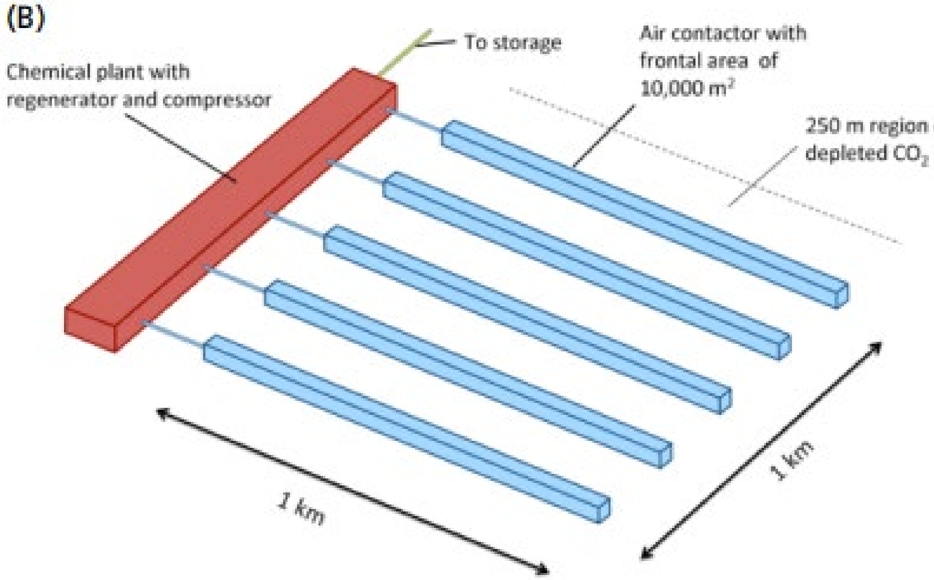
$$CO_2(air) \longrightarrow CO_2(1\ atm),$$
$$\Delta G \approx 30\ kJ/mol \quad (0.5\ GJ/ton)$$

Estimates for industrial processes hover around 5-10 GJ/ton
(1.5-3 MWh/ton CO_2)

Hypothetic facility for 1 Mt CO_2/yr

1 m^3 air con½tains 0.7 g CO_2





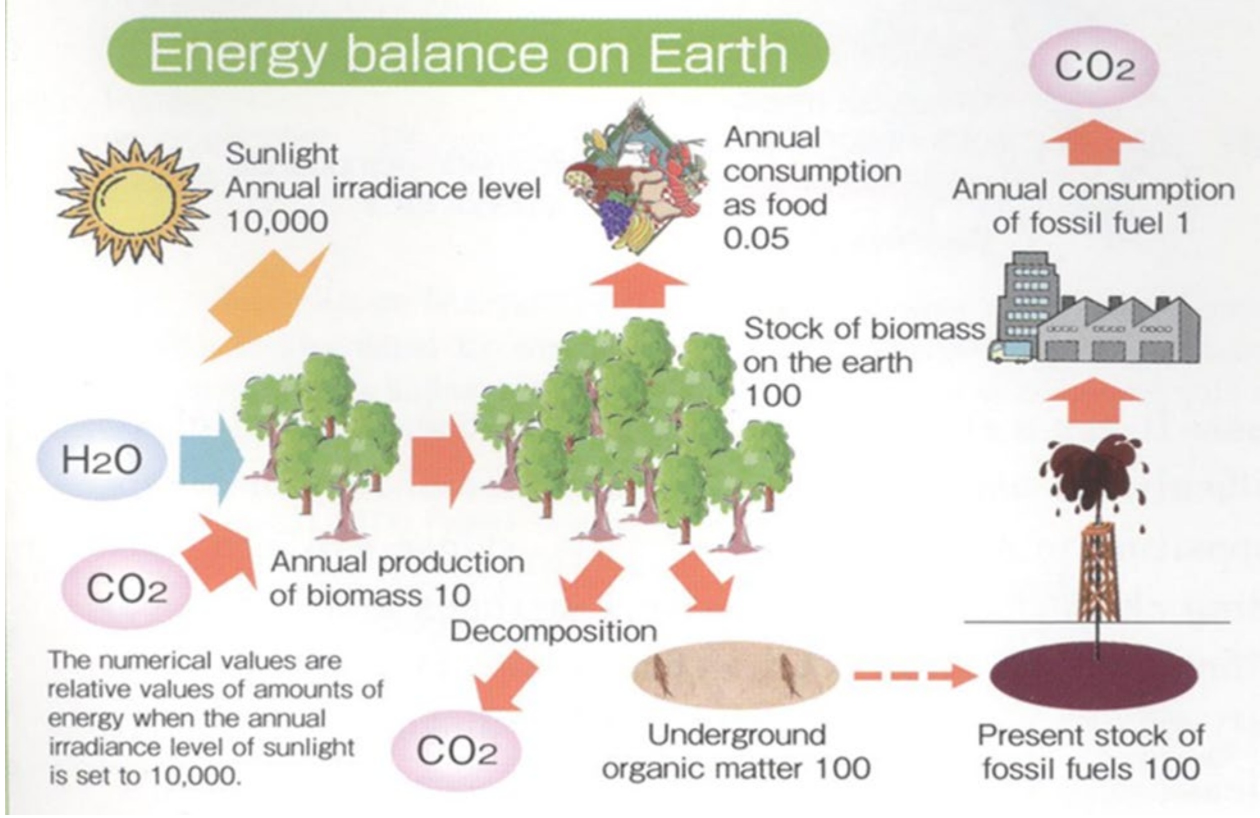
Six systems would be required to compensate for the emissions of a 1 GW coal plant.

