Solar Geoengineering & Direct Air Capture

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Tokyo
8th October 2019

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Solar geoengineering
<table>
<thead>
<tr>
<th>Method</th>
<th>Confidence that substantial global ΔRF (e.g. &gt; 3 Wm⁻²) is achievable</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strat sulfates</td>
<td>Very high: Current technologies can likely be adapted to loft materials and disperse SO₂ and relevant scales</td>
<td>Similarity to volcanic sulfate gives empirical basis for estimating efficacy and risks</td>
<td>Hard to adjust zonal distribution; ozone loss; stratospheric heating</td>
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<td>Other strat aerosol</td>
<td>Moderate: depends on aerosol, lofting similar to sulfate but aerosol dispersal much more uncertain</td>
<td>Some solid aerosols may have less strat heating and minimal ozone loss</td>
<td>Hard to adjust zonal distribution; higher uncertainty than sulfates</td>
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<tr>
<td>Marine clouds</td>
<td>Uncertain: observations support wide range of CCN impact on albedo; significant work on development of spray systems, but no system-level analysis of cost of deployment</td>
<td>Ability to make local alterations of albedo; ability to albedo modulate on short timescales.</td>
<td>Only applicable on marine stratus covering ~10% of earth means RF inherently patchy; fast timescale rases termination risk</td>
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<td>Cirrus</td>
<td>Uncertain: deep uncertainty about fraction of cirrus strongly depended on homogeneous nucleation; no studies of dispersal technologies nor system studies examining diffusion off CCN and link to flight profiles</td>
<td>Works on LW more than SW so could provide better compensation than “perfect” strat or space-based scatters; better RF uniformity that MCB</td>
<td>More ability to adjust zonal distribution that strat aerosols, perhaps less meridional adjustability.</td>
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<tr>
<td>Space based</td>
<td>Low physical uncertainty, but deep technological uncertainties about cost and feasibility</td>
<td>Possibility of near “perfect” alteration of solar constant. Spectral tailoring may be easier</td>
<td>Some methods (e.g. L1 point) would not allow zonal or meridional tailoring of RF</td>
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</tbody>
</table>

Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target, MacMartin, Ricke, and Keith, Philosophical Transactions of the Royal Society, 2018
Hardware-focused business-oriented development from day one
Direct Air Capture – Chemical Looping, CO₂ from 0.06 → 98%

**Air Contactor**

\[ \text{CO}_2(g) + 2\text{KOH}_{(aq)} \rightarrow \text{H}_2\text{O}_{(l)} + \text{K}_2\text{CO}_3(aq) \]

-95.8 kJ/mol

**Pellet Reactor**

\[ 2\text{KOH}_{(aq)} + \text{CaCO}_3(s) \rightarrow \text{K}_2\text{CO}_3(aq) + \text{Ca(OH)}_2(s) \]

-5.8 kJ/mol

**Calciner**

\[ \text{CaO}(s) + \text{CO}_2(g) \rightarrow \text{CaCO}_3(s) \]

178.3 kJ/mol

**Slaker**

\[ \text{CaO}(s) + \text{H}_2\text{O}(l) \rightarrow \text{Ca(OH)}_2(s) \]

-63.9 kJ/mol

**CO₂ concentrations shown as mass fractions**
Innovative integration of industrially proven technologies
Aqueous Air Contactor

- Aqueous capture process
- Continuous operation
- Cooling tower heritage → low capital cost, long life and tolerance for dust and impurities.
- Less than 90 kWhr/t-CO$_2$ capture energy
- More than 20 t-CO$_2$ m$^{-2}$/year capture rate
- Solution is easily transported to recovery unit via industrial pumps and pipes
Calciner/Slaker

