carbon mineralization for CO₂ removal from air
small blue building: proportion of scientists working on carbon mineralization, mainly for storage

\[ \text{Mg, Ca, ... + CO}_2 \]
\[ = \text{MgCO}_3, \text{CaO}_3, \ldots \]
small blue building: proportion of scientists working on carbon mineralization, mainly for storage

Mg, Ca, ... + CO₂ = MgCO₃, CaO₃, ...

little red room in small blue building: proportion of scientists studying carbon mineralization for CO₂ removal from air
\[
\begin{align*}
\text{Mg(OH)}_2 + \text{CO}_2 & \Rightarrow \text{MgCO}_3 + \text{H}_2\text{O} \\
\text{Ca(OH)}_2 + \text{CO}_2 & \Rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \\
\text{Mg}_2\text{SiO}_4 + 2\text{CO}_2 & \Rightarrow 2\text{MgCO}_3 + \text{SiO}_2 \\
\text{CaSiO}_3 + \text{CO}_2 & \Rightarrow \text{CaCO}_3 + \text{SiO}_2 \\
\text{Mg}^{2+} + \text{HCO}_3^- + \text{OH}^- + 2\text{H}_2\text{O} & \Rightarrow \text{MgCO}_3\cdot3\text{H}_2\text{O}
\end{align*}
\]
Mg and Ca carbonates are the “ground state” for C in many near surface geologic systems.
IPCC 2005 & DOE: expensive

The technology is … not yet ready for implementation.

The best case studied so far is [carbonation of] olivine

60-180% more energy
doubles the cost of a power plant
~ $400/ton CO₂
IPCC 2005 & DOE: slow

IPCC Report on Carbon Capture & Storage, 2005
Chapter 5: Underground geologic storage
CarbFix, Iceland: fast

Matter et al. Science 2016
CaSiO$_3$
Mg(OH)$_2$
Mg$_2$SiO$_4$
Mg$_3$Si$_2$O$_5$(OH)$_4$
NaAlSi$_3$O$_8$
CaAl$_2$Si$_3$O$_8$

25°C
180°C

CaSiO$_3$ wollastonite
Mg(OH)$_2$ brucite
Mg$_2$SiO$_4$ olivine
NaAlSi$_3$O$_8$ chrysotile serpentine
CaAl$_2$Si$_3$O$_8$ plagioclase feldspars

Kelemen et al. Frontiers, in press
carbon mineralization in peridotite max capacity, Gt CO₂
on land 5 10^3 to 5 10^4
seafloor 500 to 5000
100-500

carbon storage (minerals & pore space) in basalt max capacity, Gt CO₂ on land only
10^5 to 5 10^5
10^4 to 10^5
10^3 to 10^4

global CO₂ storage capacity in mafic and ultramafic rocks
100’s to 1000’s of trillions of tons
(1) cost per ton CO$_2$ captured:
$/\text{ton} = \text{capture process cost} / \text{tons CO}_2 \text{ captured from air}

(2) cost per ton CO$_2$ net removed:
$/\text{ton} = \text{total process cost} / [\text{tons CO}_2 \text{ captured from air} - \text{emissions to air}]

where the total process cost includes the cost of CO$_2$ capture from calcining, assumed here to be all of the CO$_2$ produced from the calciner using natural gas

CO$_2$ captured from process is not included

(3) cost per ton CO$_2$ produced:
$/\text{ton} = \text{total process cost} / [\text{tons CO}_2 \text{ captured from air} + \text{process}]

\textbf{for all: electricity at }$0.06/\text{kWh} \text{ and gas for heating at }$3.25/\text{GJ}
\text{ maintenance included (not in all NA19 calculations)}
\text{ no free lunch (waste heat, proprietary power plants)}

McQueen et al. JRSI 2019 submitted
Kelemen et al. Chem Geol 2019 submitted
## Negative Emissions Technologies and Reliable Sequestration: A Research Agenda

<table>
<thead>
<tr>
<th>Direct Air Capture System</th>
<th>Capture Cost ($/t CO₂)</th>
<th>Net Removed Cost</th>
</tr>
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<tbody>
<tr>
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<td>Captured</td>
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</tr>
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<td>147-264</td>
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<td>173-310</td>
</tr>
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<td></td>
<td>317-501</td>
<td>320-506</td>
</tr>
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<td>Solid Sorbent³</td>
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<td>89-250</td>
</tr>
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<td></td>
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<td>89-256</td>
</tr>
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</tr>
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<td></td>
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<td>166-877</td>
</tr>
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</table>

