Solar Geoengineering & Direct Air Capture

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HARVARD Kennedy School

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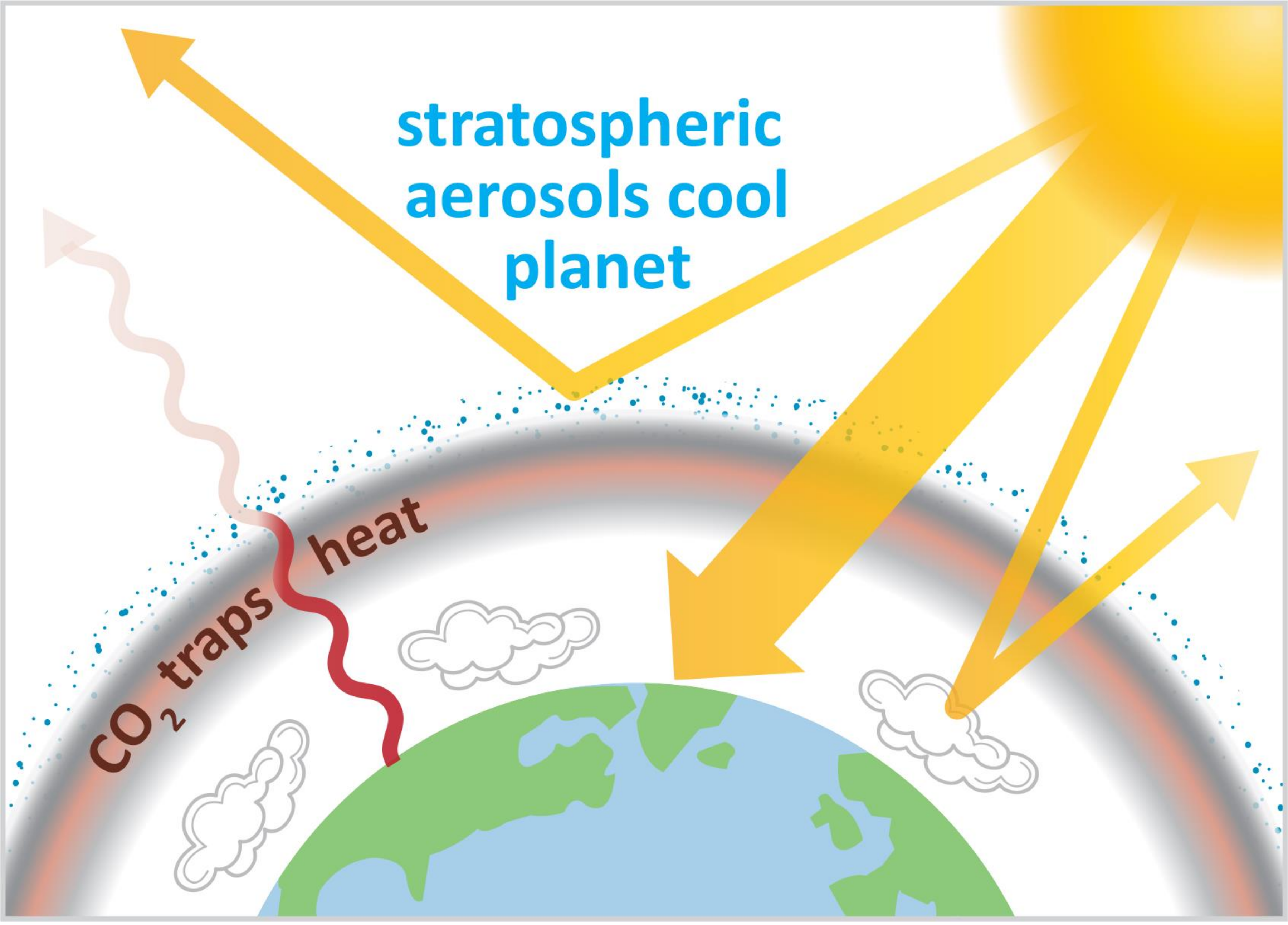
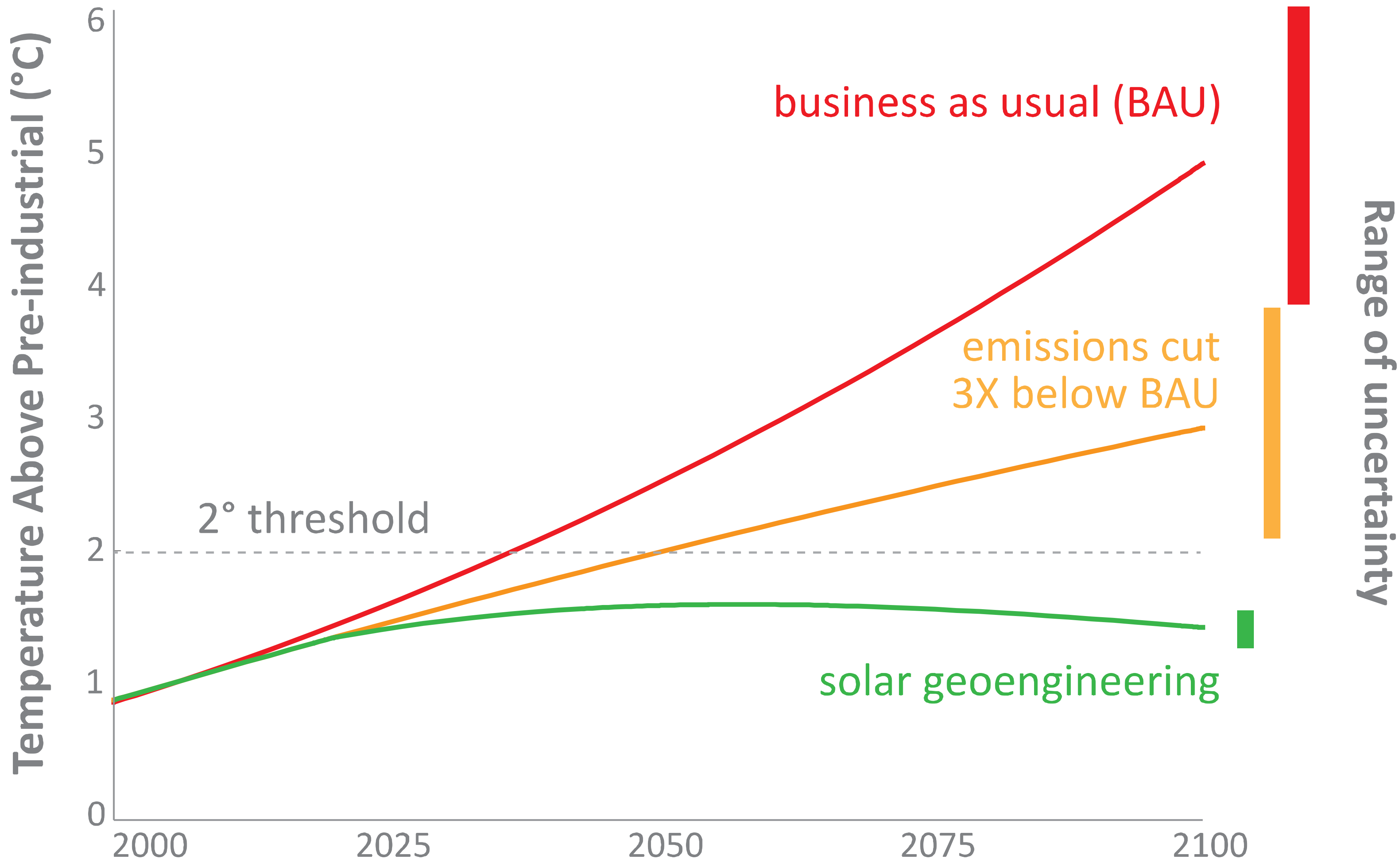
Solar geoengineering


stratospheric
aerosols cool
planet
CO_2 traps heat



Temperature Above Pre-industrial (°C)
6
5
4
3
2
1
0
2000
2025
2050
2075
2100
business as usual (BAU)
emissions cut
3X below BAU
2° threshold
solar geoengineering
Range of uncertainty

Method	Confidence that substantial global ΔRF (e.g. > 3 Wm^{-2}) is achievable	Advantage	Disadvantage
Strat sulfates	Very high: Current technologies can likely be adapted to loft materials and disperse SO_2 and relevant scales	Similarity to volcanic sulfate gives empirical basis for estimating efficacy and risks	Hard to adjust zonal distribution; ozone loss; stratospheric heating
Other strat aerosol	Moderate: depends on aerosol, lofting similar to sulfate but aerosol dispersal much more uncertain	Some solid aerosols may have less strat heating and minimal ozone loss	Hard to adjust zonal distribution; higher uncertainty than sulfates
Marine clouds	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	Ability to make local alterations of albedo; ability to albedo modulate on short timescales.	Only applicable on marine stratus covering ~10% of earth means RF inherently patchy; fast timescale rases termination risk
Cirrus	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	Works on LW more than SW so could provide better compensation than "perfect" strat or space-based scatters; better RF uniformity that MCB	More ability to adjust zonal distribution that strat aerosols, perhaps less meridional adjustability.
Space based	Low physical uncertainty, but deep technological uncertainties about cost and feasibility	Possibility of near "perfect" alteration of solar constant. Spectral tailoring may be easier	Some methods (e.g. L1 point) would not allow zonal or meridional tailoring of RF

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

Carbon Engineering's
Direct Air Capture (DAC)

