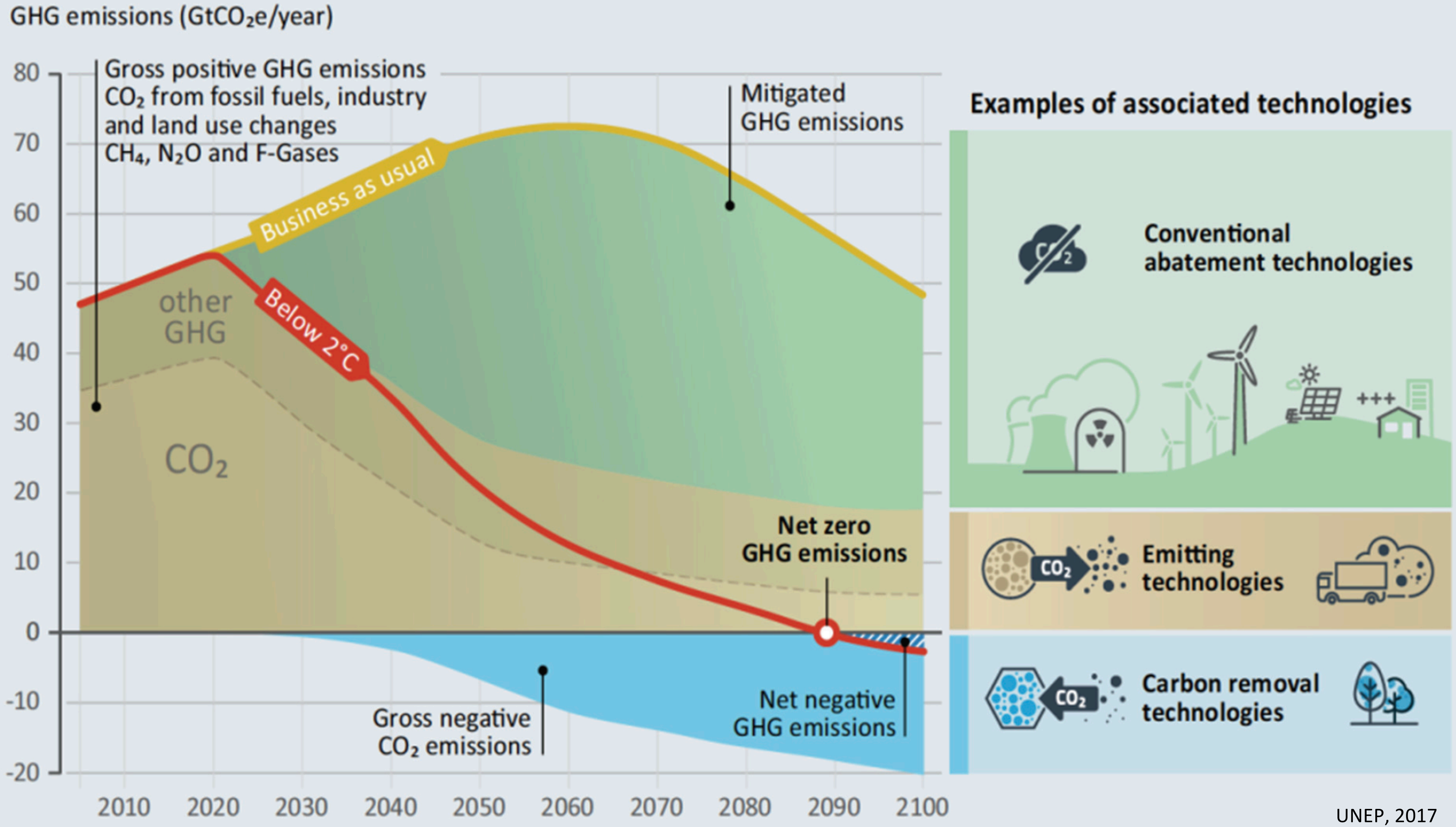
A Case for Carbon Dioxide Removal From Air

Jen Wilcox
Chemical Engineering
Worcester Polytechnic Institute

University of Pennsylvania
Kleinman Fellowship Program
February 12th, 2020


GHG emissions (GtCO₂e/year)
80
70
60
50
40
30
20
10
0
-10
-20
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Gross positive GHG emissions
CO₂ from fossil fuels, industry and land use changes
CH₄, N₂O and F-Gases
Business as usual
Mitigated GHG emissions
other GHG
Below 2°C
CO₂
Net zero GHG emissions
Gross negative CO₂ emissions
Net negative GHG emissions
Examples of associated technologies
Conventional abatement technologies
Emitting technologies
Carbon removal technologies
CO₂

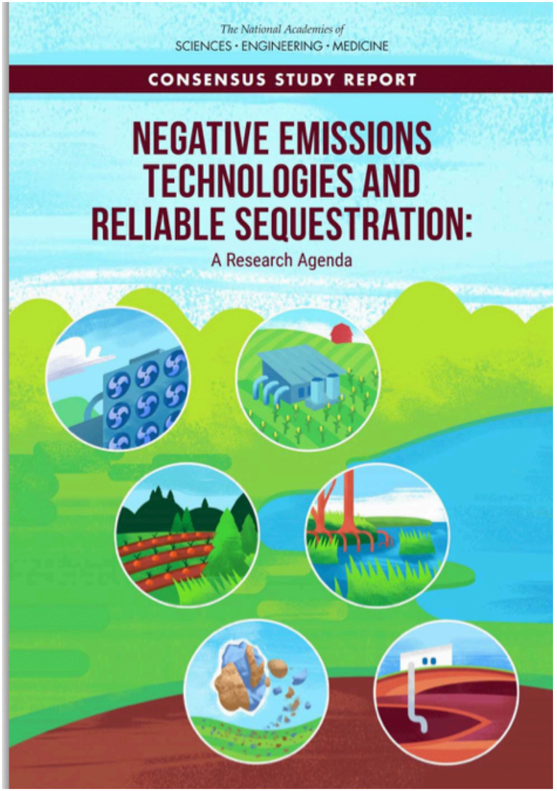
UNEP, 2017

Recent Study from National Academy of Science

Focus was on establishing a research agenda for negative emissions technologies

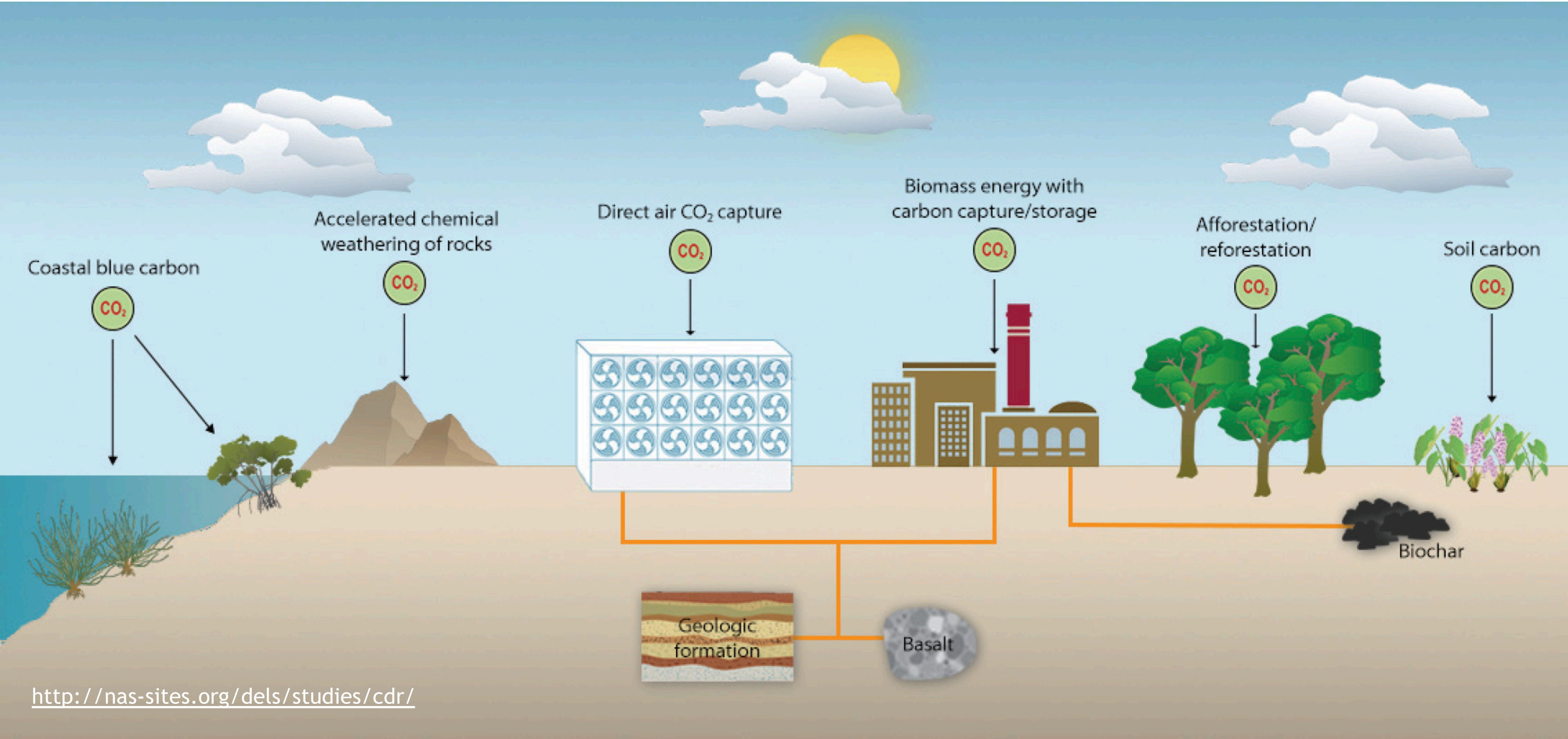
Major conclusion from the study:

"If the goals for climate and economic growth are to be achieved, negative emissions technologies will likely need to play a large role in mitigating climate change by removing globally 10 $GtCO_2$/yr by midcentury and 20 $GtCO_2$/yr by century's end."



http://nas-sites.org/dels/studies/cdr/

Negative Emissions Technologies



http://nas-sites.org/dels/studies/cdr/

What is Direct Air Capture?

