Carbon Removal - Pathways, Technologies, and Need

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Creating solutions for a NET ZERO world

October 13, 2022

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CO_2 annual emissions and atmospheric conc. (1750-2021)

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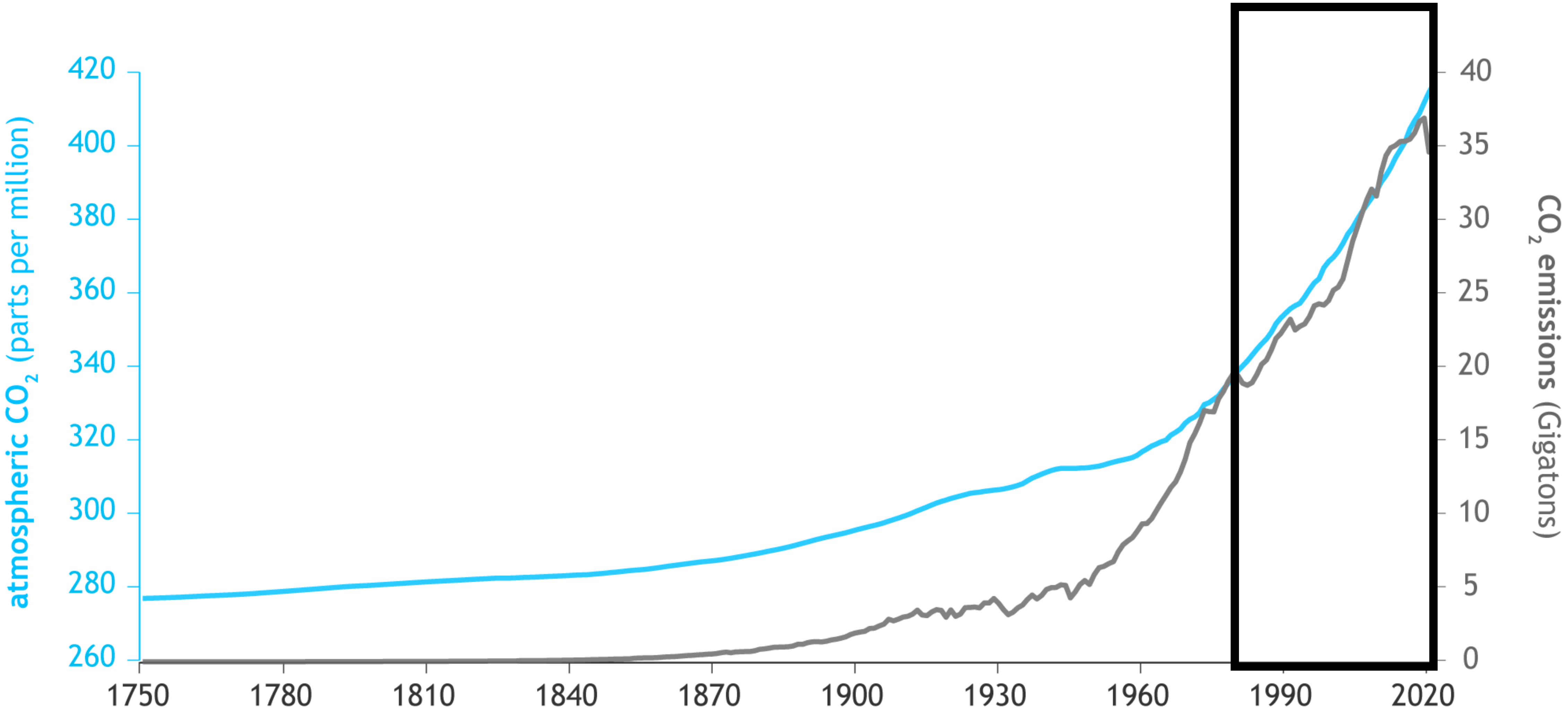

NOAA, Climate.gov

European Union policy efforts and projection

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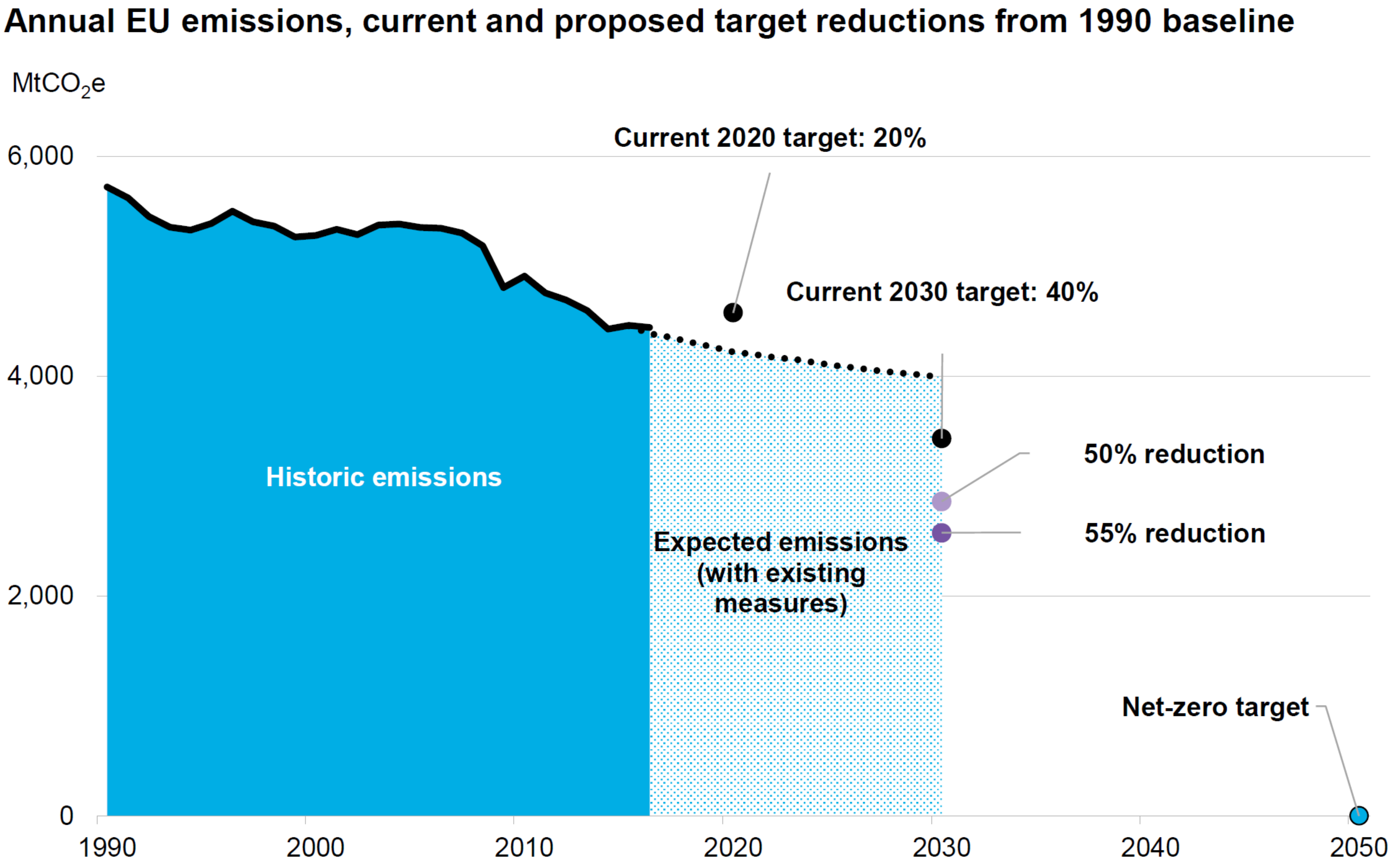
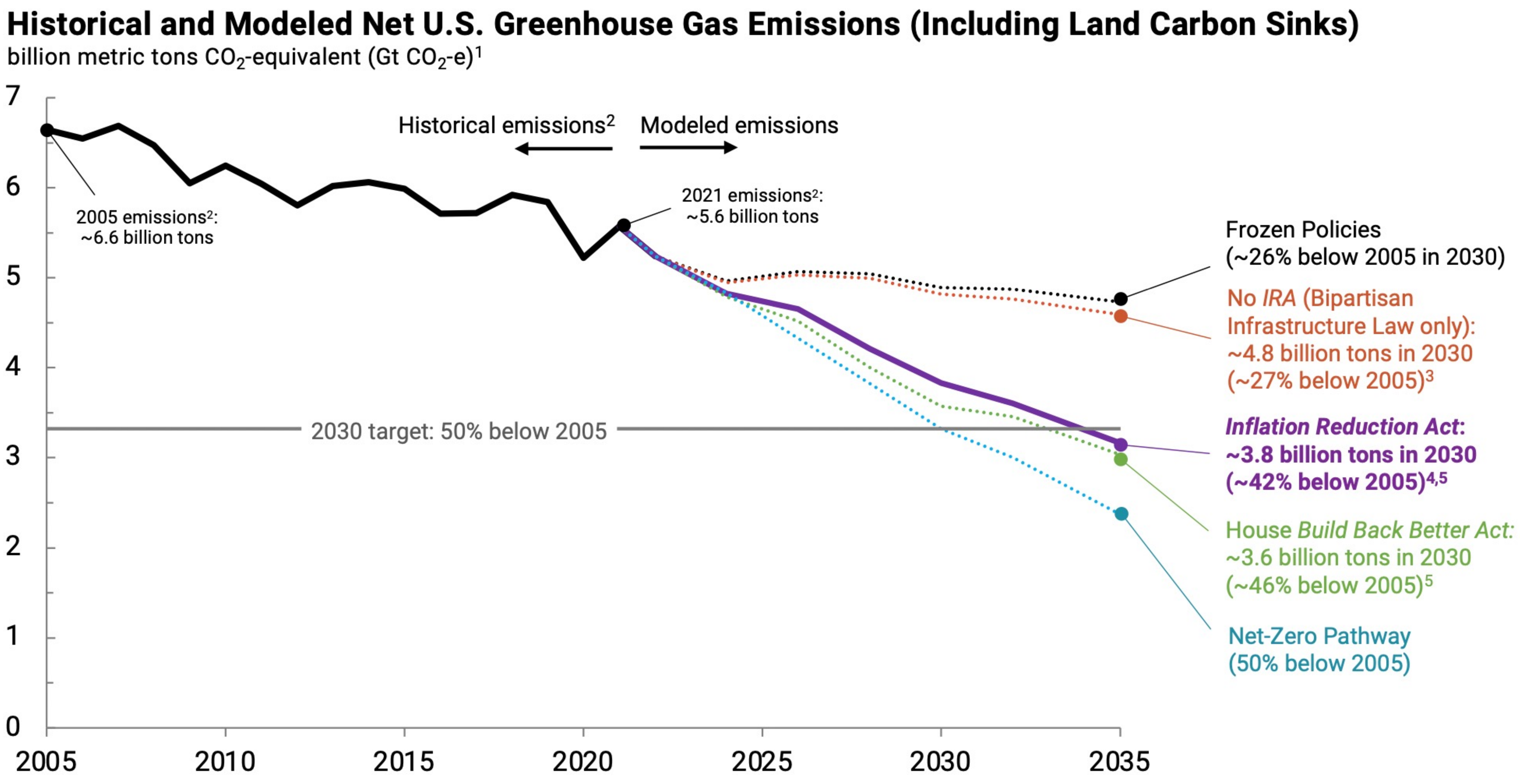