2005: Spray Tower

2008: Packed Tower

2010: Lab Air Contactor

2011: Pellet Reactor Tests

2011-2012: Air Contactor Prototype

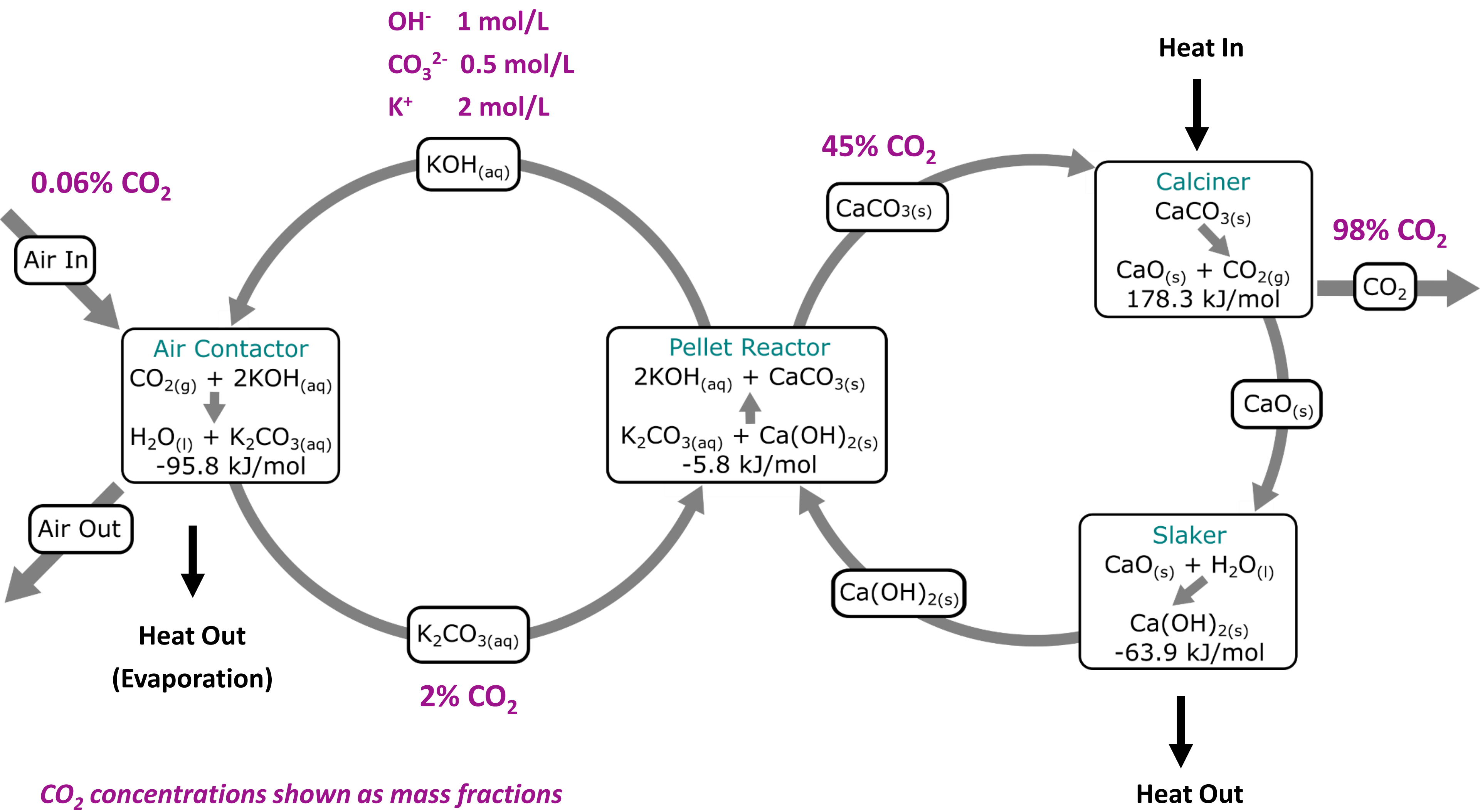
2013: Calciner Tests

2015-2018: End-to-End Pilot Plant

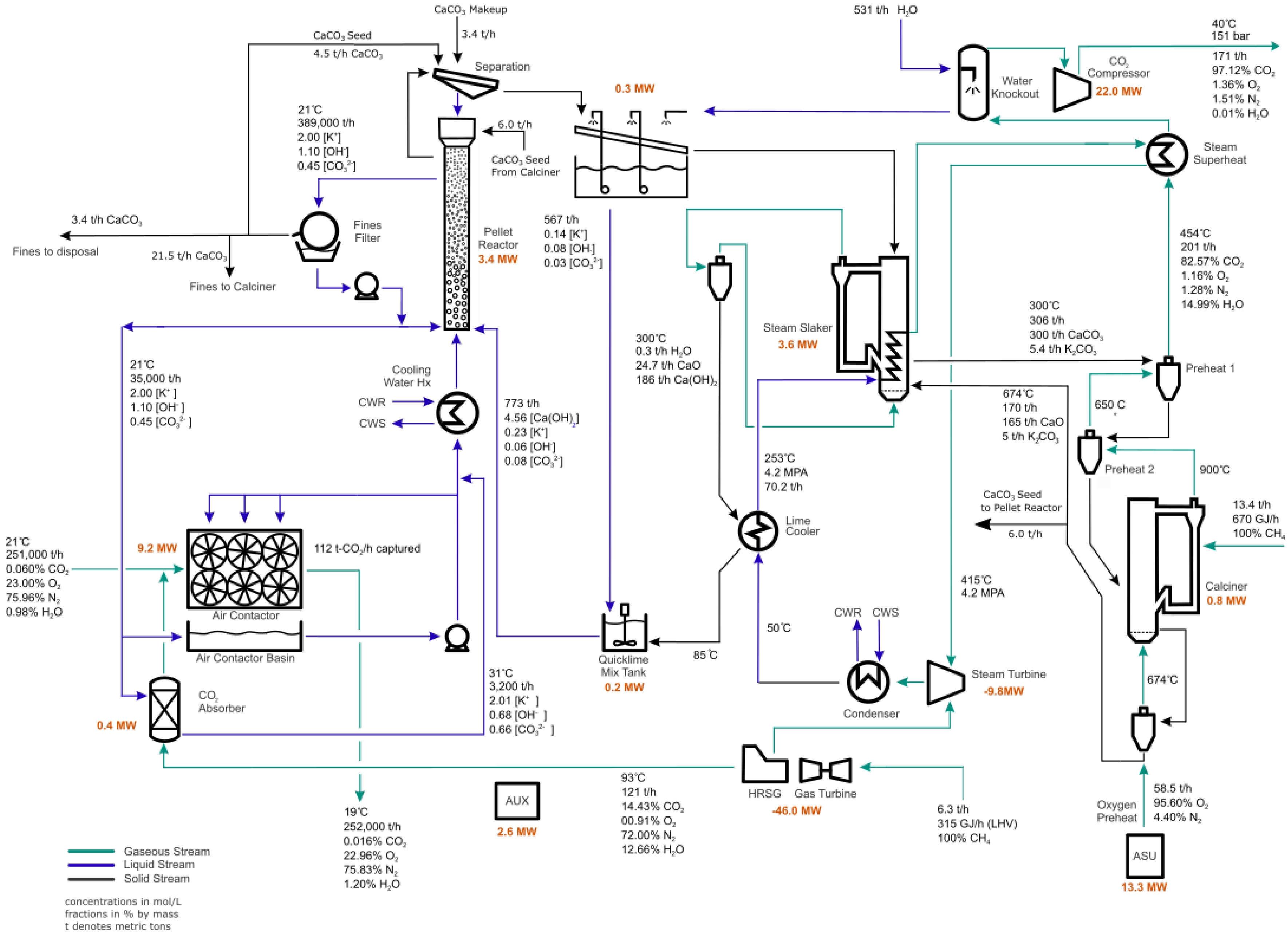
Carbon Engineering

Hardware-focused business-oriented development from day one

Direct Air Capture – Chemical Looping, CO_2 from 0.06 → 98%



CO_2 concentrations shown as mass fractions



$CaCO_3$ Makeup
3.4 t/h
$CaCO_3$ Seed
4.5 t/h $CaCO_3$
Separation
21˚C
389,000 t/h
2.00 [K⁺]
1.10 [OH⁻]
0.45 [CO_3^{2-}]
6.0 t/h
$CaCO_3$ Seed From Calciner
3.4 t/h $CaCO_3$
Fines to disposal
21.5 t/h $CaCO_3$
Fines to Calciner
Fines Filter
Pellet Reactor
3.4 MW
567 t/h
0.14 [K⁺]
0.08 [OH⁻]
0.03 [CO_3^{2-}]
0.3 MW
531 t/h H_2O
Water Knockout
CO_2 Compressor
22.0 MW
40˚C
151 bar
171 t/h
97.12% CO_2
1.36% O_2
1.51% N_2
0.01% H_2O
Steam Superheat
454˚C
201 t/h
82.57% CO_2
1.16% O_2
1.28% N_2
14.99% H_2O
21˚C
35,000 t/h
2.00 [K⁺]
1.10 [OH⁻]
0.45 [CO_3^{2-}]
Cooling Water Hx
CWR
CWS
773 t/h
4.56 [$Ca(OH)_2$]
0.23 [K⁺]
0.06 [OH⁻]
0.08 [CO_3^{2-}]
300˚C
0.3 t/h H_2O
24.7 t/h CaO
186 t/h $Ca(OH)_2$
Steam Slaker
3.6 MW
300˚C