- **CaCO\textsubscript{3} Seed**: 4.5 t/h CaCO\textsubscript{3}
- **Calciner makeup**: 3.4 t/h
- **Separation**: 0.3 MW
- **Pollut Reactor**: 3.4 MW
- **Cooling Water He**:
  - 773 t/h
  - 4.06 [Ca(OH)]
  - 2.33 [K]
  - 0.06 [OH]
  - 0.06 [CO\textsubscript{3}]
- **Air Contactor**: 112 t-CO\textsubscript{2}/h captured
- **CO\textsubscript{2} Absorber**: 0.4 MW
- **Gas Steam**: 252.0 t/h
  - 0.018% CO\textsubscript{2}
  - 22.96% O\textsubscript{2}
  - 73.33% N\textsubscript{2}
  - 1.23% H\textsubscript{2}O
- **Lime Cooler**: 31°C
  - 3.200 t/h
  - 3.01 [K]
  - 0.68 [OH]
  - 0.68 [CO\textsubscript{3}]
- **Quicklime Mix Tank**: 0.2 MW
- **AUX**: 2.6 MW
- **HRSG**:
  - 121 t/h
  - 14.43% CO\textsubscript{2}
  - 66.91% O\textsubscript{2}
  - 72.66% N\textsubscript{2}
  - 12.66% H\textsubscript{2}O
- **Gas Turbine**: -46.0 MW
- **Oxygen Preheat**:
  - 58.5 t/h
  - 35.00% O\textsubscript{2}
  - 4.40% N\textsubscript{2}

**Concentrations in mol/L**
- Fractions in % by mass
- Conway matrix tense
Calciner – Design

- Biased on circulating fluid bed ore roasters
- CFB design minimizes equipment footprint
- Oxy-firing ensures high capture fraction and puts all separation energy into the fuel-derived carbon
Summary performance of various DAC configurations

<table>
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<tr>
<th>Scenario</th>
<th>Gas input(^1) GJ/tCO(_2)</th>
<th>Electricity input(^1) kWh/tCO(_2)</th>
<th>C-gas/ C-air</th>
<th>Capital $ per t-CO(_2)/yr</th>
<th>O&amp;M(^2) $/t-CO(_2)</th>
<th>Levelized(^1)$/t-CO(_2) CRF(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Baseline: gas fired → 15 MPa CO(_2) output</td>
<td>8.81</td>
<td>0</td>
<td>0.48</td>
<td>1,127</td>
<td>37</td>
<td>168, 232</td>
</tr>
<tr>
<td>B: Baseline with N(^{th})-plant financials</td>
<td>8.81</td>
<td>0</td>
<td>0.48</td>
<td>779</td>
<td>26</td>
<td>126, 170</td>
</tr>
<tr>
<td>C: Gas and electricity → 15 MPa CO(_2) output</td>
<td>5.25</td>
<td>366</td>
<td>0.30</td>
<td>778</td>
<td>26</td>
<td>113-124, 152-163</td>
</tr>
<tr>
<td>D: Gas &amp; electricity input → 0.1 MPa CO(_2) output assuming zero cost O(_2)</td>
<td>5.25</td>
<td>77</td>
<td>0.30</td>
<td>683</td>
<td>23</td>
<td>94-97, 128-130</td>
</tr>
</tbody>
</table>

1. Gas and electrical inputs as well as levelized cost are all per ton CO\(_2\) capture from the atmosphere.

2. Non-energy operations and maintenance expressed as fixed per unit of capacity with variable costs including cost of makeup-streams included and converted equivalent fixed costs as using 90% utilization.

3. CRF is the average Capital Recovery Factor. Calculations assume NG at 3.5 $/GJ and a 90% utilization. For the C and D variants levelized costs are shown as a range using electricity at 30 and 60 $/MWhr.
Solar PV → Direct Air Capture → Hydrogen → Fuel

Water → Hydrogen

CO₂ → Direct Air Capture
Malaysia: Nel Hydrogen, 25 MW alkaline electrolysis, completed 2013. The hydrogen is used to make polysilicon.
Solar PV → Direct Air Capture → Carbon Monoxide → Hydrogen → Fuel

Water → Carbon Monoxide

$\text{CO}_2$ → Direct Air Capture
Haldor Topsoe 300 kW modular “eCOs” electrolytic CO production entered commercial production in 2018
Solar PV

Direct Air Capture

Gas-to-Liquids

Fuel

Hydrogen

Carbon Monoxide

Water

CO₂
Shell Pearl Gas-to-Liquids
140 thousand barrels per day
Air-to-fuel efficiency: 44%

With 10 $/MWhr PV the power cost of gasoline is 0.27 $/Litre
Carbon Dioxide Removal (CDR)
Geologic timescales

• Biomass energy + geologic storage (BECCS)
• Direct air capture + geologic storage (DAC-CCS)
• Addition of alkalinity to ocean

Ecological/social timescale

• Afforestation
• Protection of forests
• Wood buildings
• Enchantment of soil carbon
  • Biochar
  • Agricultural practices
  • Modification of crops