Keith et al. 2018 ≥ $94

\[
\text{Cost} \left[ \frac{\$}{\text{tCO}_2} \right] = \frac{\text{Process Cost} [\$]}{\text{CO}_2 \text{ Capture from Air} [\text{tCO}_2]}
\]

\[
\text{Net Removed Cost} \left[ \frac{\$}{\text{tCO}_2} \right] = \text{CO}_2 \text{ Capture from Air} [\text{tCO}_2] - \text{CO}_2 \text{ Released by Process} [\text{tCO}_2]
\]

\[
\text{Produced Cost} \left[ \frac{\$}{\text{tCO}_2} \right] = \frac{\text{Process Cost} [\$]}{\text{CO}_2 \text{ Capture from Air} [\text{tCO}_2] + \text{Additional CO}_2 \text{ Captured by Process} [\text{tCO}_2]}
\]

### Cost of Capture
- $300.00
- Net Removed Cost

### Cost vs Outlet Purity
- Cost [$/\text{tCO}_2]
- Outlet Purity [0.0% to 100.0%]

National Academies 2019, McQueen et al. JRSI 2019 submitted
Kelemen et al. Chem Geol 2019 submitted

Worcester Polytechnic Institute

Lamont-Doherty Earth Observatory
Columbia University | Earth Institute
“FastCompany” reported:

“in 2018, Carbon Engineering published a paper saying that it had dropped costs to around $94 to $232 a ton. Global Thermostat thinks that it can reach $50 a ton.”

“SingularHub” states:

“Global Thermostat, has already demonstrated that its technology can remove CO$_2$ for a mere $120 per ton at its facility in Huntsville, Alabama. And at scale, the startup predicts it could achieve DAC for as little as $50 a ton.”
mines:
$10/t$ to mine & grind, $5 \text{ wt}\% \text{ CO}_2 = \$
$200/t$

$200 \text{ Mt tailings} \Rightarrow 10 \text{ Mt CO}_2/\text{yr}$

mining for CDR: prospect for the best rocks,
$10\% \text{ CO}_2, \$100/t$ ....

area for $1 \text{ Gt CO}_2 (10 \text{ wt}\%)$

$50,000 \text{ km}^2 \times 10 \text{ cm deep} + \text{ mine + power}$

compare DAC

$100$ to $300$ per ton ...

$7000 \text{ km}^2/\text{Gt} + 2400 \text{ km}^2$ for power
$1 to $2/ton to “stir”

Kelemen et al. Chem Geol 2019 submitted
in situ carbon mineralization process
weathering of tectonically exposed mantle peridotite

precipitation Ca-carbonate

pH > 11, Ca\(^{2+}\)-OH\(^{-}\)
Alkaline spring water

Open system
Type I: Mg\(^{2+}\)-HCO\(_3\)\(^{-}\)
Shallow groundwater

Closed system
Type II: Ca\(^{2+}\)-OH\(^{-}\)
Deep groundwater

precipitation Mg-carbonate
Mg-silicate

CO2 removal from air
in situ carbon mineralization in peridotite

permeability, m$^2$

- 1E-12
- 1E-13
- 1E-14

$$/ton \ CO2$

1000000
100000
10000
1000
100
10
10

$tons \ CO2/yr/borehole$

10
100
1000
10000
100000
1000000

Kelemen et al. Chem Geol 2019 submitted
CO2 removal from air in situ carbon mineralization in peridotite

$\text{$/ton CO}_2$

$\text{tons CO}_2/\text{yr/borehole}$

\begin{align*}
\text{permeability} & \\
\text{gray} & \quad 1E-12 \\
\text{blue} & \quad 1E-13 \\
\text{red} & \quad 1E-14
\end{align*}

at $10^{-13}$ m$^2$

~ 500,000 wells for 1 Gt CO$_2$/yr

compare ~1M operating oil & gas wells in the US

Kelemen et al. Chem Geol 2019 submitted
### Negative Emissions Technologies and Reliable Sequestration: A Research Agenda

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Keith et al. 2018 ≥ $94

Cost $\frac{\text{\$}}{\text{tCO₂}} = \frac{\text{Process Cost [\$]}}{\text{CO₂ Capture from Air [tCO₂]}}$

Net Removed Cost $\frac{\text{\$}}{\text{tCO₂}} = \frac{\text{Process Cost [\$]}}{\text{CO₂ Capture from Air [tCO₂]} - \text{CO₂ Released by Process [tCO₂]}}$