306 t/h
300 t/h $CaCO_3$
5.4 t/h K_2CO_3
Preheat 1
674˚C
170 t/h
165 t/h CaO
5 t/h K_2CO_3
650 C
Preheat 2
900˚C
253˚C
4.2 MPA
70.2 t/h
Lime Cooler
$CaCO_3$ Seed to Pellet Reactor
6.0 t/h
13.4 t/h
670 GJ/h
100% CH_4
Calciner
0.8 MW
415˚C
4.2 MPA
21˚C
251,000 t/h
0.060% CO_2
23.00% O_2
75.96% N_2
0.98% H_2O
9.2 MW
112 t-CO_2/h captured
Air Contactor
Air Contactor Basin
50˚C
CWR
CWS
Quicklime Mix Tank
0.2 MW
85˚C
Steam Turbine
-9.8MW
Condenser
674˚C
CO2 Absorber
0.4 MW
31˚C
3,200 t/h
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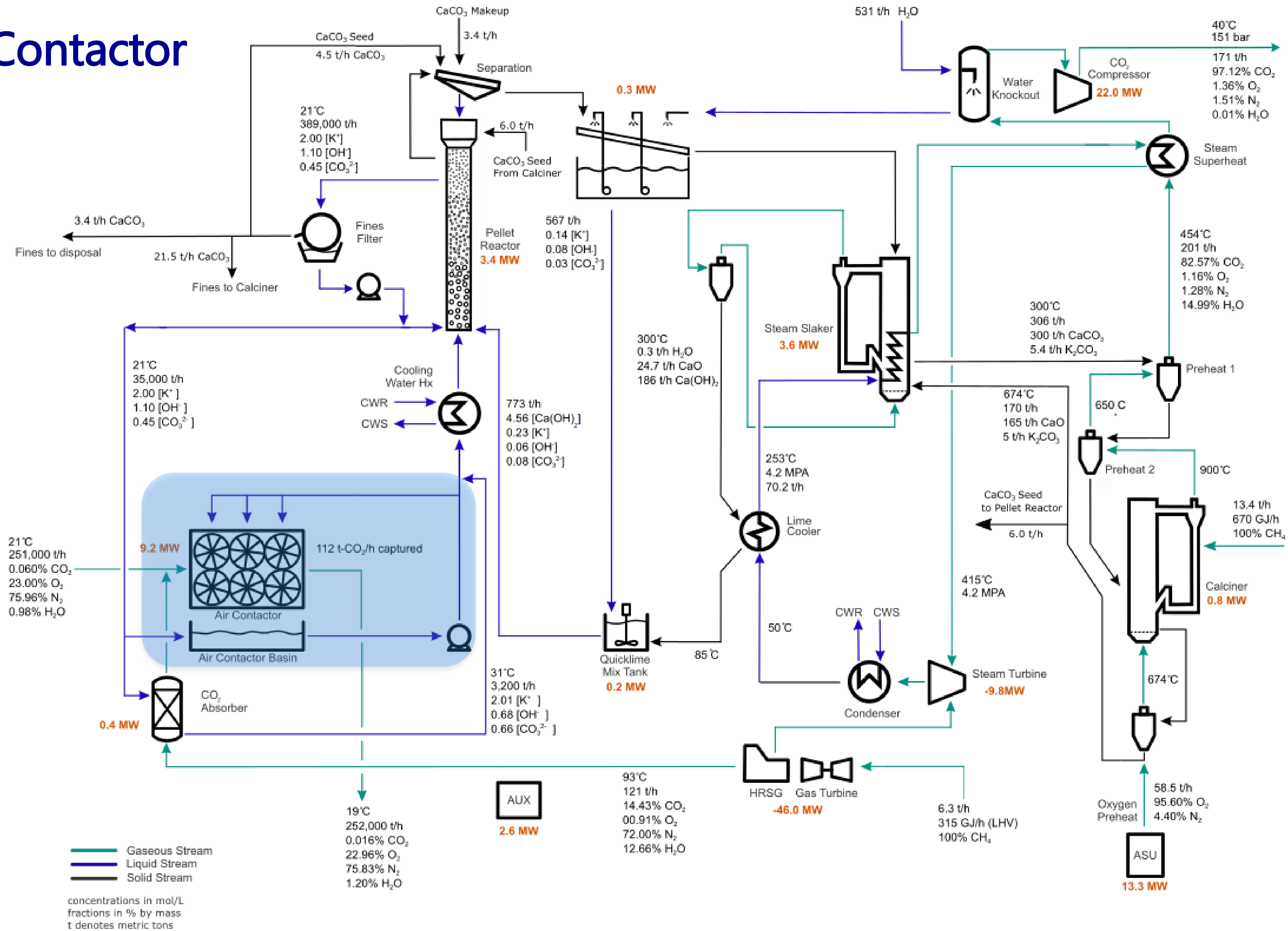
0.68 [OH⁻]
0.66 [CO_3^{2-}]
93˚C
121 t/h
14.43% CO_2
00.91% O_2
72.00% N_2
12.66% H_2O
HRSG
Gas Turbine
-46.0 MW
6.3 t/h
315 GJ/h (LHV)
100% CH_4
Oxygen Preheat
58.5 t/h
95.60% O_2
4.40% N_2
ASU
13.3 MW
AUX
2.6 MW
19˚C
252,000 t/h
0.016% CO_2
22.96% O_2
75.83% N_2
1.20% H_2O
Gaseous Stream
Liquid Stream
Solid Stream
concentrations in mol/L
fractions in % by mass
t denotes metric tons

Contactor



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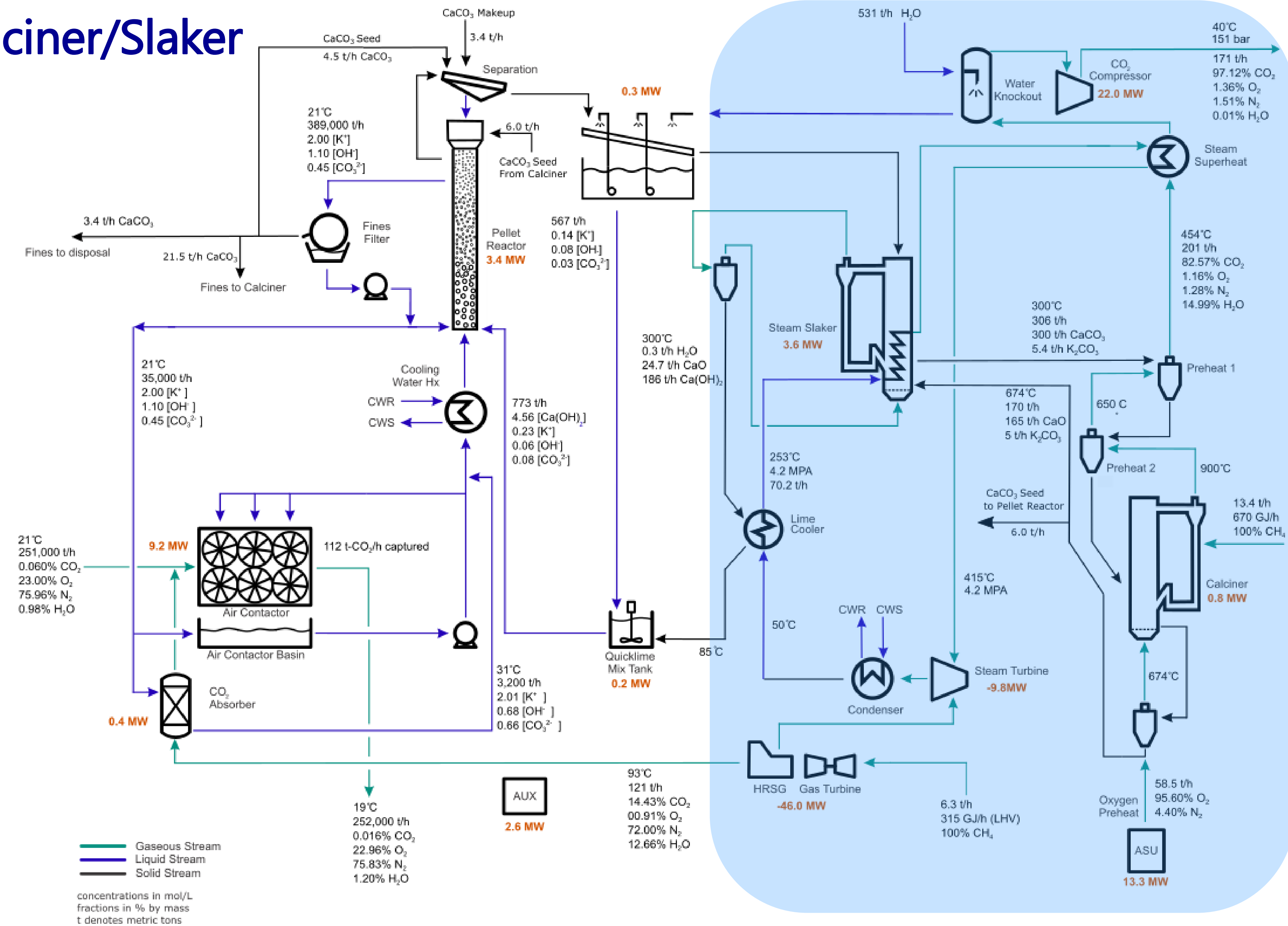
Gaseous Stream
Liquid Stream
Solid Stream
concentrations in mol/L
fractions in % by mass
t denotes metric tons

