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Status and Logic of Capturing Carbon Dioxide from the Air

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Agenda
Status and Logic of Capturing Carbon Dioxide from the Air

- Comparison with natural plants
- History, theory
- University research
- Startup companies
- Logic and cost structure of a solar fuel

Comparison with natural plants

PV cells capture light and air contactors capture carbon more effectively than natural plants

Photoefficiency of PV modules

10% - 16%

→ 10 times

Photoefficiency of plants

~ 1-2%

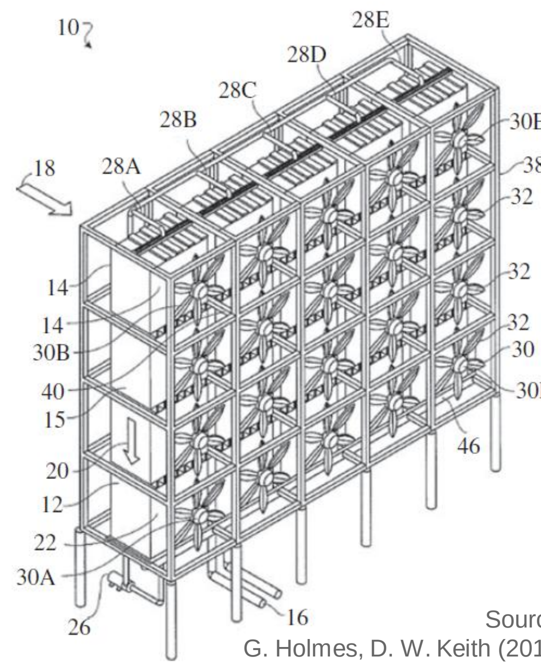
CO_2 uptake of plants

~ 3 kg / m^2 / year

← 20’000 times

CO_2 uptake of an air contactor:

60’000 kg / m^2 /year (footprint)



Source:
G. Holmes, D. W. Keith (2012)

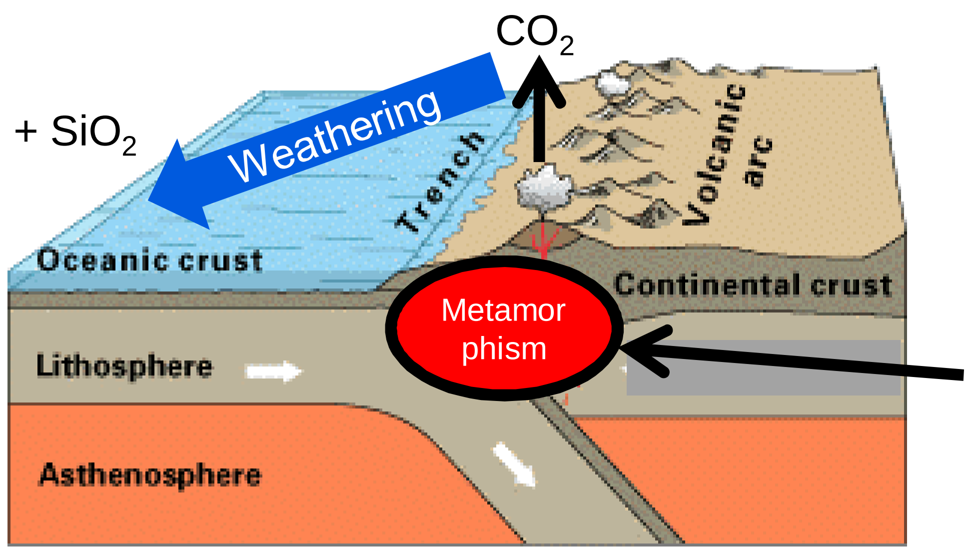
History

The idea appeared as an offspring of the understanding how the earth system controls atmospheric CO_2 over long time scales

- Berner (1983) – Carbonate geochemical cycle
- Seifritz (1990), Dunsmore (1992), Lackner (1995) – CO_2 disposal by conversion of silicate rocks to carbonates («Mineral carbonation», «Enhanced weathering»)

Weathering binds CO_2

$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$



Oceanic-continental convergence

Metamorphism releases CO_2

$CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$

Source: USGS (modified)

Theory

Thermodynamics teaches that capturing CO_2 from air requires energy. The minimum energy is ~3% of the energy converted in CH_4 combustion and 4 times that of capturing CO_2 from flue gas.