USA policy efforts and projections



Status Quo Not Sufficient: 2℃ pathway

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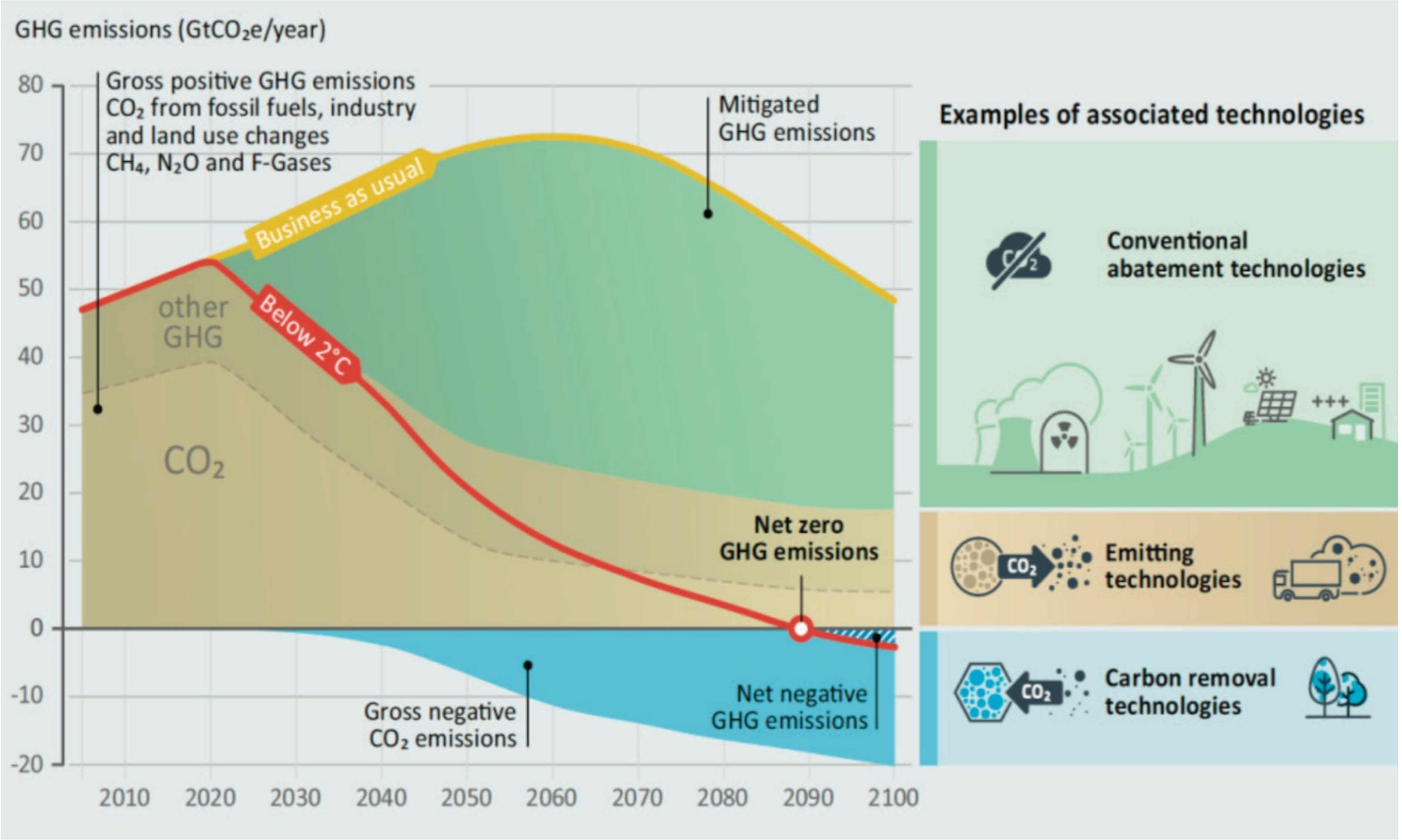
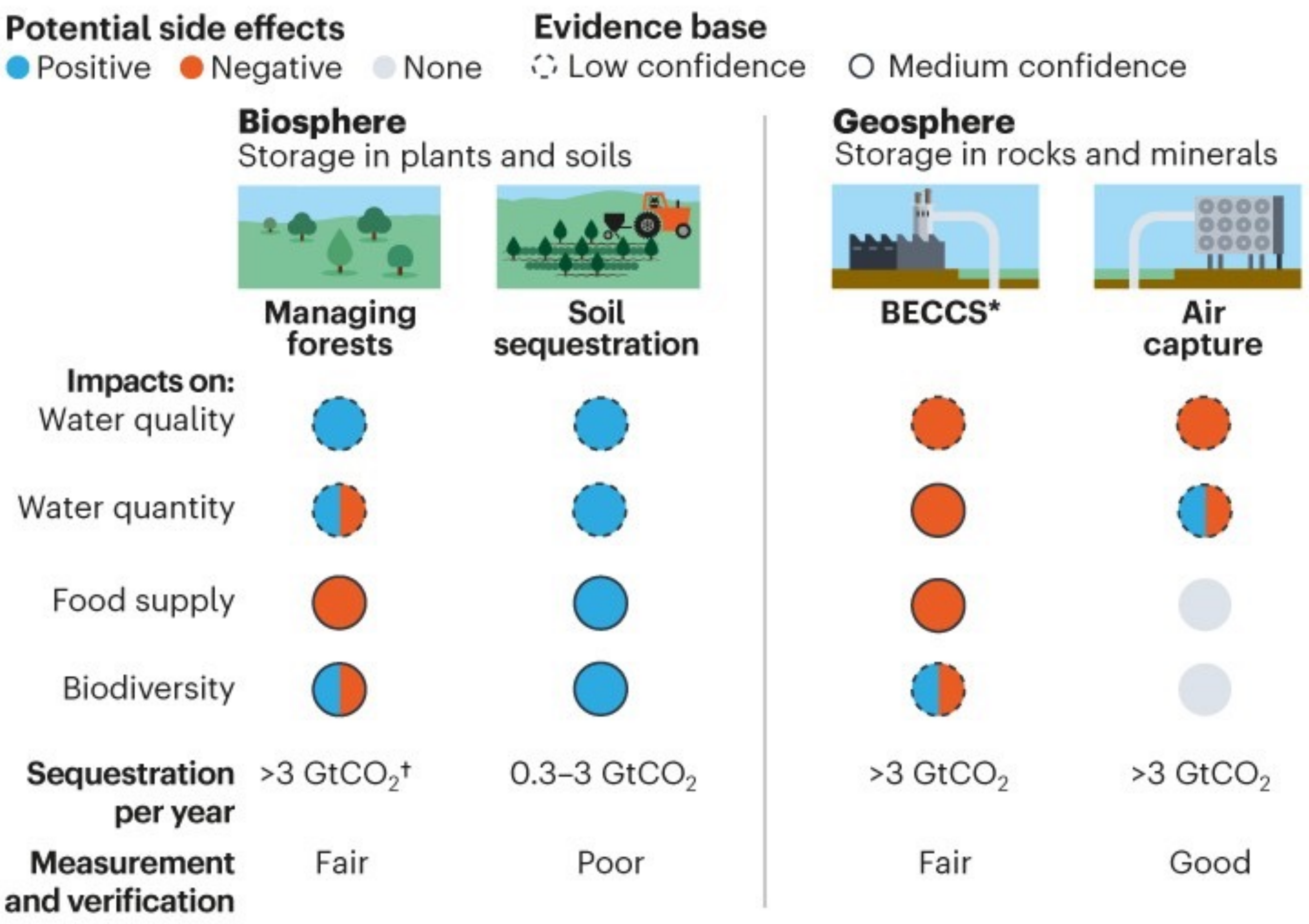


