The National Academies of SCIENCES ENGINEERING MEDICINE

# Negative Emissions Technologies and Reliable Sequestration: A Research Agenda

Stephen Pacala (Chair)
**Christopher Jones (DAC co-Lead)**

October 24, 2018
**May 16, 2019**

**Carbon Mitigation Technologies** reduce or eliminate carbon dioxide emissions from fossil fuel use, cement production and land use change.

**Negative Emissions Technologies (NETs)** remove carbon dioxide from the atmosphere and store it on or underneath the Earth's surface. This study considers only storage in terrestrial or coastal ecosystems or in geologic reservoirs. Disposal in the oceans is not considered.

**Removing $CO_2$ from atmosphere and storing it has exact same impact on atmosphere and climate as preventing an equal amount of $CO_2$ from being emitted. In some cases, deploying NETs may be cheaper and less disruptive than emissions reductions.**

**NETs are best viewed as a component of mitigation portfolio, rather than a way to decrease atmospheric concentrations of $CO_2$ only after anthropogenic emissions have been eliminated.**

## Reduce Carbon Sources

- Energy efficiency
- Low or zero-carbon fuel sources

## Enhance Carbon Sinks

Negative emissions technologies:

- Coastal blue carbon
- Terrestrial carbon removal and sequestration
- Bioenergy with carbon capture and sequestration (BECCS)
- Direct air capture
- Carbon mineralization
- Geologic sequestration

# Rationales for development and deployment of NETs in USA.

1. Reduce carbon pollution (i.e. 45Q tax credit in Freedom Act)

2. Reduce climate change

3. Economic competitiveness and technological leadership

4. Control carbon pollution/climate change with less decrease in fossil fuel use

## For example…. Commercial Aviation

| | |
|---|---|
| Option 1: Develop Cellulosic Biofuels | Could be expensive and requires land to grow feedstock |
| Option 2: Capture and store 10 kg of atmospheric $CO_2$ for each gallon of fossil fuel consumed | If this cost \$50/t$CO_2$ then the offset would cost an additional \$0.50/gallon |

# Statement of Task

- Identify the most urgent unanswered scientific and technical questions needed to:
  - assess the benefits, risks, and sustainable scale potential for carbon dioxide removal and sequestration approaches in terrestrial and coastal environments
  - increase the commercial viability of carbon dioxide removal and sequestration
- Define the essential components of a research and development program and specific tasks required to answer these questions
- Estimate the costs and potential impacts of such a research and development program to the extent possible in the timeframe of the study
- Recommend ways to implement such a research and development program

