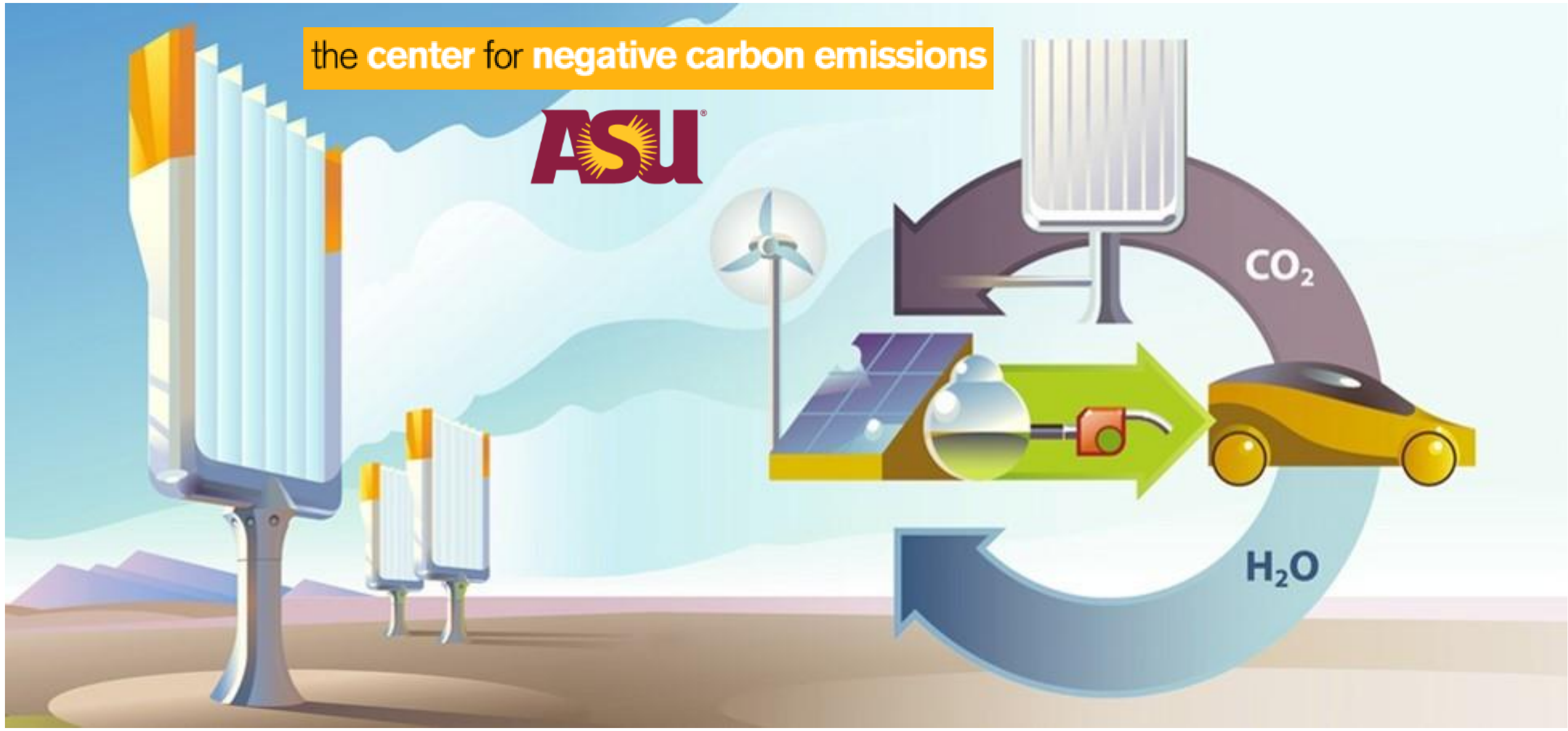


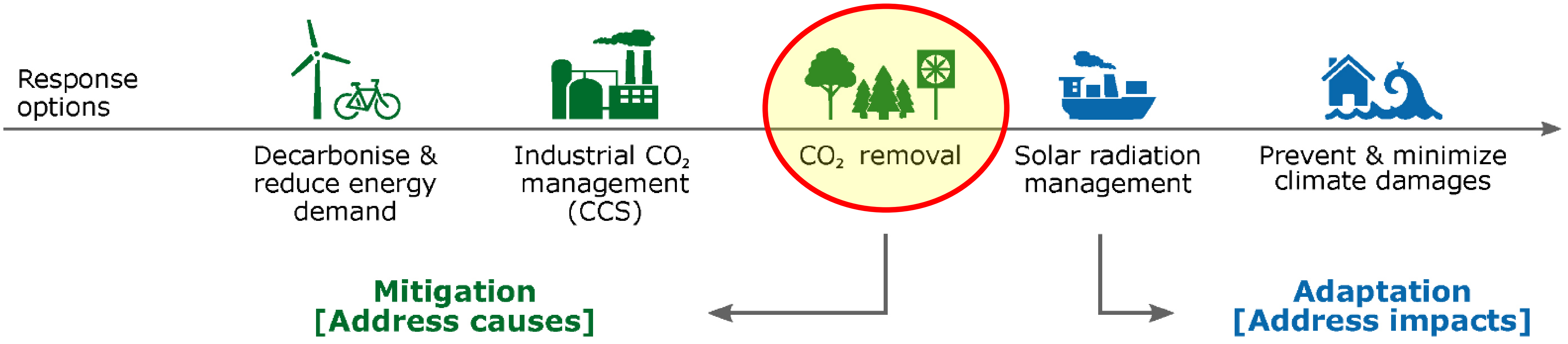
Direct Air Capture

Advances and Opportunities

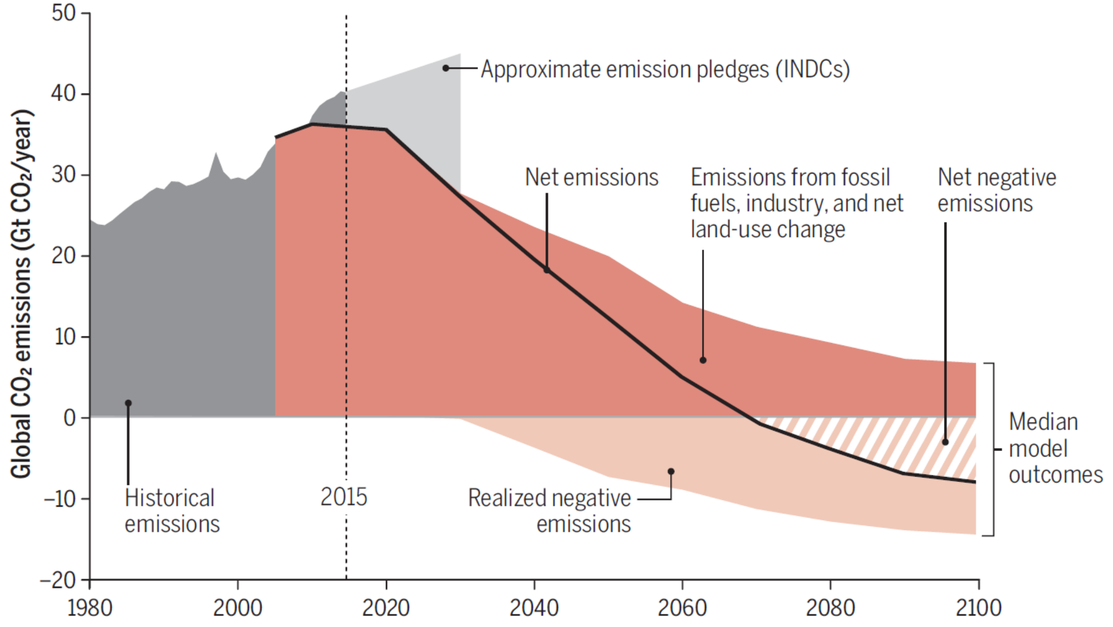
Carbon Management Technology Conference 2019