APS Report 2011

Life science and CCU/CCS

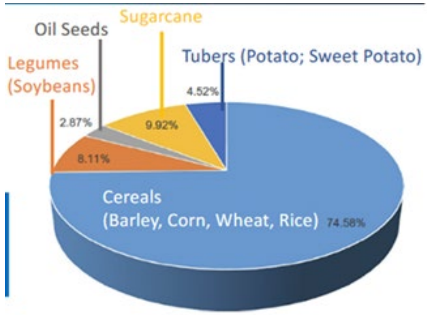
Biomass – e.g. lignocellulose





	2003	2013
Global Crop Residues (Gton)	3.3	5.0
Atmospheric CO_2 Uptake (Gton)	6.1	9.2

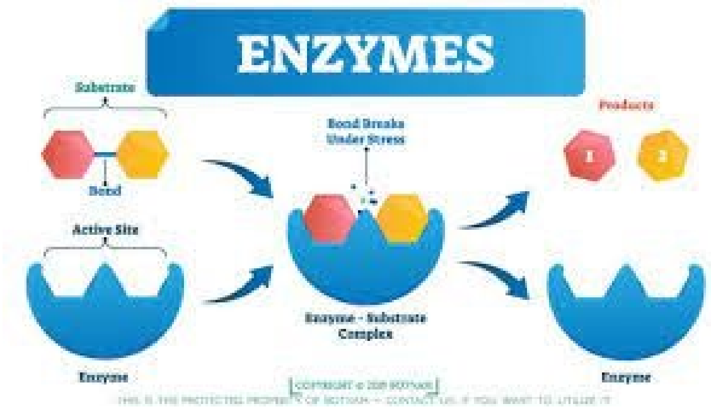
Cost of biomass ~ \$60/dry-ton
Cost of atmospheric CO_2 Capture ~ \$33/tCO_2
Carbon value of crop residue is more than its fuel value



Arun Majumdar,
Soil Man. Clim. Change (2018), 323
Sci. Agric. (2018) 75, 255

Life science and CCU/CCS

- Extremely efficient catalysts (accelerate processes 10^{10}-10^{15} times)
- Highly specific
- Moderate price
- Limited stability
- Reduced activity for industrial substrates and conditions



Two paradigms

<u>Microbes</u>

- Complex, cascade reactions
- Enzymes produced in situ.