# Carbon dioxide removal can be part of a carbon capture, utilization and sequestration system

**Captured Carbon**

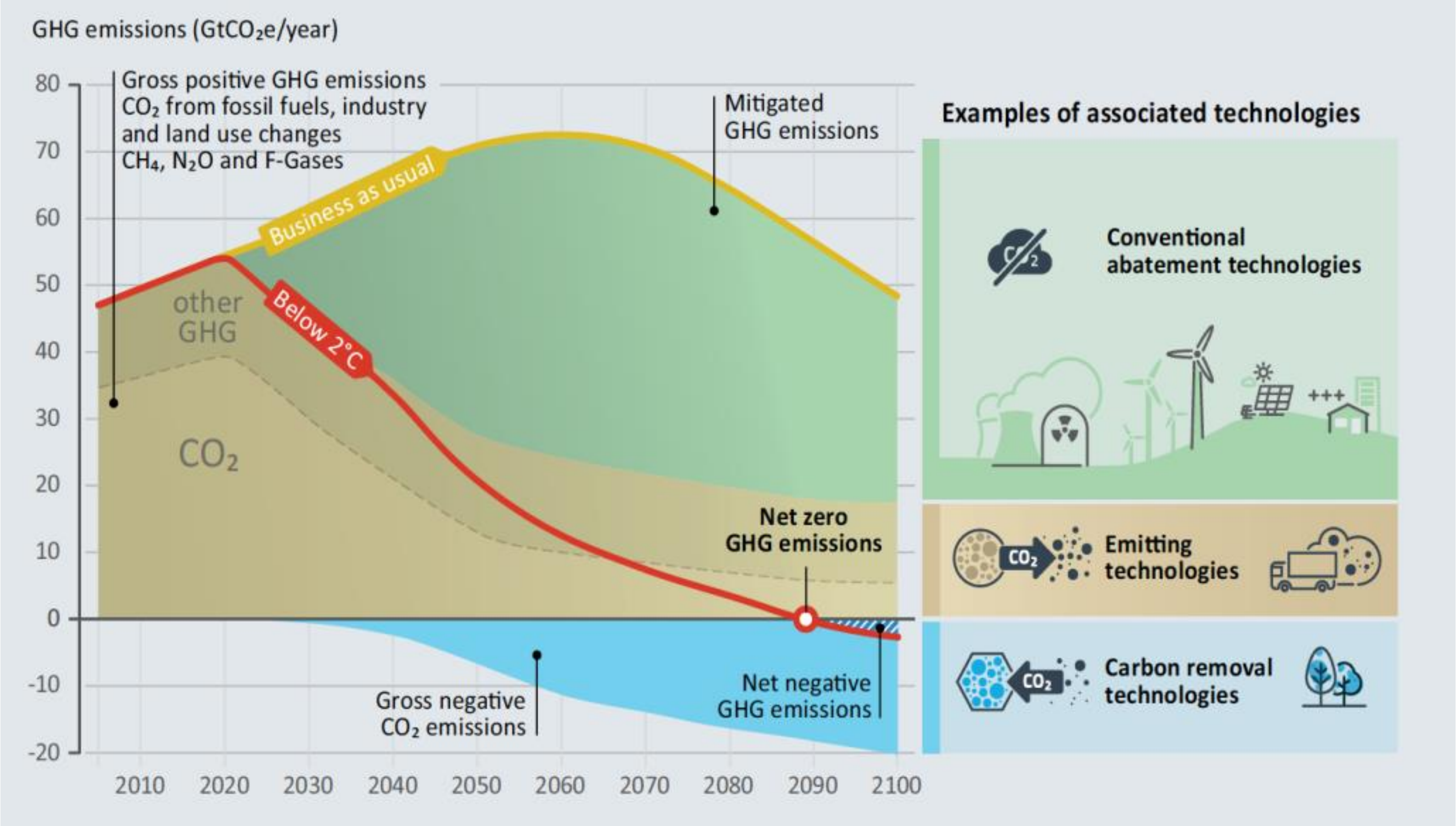
Carbon waste gases are captured at its point of production or from the atmosphere and may be separated from other byproducts, compressed and/or transported.

**Sequestered**: Captured carbon may be disposed of thousands of feet underground where it can remain permanently trapped

**Utilized:** $CO_2$, $CH_4$ and biogas may be used as a feedstock for products that have market value, such as fuels, building materials, plastics or other useful solids, chemicals or animal feed. (see also sister study: *Gaseous Carbon Waste Streams Utilization: Status and Research Needs*, *http://nas-sites.org/dels/studies/gcwu/*).

Estimate that utilization may account for ≤10% of emissions reduction

# How large is potential market for NETs likely to be? Or equivalently, how much carbon uptake is needed to meet Paris Agreement goals?