John Cirucci

Arizona State University



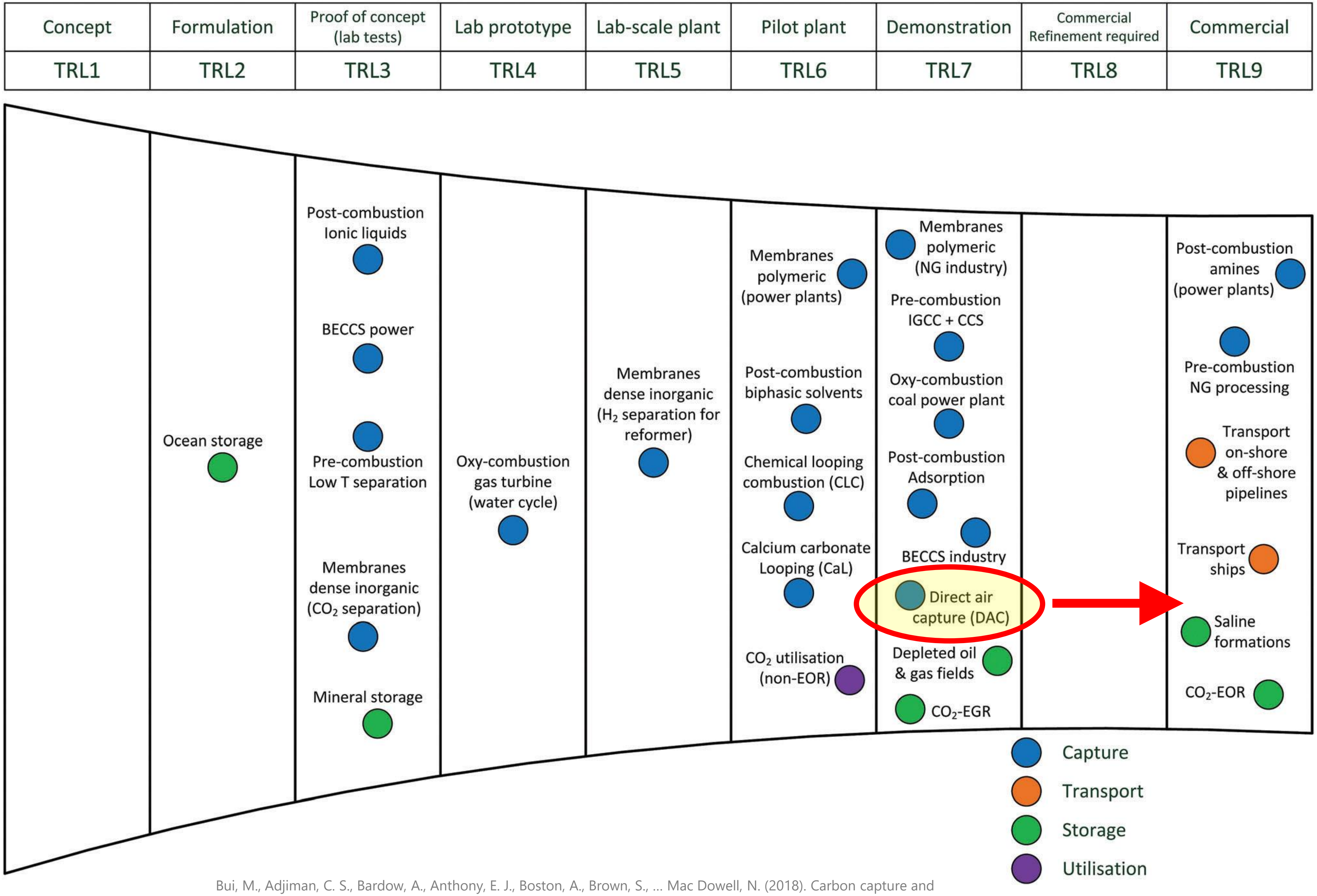
Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., ... Del Mar Zamora Dominguez, M. (2018). Negative emissions - Part 1: Research landscape and synthesis. Environmental Research Letters, 13(6). https://doi.org/10.1088/1748-9326/aabf9b



Integrated Assessment Models include substantial contribution from negative carbon emissions

Essential to meet Paris Agreement 2°C global average temperature hold

Anderson, K., & Peters, G. (2016). The trouble with negative emissions. Science, 354(6309), 182–183. https://doi.org/10.1126/science.aah4567



Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., … Mac Dowell, N. (2018). Carbon capture and storage (CCS): The way forward. *Energy and Environmental Science*, *11*(5), 1062–1176. https://doi.org/10.1039/c7ee02342a

A brief history of DAC

Proposed in the 1990s to address atmospheric CO_2

Technologies in search of a business model

"Moral Hazard" debate

Increasing active research and pilot programs

Arizona State, Georgia Tech, Columbia University, ETH Zurich, Sheffield University, Zhejiang University

Multiple startup initiatives

Commercial & investor interest

angel investors and Oil & Gas

claimed costs ↓ \$1000/t → <\$100/t

still pending demonstration at scale

LA-UR- 99-583

Approved for public release; distribution is unlimited.

Title: Carbon Dioxide Extraction From Air: Is It An Option?