<u>Free enzymes</u>

- Simple processes – breakdown and one-step conversion
- Industrial production

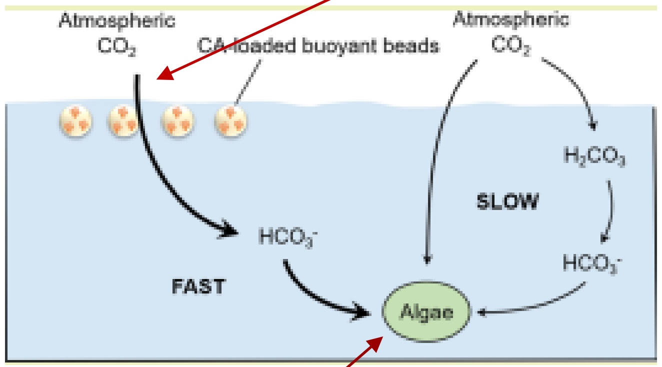
Targeted production of biomass

Free enzyme

Carbonic Anhydrase

$$CO_2(g) + H_2O \xrightleftharpoons{CA} HCO_3^-(aq) + H^+$$

Microalgea cultures



Algeal biomass for food, feed and chemical feedstock

Microbes

$$light + CO_2 \rightarrow biomass$$

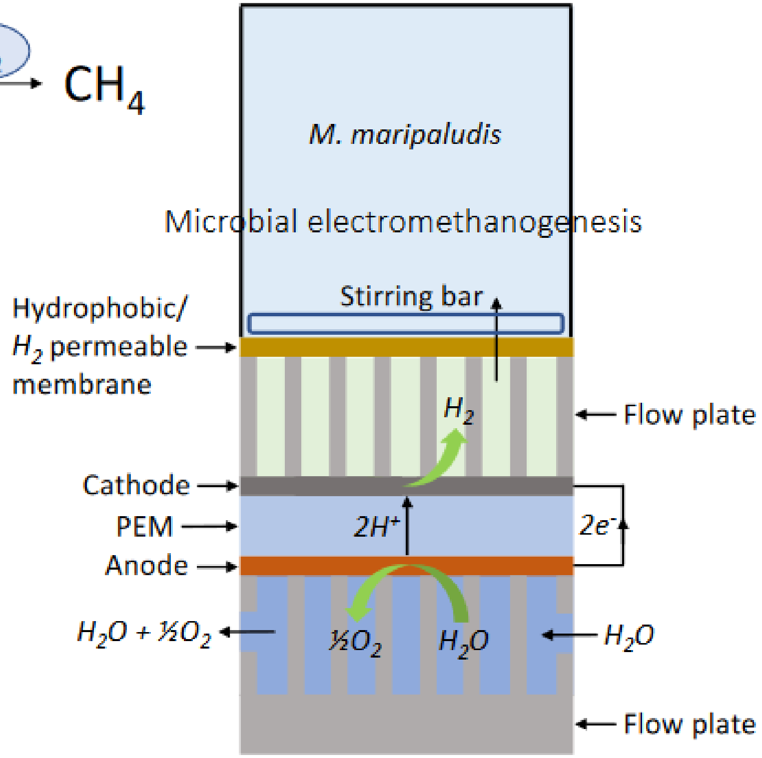
Xu et al. (2021) ACS Sust. Chem. Eng. 9, 9698

Biotransformation between chemical and electric energy

Electromethanogenesis - Integrating chemistry and life science

Bio: $CO_2 \xrightarrow{H_2} CH_4$

Electro-
chemistry



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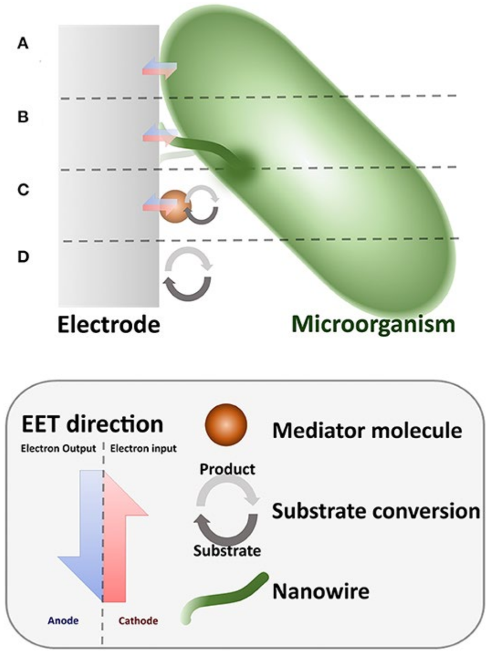
Spormann, Daasberg, Angenent