Produced Cost $\frac{\text{\$}}{\text{tCO₂}} = \frac{\text{Process Cost [\$]}}{\text{CO₂ Capture from Air [tCO₂]} + \text{Additional CO₂ Captured by Process [tCO₂]}}$

---

National Academies 2019, McQueen et al. JRSI 2019 submitted
Kelemen et al. Chem Geol 2019 submitted

[Lamont-Doherty Earth Observatory](https://www.ldeo.columbia.edu)
[Worcester Polytechnic Institute](https://www.wpi.edu)
$65 for DACSS to 3% at $10^{-13}$ m$^2$

~ 100,000 wells for 1 Gt CO$_2$/yr

wells 250 m apart 6250 km$^2$
(cows in between!)

huge optimization space
synergy with geothermal

$\text{Kelemen et al. Chem. Geol. 2019 submitted}$
compare:
(grid electricity $0.06, natural gas $3.25/GJ)

liquid solvent (Carbon Engineering):
$113-163 net removed (15 MPa output) Keith et al. 2018
$199-357 net removed National Academies 2019

solid sorbent (Global Thermostat)
$124-407 net removed National Academies 2019

comparable area footprint for all; 7000 km²/Gt CO₂ (2x Nevada Test Site)

Kelemen et al. Chem. Geol. 2019 submitted
cracking versus clogging

example

\[ \text{MgO} + \text{H}_2\text{O} = \text{Mg(OH)}_2 \]

natural systems don’t clog, persist for 10’s to 100’s of thousands of years

Zheng et al. G-cubed 2018
cracking versus clogging

element MgO
+ H₂O
= Mg(OH)₂

natural systems don’t clog, persist for 10’s to 100’s of thousands of years

Zheng et al. G-cubed 2018
enough carbonation plots to keep calciner running 24/7
## Process Economic Assumptions

<table>
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<tr>
<th>Variable</th>
<th>Value</th>
<th>Source/Notes</th>
</tr>
</thead>
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<tr>
<td>Natural Gas Cost</td>
<td>$3.25/GJ</td>
<td>Keith et al., 2018</td>
</tr>
<tr>
<td>Electricity Cost</td>
<td>$0.06/kWh</td>
<td>Keith et al., 2018</td>
</tr>
<tr>
<td>Capacity Factor</td>
<td>90%</td>
<td>Keith et al., 2018</td>
</tr>
<tr>
<td>Carbonation Plots</td>
<td>3,405</td>
<td>Continuous Calciner Operation</td>
</tr>
<tr>
<td>Environmental Losses</td>
<td>5%</td>
<td>Needs experimental validation</td>
</tr>
<tr>
<td>Layer Thickness</td>
<td>10 cm</td>
<td>Needs experimental validation</td>
</tr>
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## Process Economic Results

<table>
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<tr>
<th>Energy Type</th>
<th>Grid Electricity [$0.06/kWh]</th>
<th>Solar Electricity [$0.10/kWh]</th>
<th>Projected Solar Electricity [$0.03/kWh]</th>
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<tr>
<td>Base Cost [$/tCO\textsubscript{2}]</td>
<td>$47 - $93</td>
<td>$51 - $96</td>
<td>$44 - $90</td>
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<td>Produced Cost [$/tCO\textsubscript{2}]</td>
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## Process Cost Comparison

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**Compare:**
- (grid electricity $0.06, natural gas $3.25/GJ)
- Liquid solvent (Carbon Engineering): $113-163 net removed (15 MPa output) Keith et al. 2018
- $199-357 net removed National Academies 2019
- Solid sorbent (Global Thermostat): $124-407 net removed National Academies 2019
- Comparable area footprint for all; 7000 km\(^2\)/Gt CO\(_2\) (2x Nevada Test Site)

McQueen et al. JRSI submitted 2019
& papers in preparation
magnesite
~ 10 Gt reserves
52 wt% CO₂

Na carbonates
~ 25 Gt reserves
≤ 40 wt% CO₂

heated serpentinite
quadrillions of tons
≤ 33 wt% CO₂
optimization? layer thickness
waste heat solar thermal or electric furnaces
wet, damp, dry, sparge with air stir tailings
thank you for your attention
References

- US Patent Application 62/865,708, "Systems and Methods for Enhanced Weathering and Calcining for CO₂ Removal from Air," filed by Columbia University on June 24, 2019, including inventors Peter Kelemen (Columbia University), Noah McQueen and Jennifer Wilcox (Worcester Polytechnic Institute), Phil Renforth (Heriot-Watt University) and Greg Dipple (University of British Columbia).