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 reco… mps and…

Calciner/Slaker



Carbon Engineering

Calciner – Design

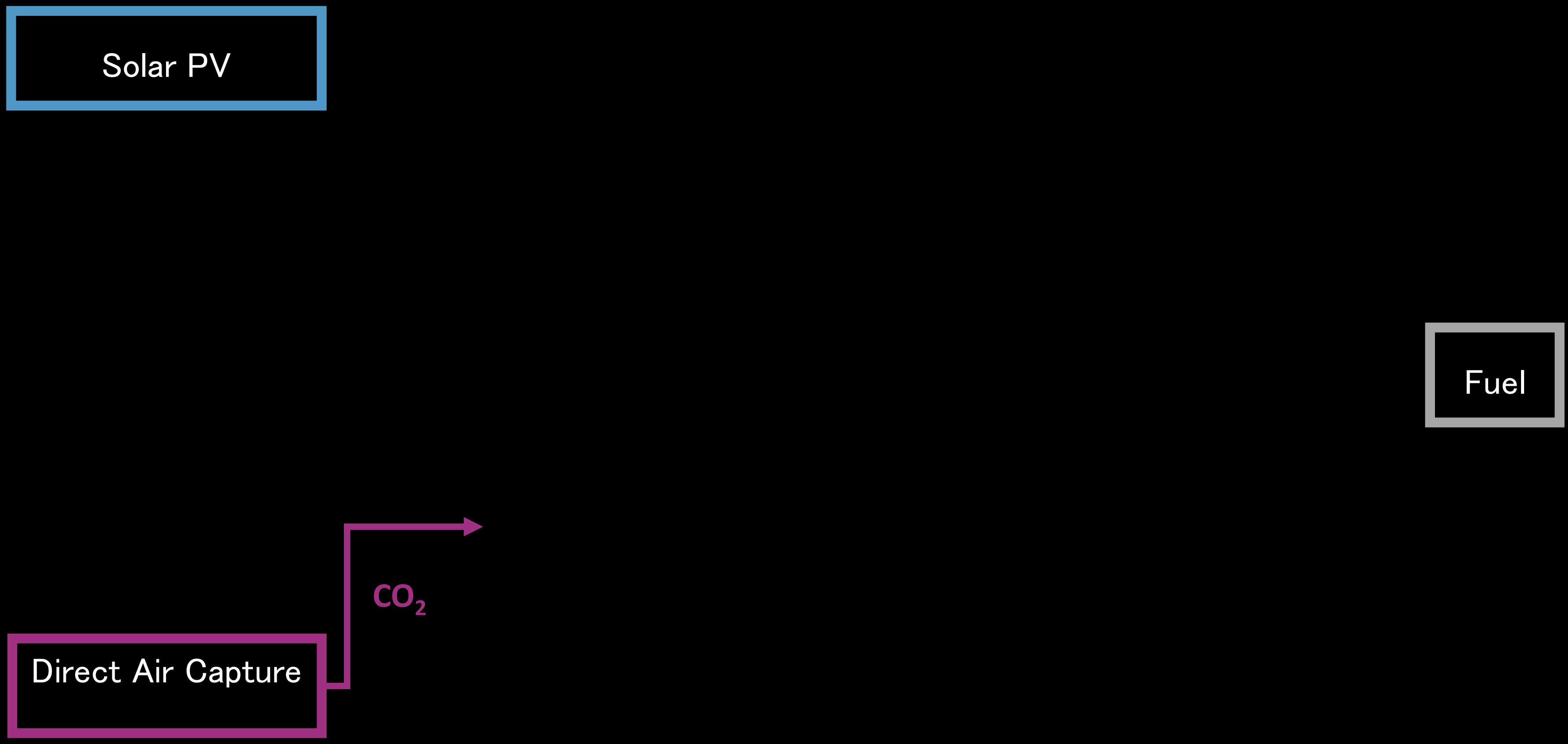
- Biased on circulating fluid bed ore roasters
- CFB design minimizes equipment footprint
- Oxy-firing ensures high capture fraction and puts all separation energy into the fuel-derived carbon

Highest single-train throughput capacity

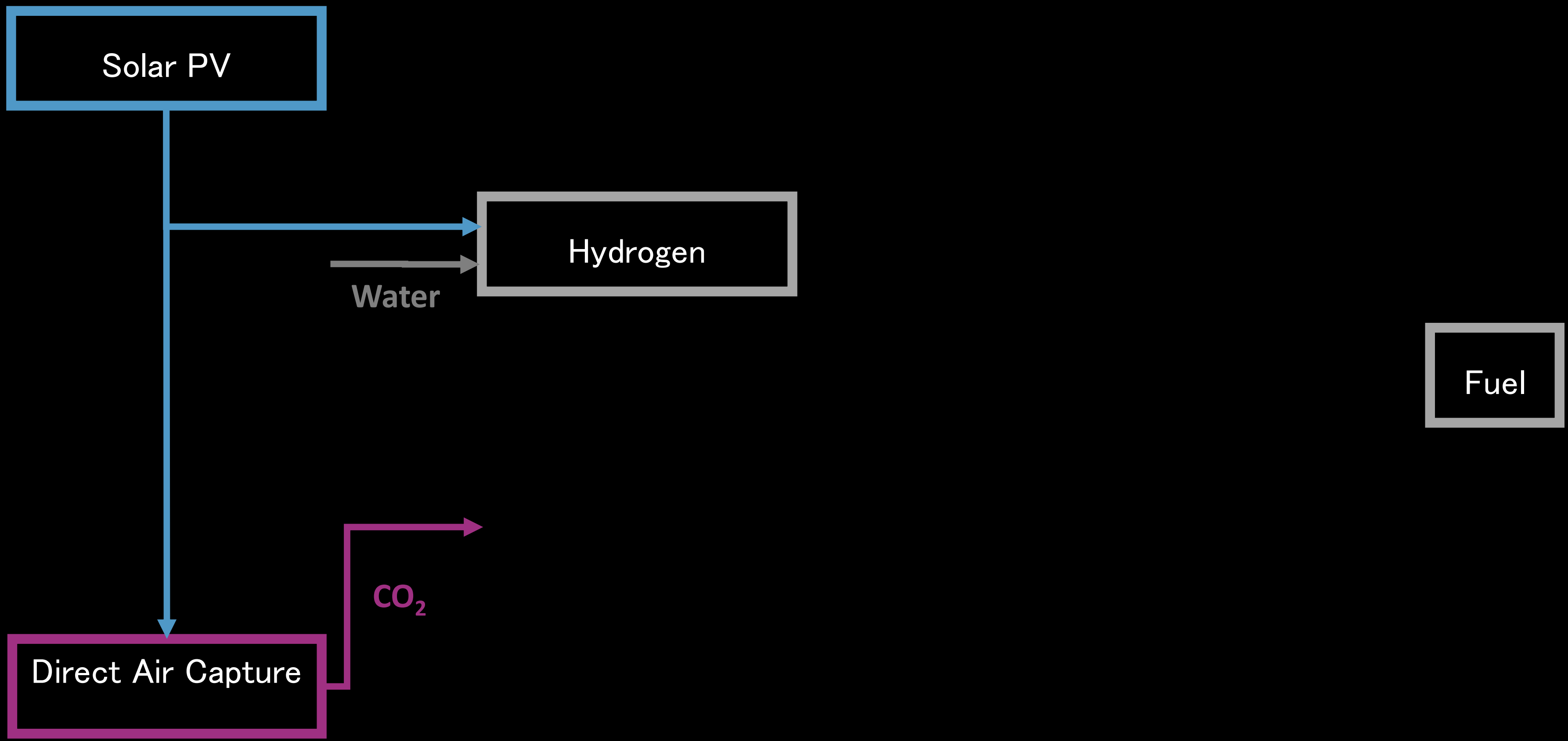
Summary performance of various DAC configurations

Scenario	Gas input[1] GJ/tCO_2	Electricity input[1] kWh/tCO_2	C-gas/ C-air	Capital $ per t-CO_2/yr	O&M[2] $/t-$CO_2$	Levelized[1] $/t-$CO_2$ CRF[3] 7.5%	12.5%
A: Baseline: gas fired → 15 MPa CO_2 output	8.81	0	0.48	1,127	37	168	232
B: Baseline with N[th]-plant financials	8.81	0	0.48	779	26	126	170
C: Gas and electricity → 15 MPa CO_2 output	5.25	366	0.30	778	26	113-124	152-163
D: Gas & electricity input→ 0.1 MPa CO_2 output assuming zero cost O_2	5.25	77	0.30	683	23	94-97	128-130

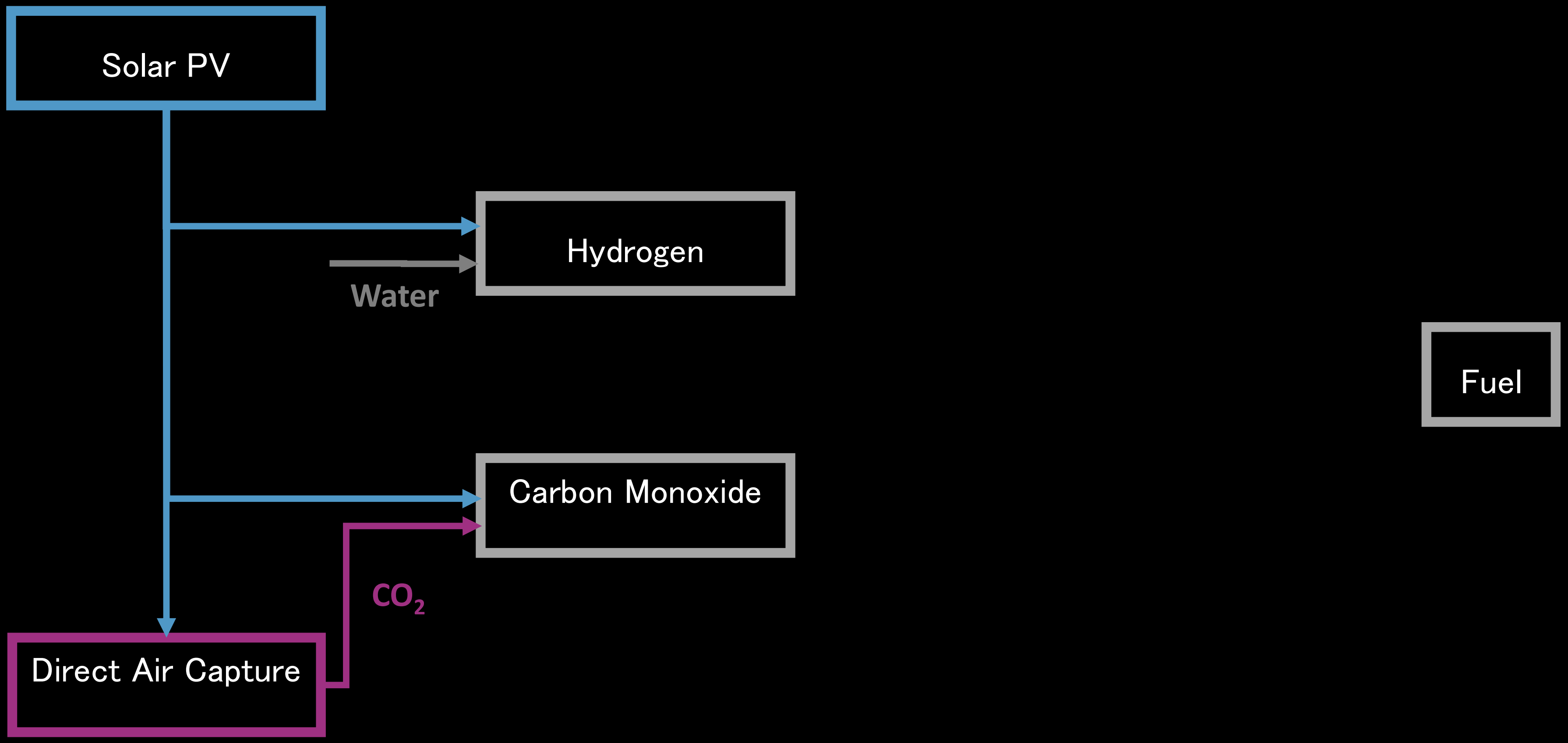
- (1) Gas and electrical inputs as well as levelized cost are all per ton CO_2 capture from the atmosphere.
- (2) Non-energy operations and maintenance expressed as fixed per unit of capacity with variable costs including cost of makeup-streams included and converted equivalent fixed costs as using 90% 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
Fuel
CO_2
Direct Air Capture