Using Chemicals to Remove CO_2 from the air

Pros:

- Has the potential to be an NET
- Method for dealing with difficult to avoid emissions
- Does not require arable land

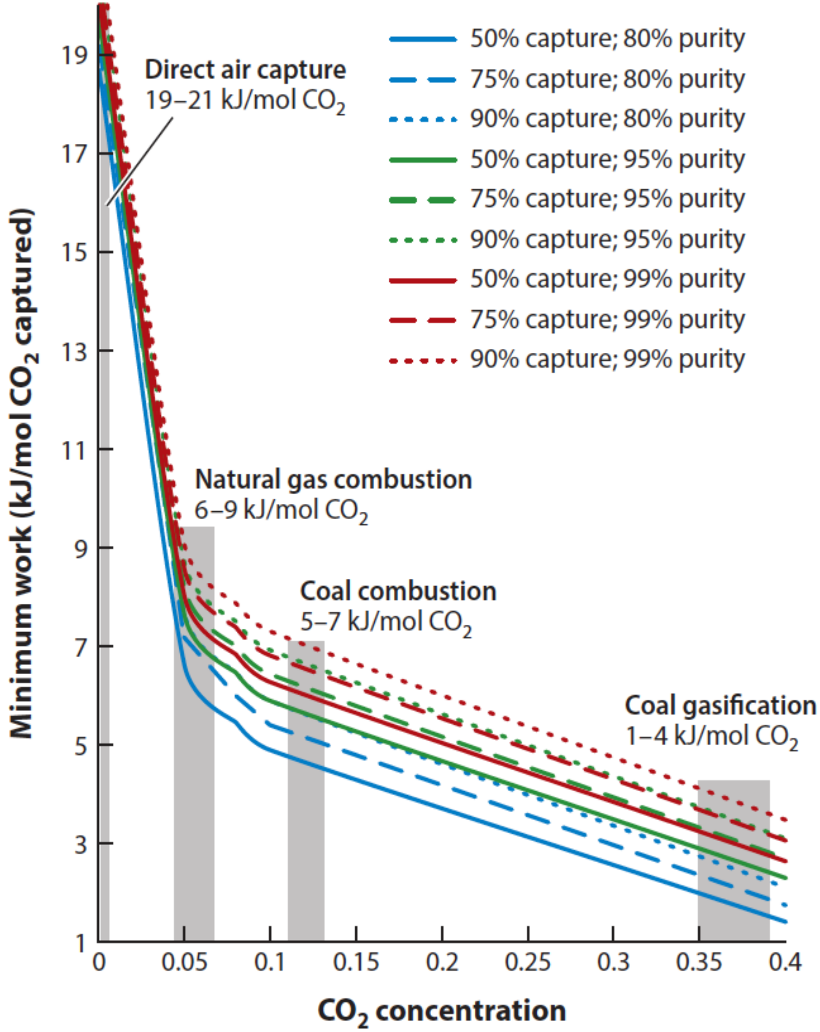
Cons:

- Energy inputs are significant
- Land footprint is large

DAC should not replace avoiding CO_2 emissions in the first place

Closer Look at the Energy

- Minimum work for separation may be derived from combined 1st and 2nd laws of thermodynamics
- Energy scales with dilution – 3× more energy to do DAC vs combustion exhaust
- 300× greater contactor area for CO_2 separation to do DAC vs combustion exhaust
- High purity is desired for transport

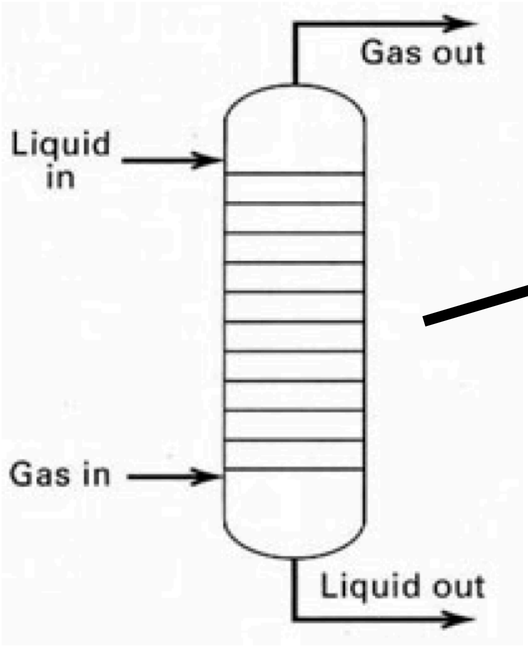


Reference: Wilcox, Carbon Capture, 2012

What Does Scrubbing CO_2 from a Point Source Look Like?

First patent filed by Bottoms in 1930!