- Mankind has already exceeded >2000 Gt of carbon budget and continuing @ 40 Gt/annum
- For 2℃ we need to retain this total below ~3000 Gt
- For 2℃ we need to have 5 Gt per annum of carbon removal per annum operating by 2050 and 20 Gt operating by 2100

IPCC, Carbonroundtable.org

Potential Carbon removal pathways



Impact ratings are from the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, apart from 'Measurement and verification', which are based on the authors' judgement.
*BECCS, bioenergy with carbon capture and storage; †$GtCO_2$, gigatonnes of CO_2.

Nature, IPCC

Direct Air Capture - Technology Landscape

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CCUS Source Concentration Challenge

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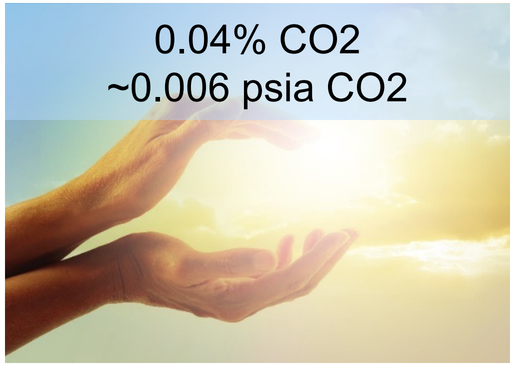
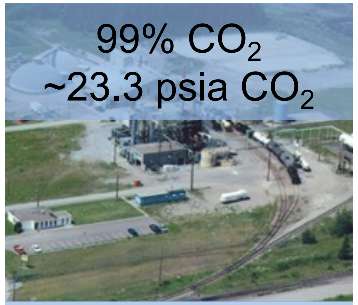
Coal Power Plant

Gas Power Plant

Air Capture

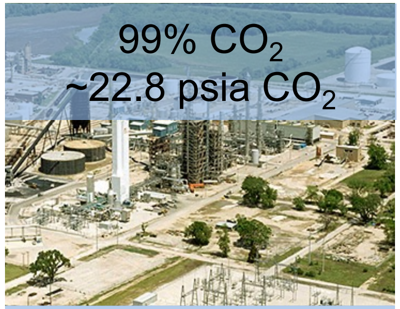


NG Processing Plant



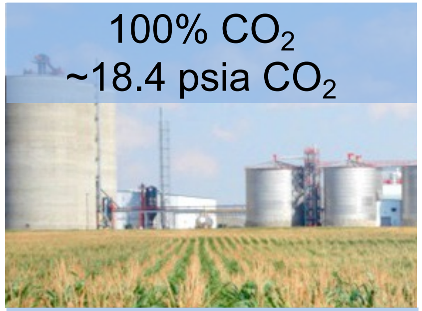
CO_2 vent

Ammonia Plant



Stripping vent

Ethanol Plant



Distillation gas

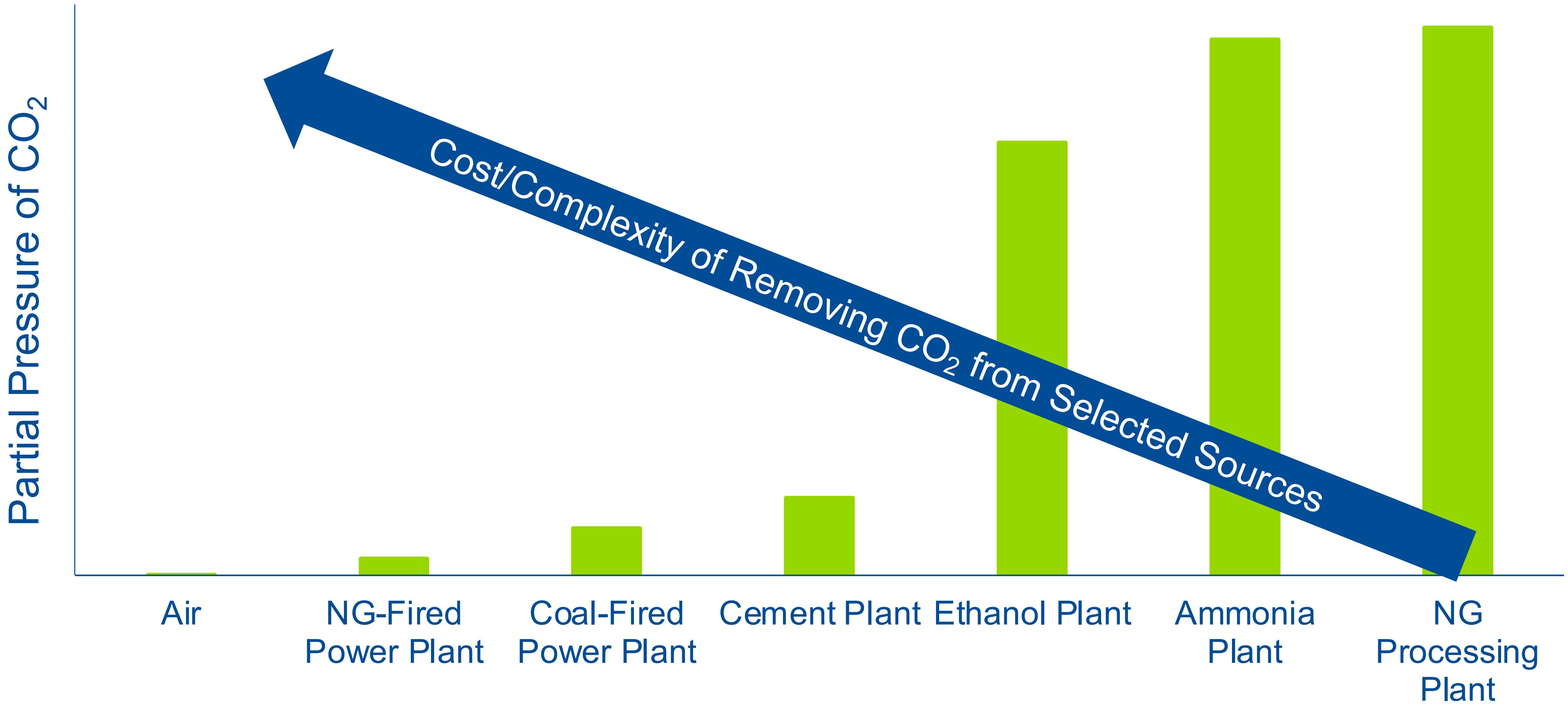
Cement Plant

Kiln off-gas

Cost of Capturing CO_2 from Industrial Sources, January 10, 2014, DOE/NETL-2013/1602