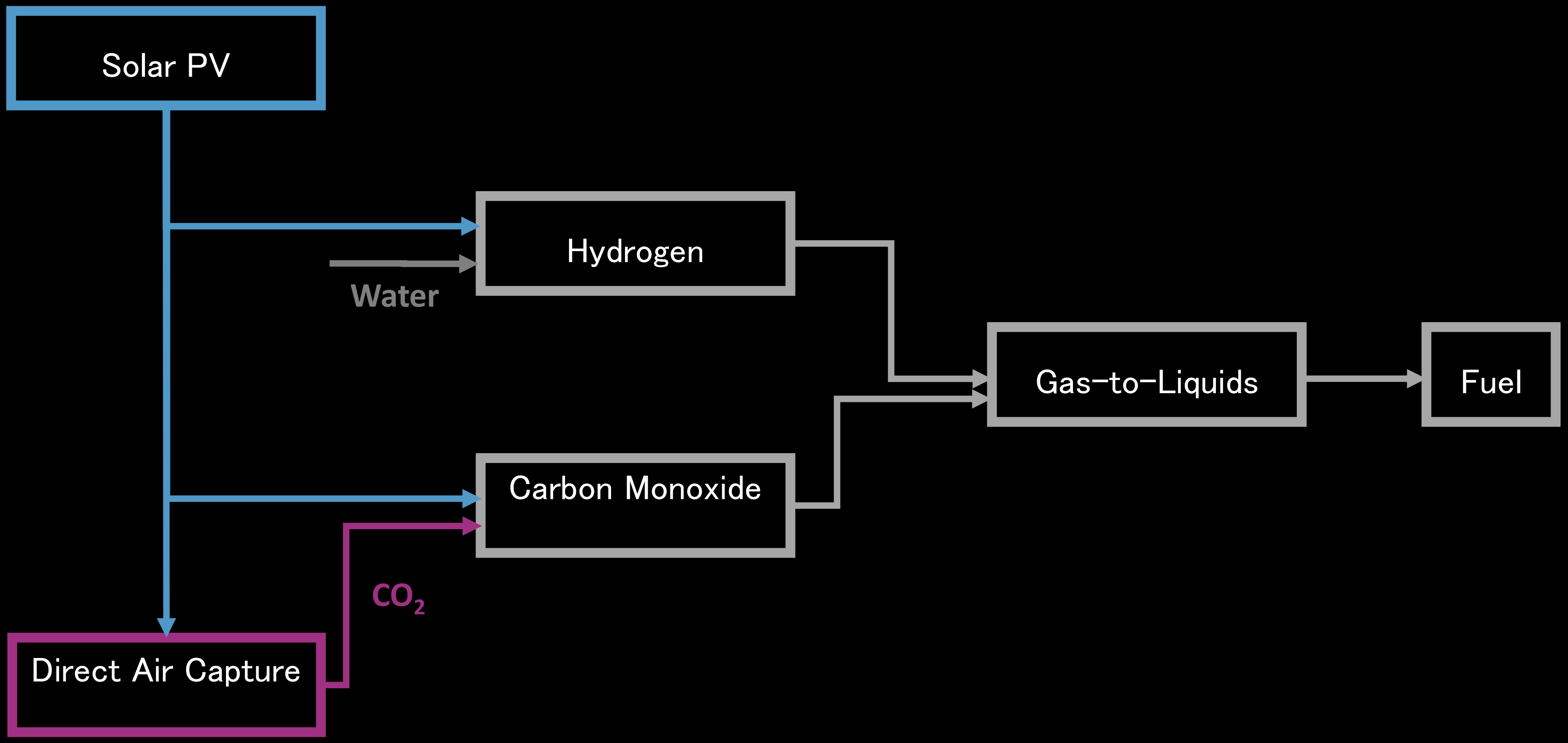



Solar PV
Hydrogen
Water
Fuel
CO_2
Direct Air Capture

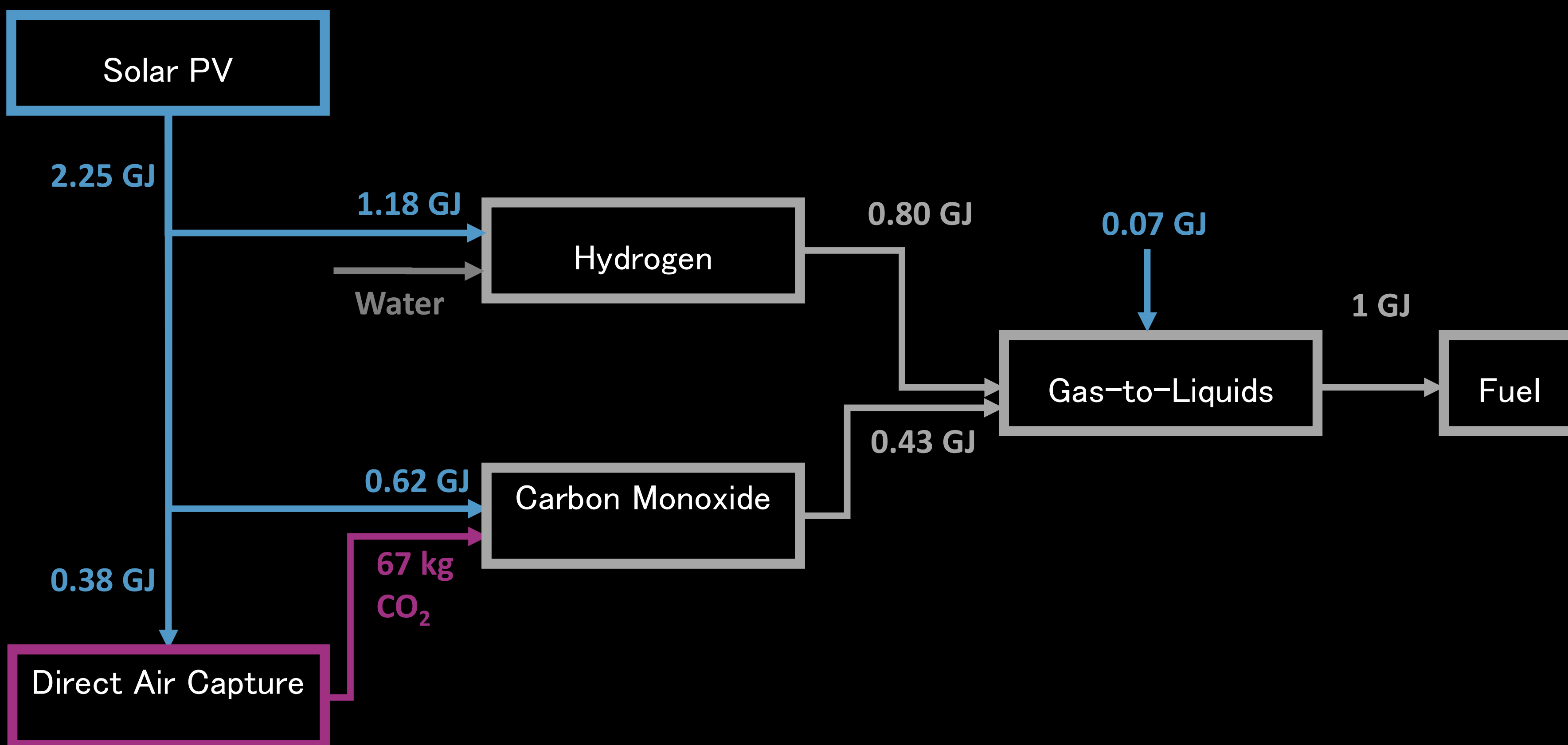
Malaysia: Nel Hydrogen, 25 MW alkaline electrolysis, completed 2013. The hydrogen is used to make polysilicon.