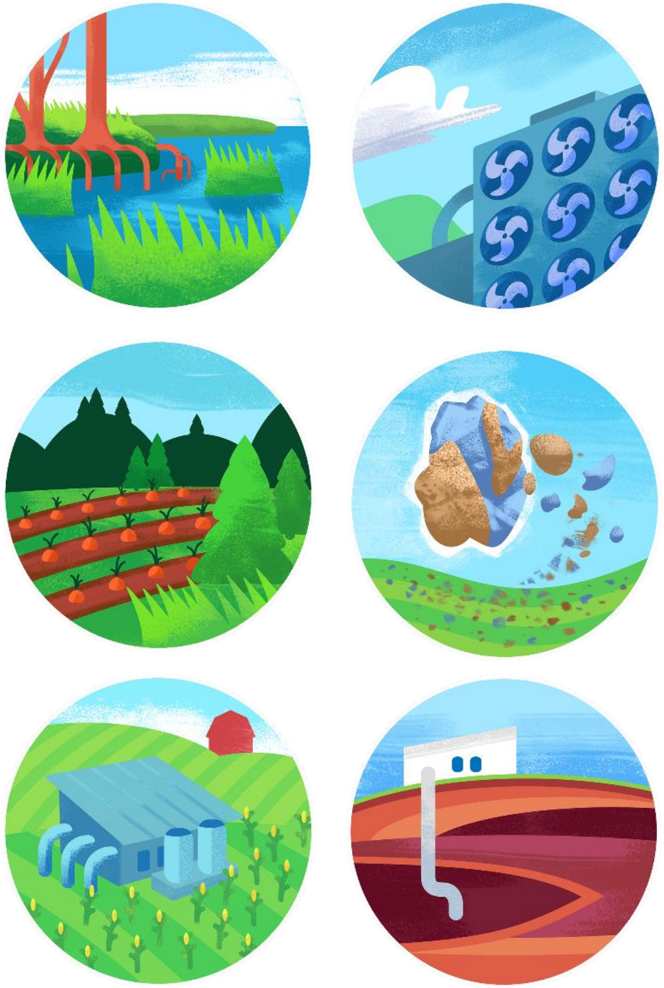



**~10 $GtCO_2$/y** globally by midcentury

**~20 $GtCO_2$/y** globally by the century's end

The National Academies of SCIENCES ENGINEERING MEDICINE

# Negative Emissions Technologies



Coastal blue carbon

Direct air capture (DAC)**

Terrestrial carbon removal and sequestration

Carbon mineralization**

Bioenergy with carbon capture and sequestration (BECCS)**

Geologic sequestration (partner with **)

| Negative Emissions Technology | Estimated Cost ($\$/tCO_2$) L = 0- 20 M =20 -100 H = >100 | Upper-bound* for safe* Potential Rate of $CO_2$ Removal Possible Given Current Technology and Understanding and at $\leq\$100/tCO_2$ ($GtCO_2/y$) | |
|---|---|---|---|
| | | US | Global |
| Coastal blue carbon | L | 0.02 | 0.13 |
| Afforestation/ Reforestation | L | 0.15 | 1 |
| Forest management | L | 0.1 | 1.5 |
| Agricultural soils | L to M | 0.25 | 3 |
| BECCS | M | 0.5 | 3.5-5.2 |

- Four options ready to be scaled up, but their capacity is substantially less than expected demand/need
- Limited due to realistic rates of adoption of agricultural soils practices, forestry management practices and waste biomass capture

- Safe and economical direct air capture or carbon mineralization would have essentially unlimited capacity to remove carbon
  - Direct air capture currently limited by high cost
  - Carbon mineralization currently limited by lack of fundamental understanding

- Blue carbon has capacity that is less than the other options, but potentially very low incremental cost given large co-benefits

**Recommendation:** The nation should launch a substantial research initiative to advance negative emissions technologies as soon as practicable:

(1) improve coastal blue carbon, afforestation/reforestation, changes in forest management, uptake and storage by agricultural soils, and BECCS to increase capacity and to reduce negative impacts and costs

(2) make rapid progress on direct air capture and carbon mineralization technologies, which are underexplored but would have essentially unlimited capacity if high costs and many unknowns could be overcome

(3) advance NET-enabling research on biofuels and carbon sequestration that should be undertaken anyway as part of an emissions mitigation research portfolio

# Rational for Research Investment

- States, local governments, corporations, and countries now make or plan large investments in NETs (e.g. ~30% of planned emissions reductions).
  - Advances in NETs will create jobs and benefit US economy, especially if intellectual property is held by US companies.

- Unlike wind, solar and unconventional gas, NETs have not yet received public investment at a scale consistent with:
  - need for NETs that can solve substantial fraction of climate problem
  - possible magnitude of return to US economy