$$\Delta G = RT \ln\left(\frac{P}{P_0}\right)$$

P_o = starting pressure

P = final pressure

For flue gas

- P_o = $1.5 \cdot 10^5$ ppm
- P = 10^6 ppm
- P/P_o = 6.7
- $\ln(P/P_o)$ = 1.9

For air

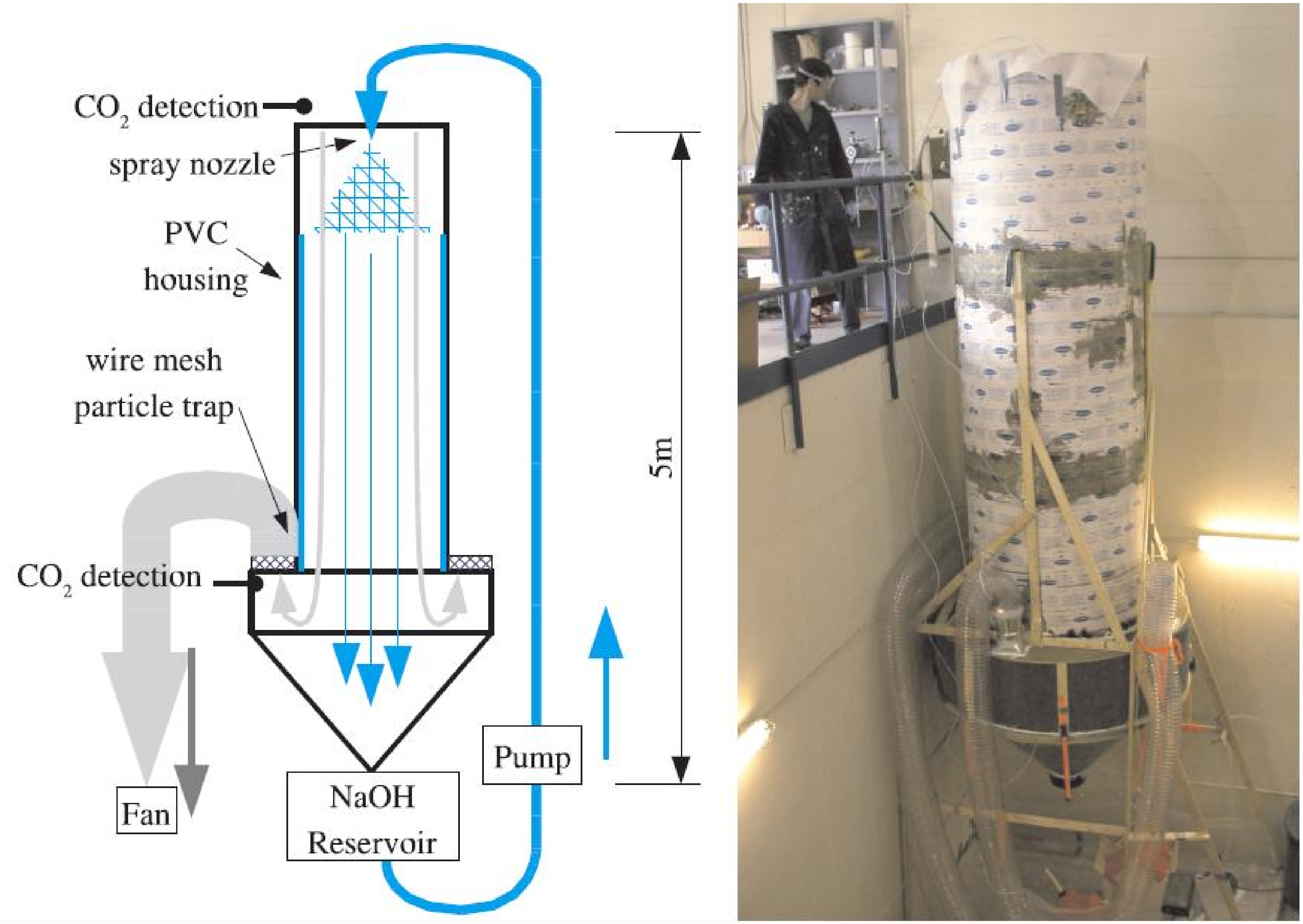
- P_o = 400 ppm
- P = 10^6 ppm
- P/P_o = 2500
- $\ln(P/P_o)$ = 7.8

$$\frac{\Delta G_{flue}}{\Delta G_{air}} = \left(\frac{1.9}{7.8}\right) \approx \frac{1}{4}$$

Real systems are far, e.g. a factor 10, from the minimum.