"CO_2-free" gas out

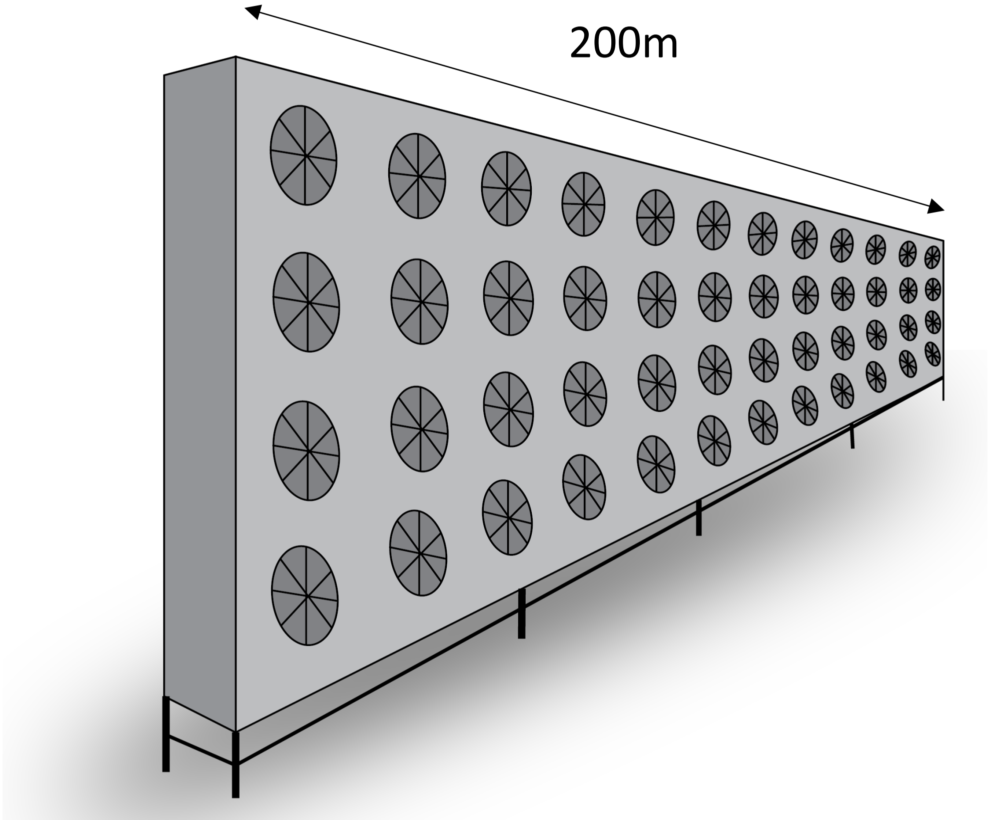


CO_2-loaded solvent out

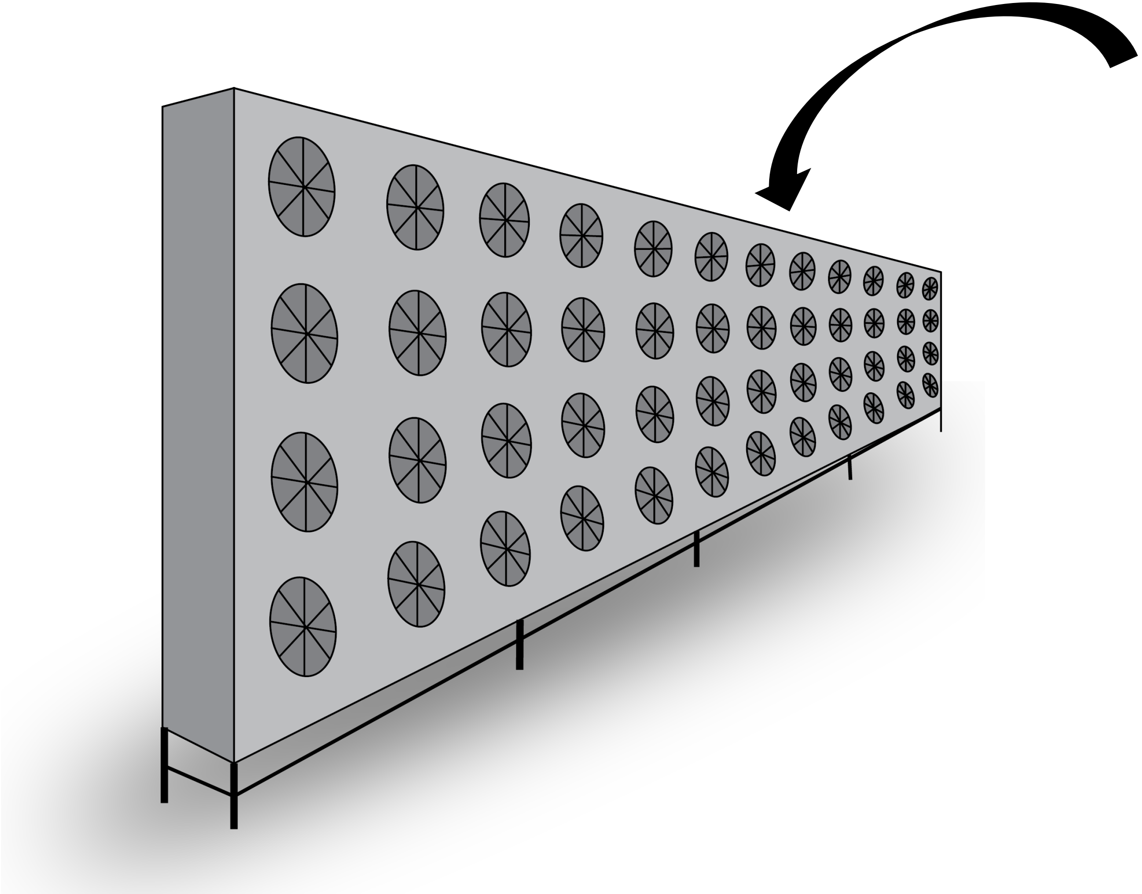
Petra Nova – 1.4 Mt CO_2/year
115 Meters Tall Absorber

Direct Air Capture Contactor Looks Very Different

need 10 of these to capture 1 $MtCO_2$ per year

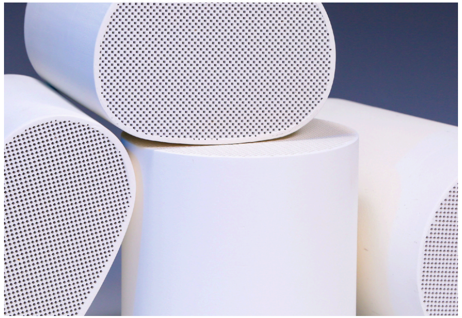


Today's technologies are based on liquids or solid materials containing CO_2-grabbing chemicals



Solvents rely on structured packing with solvent flow over the packing

Solid sorbents rely on a honey-comb structure with chemicals (amines) bound to structure



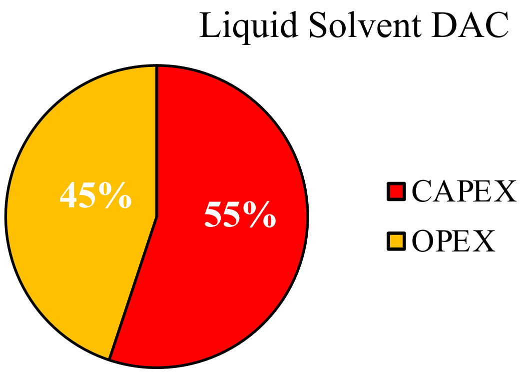
To Design a DAC Plant, you First Need to Design a Power Plant

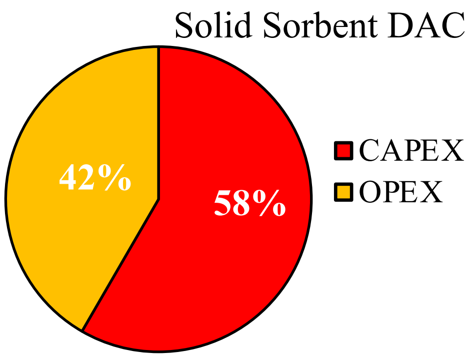
- No matter which approach you choose, the heat required to recycle the material is **dominant** over the electricity required to drive the fans,

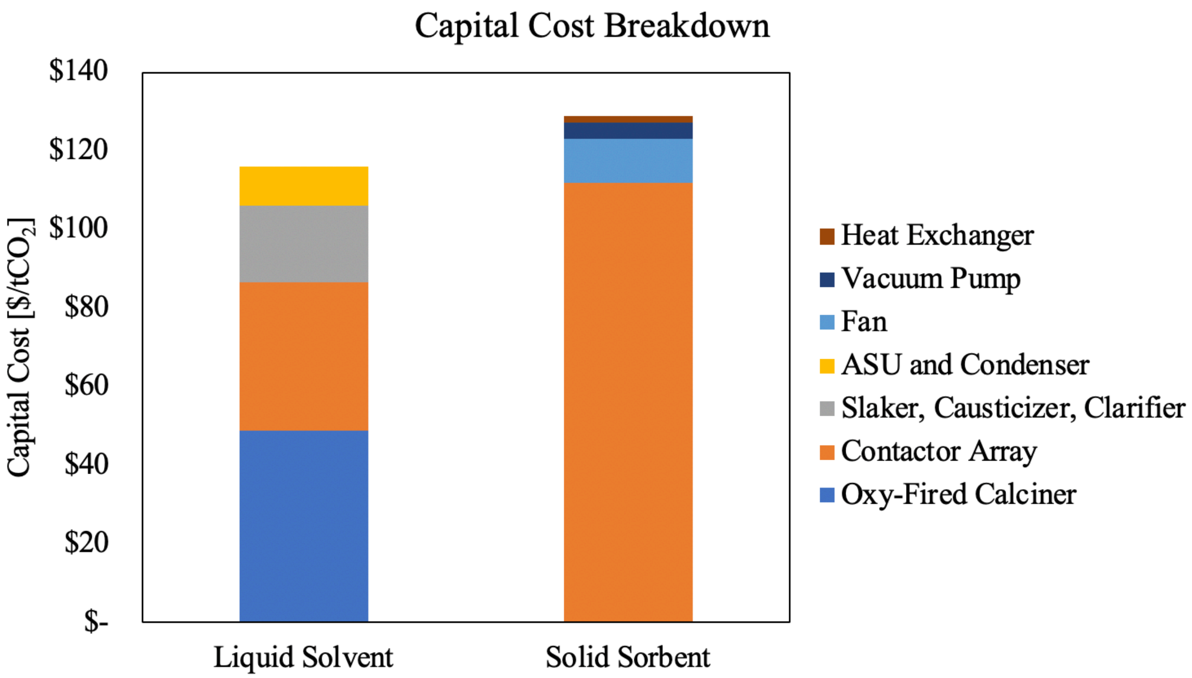
- To capture 1 MtCO_2/yr from air requires 300-500 MW of power!

- Choosing which energy resource to fuel the DAC plant will dictate the net CO_2 removed

Cost Differences - CAPEX







Reference: Pacala et al., NASEM, 2019

To drive costs down will require some technological advancement, but more will be needed

Investing as a global society is essential – whether through regulation or subsidies or taxes on carbon.

In 1966 the US invested about 1/2% of gross domestic product in the Apollo Program – today this is ~ $100 billion

… so let's say we invest 20% in DAC, knowing its one front in our fight against climate change