Author(s): Klaus Lackner, ALDSSR
Hans-Joachim Ziock, P-25
Patrick Grimes, Grimes Associates

RECEIVED
AUG 19 1999
OSTI

Submitted to: 24th Annual Technical Conference on Coal Utilization & Fuel Systems
March 8-11, 1999
Clearwater, Florida

Los Alamos
NATIONAL LABORATORY

Form 836 (10/96)

Carbon Engineering

forced air contactor with very low ΔP ~70 Pa

→ KOH_{aq} absorber loop

→ $CaO/CaCO_3$ loop

$CaCO_3$ liquid FB crystallizer

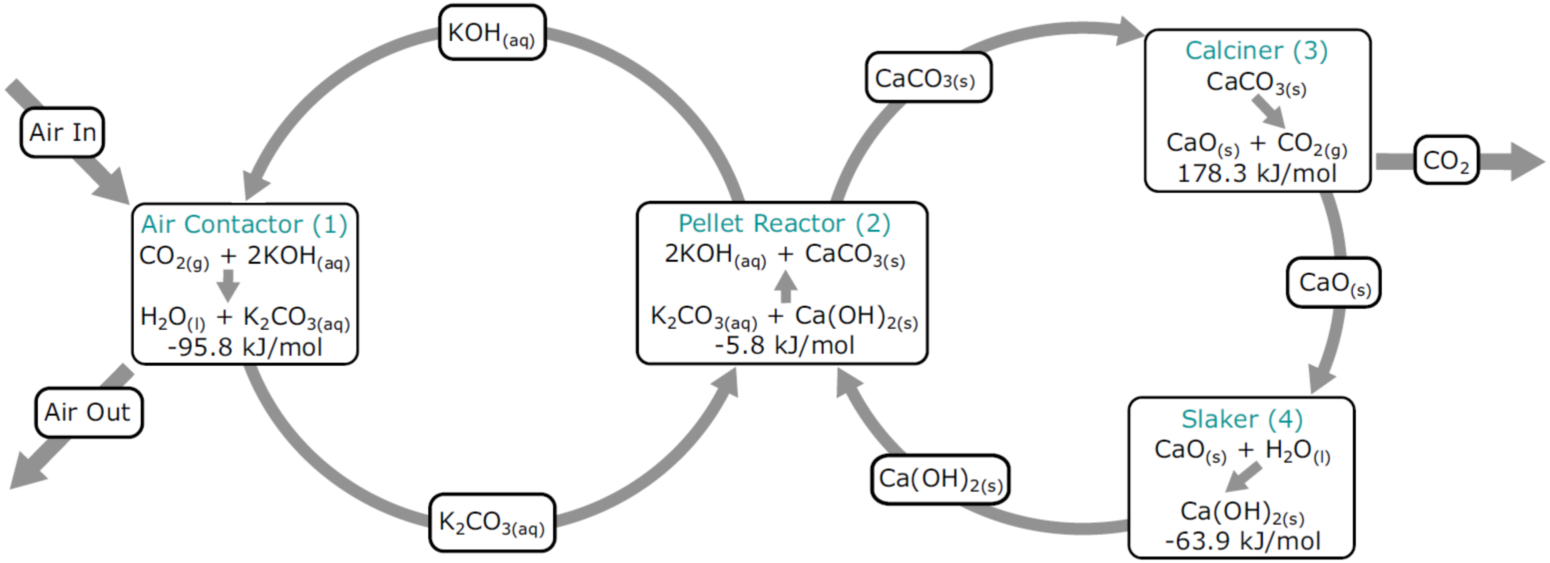
oxy-fired fluidized bed calciner

$100-200/tonne claimed

New 500,000 tCO_2/y plant in West Texas announced

1 tpd pilot plant 2015

1 Mtpy facility concept



Keith, D. W., Holmes, G., Angelo, D. St., Heidel, K., St. Angelo, D., & Heidel, K. (2018). A Process for Capturing CO2 from the Atmosphere. Joule, 2(8), 1573–1594. https://doi.org/10.1016/J.JOULE.2018.05.006

CLIMEWORKS

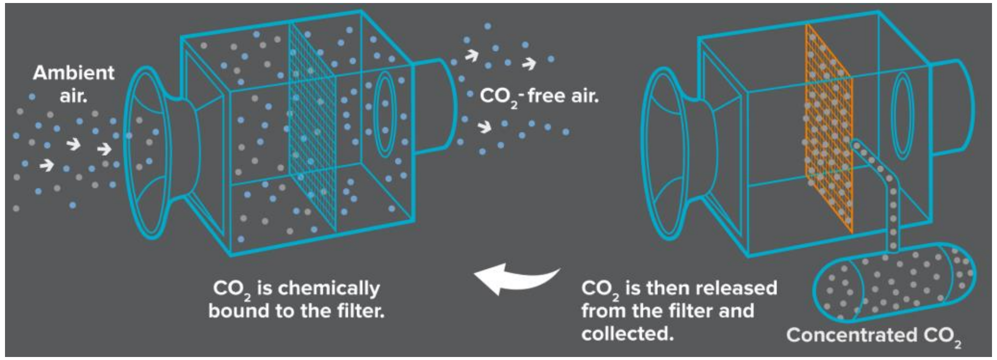
Capturing CO_2 from air

forced air convection

solid amine-functionalized sorbent

low temperature-swing regeneration (100°C)

modular 135 kg/d units



multiple commercial/demo units in operation

CCS demonstration plant in Iceland with geothermal regen to underground sequestration

900 tpy 18 module commercial plant in Zurich with waste heat supplying greenhouse CO_2

Julia Dunlop (photographer). (2019, June 11). Climework's facility in Zurich [digital image]. Retrieved from //www.fastcompany.com/90356326/

www.climeworks.com accessed 21 January 2019 proprietary amino-polymer solid sorbent

low temperature swing regeneration

short cycle time

4000 tpy demonstration facility in Huntsville AL

recently announced JDA with ExxonMobil

Global Thermostat

Global Thermostat. (2019, June 11). Global Thermostat’s Commercial Plant in Huntsville, Alabama [digital image]. Retrieved from //www.fastcompany.com/90356326/