DOE/FE, 2021

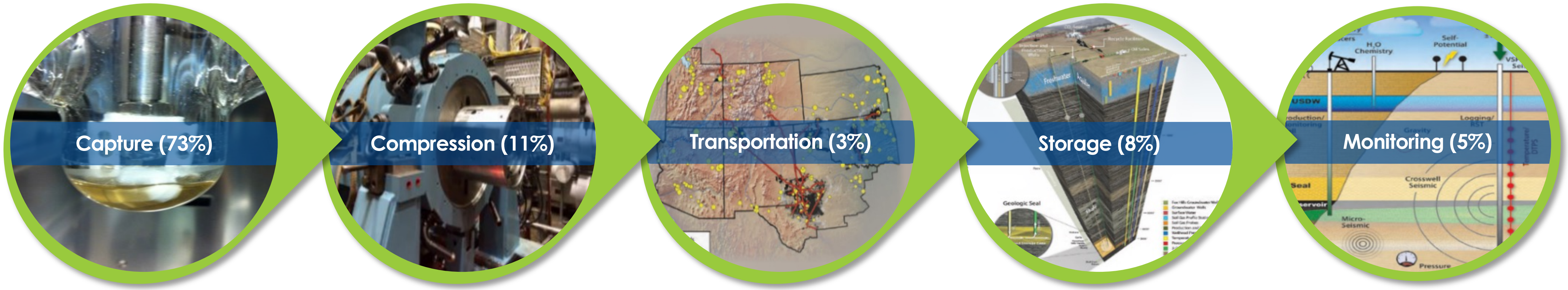
CO_2 Partial Pressure and Capture Cost



Cost of Capturing CO_2 from Industrial Sources, January 10, 2014, DOE/NETL-2013/1602

Source: U.S. Department of Energy, National Energy Technology Laboratory

Conventional CCUS Value Chain Costs



DAC Problem Definition

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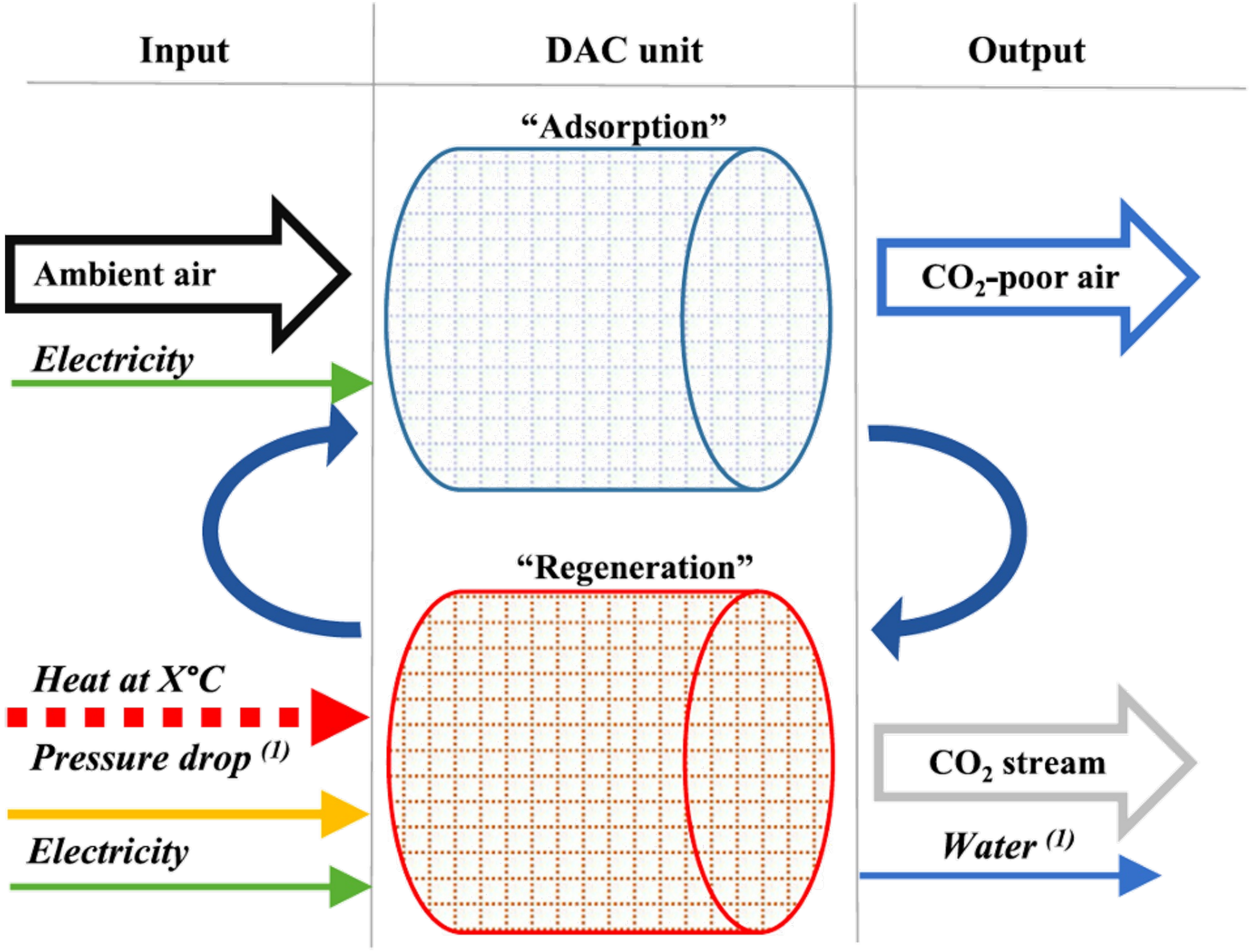
Needs:

- **Highly selective**
- **Minimal binding energy**
- **Fast kinetics**
- **High capacity**
- **Economic**
- **Long life - Durability**



Current DAC Technologies

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Direct Air Capture (DAC) Technologies

1. Membranes

2. Solid Sorbents

- Alkali metals (chemisorption)
- Amines (chemisorption)
- Activated carbons (physisorption)
- Zeolites (physisorption)
- MOFs (physisorption)
- Resins (humidity swing)