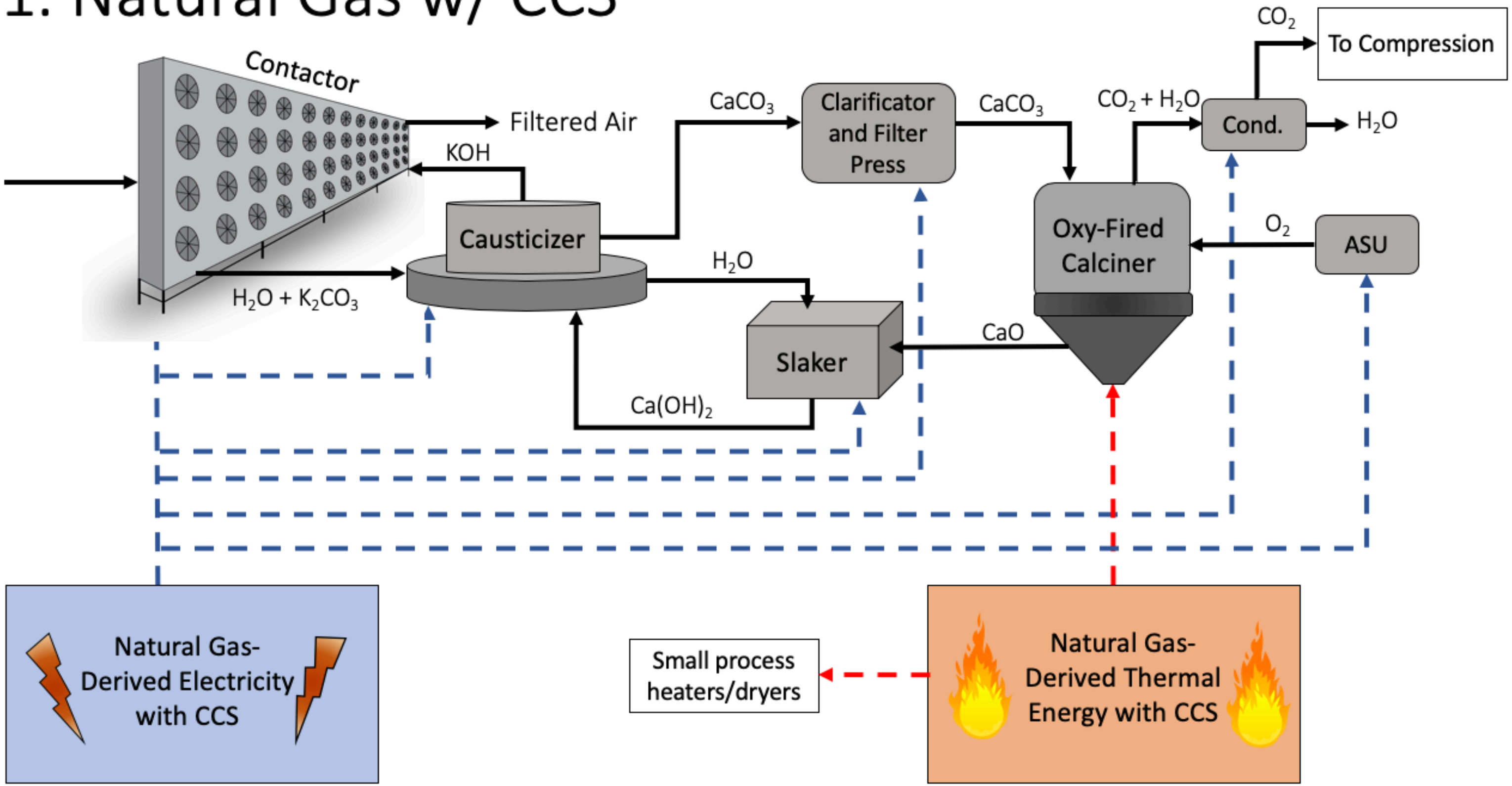
Where does a \$20 billion investment and a cost reduction down to \$100/tCO_2 get us?

This would mean building 200 DAC plants each capturing 1 MtCO_2 per year. This is equivalent to nearly 5% of our annual emissions.

Determining the land area required depends on what energy system you decide on for fueling your DAC plant.

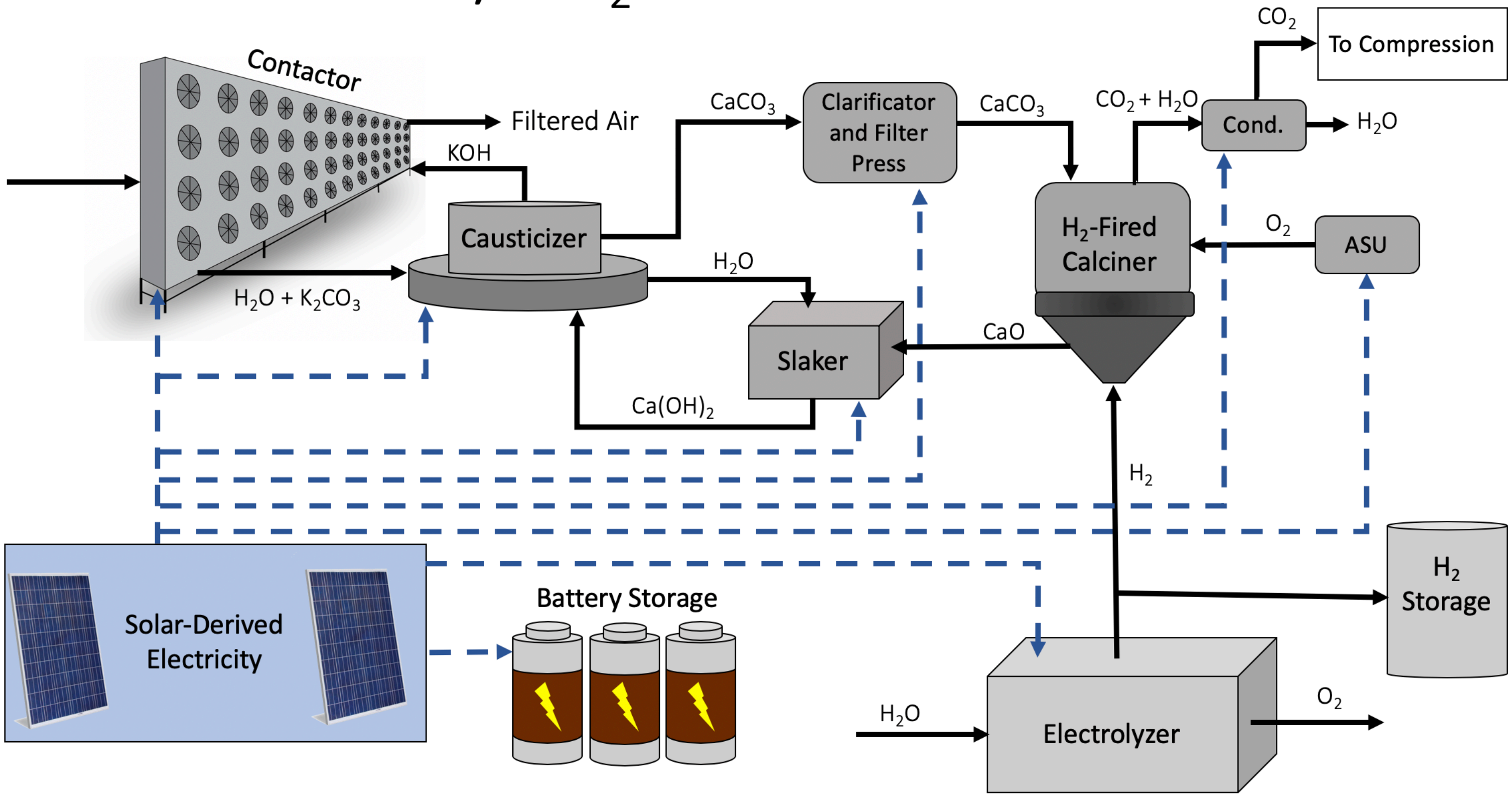
Consider 2 Different Energy System Scenarios

1. Natural Gas w/ CCS



Consider 2 Different Energy System Scenarios

2. Solar Electricity + H_2-Fired Kiln



Capturing 200 million tonnes from the air?

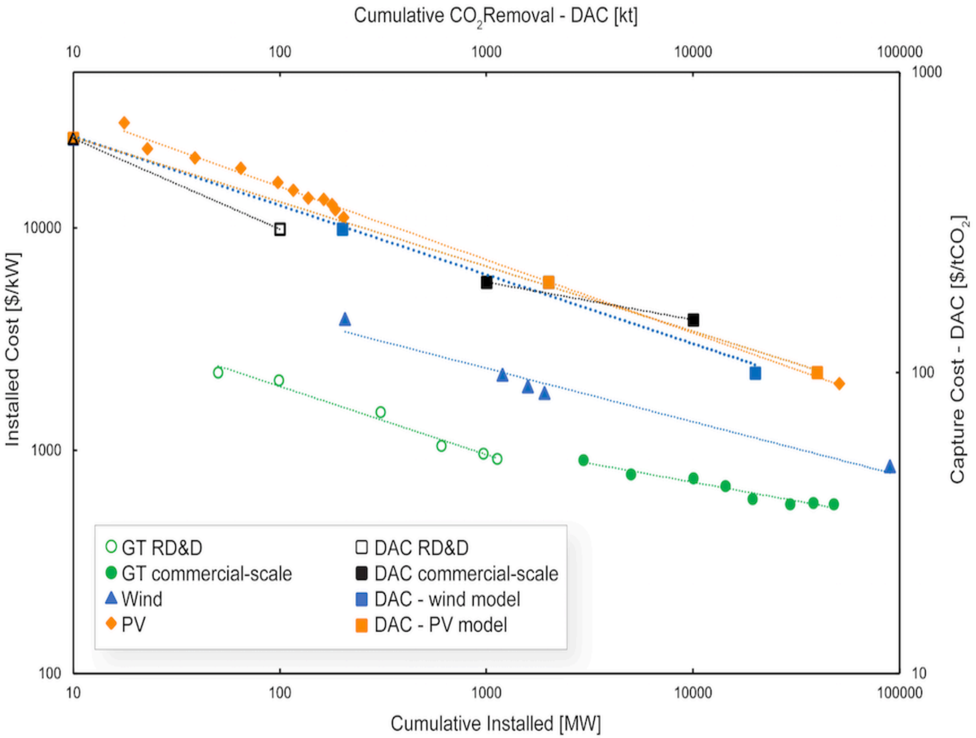
Powered by natural gas with CCS?

200 DAC plants ~ 1/4 land area
Philadelphia, roughly 96 km^2

Powered by solar and H_2?

Land area if Maryland
roughly 32,000 km^2

Today DAC is Taking Place at the Kiloton Scale
How Might we Get to a Gigaton by Mid Century?