Carbon Dioxide Removal (CDR)
How might emissions cuts, CDR, and SRM fit into climate strategy?
Emissions cut to zero

Fossil fuels forever

Emissions cut to zero

Carbon removal

Solar geoengineering
Climate risks

Time

Start emission cuts

Emissions cuts & Carbon removal

Fossil fuels forever
Day of zero net emissions
Peak concentrations

Start emission cuts

Emissions cuts & Carbon removal
Day of zero net emissions
Peak concentrations

Start large-scale carbon removal

Start solar geoengineering

End solar geoengineering

Start emission cuts
How much can solar geoengineering reduce climate risks?
Can solar geoengineering reduce climate risks?

It depends…

• On the **method** used (marine clouds, cirrus, or some stratospheric aerosol)
• On the **spatial distribution** of material and resulting radiative forcing
• On the **magnitude** (peak-shaving vs substitute for emissions cuts)

One cannot meaningfully evaluate the risks & efficacy of solar geoengineering without a well-specified **scenario** for deployment.

Lesson: Distrust generic answers: (e.g., solar geoengineering **will** reduce precipitation)
Can solar geoengineering reduce climate risks?

Scenario: *moderate* spatially-*uniform* solar geoengineering
- *Moderate* = combined with emissions cuts to reduce the rate of change
- *Uniform* = an approximately uniform global distribution of radiative forcing

**Question 1**: how much would this scenario reduce important human and environmental climate risks?
- How equitable?
- Are there regions that see increased risks?

Tools: climate models and historical analogs

**Question 2**: is it feasible to engineer uniform radiative forcing?
- With what side-effects?
- What cost?
- How controllable?

Tools: engineering, stratospheric models, aerosol micro-physics, control theory...
Question 1: Does a moderate & uniform reduction in RF reduce policy-relevant climate risks?

Evidence is strong that it would reduce hazards:
• Reduce regional changes in water availability
• Reduce regional increases in extreme precipitation
• Reduce tropical cyclone intensity
• Reduce regional changes in extreme temperatures
HiFLOR (25km FV3 atmosphere coupled to 1° MOM5)

T  Tx  PE  Px
Surface Air Temp
Max annual Temp
Precip - Evap
Max 5-day Precip

T  Tx  PE  Px
GFDL results

Moderated and significant
Moderated but insignificant
Exacerbated but insignificant
Exacerbated and significant
Question 1: Does a moderate & uniform reduction in RF reduce policy-relevant climate risks?

Evidence is strong that it would reduce hazards:
• Reduce regional changes in water availability
• Reduce regional increases in extreme precipitation
• Reduce tropical cyclone intensity
• Reduce regional changes in extreme temperatures
• Reduce sea level rise
• Reduce carbon concentrations and ocean acidification
Solar geoengineering might reduce CO$_2$ burden in 2100 by 5-25% at a cost of <0.5 $/tCO$_2$
Question 1: Does a moderate & uniform reduction in RF reduce policy-relevant climate risks?

Evidence is strong that it would reduce hazards:

- Reduce regional changes in water availability
- Reduce regional increases in extreme precipitation
- Reduce tropical cyclone intensity
- Reduce regional changes in extreme temperatures
- Reduce sea level rise
- Reduce carbon concentrations and ocean acidification
- And—of course—reduce global average temperatures

Evidence from 12-model GeoMIP comparisons and from high-resolution state-of-art models.

Absence of strong counter evidence: 19 years of climate model studies of solar geoengineering combined a strong—and healthy—bias to look for problems yet no strong evidence that contradict these conclusions.
Question 2: Is it possible to engineer uniform radiative forcing?

Evidence
- Models of dynamics and aerosol microphysics $\leftrightarrow$ observations of aerosols and tracers
- Feedback experiments & control theory $\rightarrow$ reasonable uniformity can be achieved even with substantial model uncertainty.
- Solid aerosols exist which have better properties than sulfates including less stratospheric heating, less ozone loss or even ozone recovery.
- Multiple methods for remote sensing of stratospheric aerosol

Caveats
- Practical aircraft do not exist today
- While solid aerosols can be produced and lofted to stratosphere there are deep uncertainties about dispersal
- Existing models do not resolve plume-scale processes