3. Electrochemical

4. Cryogenic

- Arctic/Antarctica
- Tropopause

5. Kelp/Seaweed-Based Capture

6. Liquid Solvents

- KOH
- Retrofitting cooling towers
- Amines

7. Ocean Capture

- Electrodialysis
- Electrolysis

8. Carbon Mineralization (+ Regeneration)

- Coastal
- Forests
- Land

Established Players

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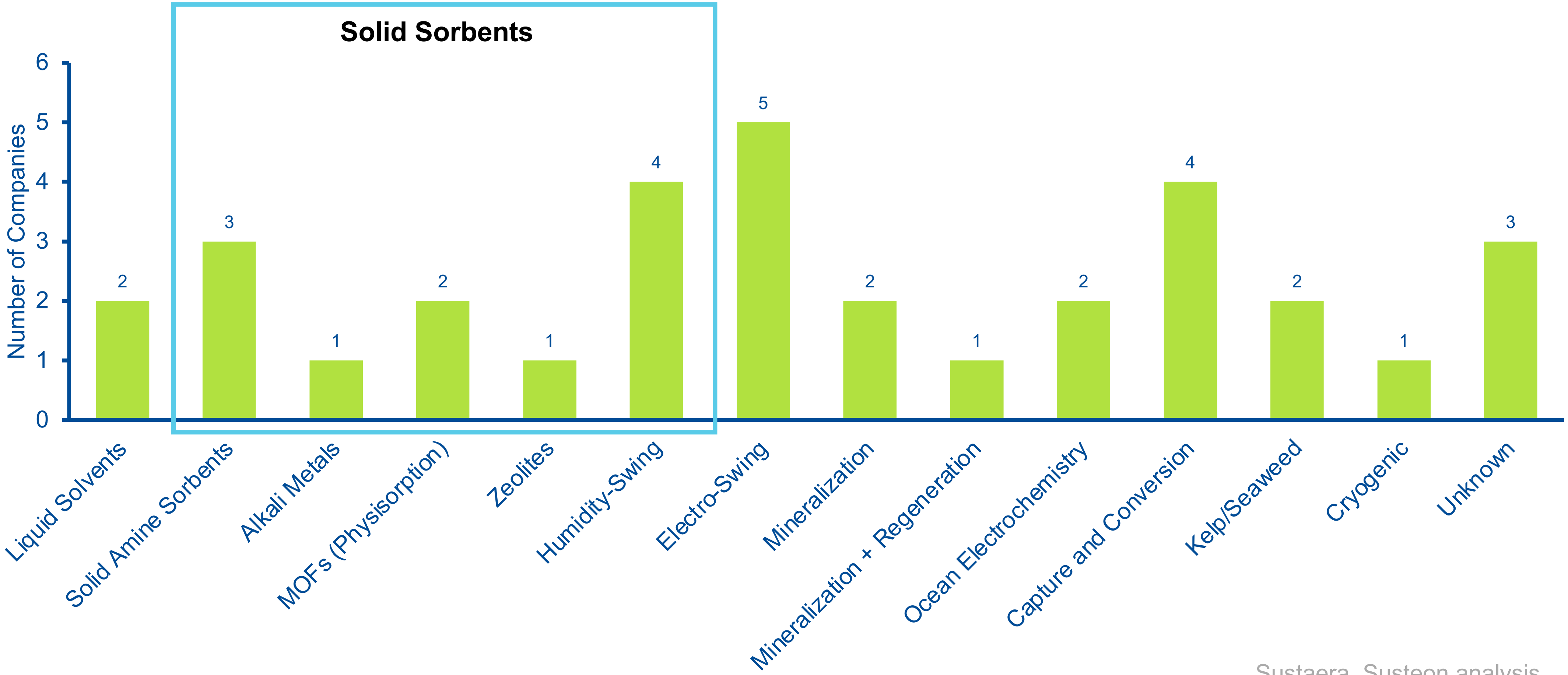
Company	Material	Challenges	Cost
Global Thermostat	▪ PEI ▪ Monoliths	▪ Desorption steam could condenses, stripping amine ▪ Amine reactivity with O_2 in air	▪ >100 \$/t-CO_2
climeworks	▪ Amine ▪ Amine+ MOFs ▪ Laminate Filters	▪ Amine reacts with O_2 in air ▪ Higher pressure drop	▪ ~300 to 600 \$/t-CO_2
Carbon Engineering	▪ K_2CO_3 – $CaCO_3$ loop ▪ Liquid Solution	▪ Equipment count and cost ▪ Oxygen impurity in CO_2	▪ ~94 to 232 \$/t-CO_2 (?)
Sustæra	▪ Alkali carbonate ▪ Monoliths	▪ Electricity for regeneration	▪ Commercial projection <\$100/t-CO_2

Approaches to DAC

- **Mature players like Carbon Engineering, Climeworks etc.**
- **29 younger companies, many of which have emerged in the last couple of years**



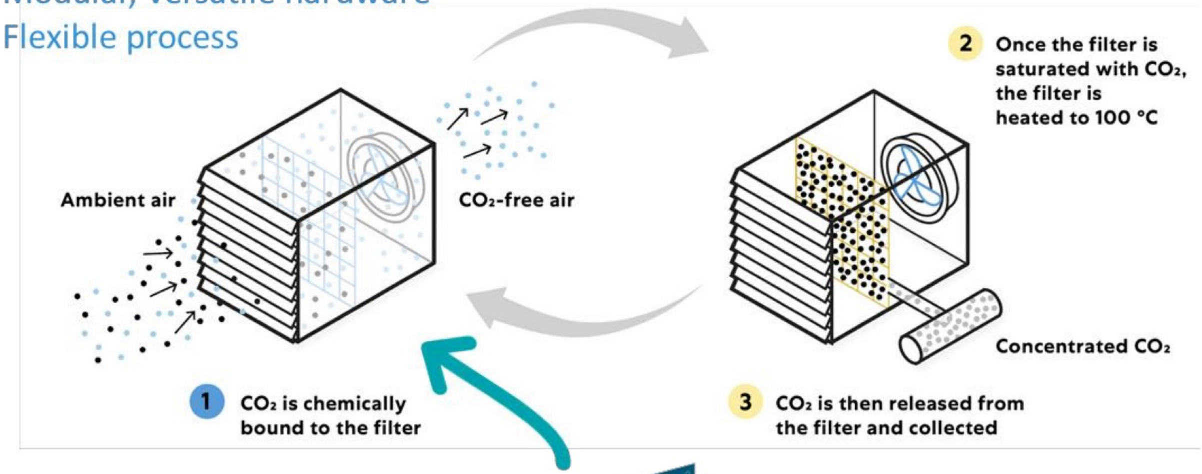
Sustaera, Susteon analysis

Climeworks

Climeworks technology demonstrated in 14 plants to date:

Combining Climeworks' temperature-vacuum swing adsorption technology with Svante's structured adsorbents:

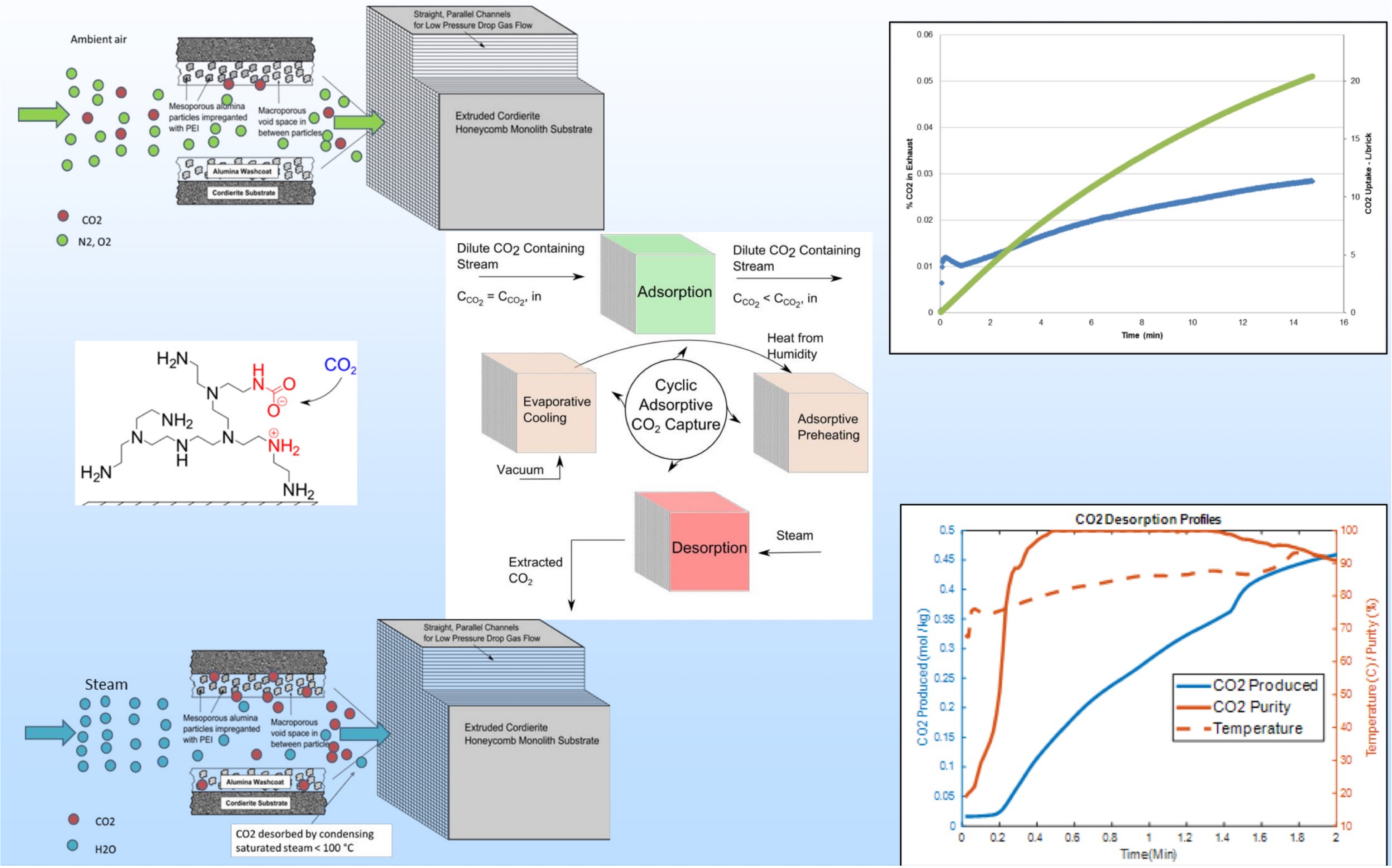
Climeworks' DAC technology
+ Proven technology
+ Modular, versatile hardware
+ Flexible process



Project goals
+ Combined sorbent/process optimization for DAC
+ Demonstrate at TRL 5

Svante's structured adsorbent technology
+ Rapid cycling
+ Adaptable geometry
+ Active phase flexibility