Source: discussed in many places, see e.g. Lackner (2013)

University research has addressed two key topics:
1) How to arrange a large contactor surface area?



Sodium hydroxide spray contactor. Source: J. Stolaroff (2006)

University research has addressed two key topics:
1) How to arrange a large contactor surface area?
2) What is the best kind of energy for regeneration?

Lime kiln
$CaCO_3$ + heat → $CaO + CO_2$
Source: Maerz Ofenbau AG

- ← High temperature heat
- Low temperature waste heat or solar heat
- Humidity differences →

Anionic exchange resin releases CO_2 when wetted
Source: K. Lackner

Four startup companies are differentiated by the air contactor design and the regeneration process

Carbonengineering

- Cross flow slab-geometry packed structure with Kalium hydroxide solution
- Regenerated by high temperature heat

Climeworks

- Amine containing fiber structure
- Regenerated with low temperature heat

Global Thermostat

- Porous ceramic blocks coated with amine
- Regenerated with low temperature heat

Lackner (Kilimanjaro)

- Anionic exchange resin
- Regenerated by drying in air

Critical Points / Figures of Merit

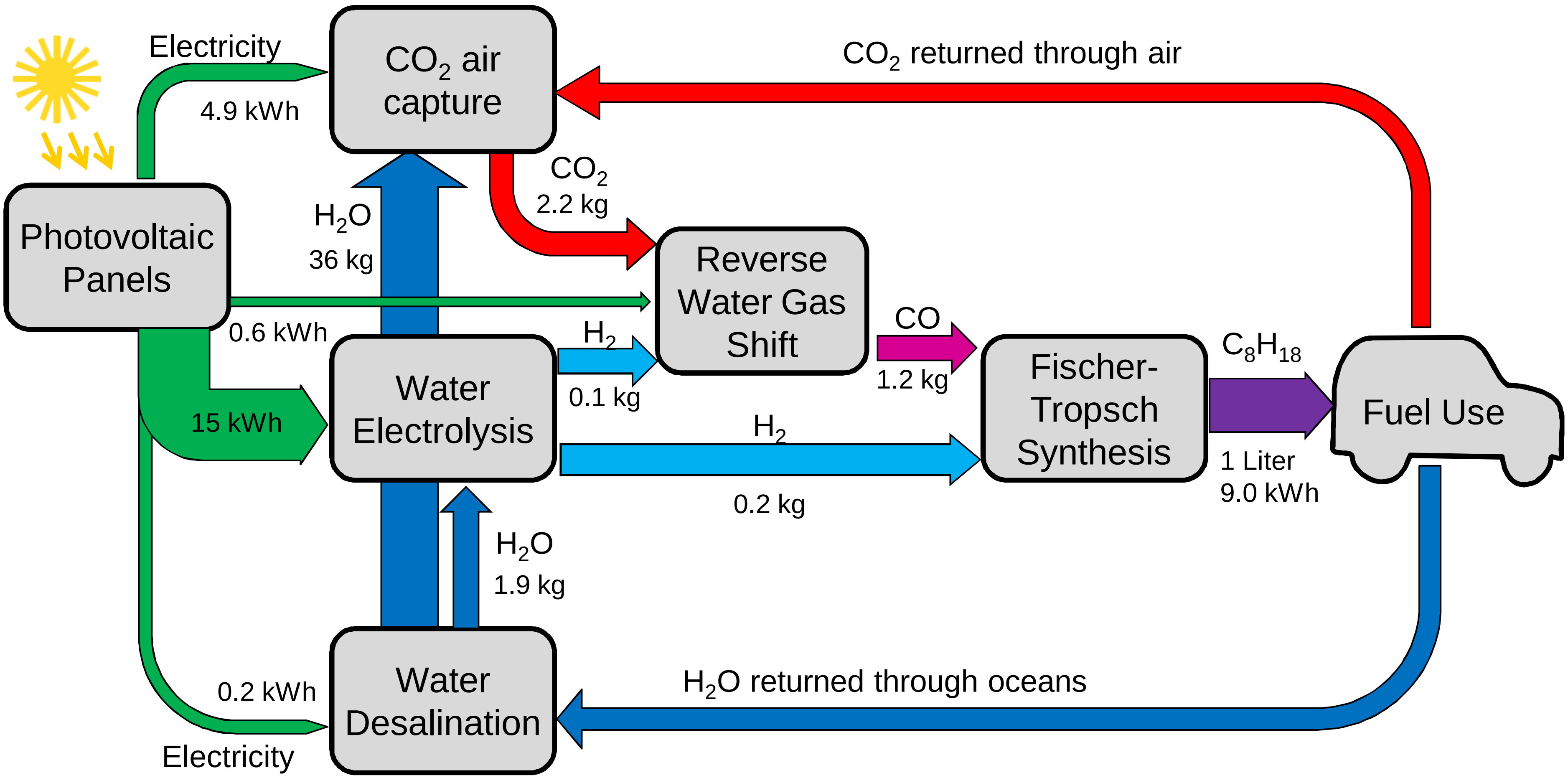
The air capture system has to process about 2 million cubic meters per ton of carbon dioxide captured