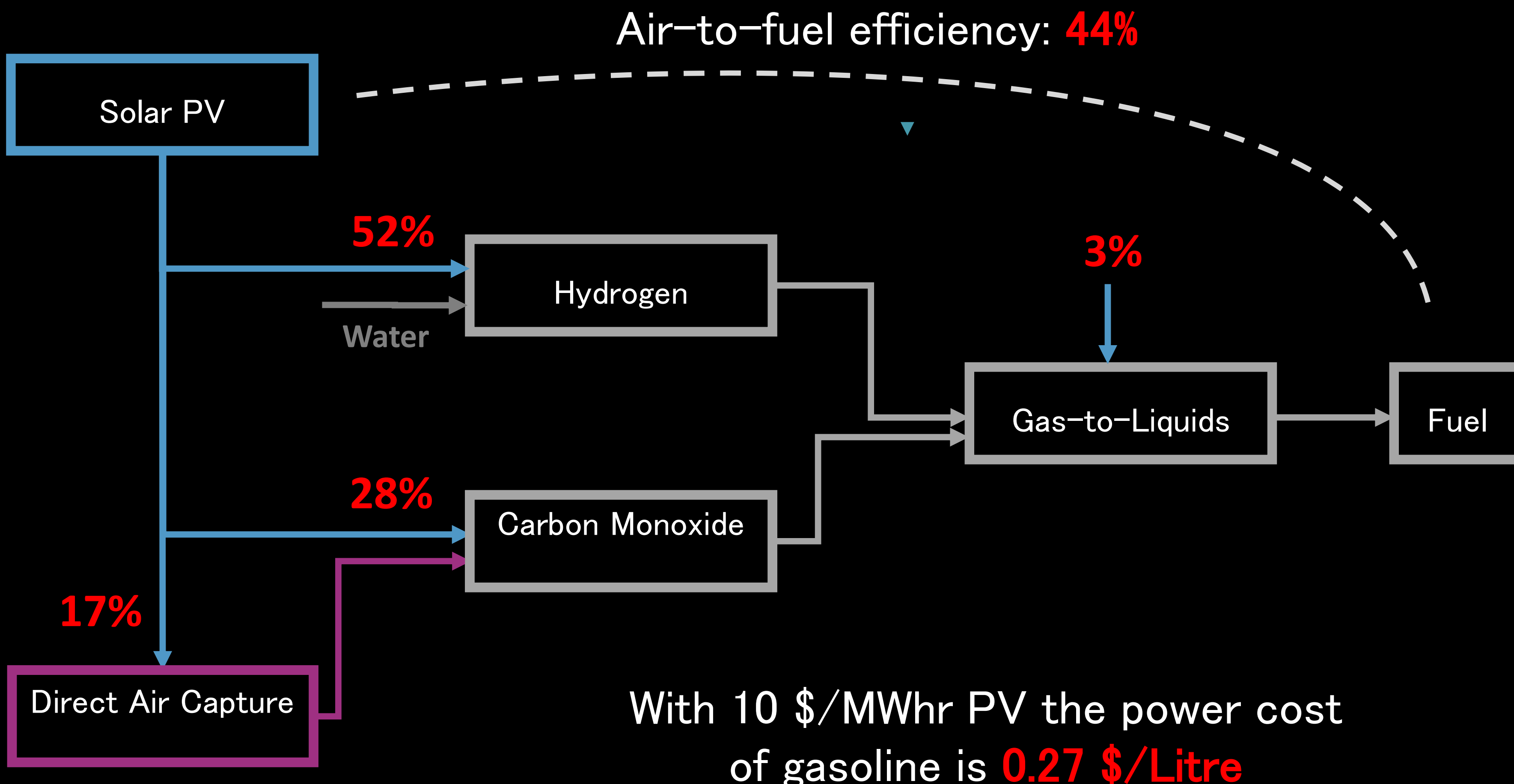

Solar PV
Hydrogen
Water
Fuel
Carbon Monoxide
CO_2
Direct Air Capture

Haldor Topsoe 300 kW modular “eCOs” electrolytic CO production entered commercial production in 2018


Solar PV
Hydrogen
Water
Gas-to-Liquids
Fuel
Carbon Monoxide
CO2
Direct Air Capture


Shell Pearl Gas-to-Liquids
140 thousand barrels per day


Solar PV
2.25 GJ
1.18 GJ
Hydrogen
Water
0.80 GJ
0.07 GJ
1 GJ
Gas-to-Liquids
Fuel
0.43 GJ
0.62 GJ
Carbon Monoxide
67 kg
CO_2
0.38 GJ
Direct Air Capture


Air–to–fuel efficiency: 44%
Solar PV
52%
Hydrogen
Water
3%
Gas–to–Liquids
Fuel
28%
Carbon Monoxide
17%
Direct Air Capture
With 10 $/MWhr PV the power cost
of gasoline is 0.27 $/Litre

Carbon Dioxide Removal (CDR)

Carbon Dioxide Removal (CDR)