Global Thermostat



Carbon Engineering

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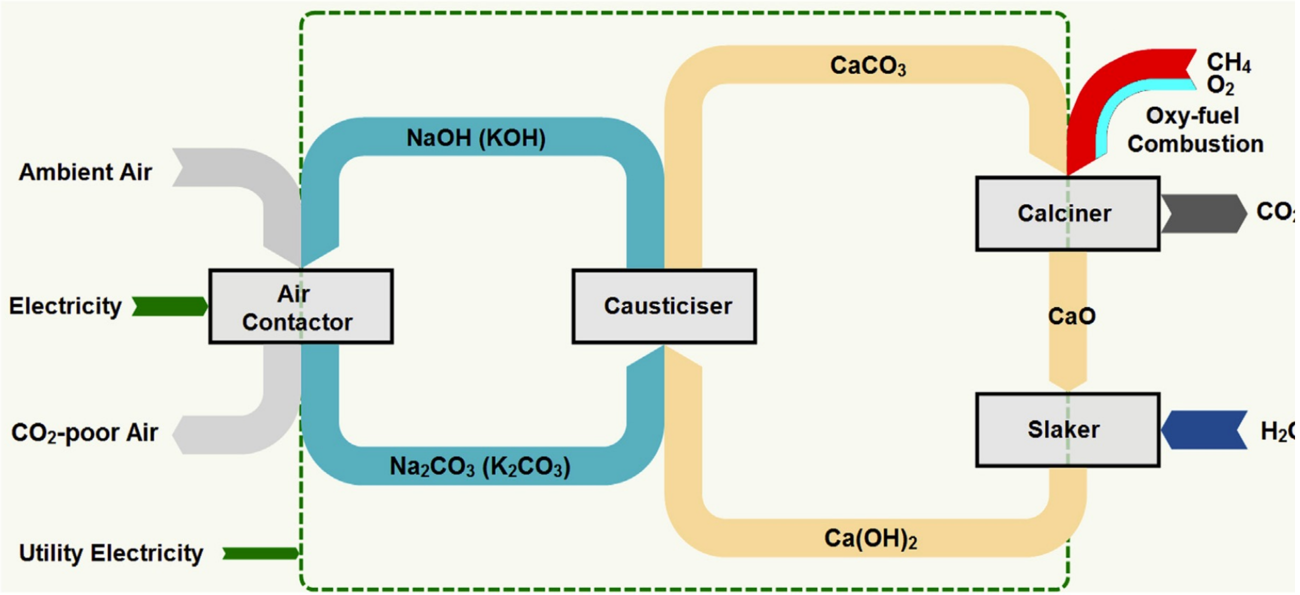
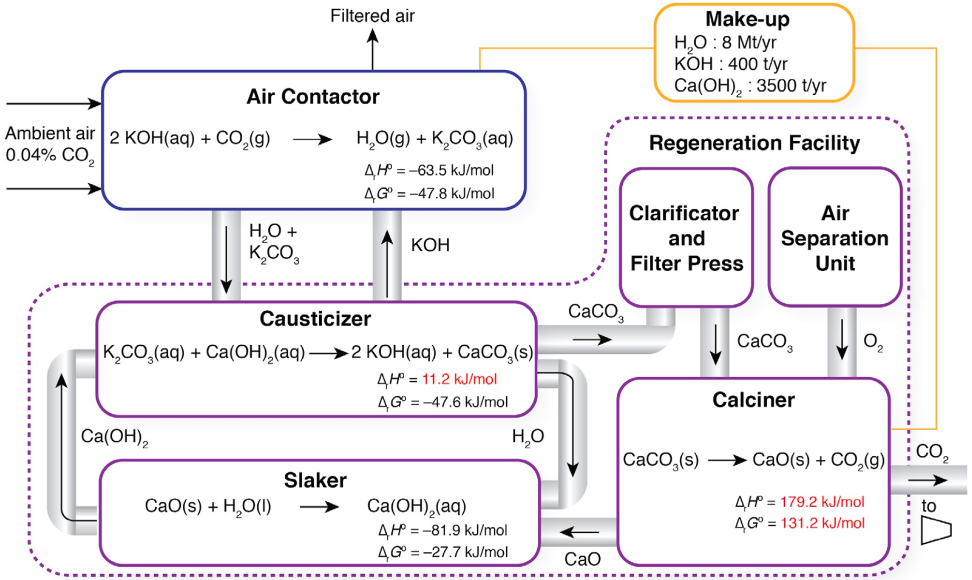
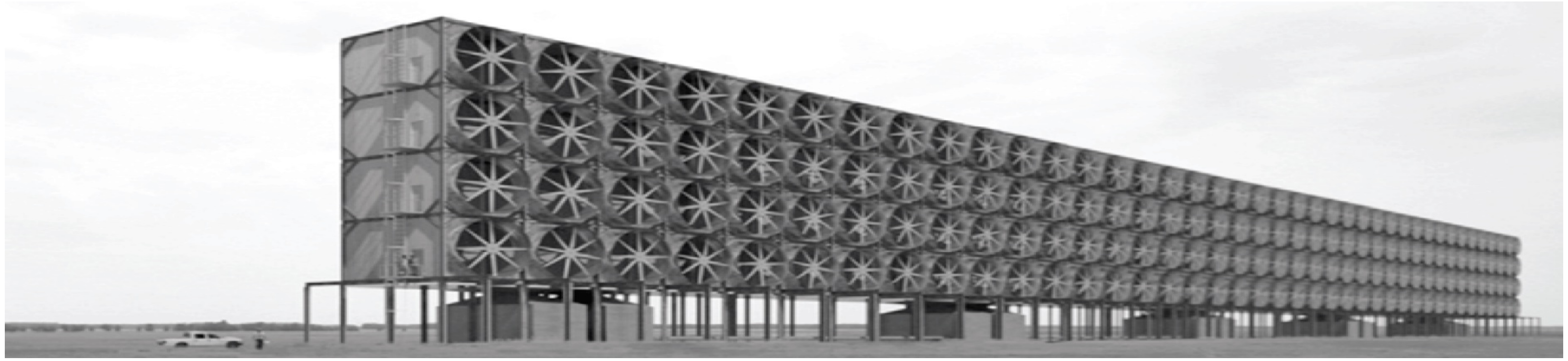
Plans to scale up to 1 million ton/yr of CO_2.