- What amount of the contact medium is lost to the exhaust?
- Is there any degradation / fouling of the air contactor?
- How many absorption-regeneration cycles does the contact medium survive? How is one of these cycles defined? (CO_2 coverage per number of available contact sites)
- How close is the real system to the thermodynamic energy minimum?

Current status of the companies: building and operating prototypes

Logic

Capture from the atmosphere would provide the carbon dioxide for a “solar” fuel and close the transportation fuel cycle

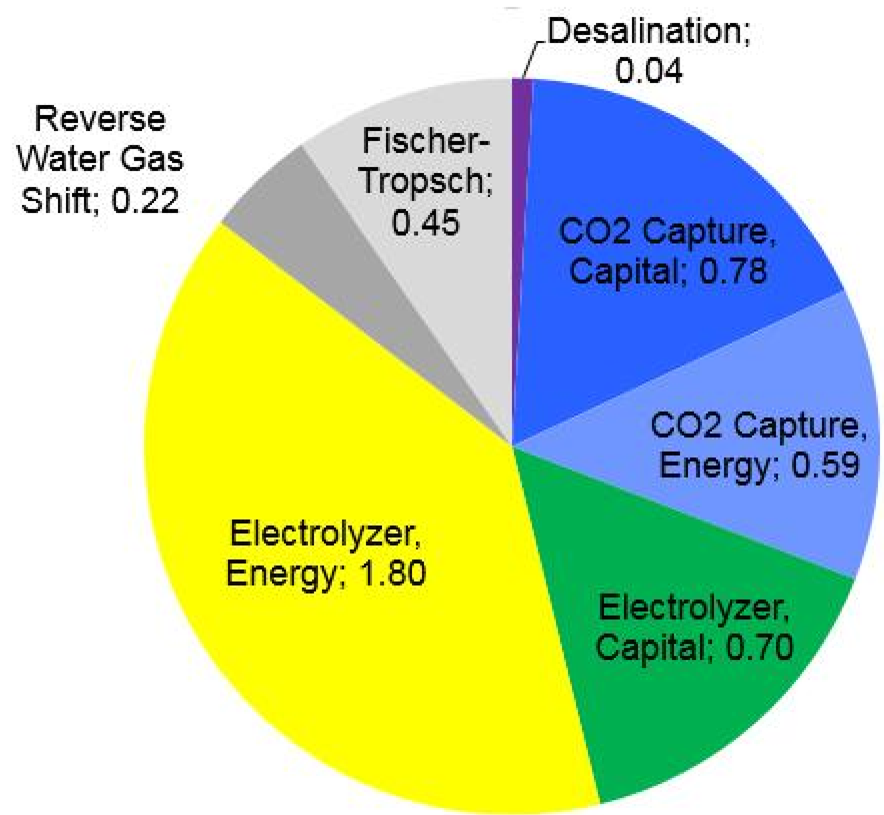


Source: K. Lackner (2012), modified

Cost structure of a solar fuel

Capital and energy cost of CO_2 capture are <u>not</u> the dominating components even with conservative estimates for CO_2 capture