Technology	Experience Rate (%)
PV	25
Wind	18
Gas Turbine RD&D	23
Gas Turbine -commercial	12
DAC – learning by doing	
RD&D	23
commercial	9
DAC – wind model	17
DAC – solar model	25

- PV Model - $100 by 2040 – 40 MT – 1 Gt by 2050
- Wind Model - $100 by 2050 – 20 MT – 1 Gt 2070
- Conventional - $100 by 2060 – 100 MT - 1 Gt 2070

Reference: Wilcox et al., under review ES&T (2019)

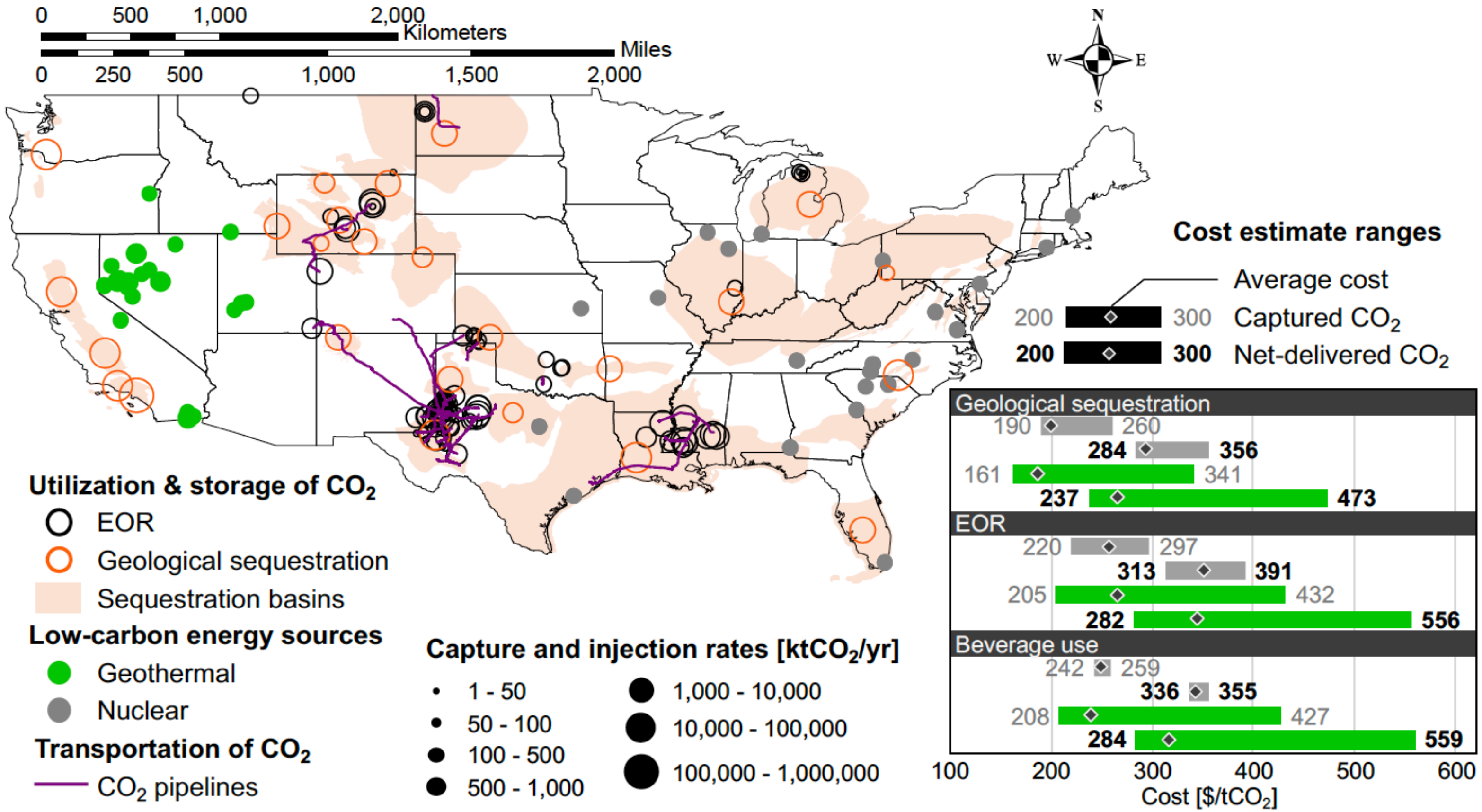
DAC Siting Low-Carbon Available Thermal Energy

Results of a Recent Study from Our Team

- Regardless of the technology (solvent or sorbent), the energy distribution is 80% thermal and 20% electric for DAC
- Solid sorbent selected due to low-quality of thermal energy required (i.e., 100 °C)
- Thermal we're considering from 2 pathways:
  - Geothermal – "waste" heat
  - Nuclear – 5% slipstream of steam
- Beneficial Reuse: EOR and beverage bottling industry
- Geologic Storage: USGS basin-level storage
- Ultimate Goal: delivered cost of compressed CO_2 at 99% purity in light of 45Q
- Electricity prices and carbon intensity based upon grid mix of a given DAC site
- Careful of Definitions:
  - Cost of Capture – "break-even cost"
  - Cost of CO_2 Avoided – considering fossil-based energy to fuel DAC
  - Cost of Net Removed CO_2 – true cost from climate's perspective

Reference: Wilcox et al., under review ES&T (2019)

Geological Sequestration – satisfying the 45Q criteria, i.e., > 100 ktCO_2/yr



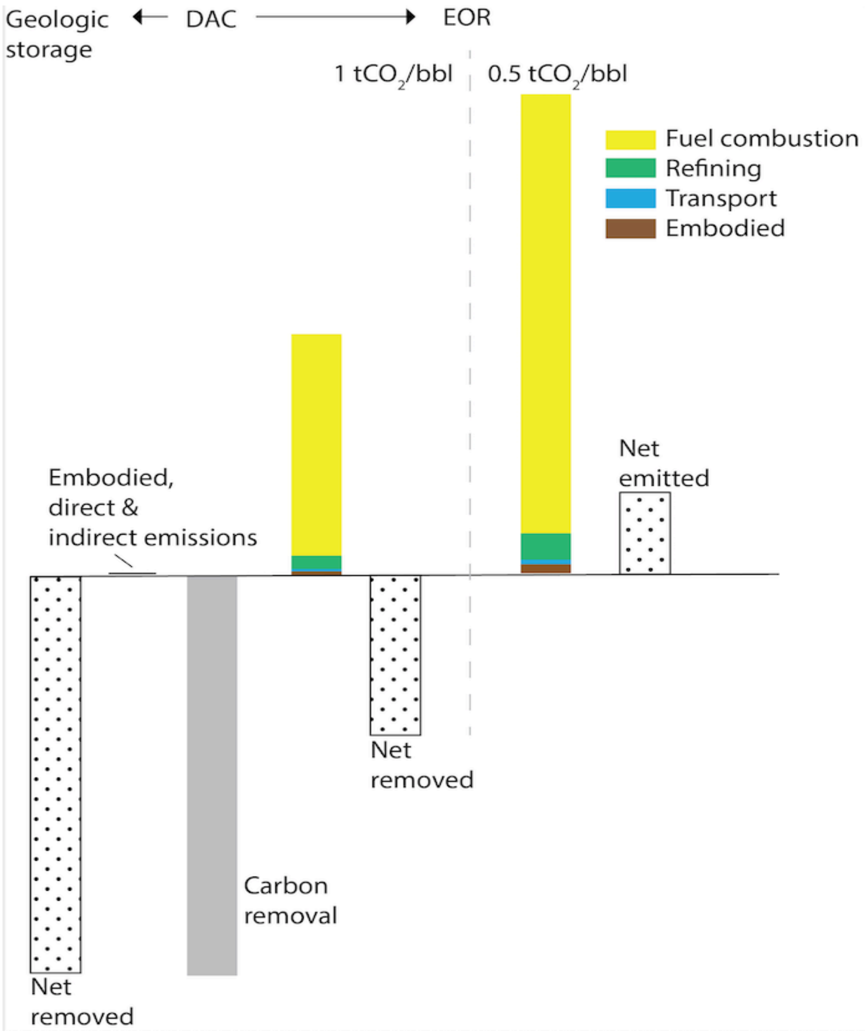
Reference: Wilcox et al., under review ES&T (2020)

CO_2-EOR LCA

- CO_2-EOR started in 1972 with the first project in the Permian Basin

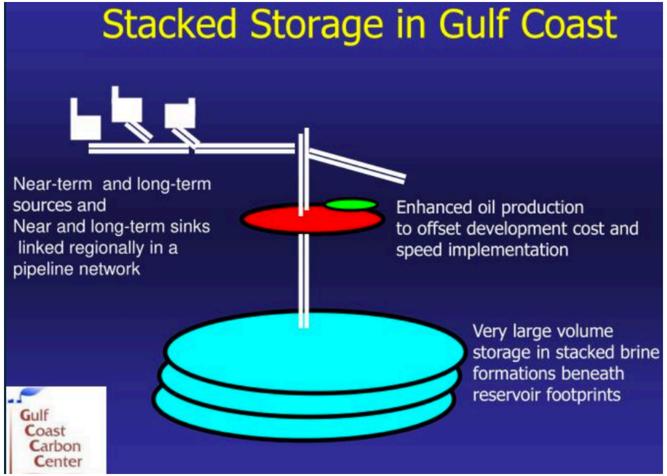
- CO_2-neutral or negative fuel is technically-feasible through CO_2-EOR only if:

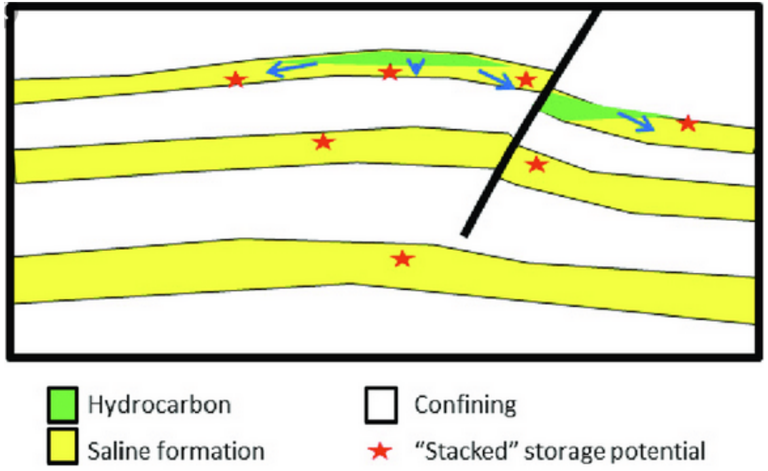
    CO_2 is from DAC and stacked storage is carried out



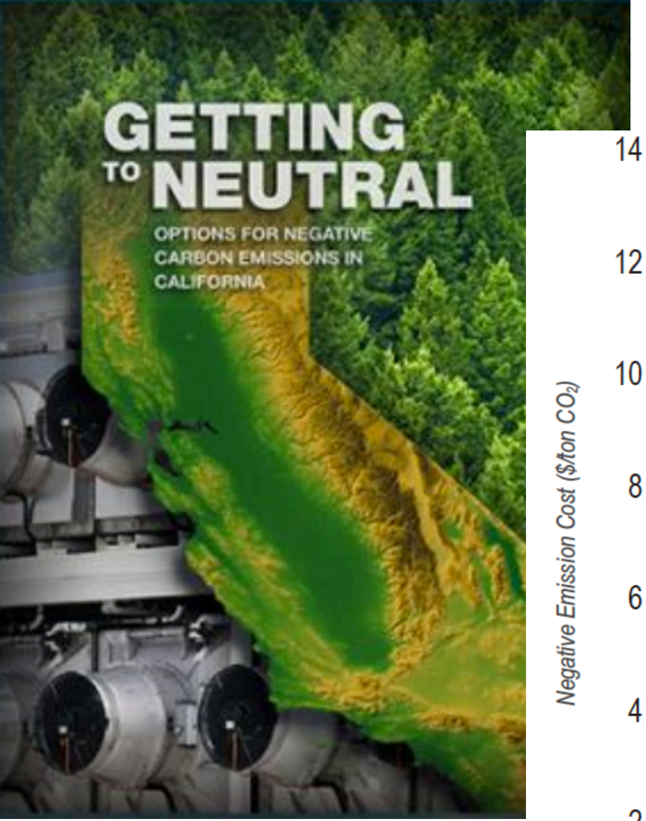
CO_2-EOR as a Bridge to Dedicated CO_2 Storage

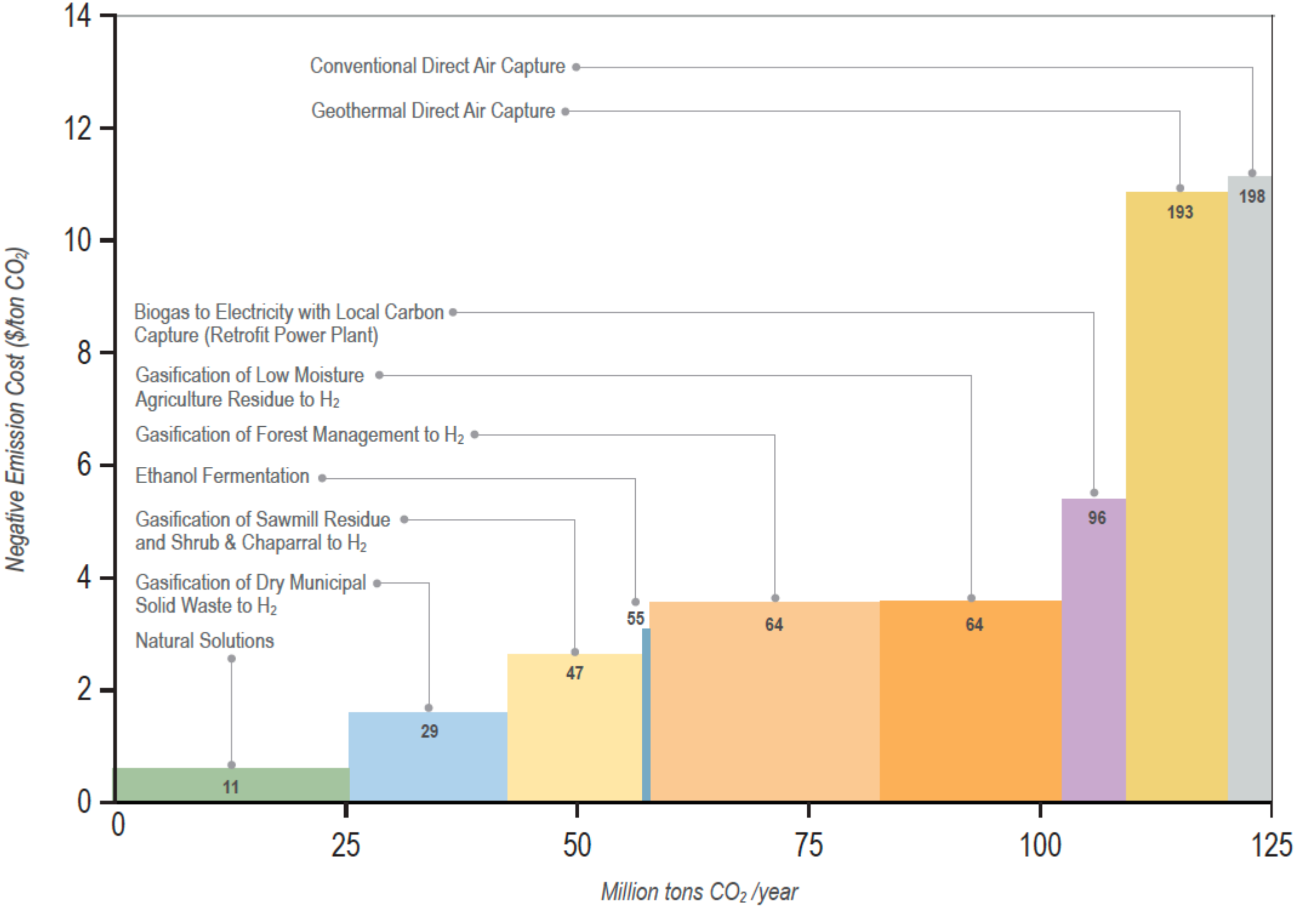
- Through stacked storage, operators can **transition** from sole EOR projects (today) to co-optimization of EOR and CO_2 storage via **stacked storage** to **sole CO_2 storage**
- We need gigatons of storage to impact climate – who will build and operate the fleet?
  - Oil and gas industry supports roughly 2% (155.66 thousand jobs as of 2018) of US jobs – geologists, geophysicists, drilling engineers, petroleum engineers, chemical engineers – these jobs will be strikingly similar to those required for the dedicated storage projects



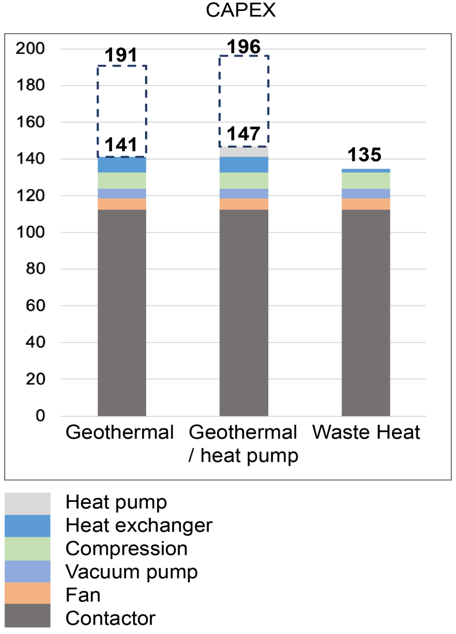


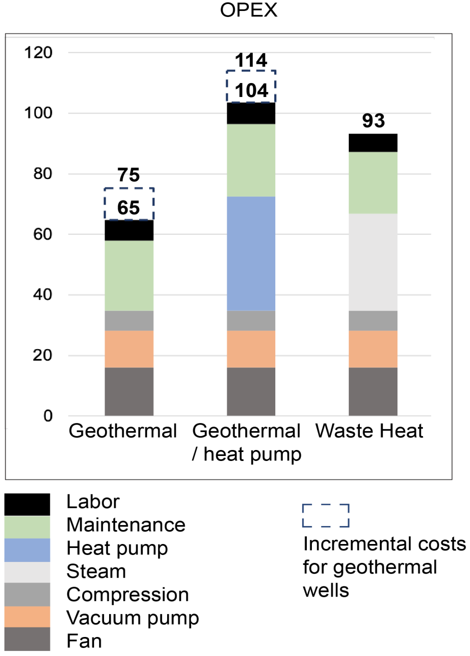
References: Sue Hovorka, Energy Procedia 2013; Lopez and Moskal, Frontiers in Climate, Negative Emissions Technologies, 2019