Other chemical-electric biotransformations

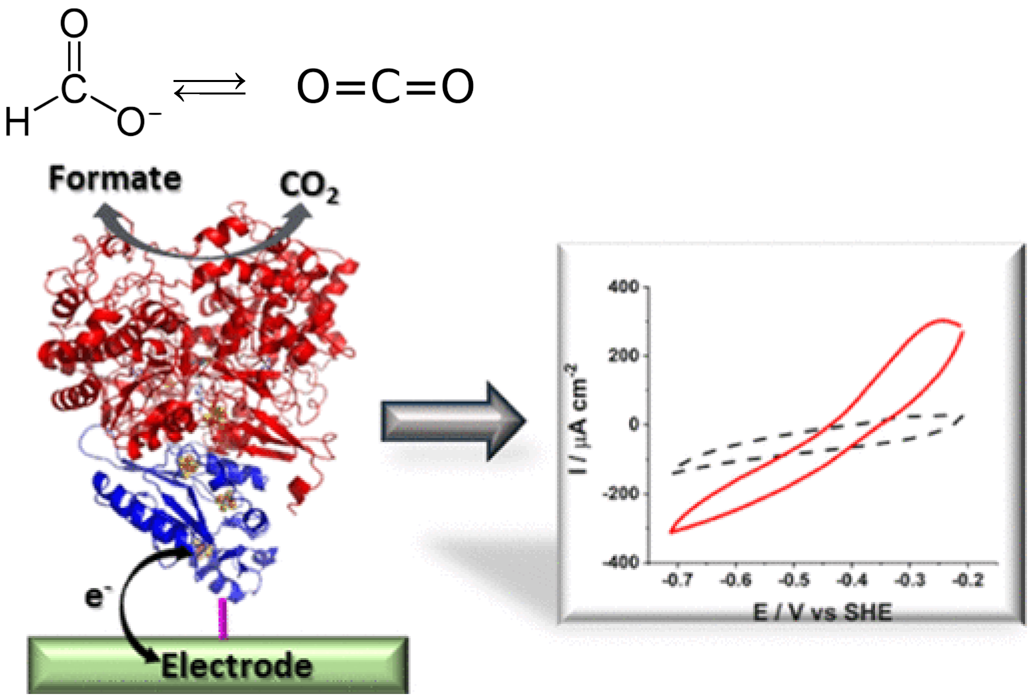
Microbial approach

Extracellular electron transfer (EET)



Hernandez & Osma (2020) Front. Environ. Sci., 12

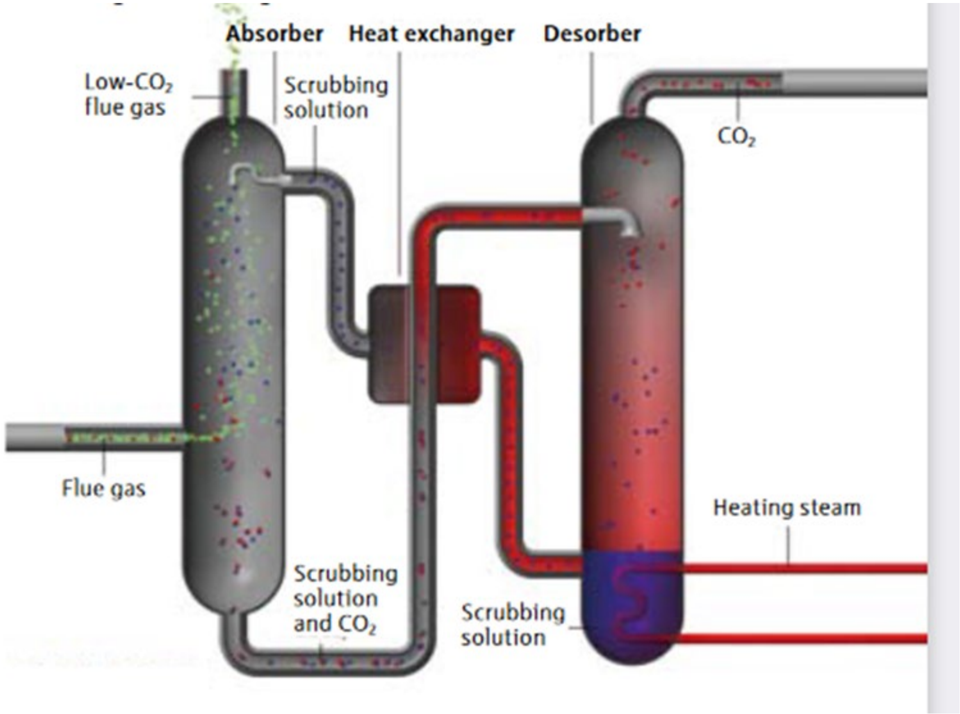
Free enzyme approach



Malmagro (2021) ACS Appl. Mater. Interf. 13, 11891

Enzyme assisted carbon capture

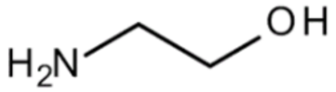
CO_2 scrubbing of flue gas



CO_2 may be absobed and carried by amines.