Total cost: 4.60 USD / liter octane



Source: ABB

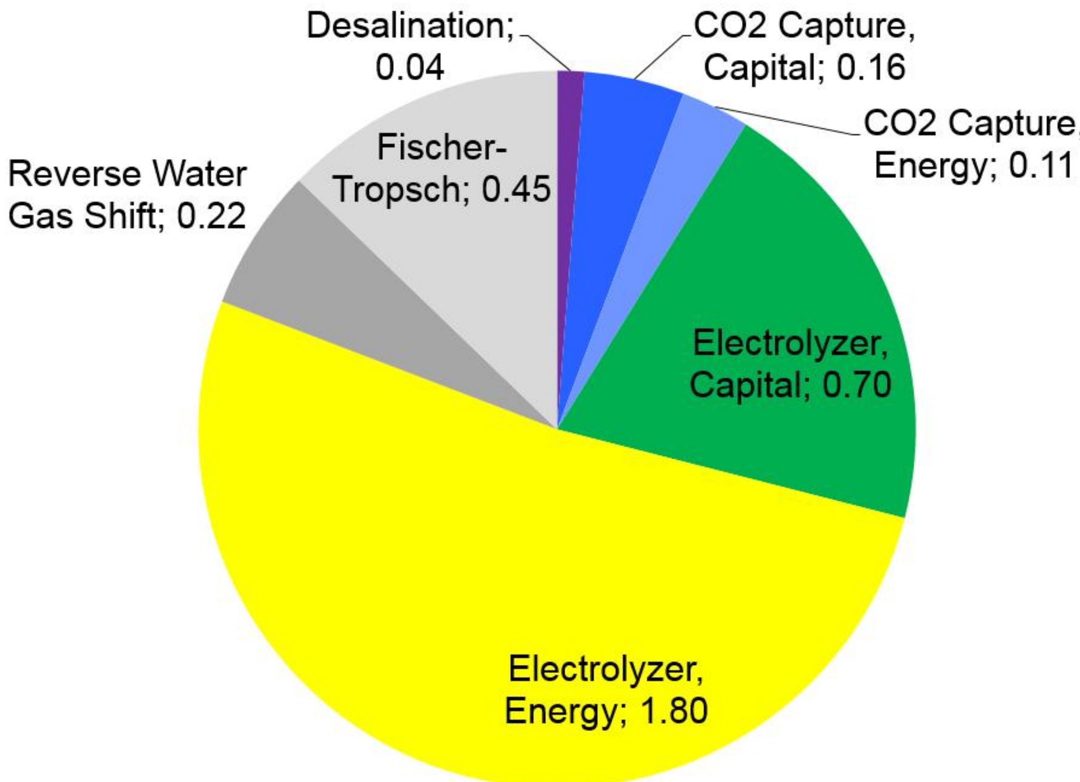
Assumptions:

- All types of energy from PV with «Sahara» conditions → 0.12 USD/kWh
- Alkaline electrolyzer (1100 USD/kW)
- Electrolyzer load factor: 20% (PV power pattern over day)
- Conservative CO_2 capture cost estimates from APS-Report (2011)
- Capital cost of CO_2 capture: 350 USD/ton CO_2
- Energy requirement of CO_2 capture: 2.2 kWh/kg CO_2 (lime kiln process)

Cost structure of a solar fuel

Capital and energy cost of CO_2 capture are <u>not</u> the dominating components even with conservative estimates for CO_2 capture and more so with an extremely optimistic scenario

Total cost: 3.50 USD / liter octane



Assumptions:

- All types of energy from PV with «Sahara» conditions → 0.12 USD/kWh
- Alkaline electrolyzer (1100 USD/kW)
- Electrolyzer load factor: 20% (PV power pattern over day)
- Conservative CO_2 capture cost estimates from APS-Report (2011)
- Capital cost of CO_2 capture: 70 USD/ton CO_2
- Energy requirement of CO_2 capture: 0.4 kWh/kg CO_2

Source: ABB and Meinrenken, Wright, Lakner (unpublished)

Conclusion

Two R&D directions of carbon dioxide capture from the air to be further explored: power-to-liquid and power-to-carbon fixation.

- Direction 1: What are the most valuable uses of CO_2 captured from the air and what are the corresponding business models?
  - Power-to-gas? Not sure.
  - Power-to-liquid? The cost of a synthetic solar fuel is 5-10 times that of a fossil fuel and needs a corresponding premium business model. Capital and energy cost of CO_2 capture are not the dominating cost component.
  - Power-to-food? (Adding captured CO_2 to a farm greenhouse.)
- Direction 2: «Power-to-carbon fixation». Negative emission technologies that capture CO_2 from the air *and fix it permanently* deserve more publicly funded research. What is the best way to use of intermittent excess power for this purpose?

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