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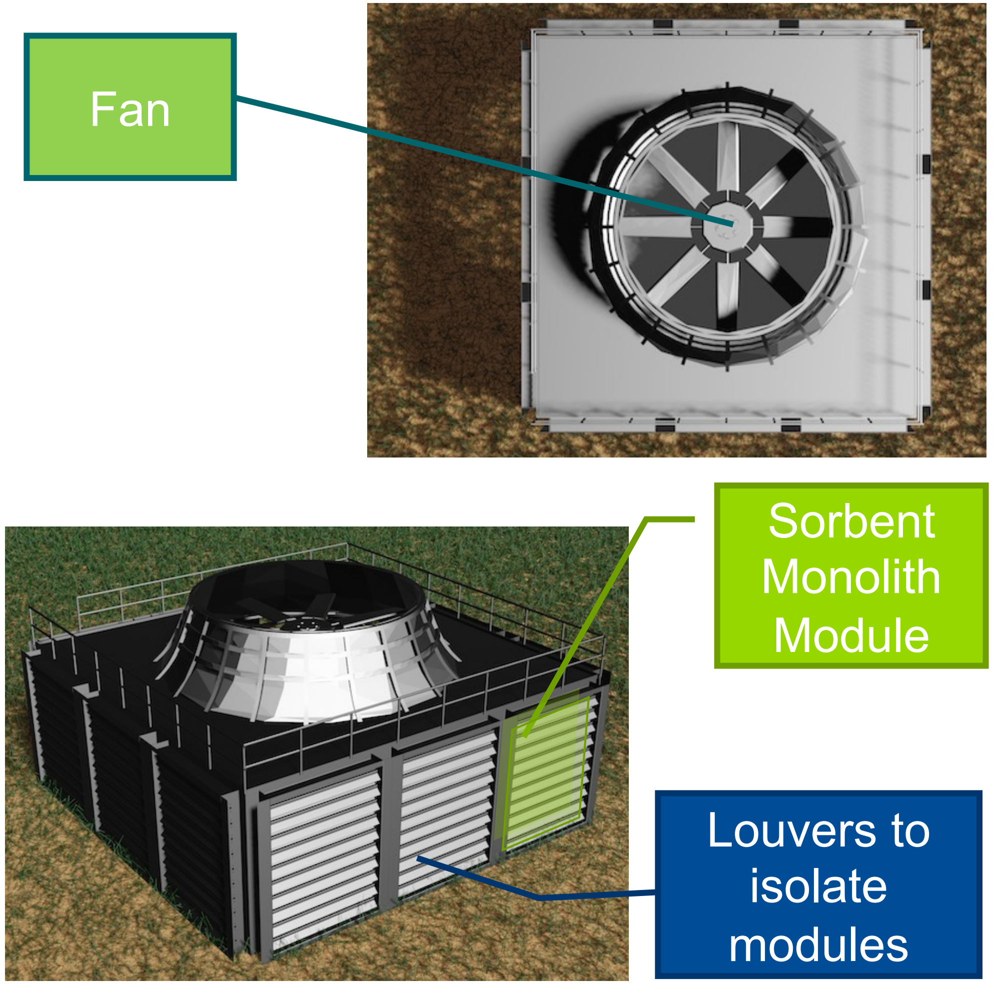
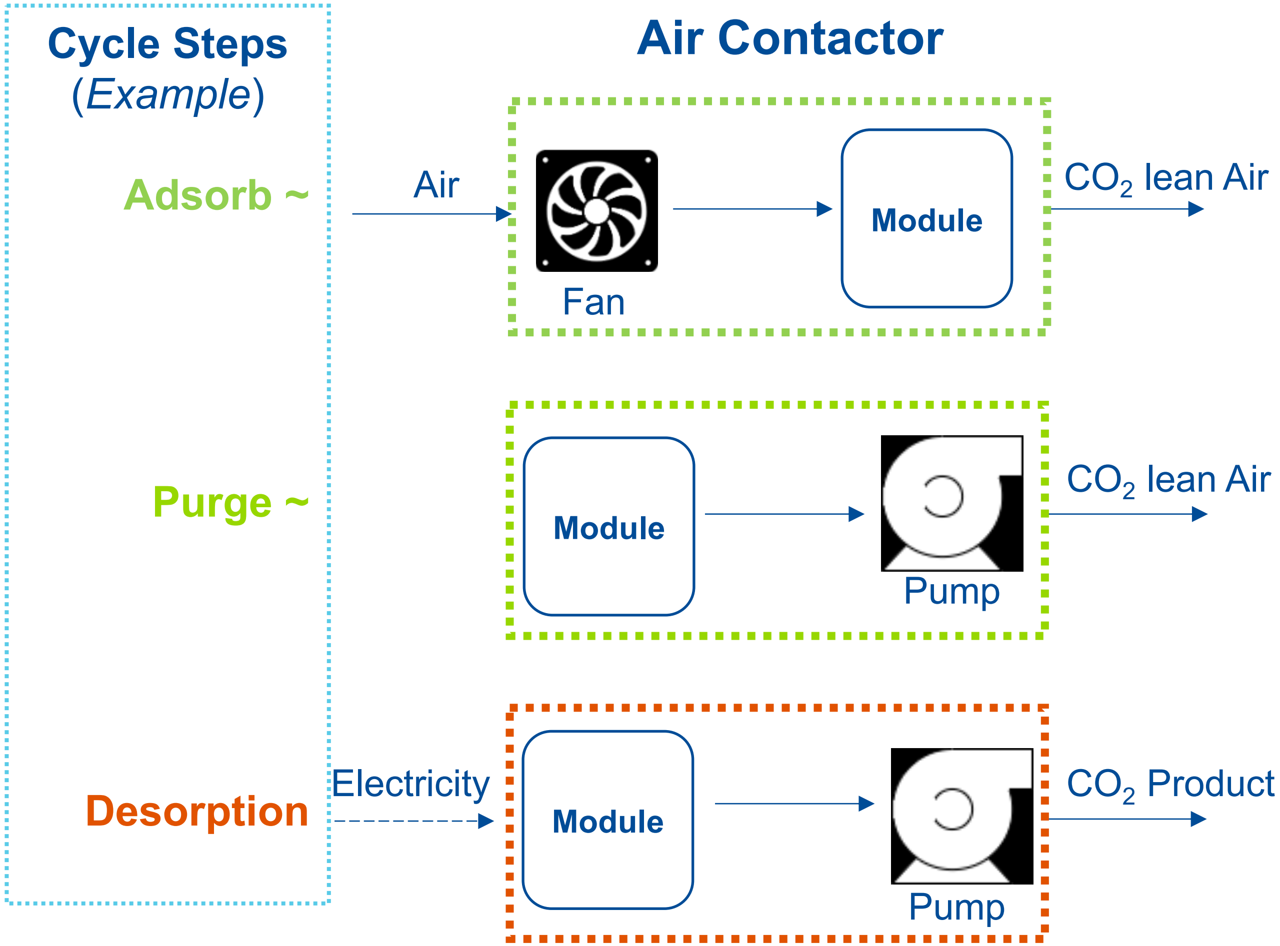
Faster kinetics allows for quick cycles and better utilization of capex





Current Capture costs and permanence

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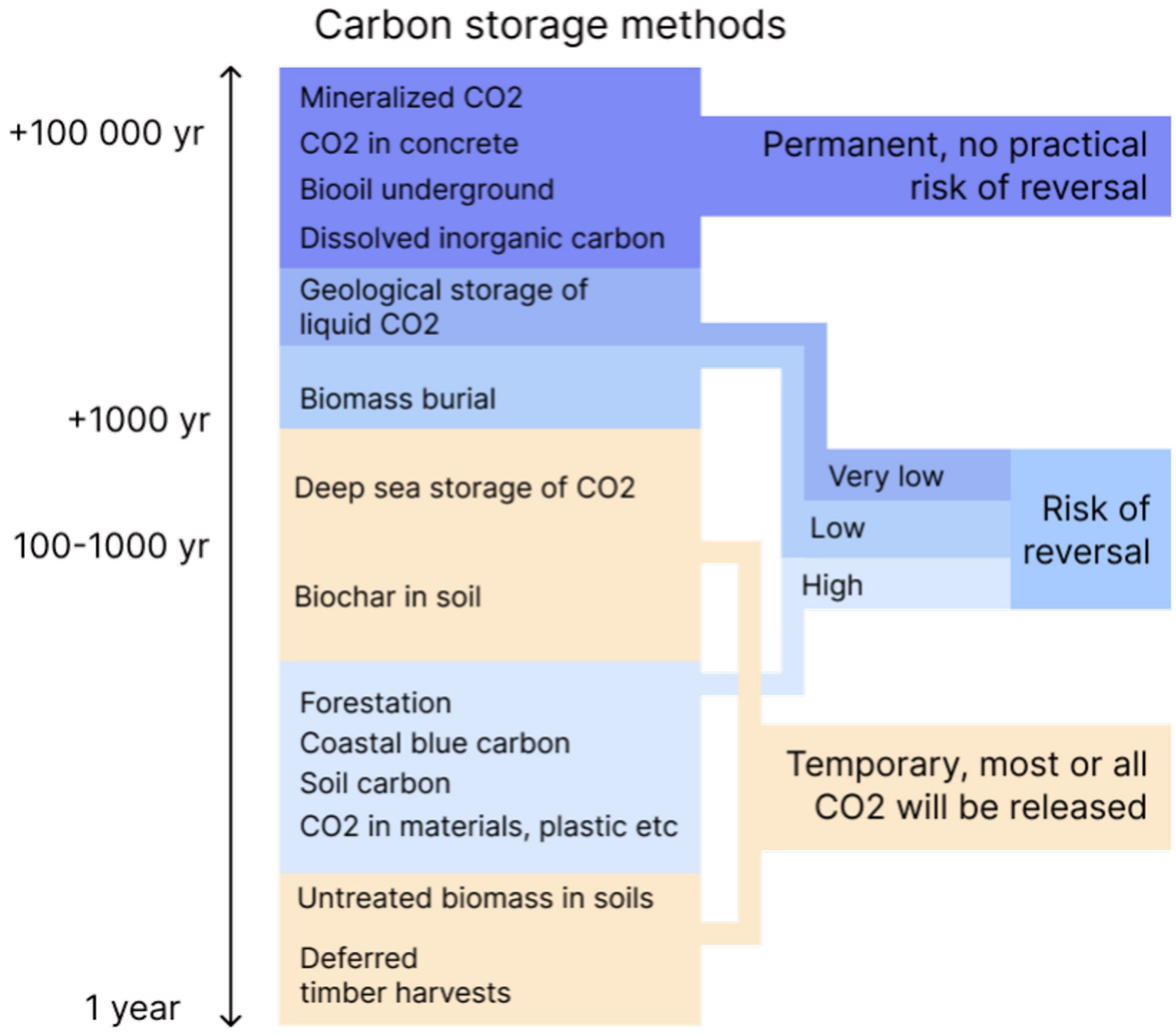
Pathways	Technology Readiness	Price
Afforestation	ready for large-scale deployment	
Biochar	limited pyrolysis capacity	
Soil Carbon Sequestration	ready for large-scale deployment	
Enhanced Weathering	limited mineral production	
Ocean Biomass	only small-scale demonstrations	
BECCS	only 1 full-scale demonstration	
DACCS	deployed at small scale	