ANTECY

CLIMEWORKS

Carbon Engineering

Global Thermostat

INFINITREE

hydrocell

skytree®

SILICON KINGDOM HOLDINGS

ASU

DAC advantages relative to point source capture

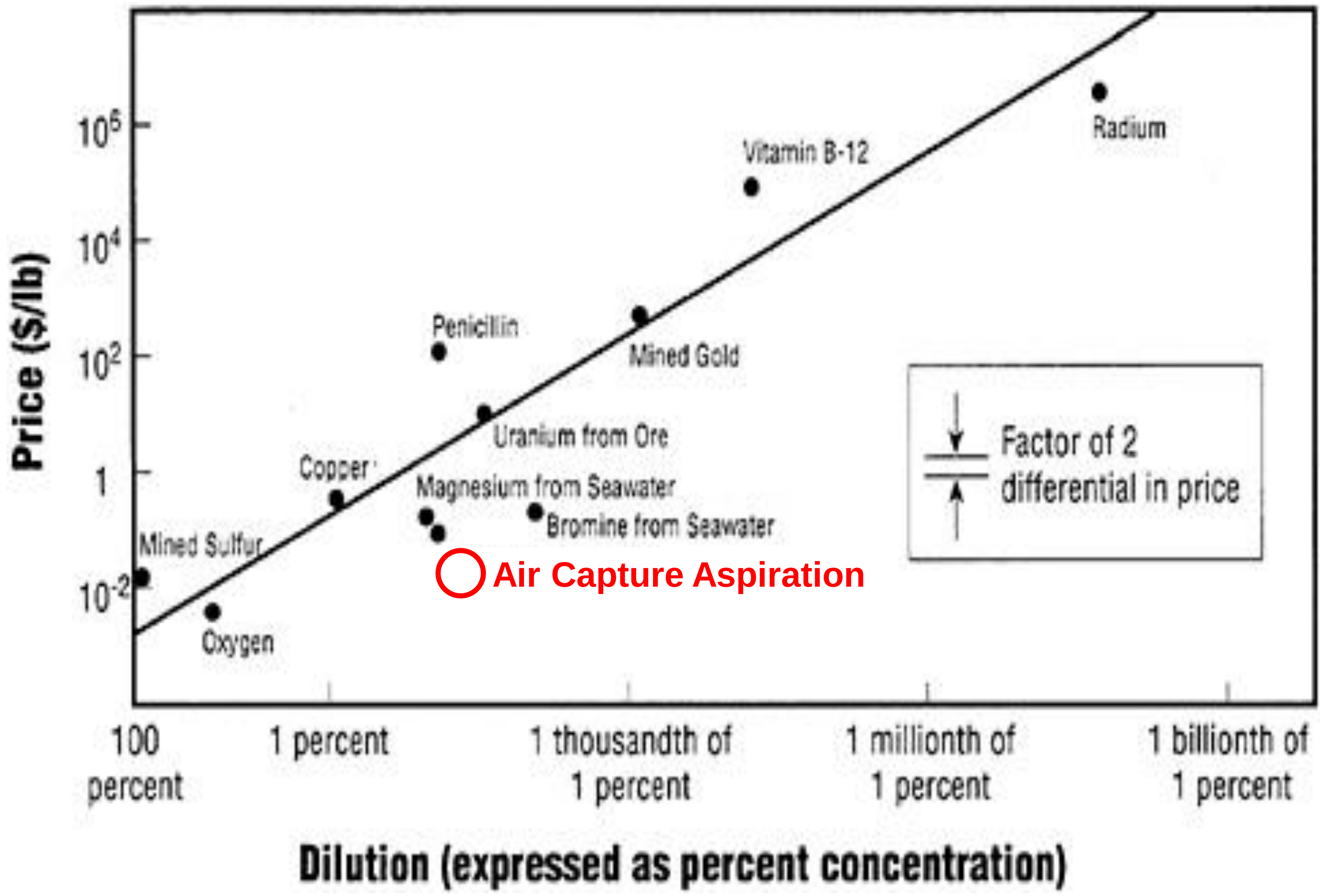
Shutterstock

- ✓ infinite feedstock reservoir
- ✓ unconstrained scale flexibility
- ✓ minimal contaminants
- ✓ location independence

DAC challenges – it's all about the concentration

Sherwood's Rule $Cost = aD + b + \log D$

Cost of separation scales linearly with dilution



SOURCE: National Research Council (1987)