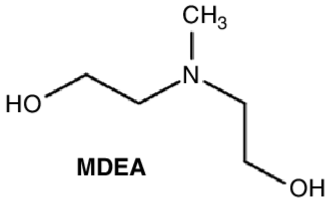
$$CO_2 + \text{Amine} \underset{}{\overset{\Delta H \square\ 0}{\rightleftarrows}} \text{Carbamate}$$

Typical sorbent MEA binds CO_2 rapidly and tightly (ΔH=-70 kJ/mol).

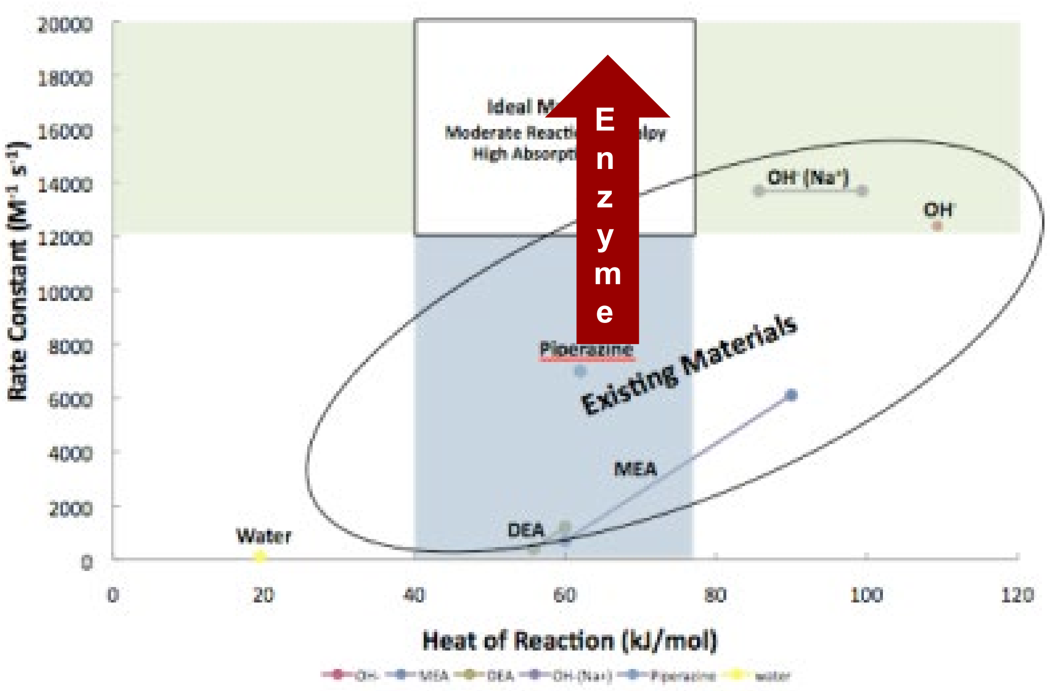


This provides easy absorbtion, but generates a requirement of high temperatures in the desorber .

Other sorbents, e.g. MDEA, binds less tightly. This facilitates desorbtion but leads to slow absorption



Scaling of kinetics and thermodynamics



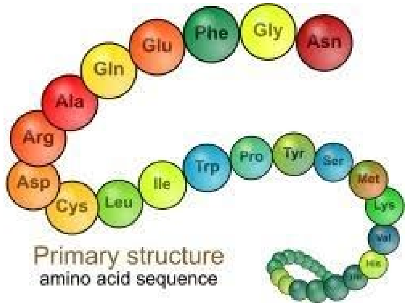
Carbonic Anhydrase (CA)

$$CO_2 + H_2O \underset{}{\overset{CA}{\rightleftarrows}} HCO_3^- + H^+$$

maximal turnover, k_{cat} around $10^4 – 10^6$ s^{-1}

Main challenge: Physical instability of enzymes
(high temperature and pH)

Natural enzyme

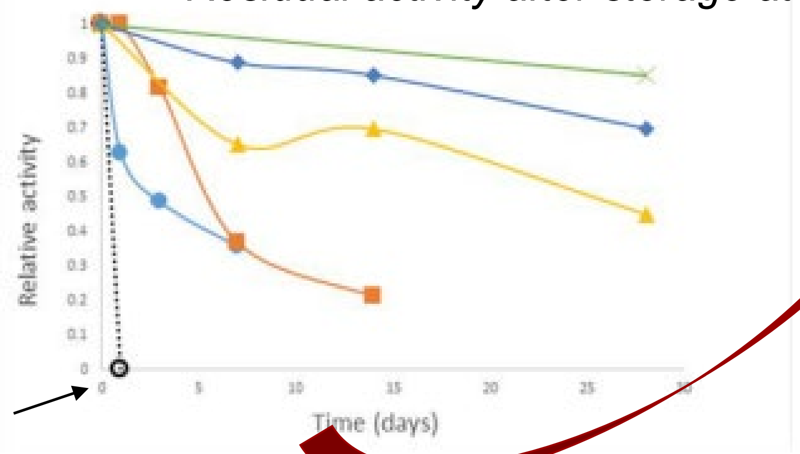


Enzyme engineering

- Molecular biology
- Sequence analysis
- Machine learning
- Protein science
- Microbiology
- Crystallography
- High-Throughput screens