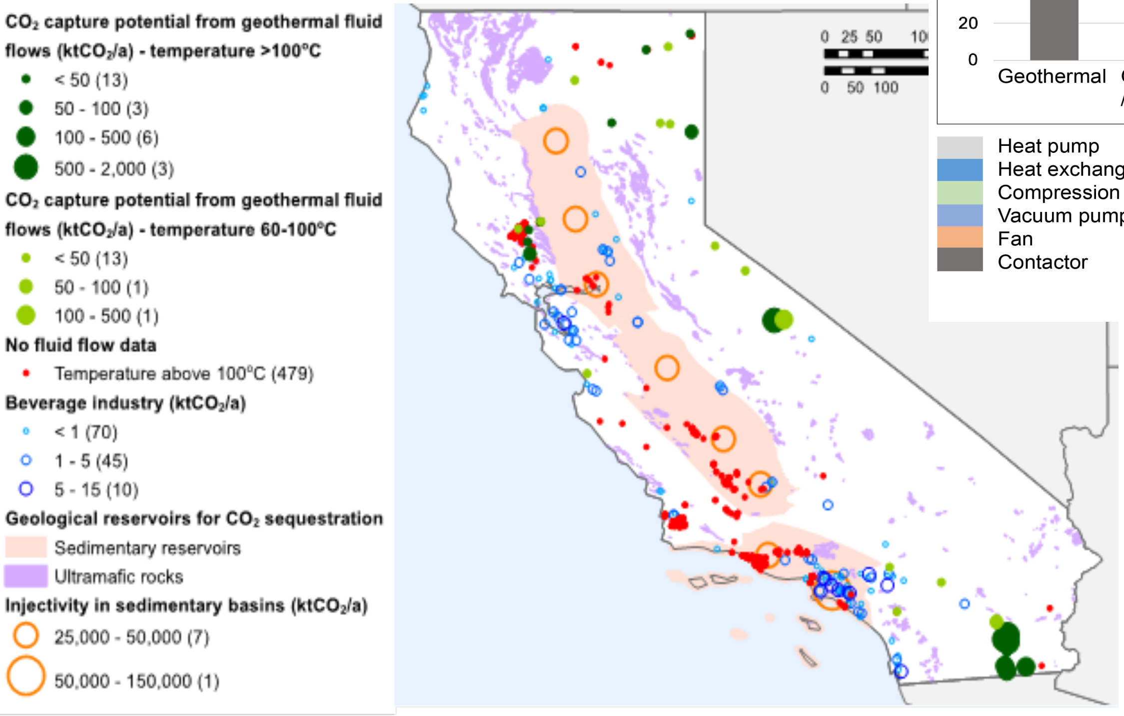

GETTING
TO NEUTRAL
OPTIONS FOR NEGATIVE
CARBON EMISSIONS IN
CALIFORNIA


Negative Emission Cost ($/ton CO2)
Million tons CO2 /year
0
2
4
6
8
10
12
14
0
25
50
75
100
125
Conventional Direct Air Capture
Geothermal Direct Air Capture
Biogas to Electricity with Local Carbon Capture (Retrofit Power Plant)
Gasification of Low Moisture Agriculture Residue to H2
Gasification of Forest Management to H2
Ethanol Fermentation
Gasification of Sawmill Residue and Shrub & Chaparral to H2
Gasification of Dry Municipal Solid Waste to H2
Natural Solutions
11
29
47
55
64
64
96
193
198

Solid sorbent-based DAC technology couples well to isolated and low-quality geothermal







frontiers in Climate | Negative Emission Technologies

New Journal First-of-a-kind Negative Emissions

Editorial: The Role of Negative Emission Technologies in Addressing Our Climate Goals

Phil Renforth and Jennifer Wilcox

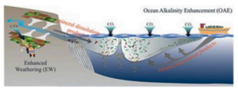
Editorial

Published on 28 January 2020
Front. Clim. doi: https://doi.org/10.3389/fclim.2020.00001

624 total views | Altmetric 10

CO2 Removal With Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for Marine Pelagic Ecosystems

Lennart T. Bach, Sophie J. Gill, Rosalind E. M. Rickaby, Sarah Gore and Phil Renforth



Original Research Humankind will need to remove hundreds of gigatons of carbon dioxide (CO2) from the atmosphere by the end of the twenty-first century to keep global warming below 2°C within the constraints of the global carbon budget. However, so far it is unclear ...

Published on 11 October 2019
Front. Clim. doi: https://doi.org/10.3389/fclim.2019.00007

3,886 total views | Altmetric 55

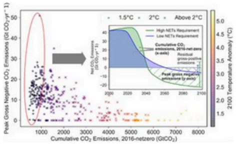
Opportunities for Carbon Dioxide Removal Within the United States Department of Agriculture

Rory Jacobson and Daniel L. Sanchez

Policy and Practice Reviews Farming and ranching communities in the United States sit at the front lines of climate change impacts and responses. In

From Zero to Hero?: Why Integrated Assessment Modeling of Negative Emissions Technologies Is Hard and How We Can Do Better

Jay Fuhrman, Haewon McJeon, Scott C. Doney, William Shobe and Andres F. Clarens



Review Climate change mitigation strategies informed by Integrated Assessment Models (IAMs) increasingly rely on major deployments of negative emissions technologies (NETs) to achieve global climate targets. Although NETs can strongly complement emissions ...

Published on 04 December 2019
Front. Clim. doi: https://doi.org/10.3389/fclim.2019.00011

1,400 total views | Altmetric 20

Engineered CO2 Removal, Climate Restoration, and Humility

S. Julio Friedmann

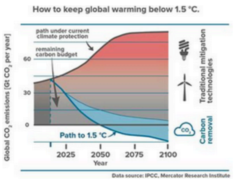
Perspective Over the past 200 years, humans have dramatically altered our global environmental envelope accidentally through uncontrolled greenhouse gas emissions. Humans have also developed the technology to both stop emitting greenhouse gases and ultimately to ...

Published on 26 July 2019
Front. Clim. doi: https://doi.org/10.3389/fclim.2019.00003

5,959 total views | Altmetric 42

The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions

Christoph Beuttler, Louise Charles and Jan Wurzbacher



Perspective In recent years Direct Air Capture (DAC) has established itself as a promising approach to atmospheric Carbon Dioxide Removal (CDR) also referred to as Negative Emissions. However, due to the amounts likely needed to be removed CDR technologies like ...

Published on 21 November 2019
Front. Clim. doi: https://doi.org/10.3389/fclim.2019.00010

2,525 total views | Altmetric 14

Beyond "Net-Zero": A Case for Separate Targets for Emissions Reduction and Negative Emissions

Duncan P. McLaren, David P. Tyfield, Rebecca Willis, Bronislaw Szerszynski and Nils O. Markusson

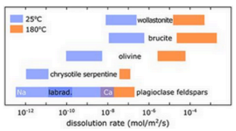
Policy Brief Targets and accounting for negative emissions should be explicitly set and managed separately from existing and future targets for emissions reduction. Failure to make such a separation has already hampered climate policy, exaggerating the expected ...

Published on 21 August 2019
Front. Clim. doi: https://doi.org/10.3389/fclim.2019.00004

6,873 total views | Altmetric 151

An Overview of the Status and Challenges of CO2 Storage in Minerals and Geological Formations

Peter Kelemen, Sally M. Benson, Hélène Pilorgé, Peter Psarras and Jennifer Wilcox



Review Since the Industrial Revolution, anthropogenic carbon dioxide (CO2) emissions have grown exponentially, accumulating in the atmosphere and leading to global warming. According to the IPCC (IPCC Special Report, 2018), atmospheric warming should be ...

Published on 15 November 2019
Front. Clim. doi: https://doi.org/10.3389/fclim.2019.00009

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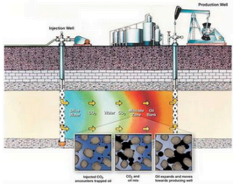
Potential of CO2-EOR for Near-Term Decarbonization

Vanessa Núñez-López and Emily Moskal



Review This paper provides an overview of carbon dioxide enhanced oil recovery (CO2-EOR) and its ability to reduce greenhouse gas (GHG) emissions (even to the point of negative emissions), the role it needs to play in the challenge of decarbonization, and ...

Published on 27 September 2019
Front. Clim. doi: https://doi.org/10.3389/fclim.2019.00005

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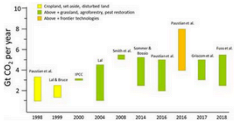
Soil C Sequestration as a Biological Negative Emission Strategy

Keith Paustian, Eric Larson, Jeffrey Kent, Ernie Marx and Amy Swan



Review Soil carbon (C) sequestration is one of three main approaches to carbon dioxide removal and storage through management of terrestrial ecosystems. Soil C sequestration relies of the adoption of improved management practices that increase the amount of ...