first-order empirical estimate

assumes linear term dominates

comes down to

1) separation energy
2) movement of air
3) capital intensity

DAC separation energy requirement

400 ppm → 1 atm @25°C

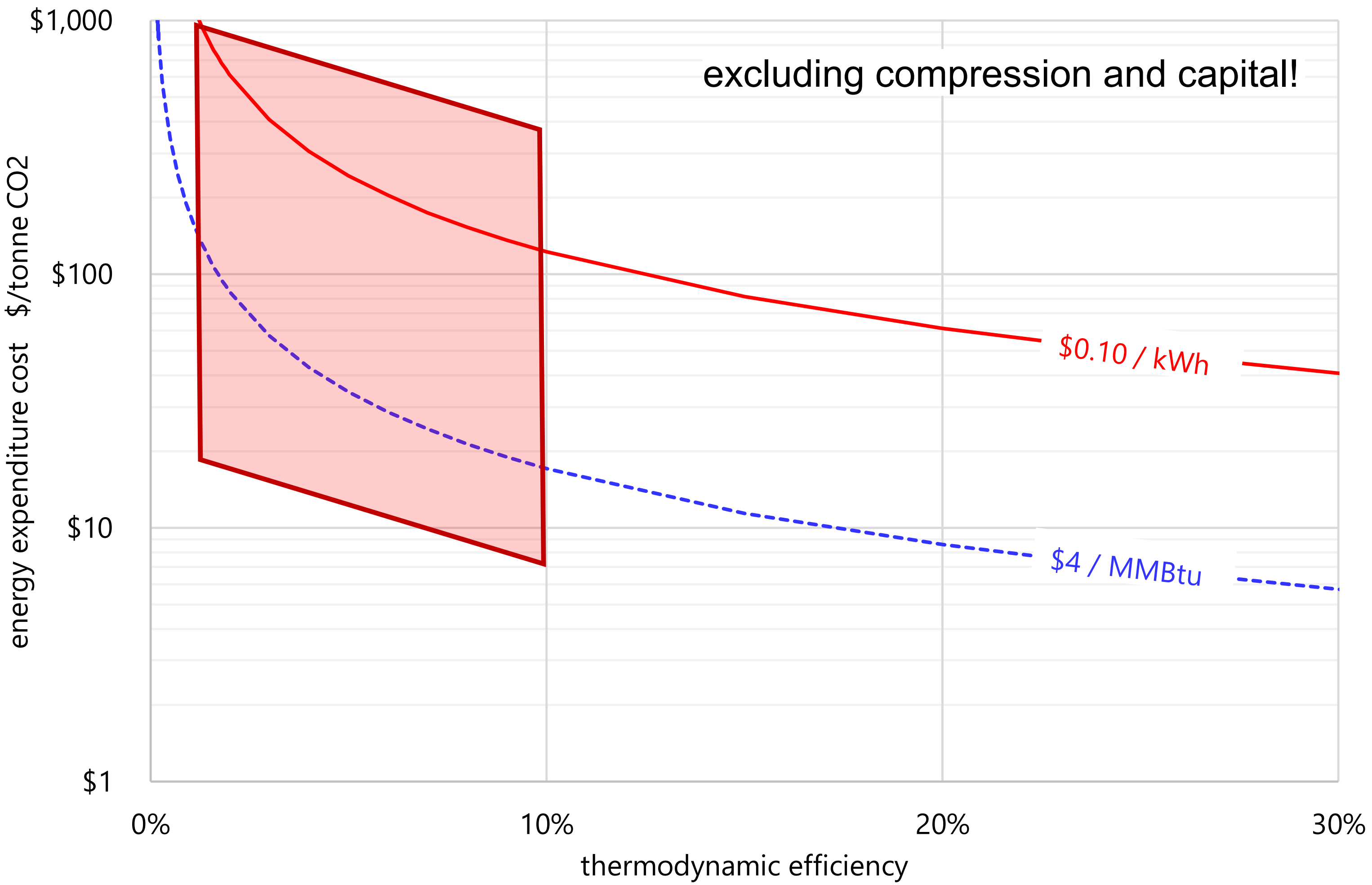
$\Delta G_{separation}$ = ~20 kJ/mol

<u>DAC requires</u>

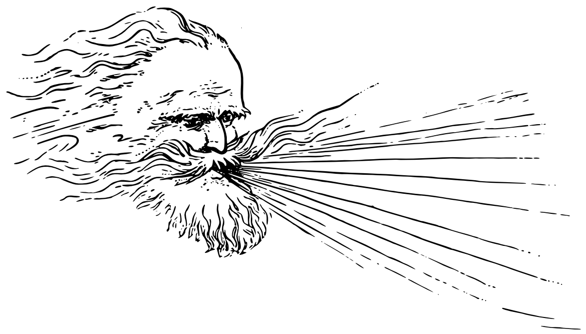
Low cost energy source

and/or

Step change in efficiency



Movement of Air



forced air + typical ΔP

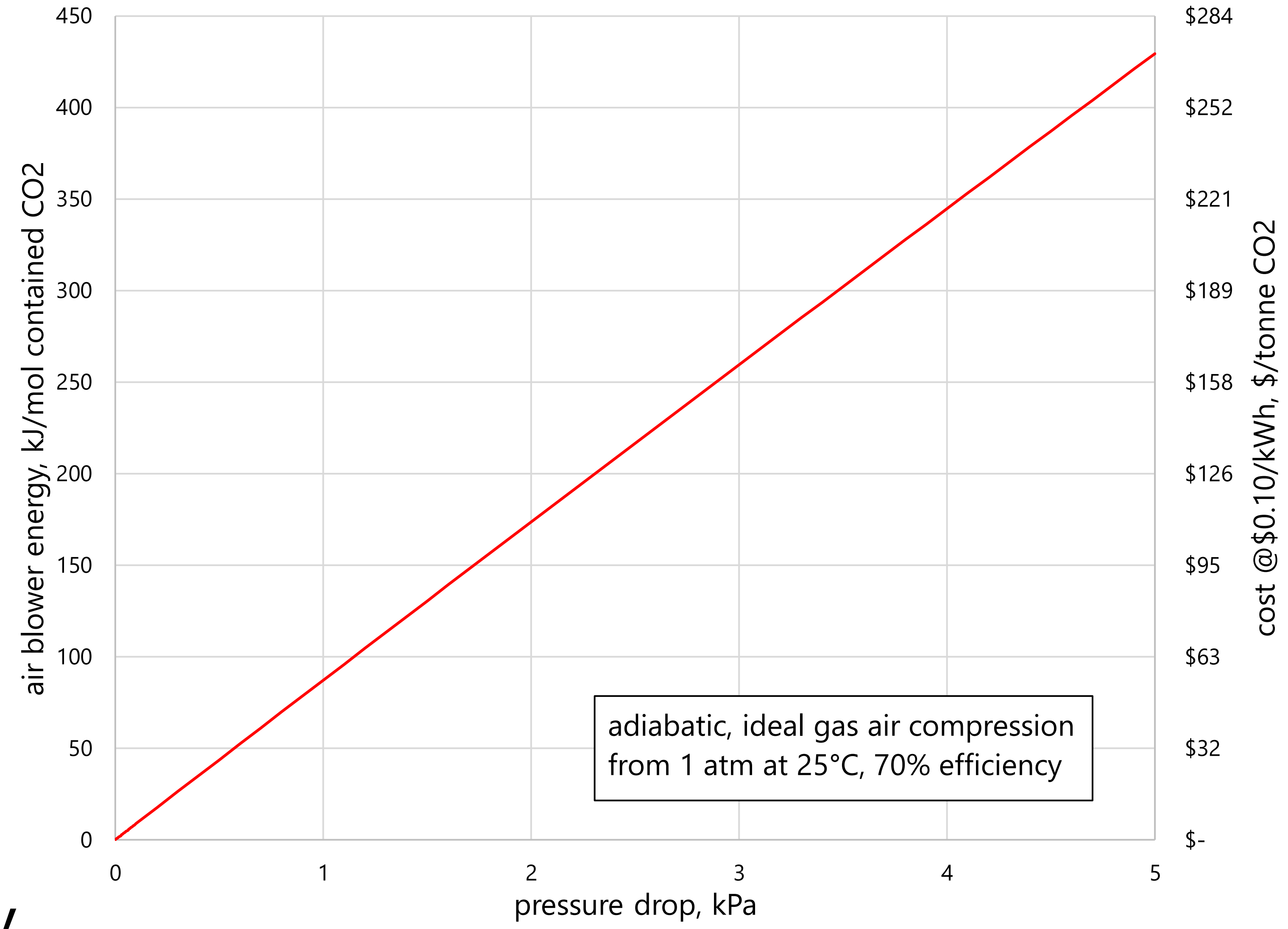
= $$$ + positive emissions

<u>DAC requires</u>

Very low pressure drop

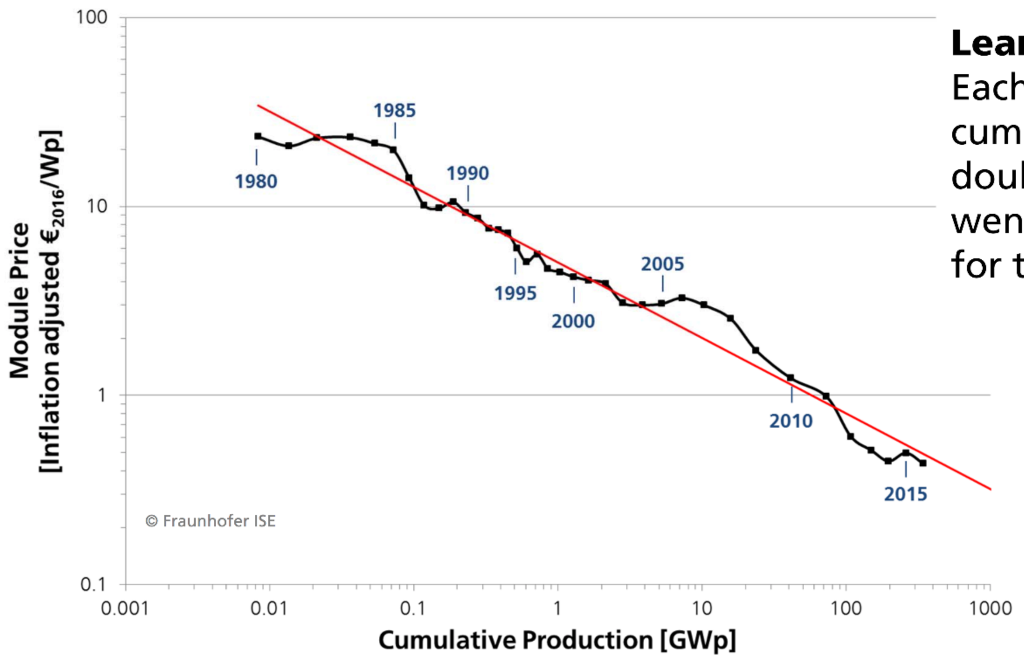
and/or

low-cost, low-carbon energy



Capital Intensity

Modularization and mass production enable significant cost reduction



Learning Rate:
Each time the cumulative production doubled, the price went down by 24 % for the last 36 years.

Data: from 1980 to 2010 estimation from different sources : Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011 to 2016: IHS. Graph: PSE AG 2017

Car engines are 100 times cheaper than power plants

- Economies of mass production can win out over the economy of scales
- Small scales shorten time to deployment
- incremental capacity expansion minimizes investment risk and technology obsolescence risk

how low can it go?