Enzyme variant with desired properties

Residual activity after storage at 60 C

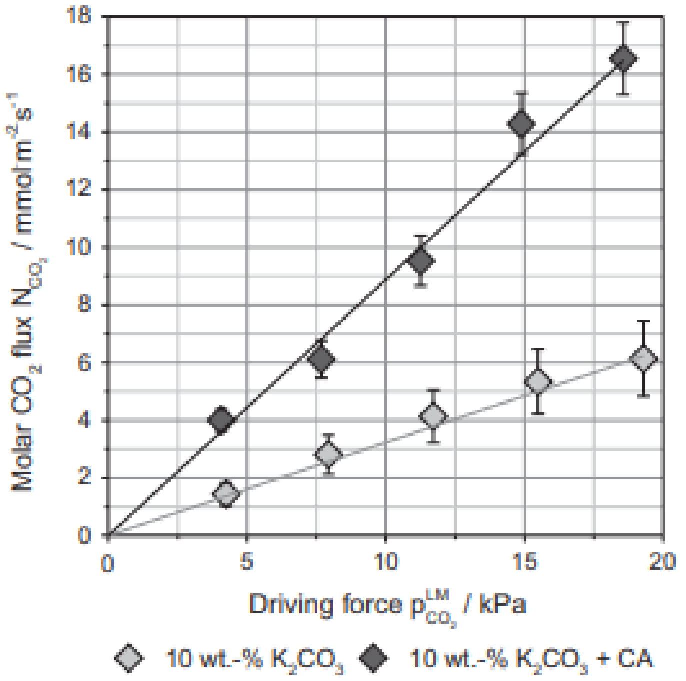


Natural enzyme

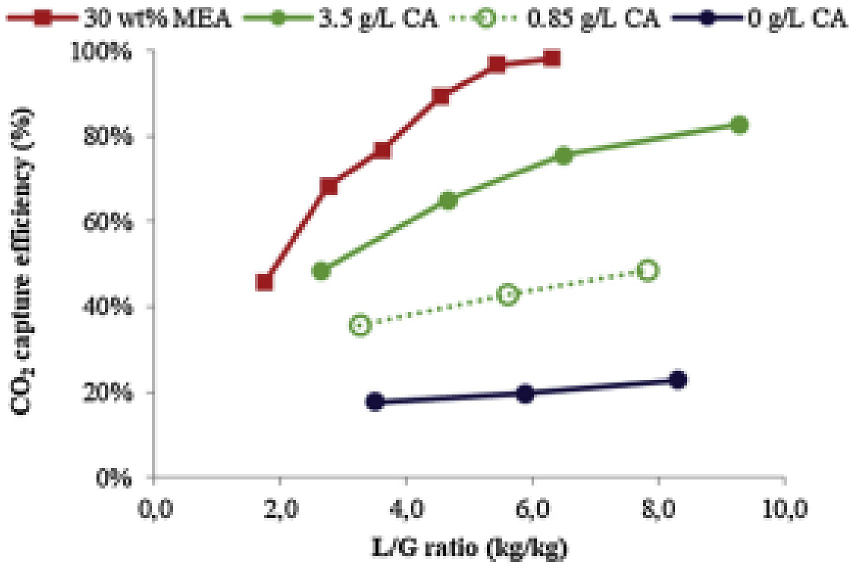
Engineered enzyme variants

Fradette et al. (2017) Energy Procedia 114, 1100.

Enzyme assisted capture: lab and pilot scale



Kunze et al (2015) Applied Energy 156, 676



Gladis (2019) Int. J. Greenh. Gas Control. 82, 69

Closing remarks

Life science offers promising CCS/CCU technologies.

A range from:
From low tech. deposition of lignocellulose
over enzyme assisted carbon capture
to advanced chemical-electrical transformations

Do these technologies scale to the Gt range?
Are Mt technologies relevant?