<$20 / tCO_2 >$500 / tCO_2



Carbon removal will follow proven cost curves as it scales

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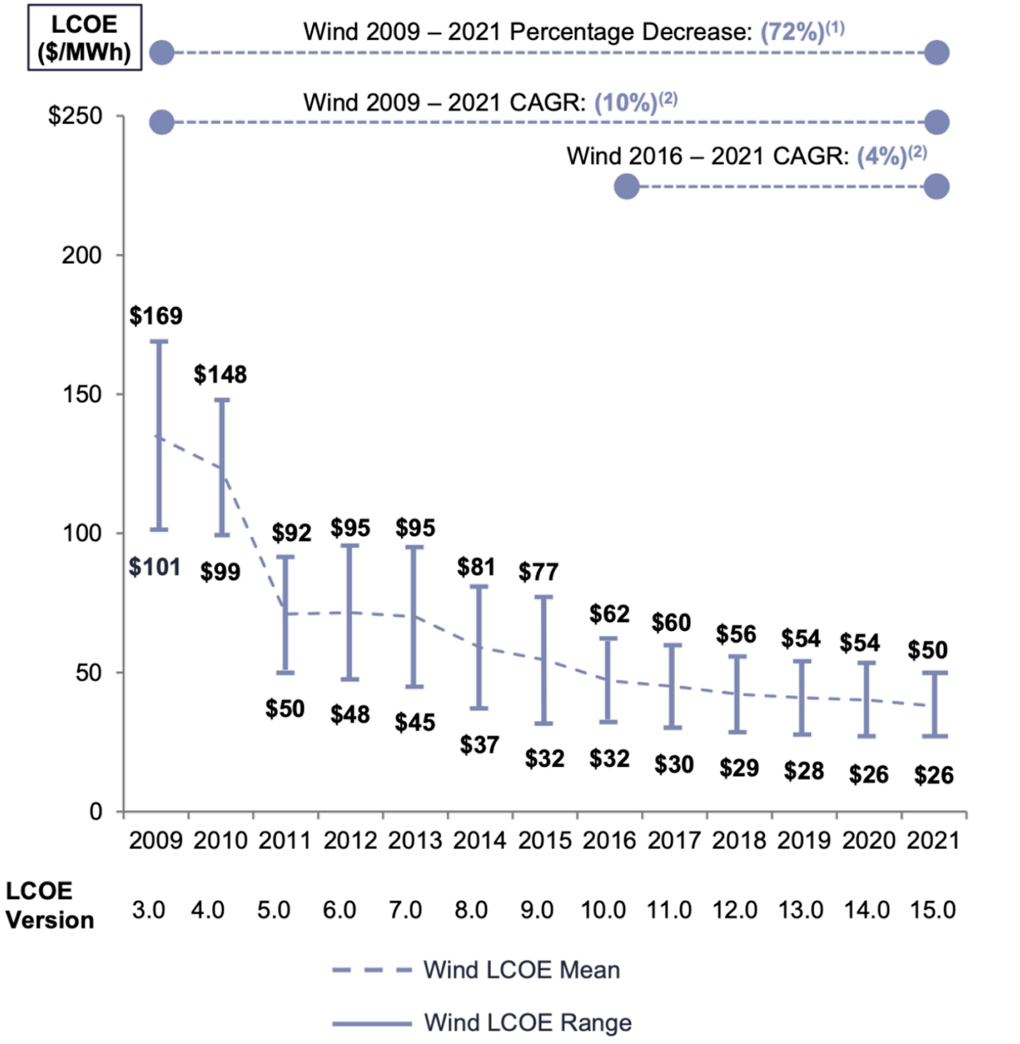
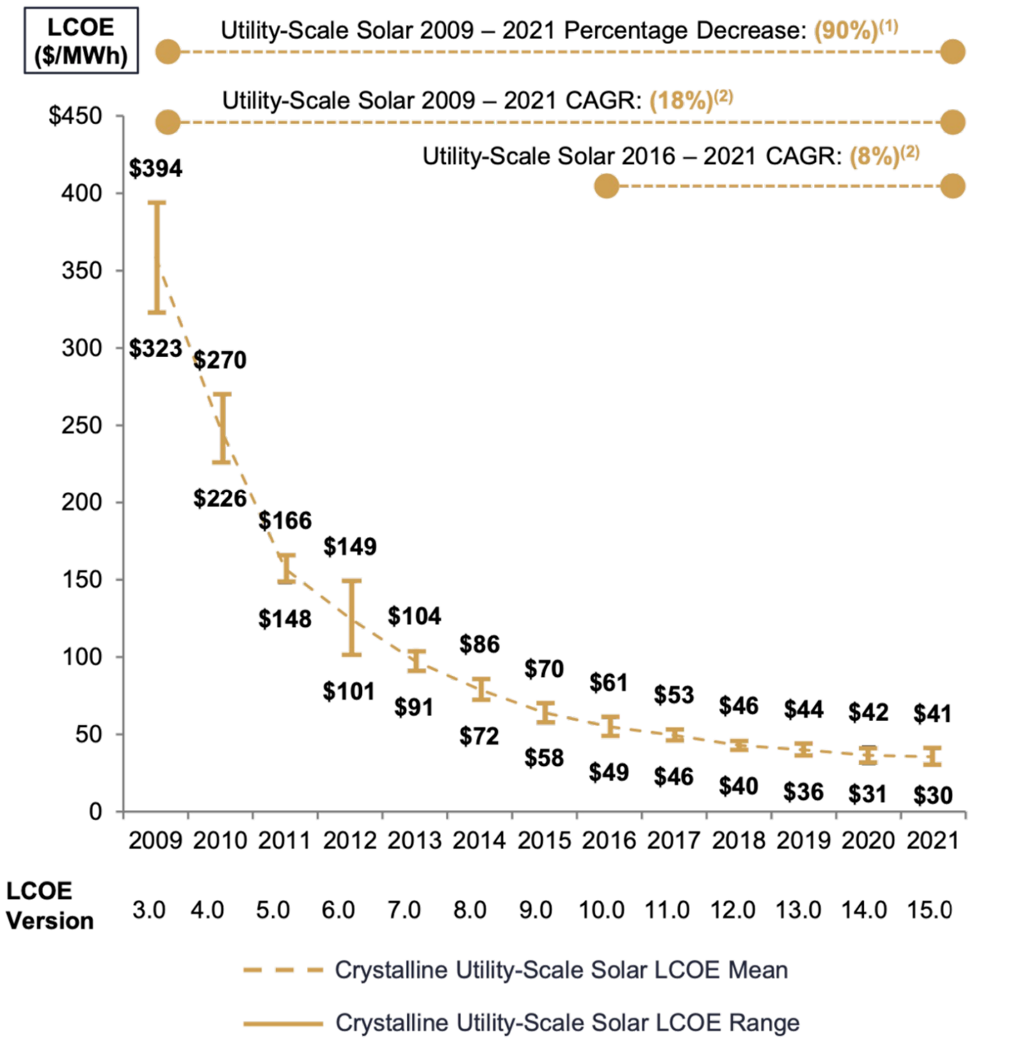
Unsubsidized Wind LCOE



Unsubsidized Solar PV LCOE



Lazard

Scale of the Challenge and Opportunities for innovators

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Birth of a new trillion-dollar industry with large opportunity set for innovators.

Scale	~10000 tCO_2 / annum in 2021 to 5,000,000,000 tCO_2/annum in 2050 **500,000x Scale-up** for 5 $GtCO_2$
Energy	**150 to 250 GWyr of energy** / $GtCO_2$ Compare to ~2,600 GWyr of global annual electricity consumption
Land	**~0.5 Mha** for capture + **~3 Mha** for electricity generation / $GtCO_2$ Compare with 80 MHa of forests for equivalent capture Texas is 70 Mha
Capital	~$1B / $MtCO_2$ OR **$1T** / $GtCO_2$
Other	Water, Specialized manufacturing, Sequestration sites etc.

Thank you

Creating solutions for a NET ZERO world

www.susteon.com