# Existing DAC Approaches

**<u>Classical, high T solvent approach</u>**

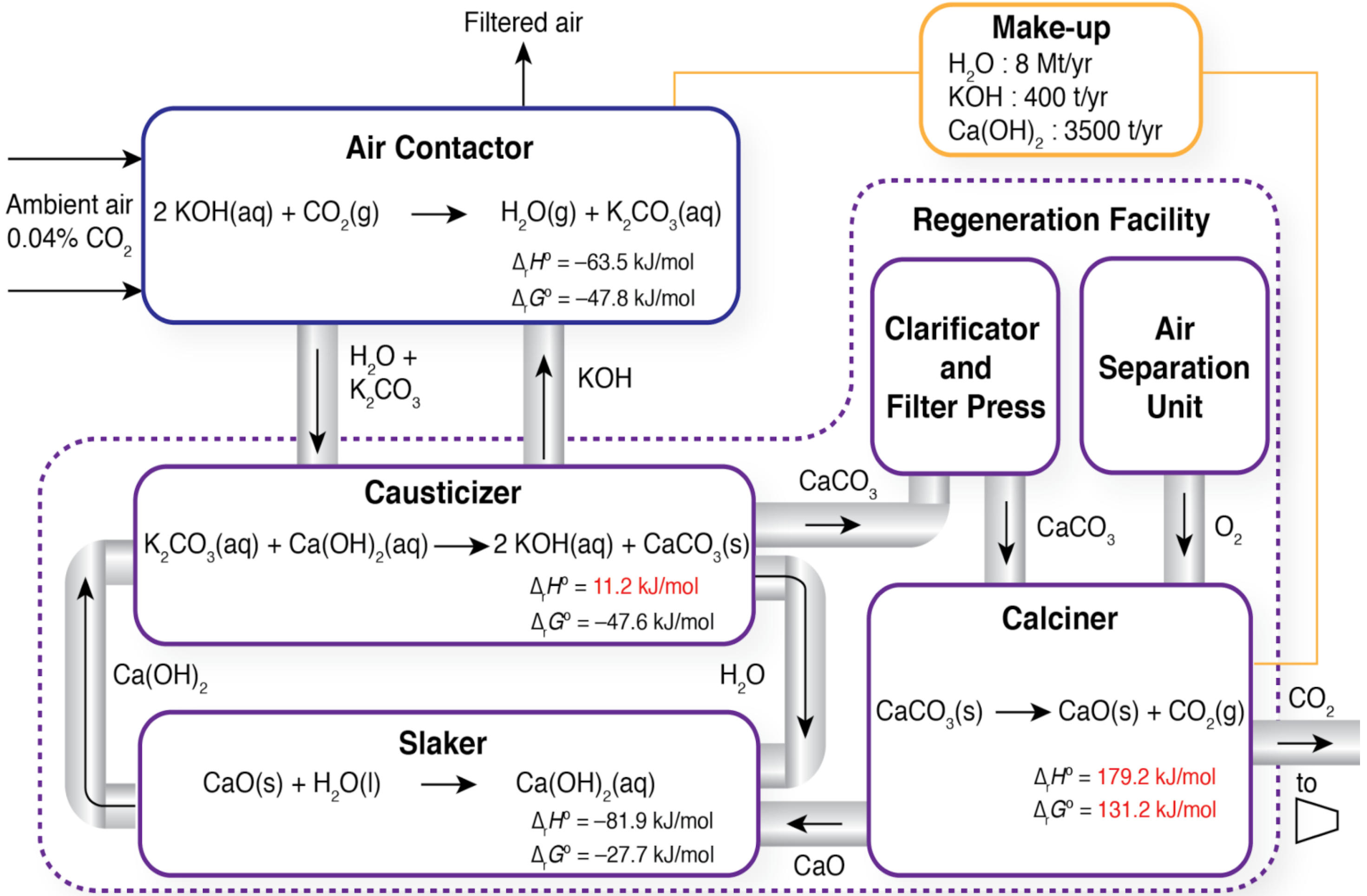
- Evaluated previously in APS study, 2011
- Refine over ensuing years
- Capital intensive, ~800 ℃ heat needed

*Carbon Engineering*

https://www.cell.com/joule/fulltext/S2542-4351(18)30225-3

- New, low T approaches emerging

https://www.nature.com/articles/s41560-018-0150-z



# TEA for Carbon Engineering-Inspired Process

TABLE 5.4. Summary of carbon capture costs for a liquid solvent direct air capture system powered by natural gas or coal.

| Cost ($/t$CO_2$) | Natural Gas | Coal |
|---|---|---|
| Capture Cost[i] | 147-264 | 140-254 |
| Net-Removed Cost[ii] | 199-357 | ∞ |
| Produced Cost, Oxy-Fired Calciner[iii] | 113-203 | ∞ |