Photovoltaic learning curve from "Photovoltaics Report," Fraunhofer Institute for Solar Energy, Freiburg July 2017

Passive Direct Air Capture

Passive Direct Air Capture

Direct Air Capture

Passive System
artificial tree

Moisture Swing Sorbent
evaporative regeneration in wind

Mass Manufacturing Approach
modular process intensification

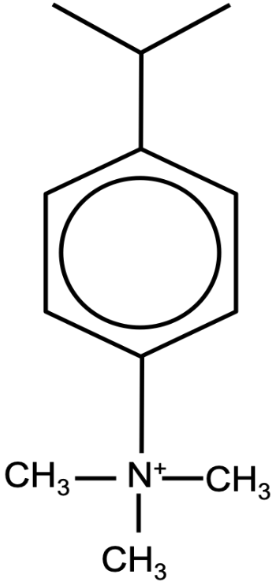
Two Stage Concentration
4 Pa → 5 kPa

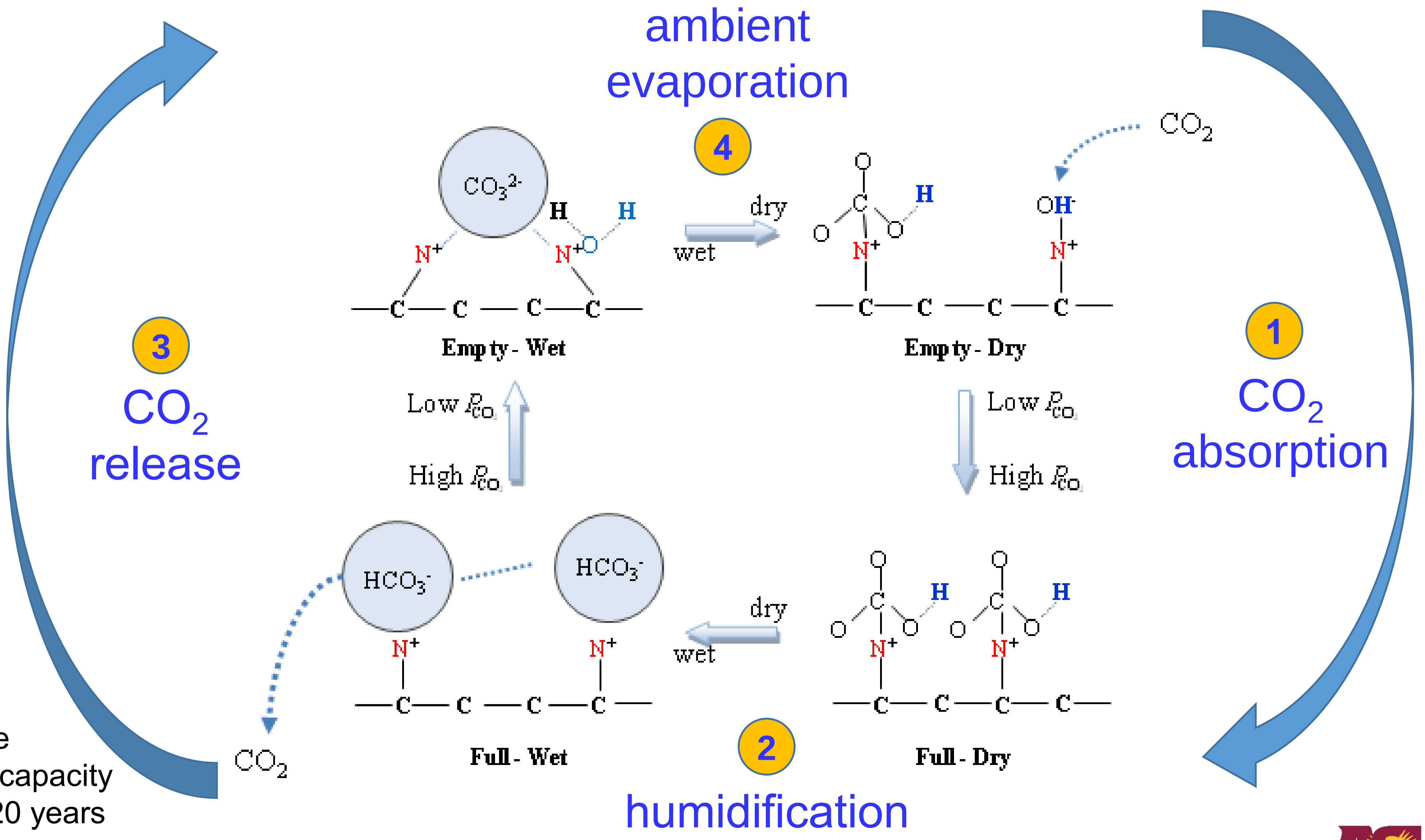
5 kPa → product pressure & purity

Moisture swing cycle – ambient energy source

solid absorbent

Type I Strong Base Resin



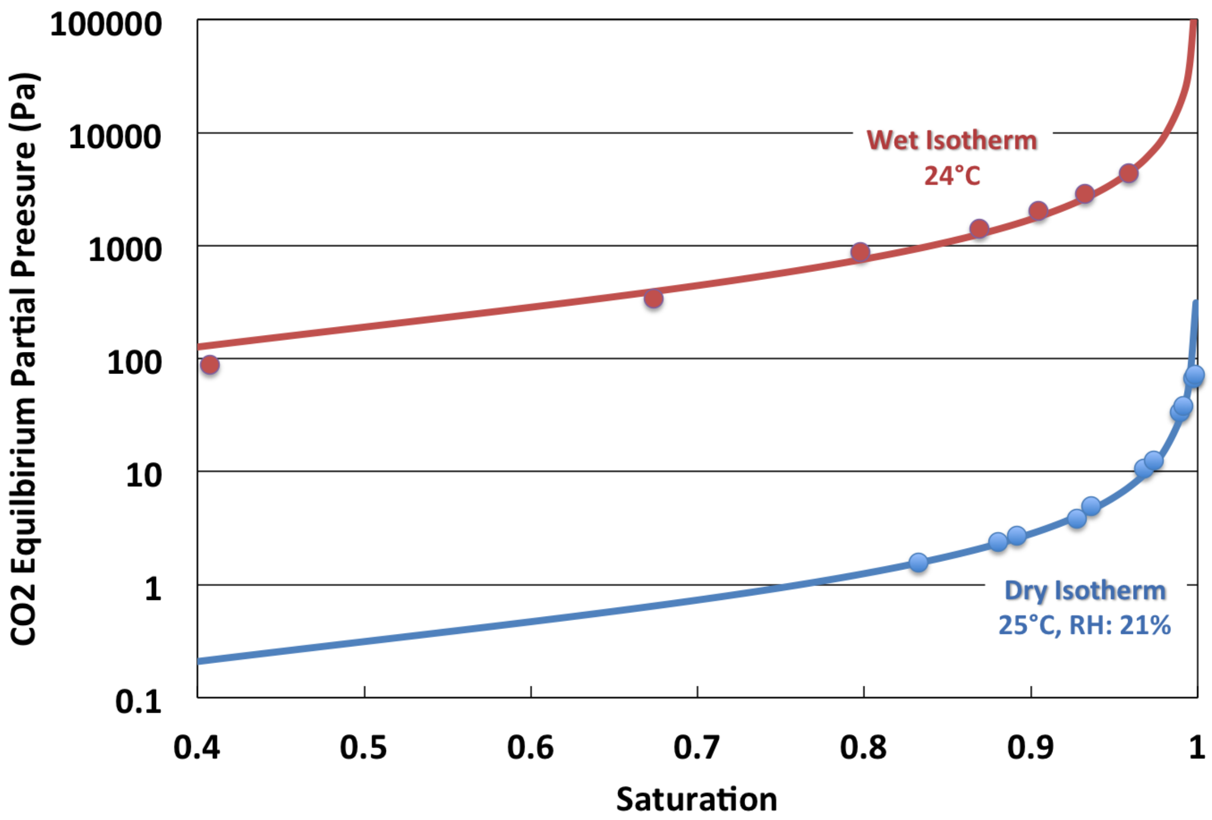


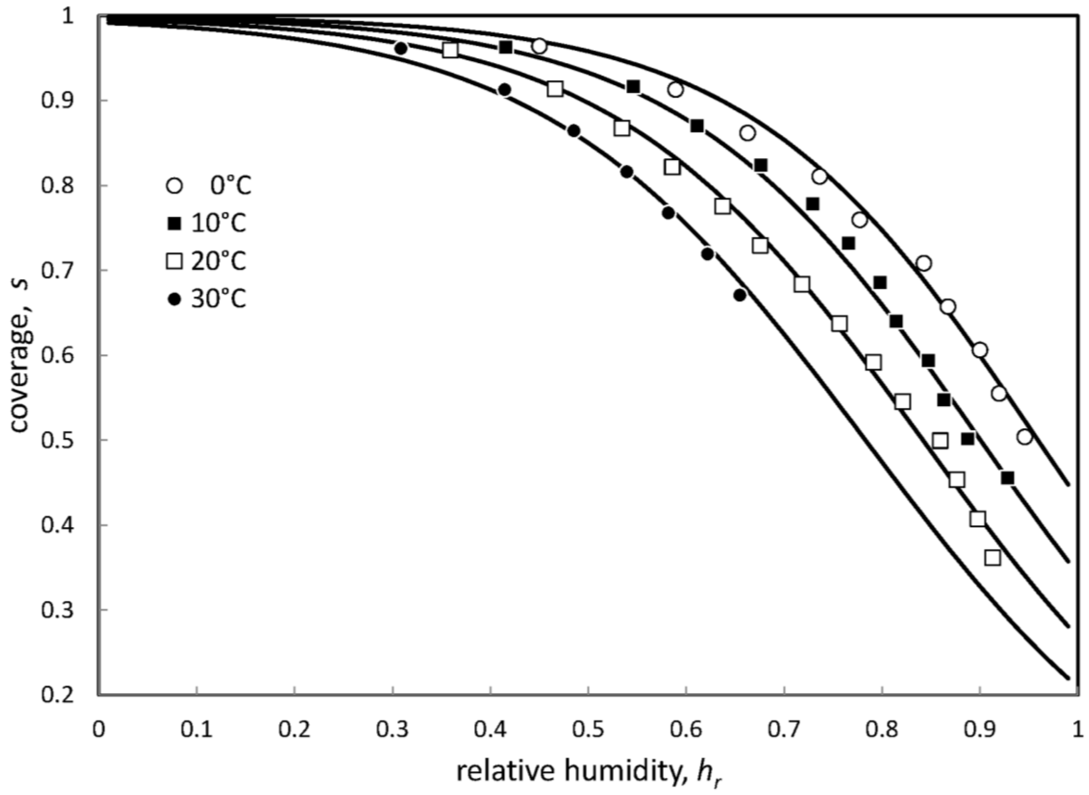
2 to 2.5 mol/kg of charge
1 to 1.25 mol/kg of CO_2 capacity
Durable, life time 10 to 20 years

Moisture Swing

DRY: equilibrium at 40 Pa CO_2