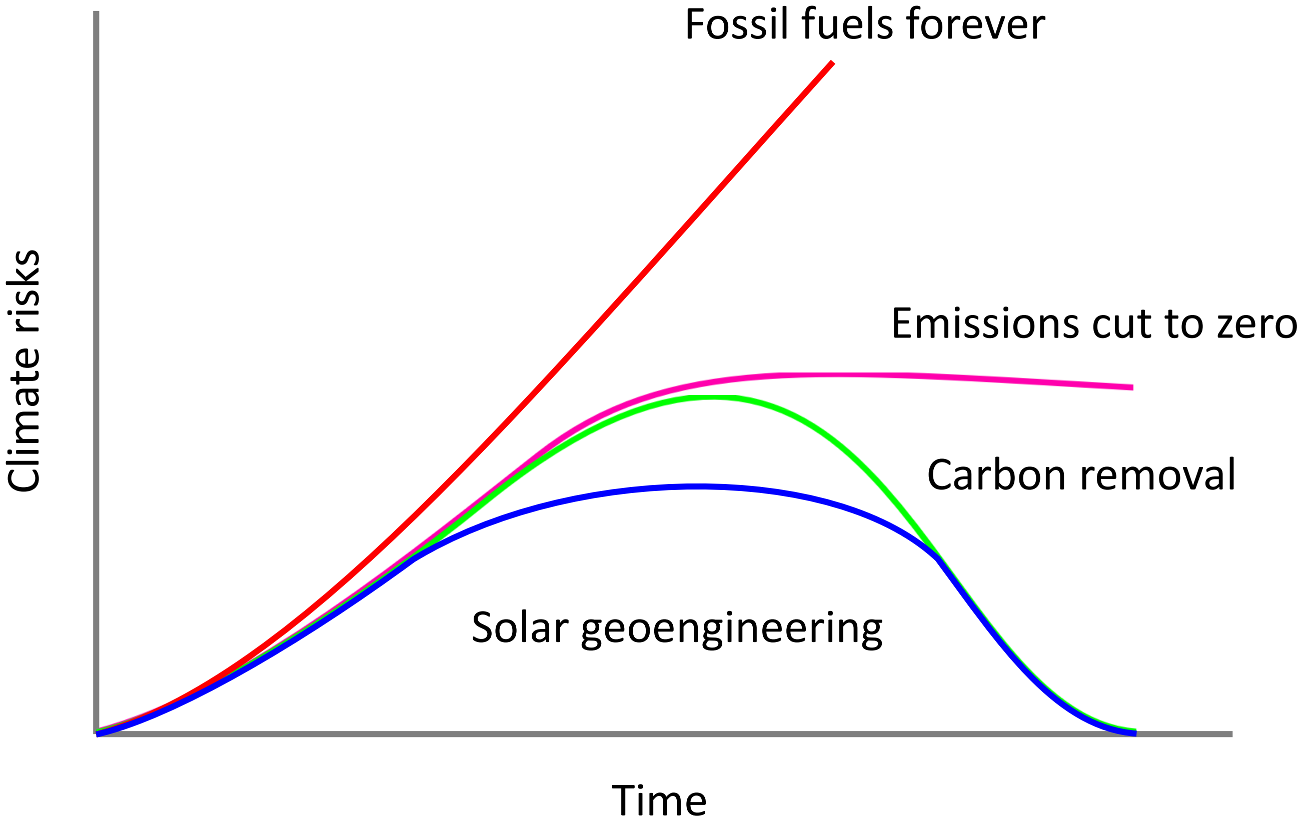
Ecological/social timescale

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

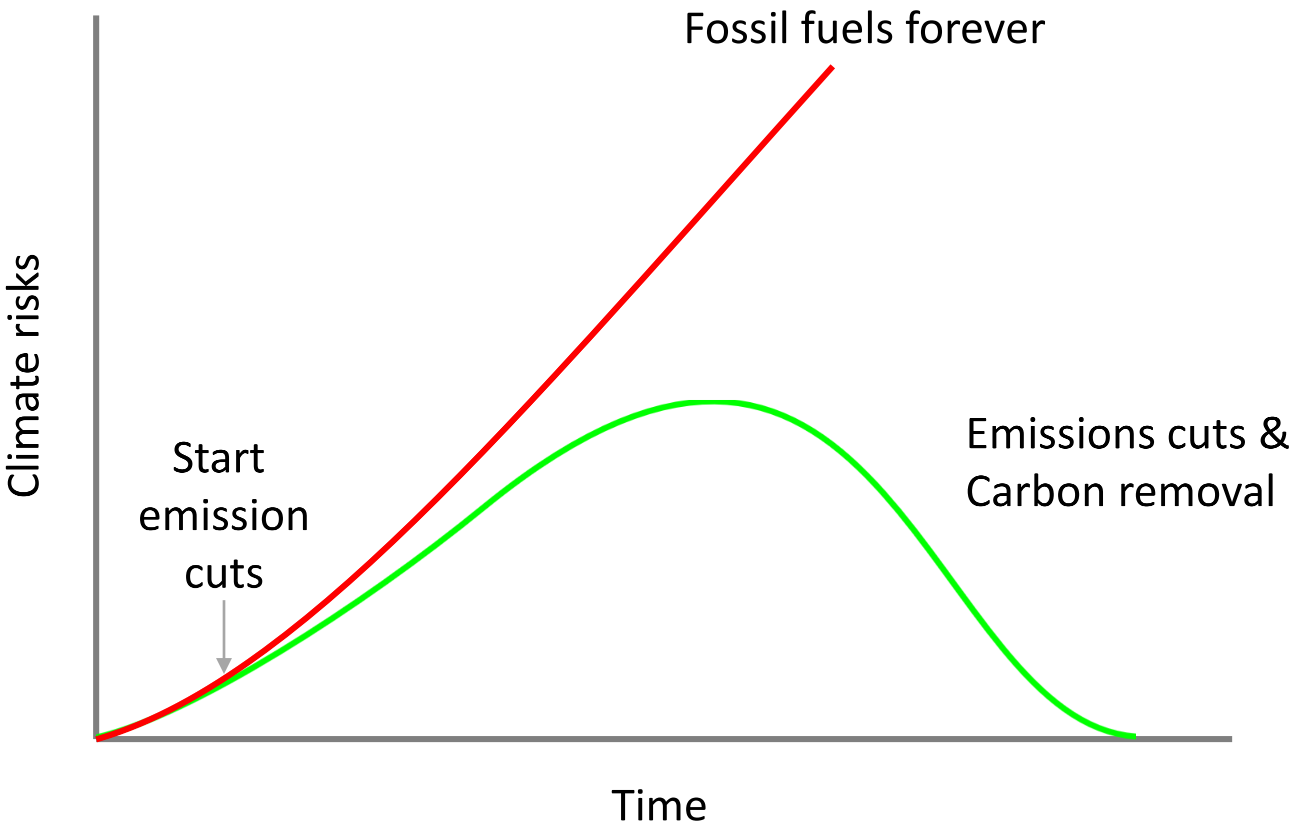
Geologic timescales

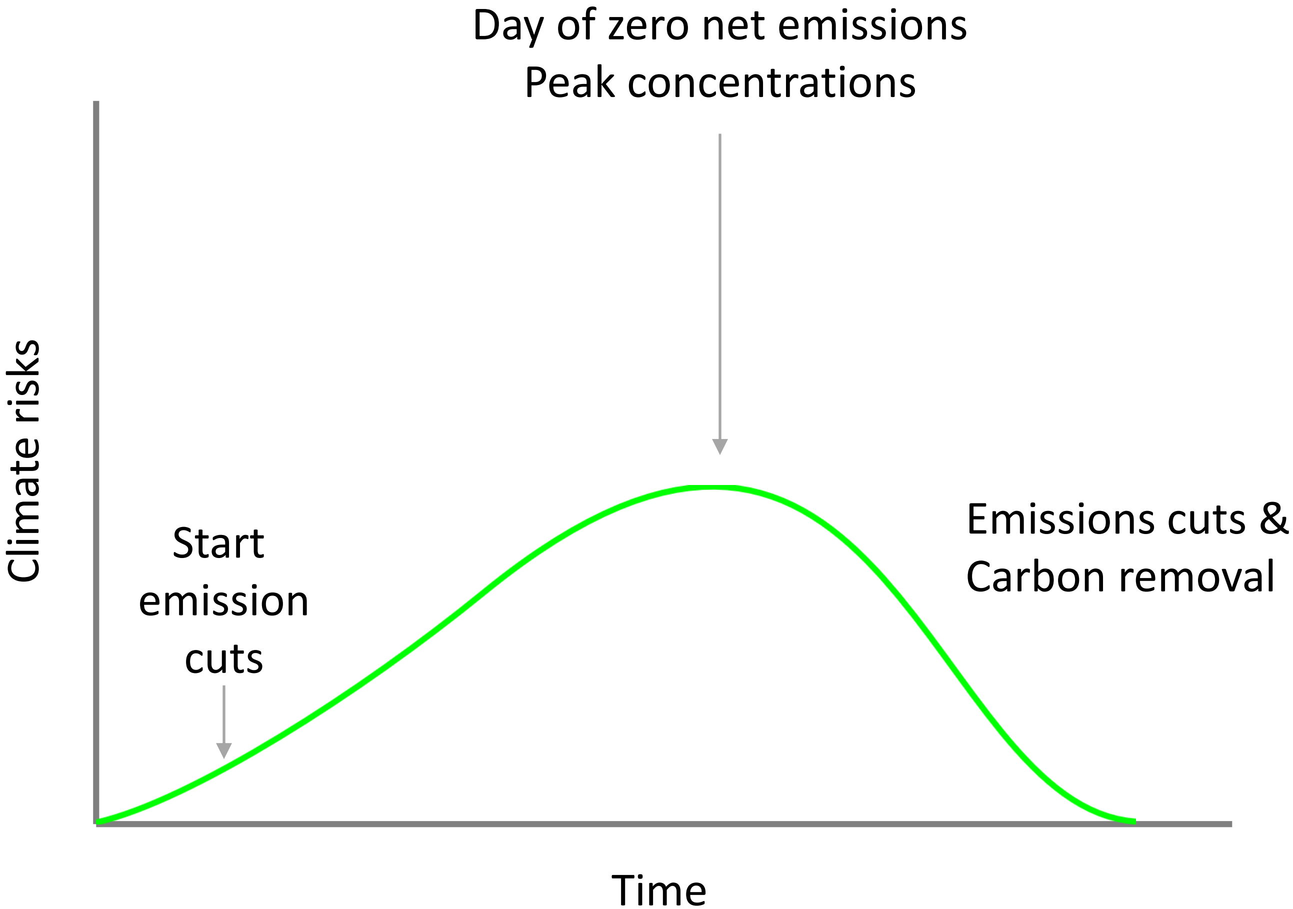
- Biomass energy + geologic storage (BECCS)
- Direct air capture + geologic storage (DAC-CCS)
- Addition of alkalinity to ocean

How might emissions cuts, CDR, and SRM fit into climate strategy?

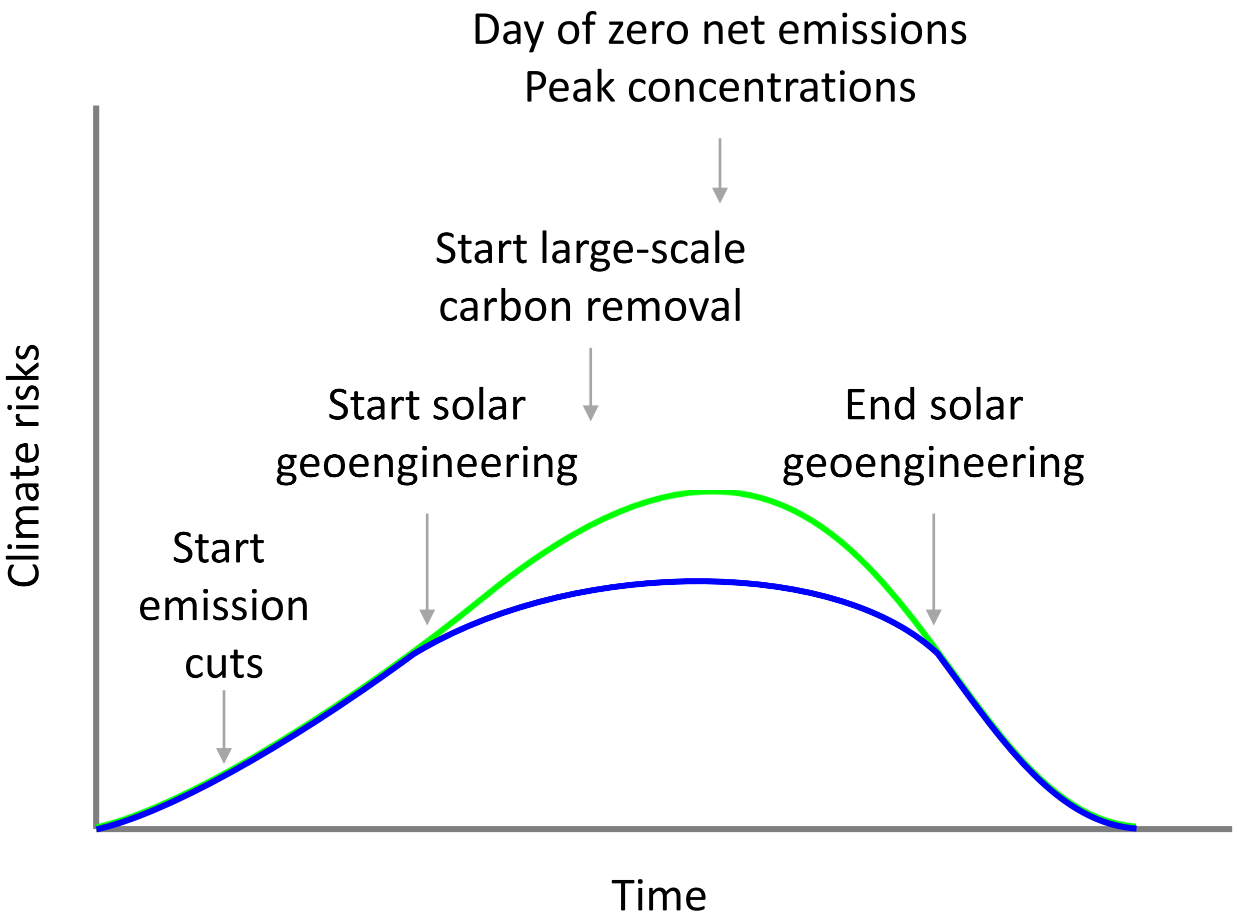


Fossil fuels forever
Emissions cut to zero
Carbon removal
Solar geoengineering
Climate risks
Time


Fossil fuels forever
Climate risks
Start
emission
cuts
Emissions cuts &
Carbon removal
Time



Day of zero net emissions
Peak concentrations
Climate risks
Start
emission
cuts
Emissions cuts &
Carbon removal
Time



Day of zero net emissions
Peak concentrations
Start large-scale carbon removal
Start solar geoengineering
End solar geoengineering
Start emission cuts
Climate risks
Time

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?