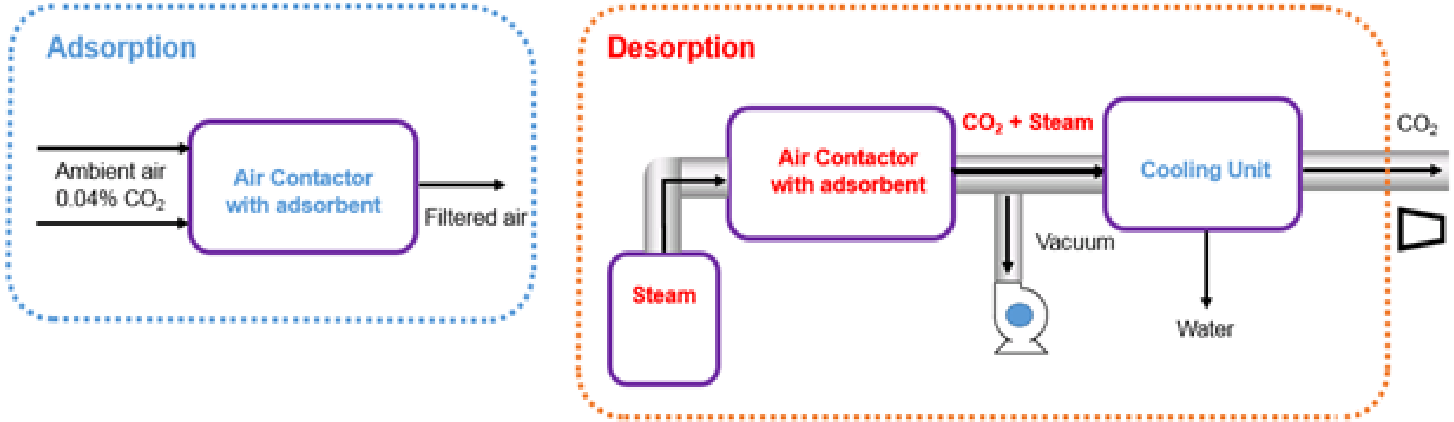
[i]Basis = 1Mt net $CO_2$ removed from air.
[ii]Basis = per net unit of $CO_2$ removed with an average of 0.3 Mt$CO_2$ for natural gas and zero for coal
[iii]Basis = per net unit of $CO_2$ *produced* including co-capture of $CO_2$ from natural gas oxy-fired kiln with an average of 1.3 Mt$CO_2$.

- Complex process, costs vary depending on how to draw system boundary.
- *Carbon Engineering* targets fuel production
- Co-fires natural gas for high T heat, captures $CO_2$ and blends with $CO_2$ from air
- Generally speaking, costs range from ~$100-$400/t, depending on assumptions
- All scenarios offer substantially lower costs than anticipated from the APS 2011 report

# Existing DAC Approaches

**<u>Solid adsorbent, low T, T/VSA</u>**

- *Climeworks*, *Global Thermostat*, others?
- Much less complex, but contingent on long-lifetime sorbent materials
- Capital intensive, sorbent cost largest driver




Adsorption based approach TEA completed, building upon prior work:

https://pubs.acs.org/doi/10.1021/acs.iecr.6b03887

Costs per ton $CO_2$ can be much lower than anticipated (APS report, 2011, $600+/t$CO_2$)

# TEA for Generic Solid Sorbent Process

TABLE 5.8. Input parameters used for cost estimates for the generic solid sorbent direct air capture system, with selected outputs.

| Parameters | 1-Best | 2-Low | 3-Mid | 4-High | 5-Worst |
|---|---|---|---|---|---|
| Adsorbent Purchase Cost ($/kg) | 15 | 50 | 50 | 50 | 100 |
| Adsorbent Life (y) | 5 | 0.5 | 0.5 | 0.5 | 0.25 |
| Sorbent Total Capacity (mol/kg) | 1.5 | 1.0 | 1.0 | 1.0 | 0.5 |
| Desorption Swing Capacity (mol/mol) | 0.90 | 0.8 | 0.8 | 0.8 | 0.75 |
| Contactor to Adsorbent Ratio (kg/kg) | 0.1 | 0.1 | 0.2 | 1.0 | 4.0 |
| Desorption Pressure (bar) | 0.2 | 0.5 | 0.5 | 0.5 | 1.0 |
| Outputs | | | | | |
| Final Desorption Temperature (K) | 340 | 360 | 360 | 360 | 373 |
| Cycle Time (min) | 39 | 16 | 28 | 42 | 26 |

TABLE 5.9. Estimated annualized capital (CAPEX) and operating (OPEX) costs for a generic solid sorbent direct air capture system with a capacity of 1 Mt/y $CO_2$ removal.