WET: equilibrium at ~5 kPa CO_2



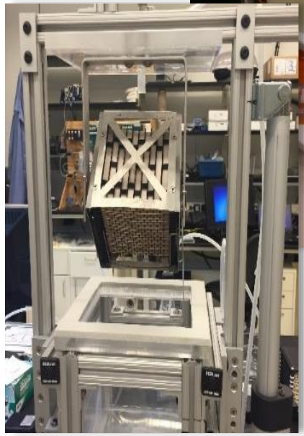


resin form factors

ASU

ASU's collector prototype development

filter



benchtop
versions

rooftop
unit

feeding algae

Tiburio™

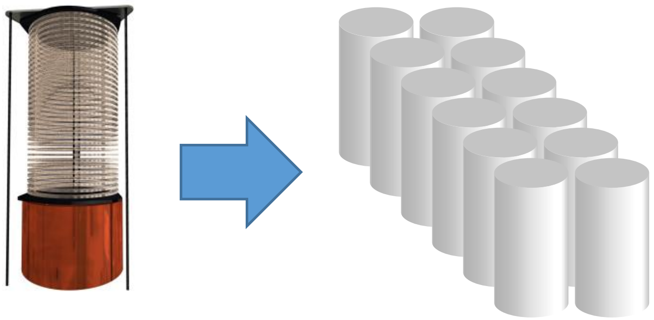
Tiburio™ Design

SILICON KINGDOM HOLDINGS

- Harvest
  - Wind flows through gaps between horizontal sorbent disks, disks dry and load up with CO_2
- Moisture sensitive sorbent
  - releases CO_2 if exposed to moisture and/or heat
  - First concentration step requires only minimal energy
- Regeneration
  - Disks are regenerated through moisture inside the bottom chamber, creating low pressure CO_2 (in air, or in vacuum)
  - Upgrade through innovative evacuation/compression in the future with built-in energy storage
- Designed for mass-manufacture
- Commencing commercialization