Operational definition of “uniform”: Global mean 2 Wm$^{-2}$, NH-SH balance to 2%, Max deviation in 10-degree zonal bands < 20%, Strat heating less that 1 K zonal mean
Active Research Program
- International, open-access, multi-disciplinary, non-commercial
  - Positive Findings
    - Solar geoengineering can reduce climate risks
  - Informed deployment decision
    - Yes → Climate risks reduced
    - No → No Change

Negative Findings
- Is risky, does not work
  - No Change

Start Serious Research Program?
- No Research Program
  - Occasional academic papers & debate, no systematic risk assessment
  - Uninformed deployment decision
    - Yes → ???
    - No → No Change

- Yes → Start Serious Research Program?
  - No → No Change
Probability of <1.5: trade off between rate of decarbonization & ramp solar geoengineering

Model: FIAR v1.3
No overshoot
CO₂ linear fit to last 3 decades
Exponential decline starts in 2020
Risk and efficacy

**Forcing**

**Risks (of stratospheric sulfates)**
- Stratospheric ozone loss
  - Direct Cl and Br activation
  - NOx cycle
- Warming of lower stratosphere
  - increased water vapor
  - changes in stratospheric dynamics
- Impacts in the troposphere
  - Health impacts of particulates.
  - Acid rain
  - Upper tropospheric cirrus
- Increase in diffuse light
  - Ecosystem changes
  - Tropospheric chemistry impacts of increased fluence

**Response**

**Efficacy (of SRM)**
- Regional response
- Precipitation
- Variability
- Cryosphere
- “Standard” climate impacts:
  - Crops
  - Hydrology
  - Unmanaged ecosystems.
  - Air quality
Halving warming with idealized solar geoengineering moderates key climate hazards, NCC, forthcoming.
Stratospheric Controlled Perturbation Experiment (SCoPEx)

Overall goal: quantitative measurements of aerosol microphysics and atmospheric chemistry to improve large-scale models used to assess the risks and benefits of solar geoengineering

Specific objectives:

- Test models of chlorine activation by aerosols under mid-latitude conditions.

- Test predictions of chemical response to CaCO$_3$ aerosol.

- Testing models of small scale stratospheric mixing.

- Test ability to generate and observe regions with perturbed aerosols and chemical constituents.

- Develop and test a propelled balloon that creates and monitors region of perturbed chemistry in the stratosphere.
SCoPEx: Basic design and concept of operations

Perturbative experiment requires:
(a) means to create a well-mixed, small perturbed volume
(b) observation of time evolution of chemistry and aerosols in the volume.

SCoPEx will used a propelled balloon gondola containing all instruments and drive system.

Aircraft are the usually the best platform for studying the current atmosphere where experiments exploit natural variability over a long flight track, but aircraft move too fast and may have insufficient loiter time for creating and observing a small perturbed volume.

A balloon naturally follows perturbed air mass, with little disturbance to surrounding air.
SCoPEx payload structure concept

Commercially available materials and demonstrated designs allow for parametric payload design.

- Leverage demonstrated Structural Designs and Concepts
  - SPIDER Balloon-borne Telescope
  - ASCENA Proposal
- Modular structural components
  - Multiple payload configurations
  - Scalable platform sizes
- Capitalize on World View balloon improved flight dynamics and control
  - “Controlled” landing
  - <10 g impact loading
The SCoPEx propellers serve two linked functions

- The propeller wake forms a well mixed volume (roughly 1 km long and 100 meters in diameter) that serves as an experimental ‘beaker’.
- The propellers then allow the gondola to fly back and forth through the volume to measure the properties of the perturbed air mass.

Representative dense plume

- 2 km × 100 m radius
- 0.3 μm radius CaCO$_3$ particles at 50 cm$^{-3}$
- Total aerosol mass 1 kg
Why not do it in the lab?

Very hard to reproduce know stratospheric conditions in the lab

- Can’t make wall-less environment. Surfaces and trapped volumes can act as reservoir and reactors.
- Radicals which play central roles in stratospheric chemistry are destroyed by contact with wall.
- Hard to impossible to duplication radiative environment
  - The hard UV flux
  - Scattering and polarization from atmospheric gas, aerosols and clouds

We don’t know all the relevant details of stratospheric condition.

- So, even if lab could perfectly replicate a prescribed stratospheric environment, it might differ in detail from the real environment.
  - For example, composition of stratospheric aerosol may have less sulfate than previously assumed.