Published on 16 October 2019
Front. Clim. doi: https://doi.org/10.3389/fclim.2019.00008

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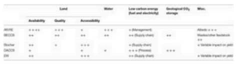
Negative Emissions: Priorities for Research and Policy Design

Mathilde Fajardy, Piera Patrizio, Habiba Ahut Daggash and Niall Mac Dowell



Perspective The large-scale removal of carbon dioxide from the atmosphere is likely to be important in maintaining temperature rise "well below" 2°C, and vital in achieving the most stringent 1.5°C target. Whilst various literature efforts have estimated the ...

Published on 01 October 2019
Front. Clim. doi: https://doi.org/10.3389/fclim.2019.00006

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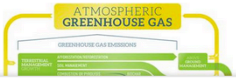
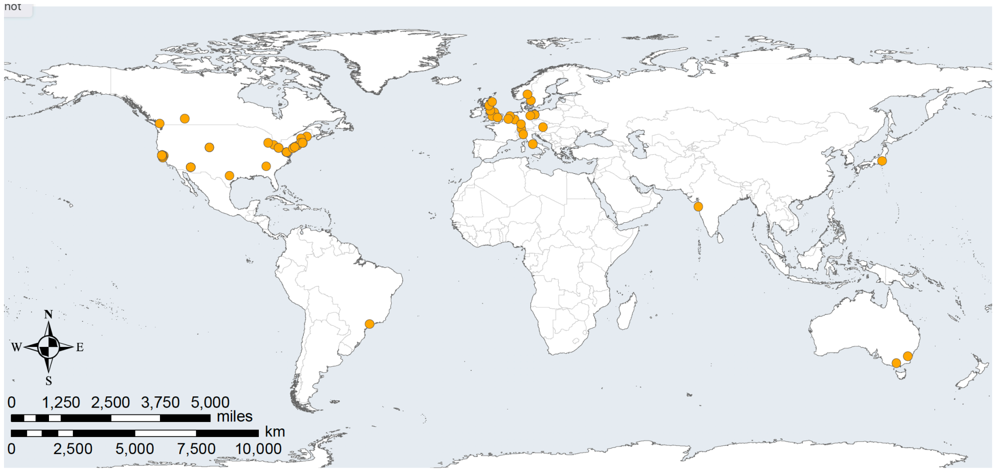
Specialty Grand Challenge: Negative Emission Technologies

Phil Renforth and Jennifer Wilcox



The Goddard Project - an online tool to access information, mentors, collaborators and exciting projects in this space

“When I was little, I looked at the space race and dreamed the world would rally around a huge science project again. 10+ gigaton scale negative emissions is that! It’s urgent, necessary, hard, dramatic, all of it. It’s the defining project of our generation.” - Ryan Orbuch, Stripe

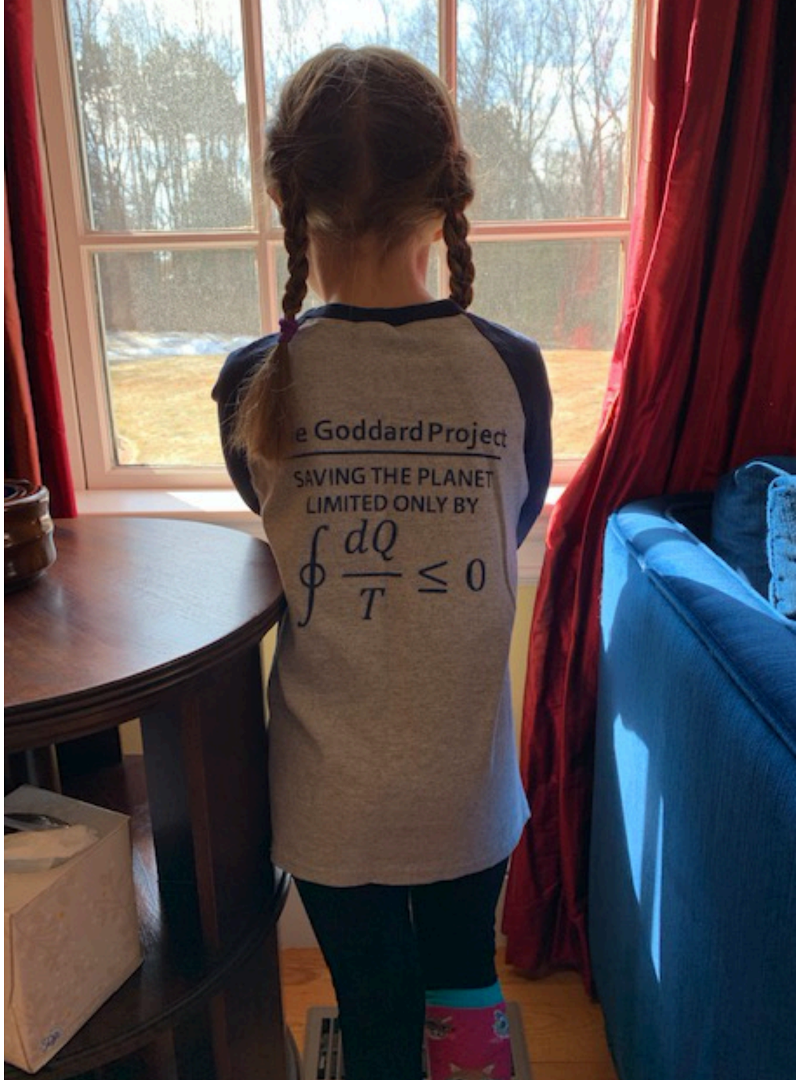


We know how to get to millions of tonnes of removal today but getting to gigatons may just take some rocket scientists! Some Goddards!

goddardproject.org

Climate scientist Katharine Hayhoe said the first step to fighting climate change is: "Talk about it." "The majority of the people in the country don't talk about it. And if we don't talk about it, why would we care?”

So let’s talk about it and engage the next generation of future scientists, engineers, and policy makers in this field.



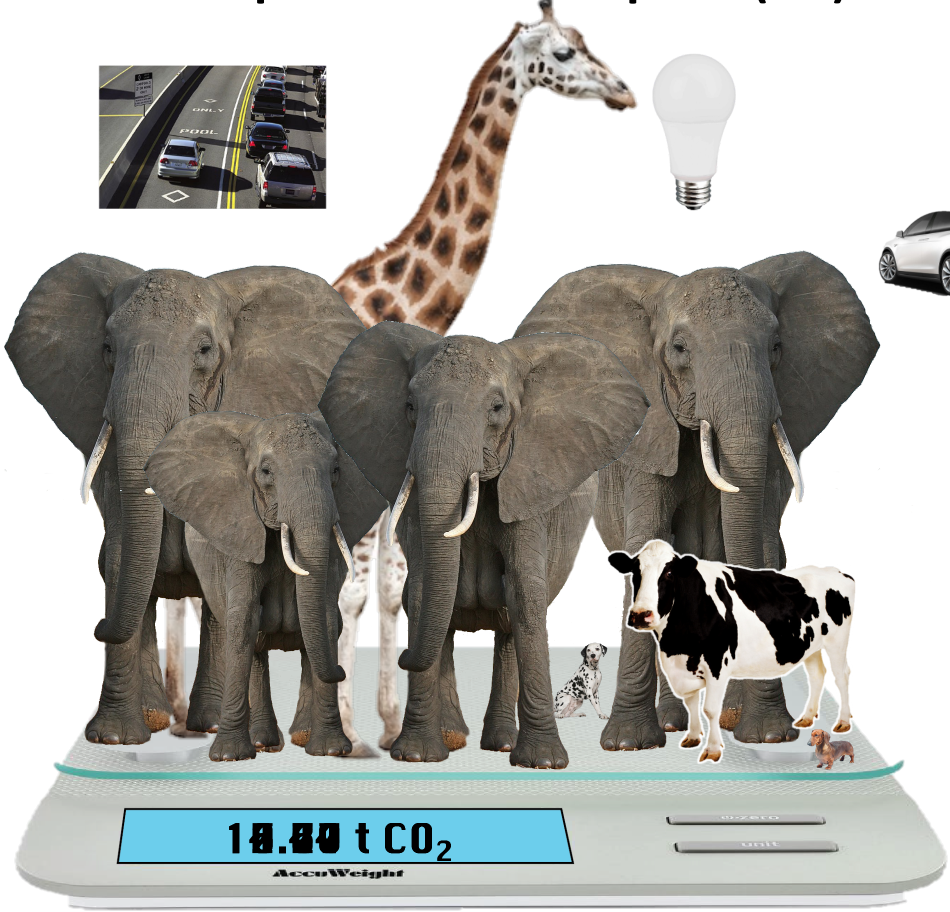
"It is difficult to say what is impossible, for the dream of yesterday is the hope of today and the reality of tomorrow."   - Robert Goddard

Graduated from WPI in 1908

First launch took place in Auburn, MA
March 16, 1926

Don’t dismiss the impact of individual efforts and informed decisions

Per capita carbon footprint (US)



Climate change mitigation portfolios should include both avoiding CO_2 and removal of CO_2 from the atmosphere as both will be required at this late stage to meet our climate goals.

We Choose our Legacy

More Information:

https://users.wpi.edu/~jlwilcox/

https://www.ted.com/talks/jennifer_wilcox_a_new_way_to_remove_co2_from_the_atmosphere

https://www.npr.org/2019/06/07/730392105/jennifer-wilcox-how-can-we-remove-co2-from-the-atmosphere-will-we-do-it-in-time

http://nas-sites.org/dels/studies/cdr/