ASU

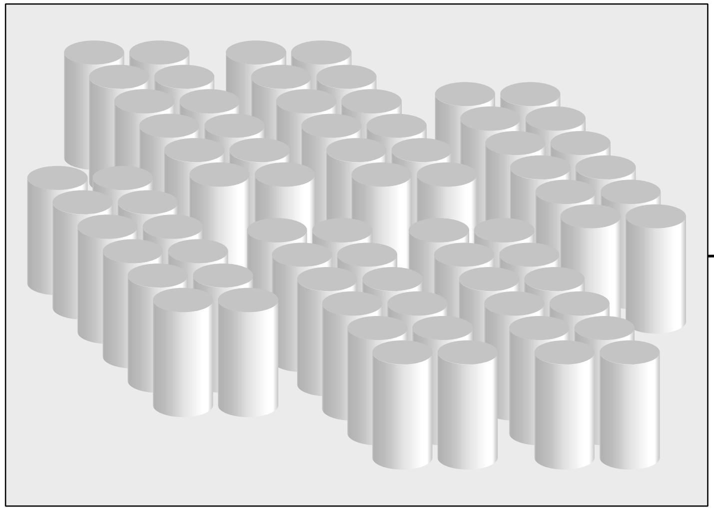
Facility Scale Concepts



n collectors = 1 TPD cluster

economies of modular mass production

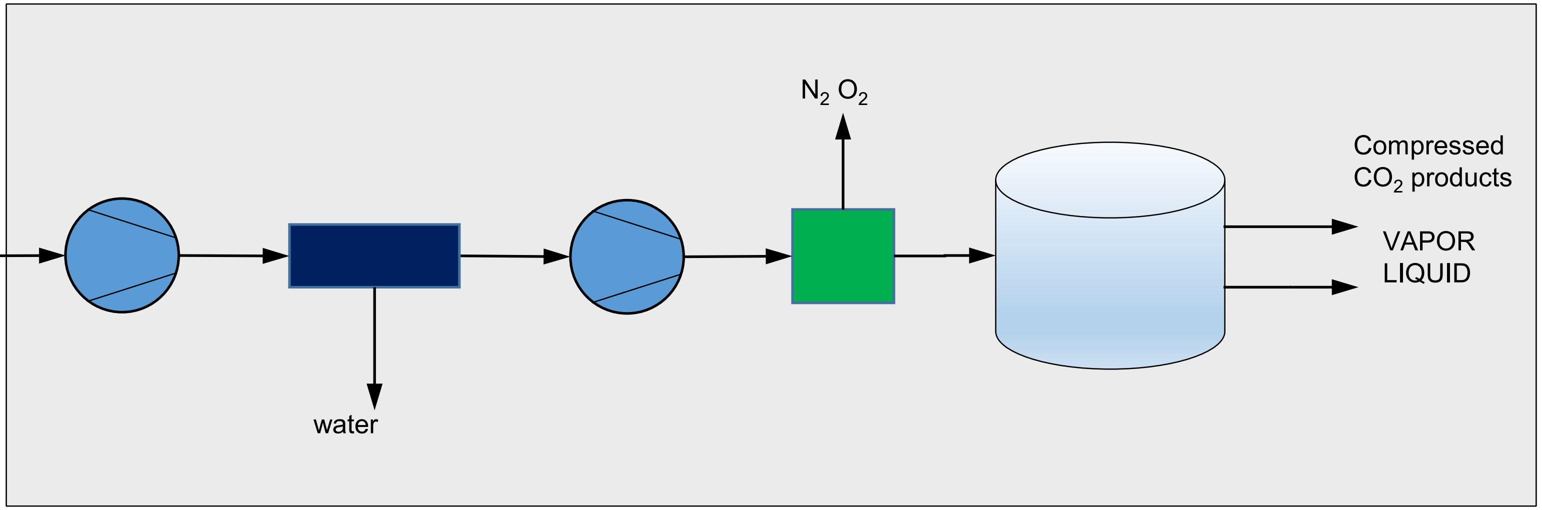
100+ clusters = train



CO_2 collectors

economies of scale

100-1000 TPD compression and purification unit (CPU)



vacuum compressor | *dehydrator* | *booster compressor* | *non-condensables separator* | *CO_2 storage*

Acknowledgements

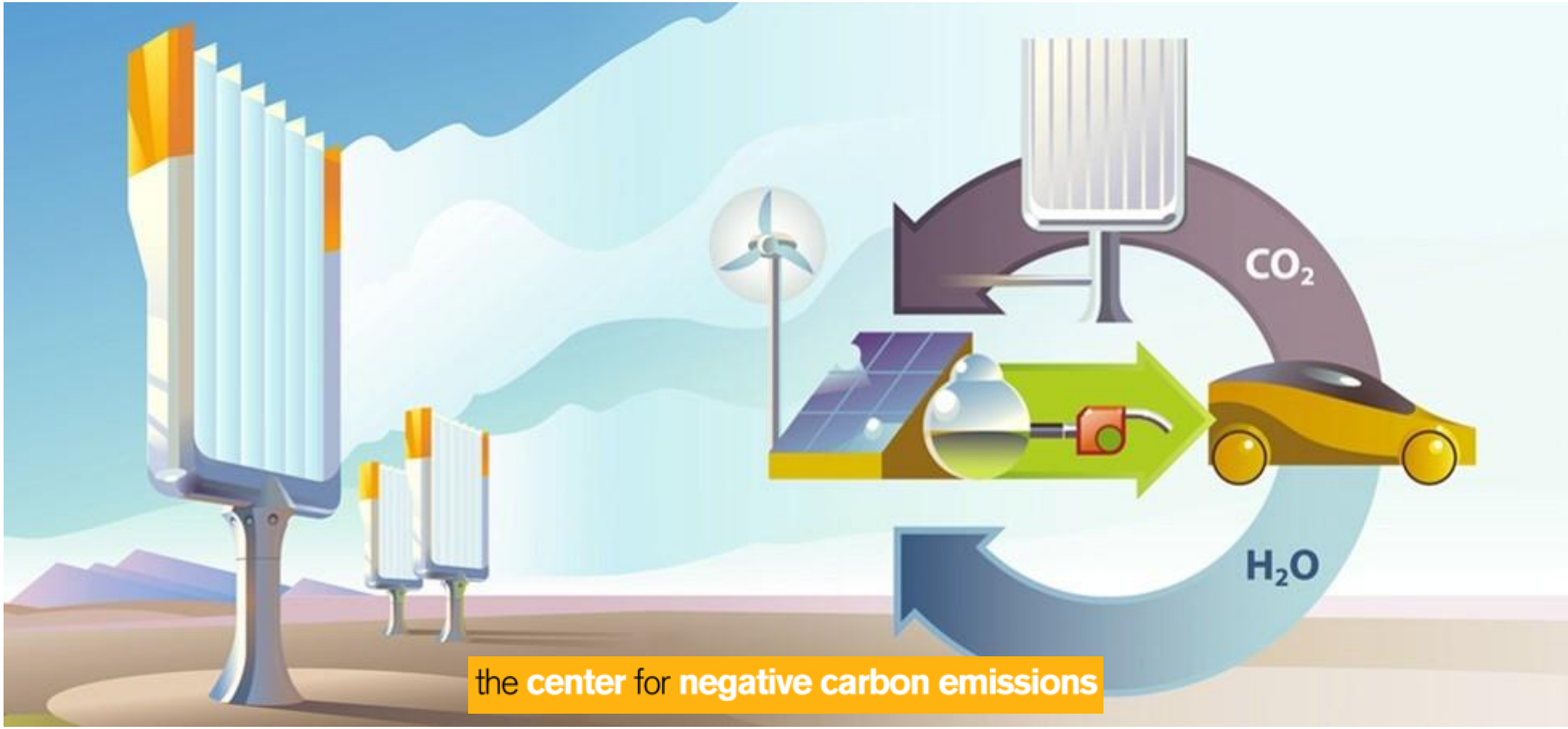
Arizona State University

the center for negative carbon emissions

Klaus Lackner
Allen Wright
Robert Page

LightWorks
Arizona State University

Bill Brandt



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