| Parameters | 1-Best | 2-Low | 3-Mid | 4-High | 5-Worst |
|---|---|---|---|---|---|
| Adsorbent Capex | 3.6 | 70 | 122 | 186 | 988 |
| Adsorption Opex | 1.3 | 9 | 12 | 19 | 4.3 |
| Blower Capex | 3.6 | 2.1 | 3.7 | 6.7 | 13.7 |
| Vacuum Pump Capex | 4.5 | 2.6 | 4.7 | 8.5 | 17.4 |
| Steam Opex | 2.5 | 2.2 | 2.4 | 3 | 43 |
| Condenser Capex | 0.03 | 0.07 | 0.075 | 0.1 | 0.4 |
| Contactor Capex | 2.2 | 1.3 | 2.3 | 4.1 | 8.4 |
| Vacuum Pump Opex | 0.3 | 0.2 | 0.2 | 0.24 | 0.3 |
| Total Cost | 18 | 88 | 148 | 228 | 1080 |

Annualized capital costs assume 10 year lifetime of non-sorbent materials

- $18-$1080+/t
- Lower bound likely unattainable in short term
- Cost for first *Climeworks* plant $600/t
- Study projects costs of $100-300/t in next decade

# Conflict of Interest Statement

- Georgia Tech receives research funding from *Global Thermostat, LLC*
- Georgia Tech has licensed intellectual property to *Global Thermostat, LLC*
- Jones has a (very small) financial interest in *Global Thermostat, LLC*.

Useful overview papers:

Sorbent design and development:

Didas et al.
*Acc. Chem. Res.* **2015**, 48, 2680.

Review of DAC:

Sanz et al.
*Chem. Rev.* **2016**, 116, 11840.

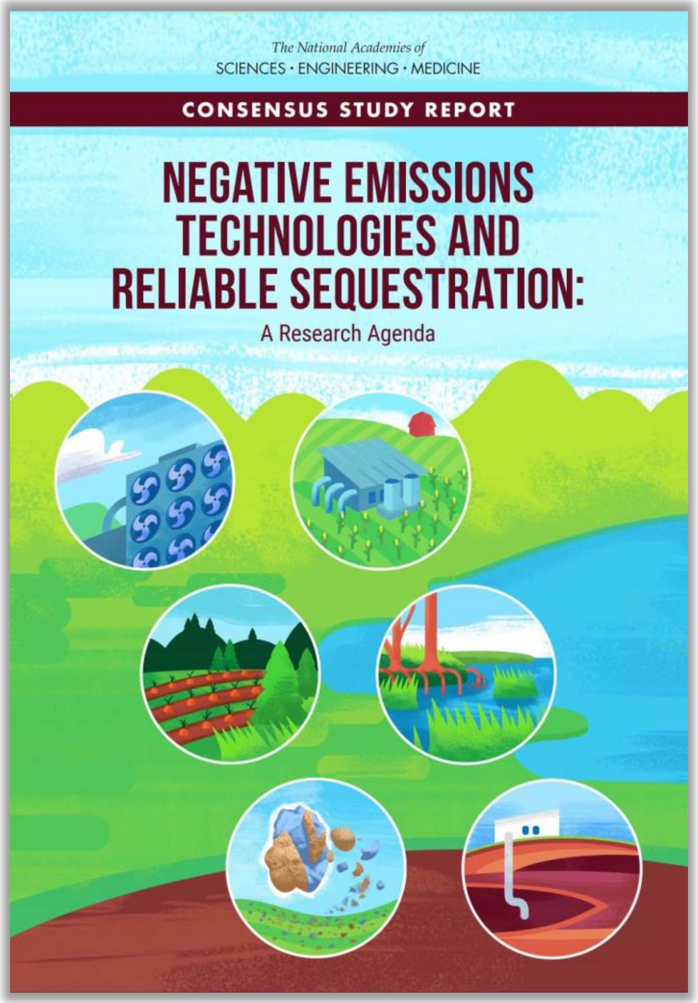
Global Thermostat, LLC, 3000 t/yr unit
Huntsville, AL, September 2018

# Thank you!

For more information and to subscribe for updates:

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

Join the conversation on Twitter:
**#CarbonRemoval**





DAC Team:
**Christopher Jones (GT)** **cjones@chbe.gatech.edu**
Jennifer Wilcox (WPI)
Dane Boysen (Modular Chemical)
Mark Barteau (Texas A&M)