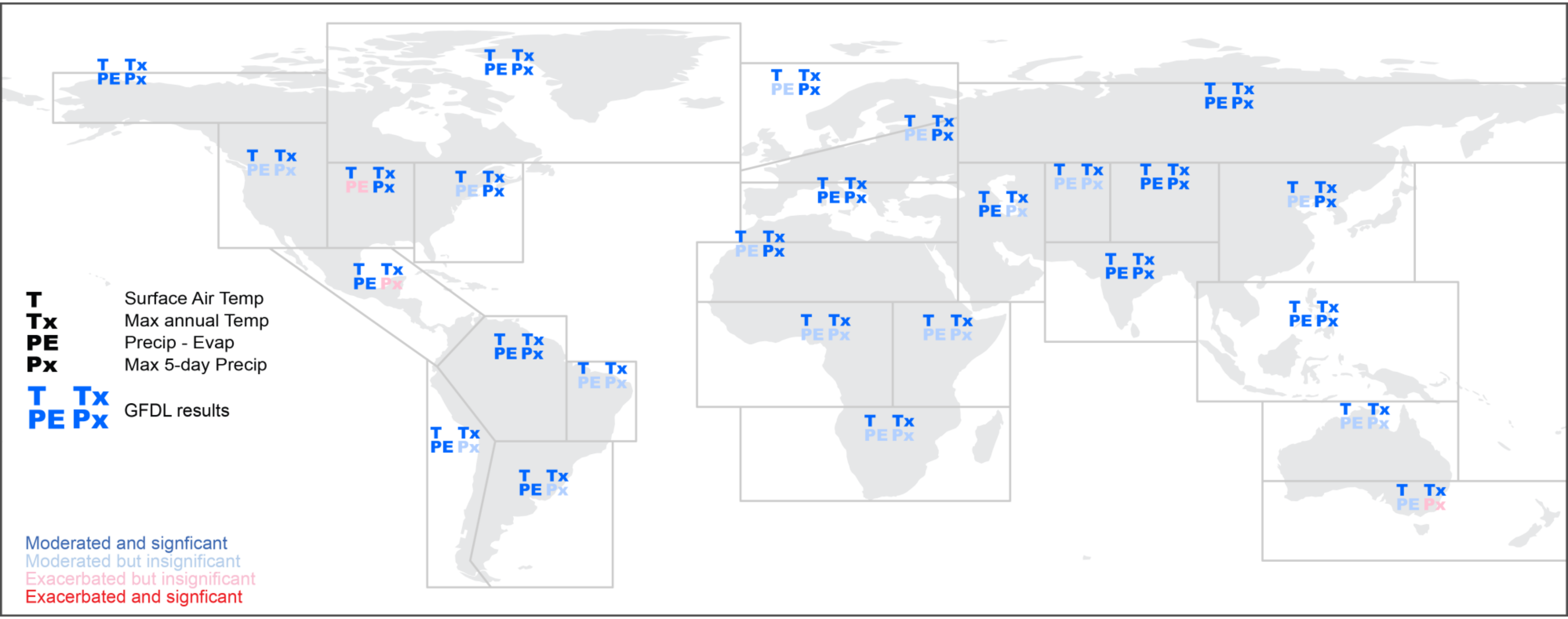
- With what side-effects?
- What cost?
- How controllable?

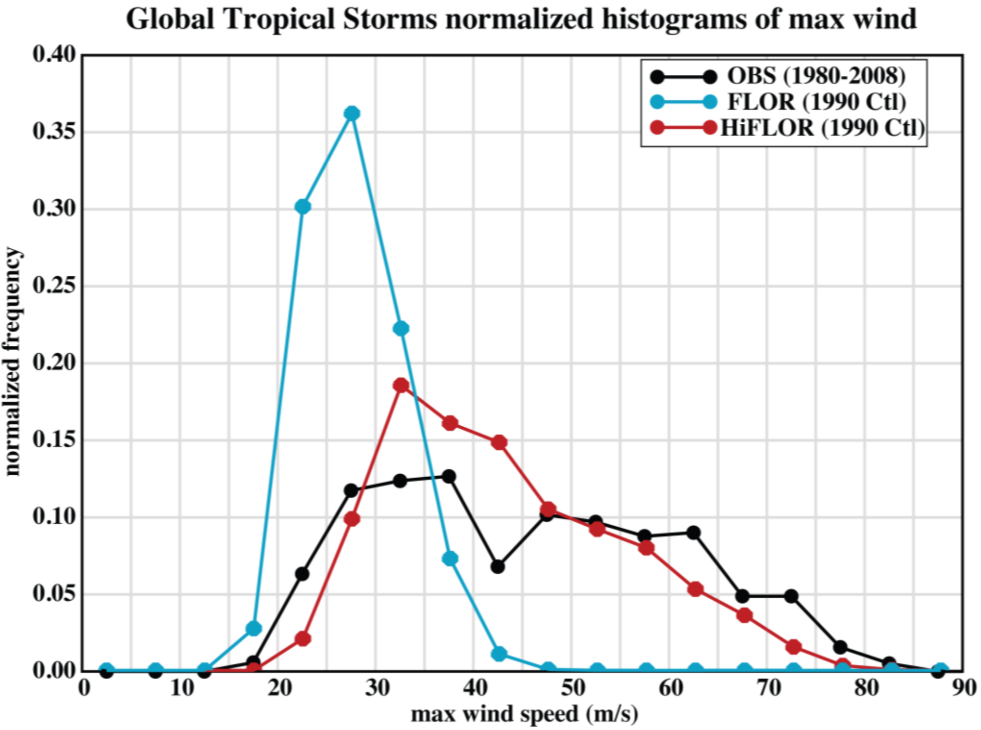
Tools: engineering, stratospheric models, aerosol micro-physics, control theory…

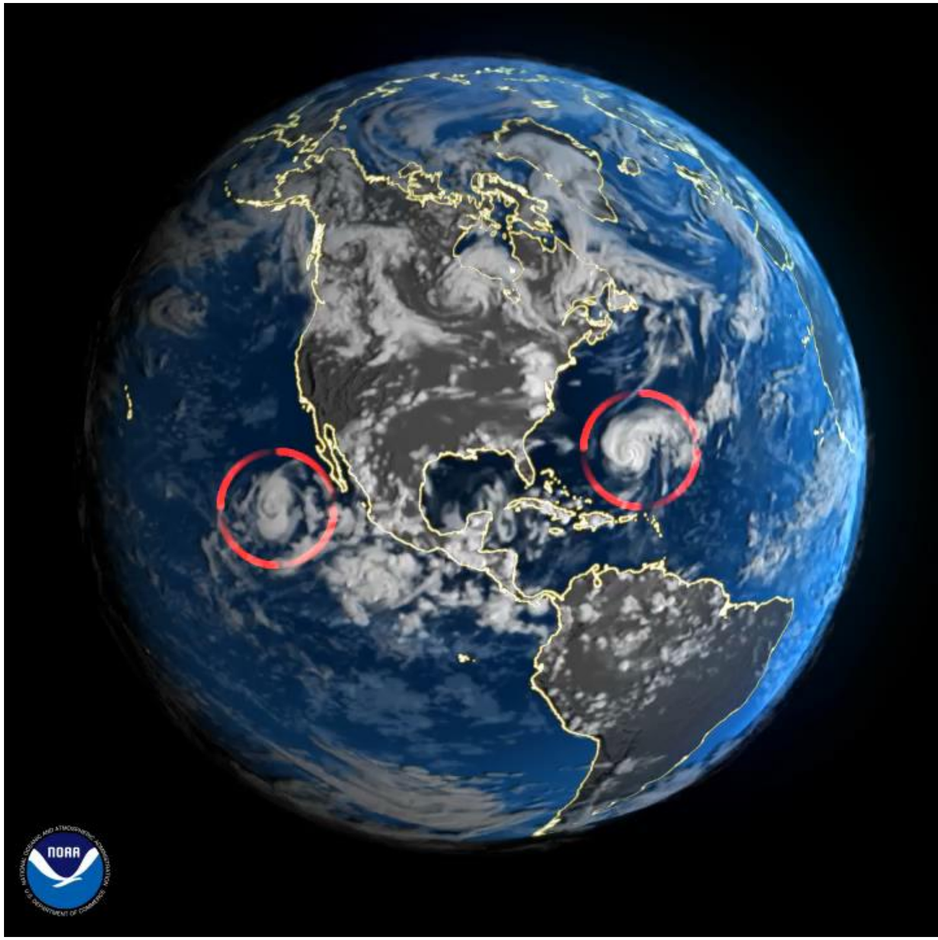
Question 1: Does a moderate & uniform reduction in RF reduce policy-relevant climate risks?

Evidence is strong that it would reduce hazards:

- Reduce regional changes in water availably
- Reduce regional increases in extreme precipitation
- Reduce tropical cyclone intensity
- Reduce regional changes in extreme temperatures


T Surface Air Temp
Tx Max annual Temp
PE Precip - Evap
Px Max 5-day Precip
T Tx PE Px GFDL results
Moderated and signficant
Moderated but insignificant
Exacerbated but insignificant
Exacerbated and signficant





HiFLOR (25km FV3 atmosphere coupled to 1° MOM5)

Murakami et al. (2015, J. Clim., in press

T Surface Air Temp
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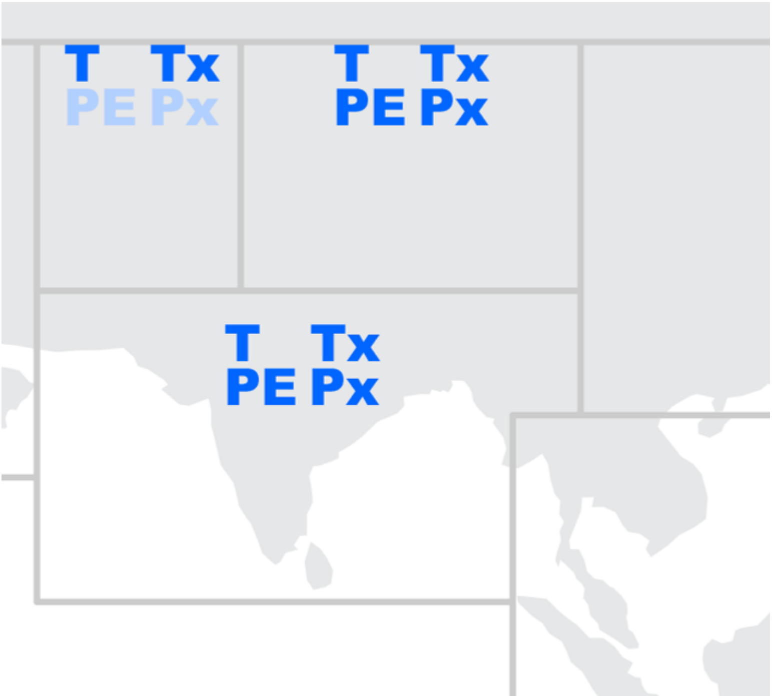

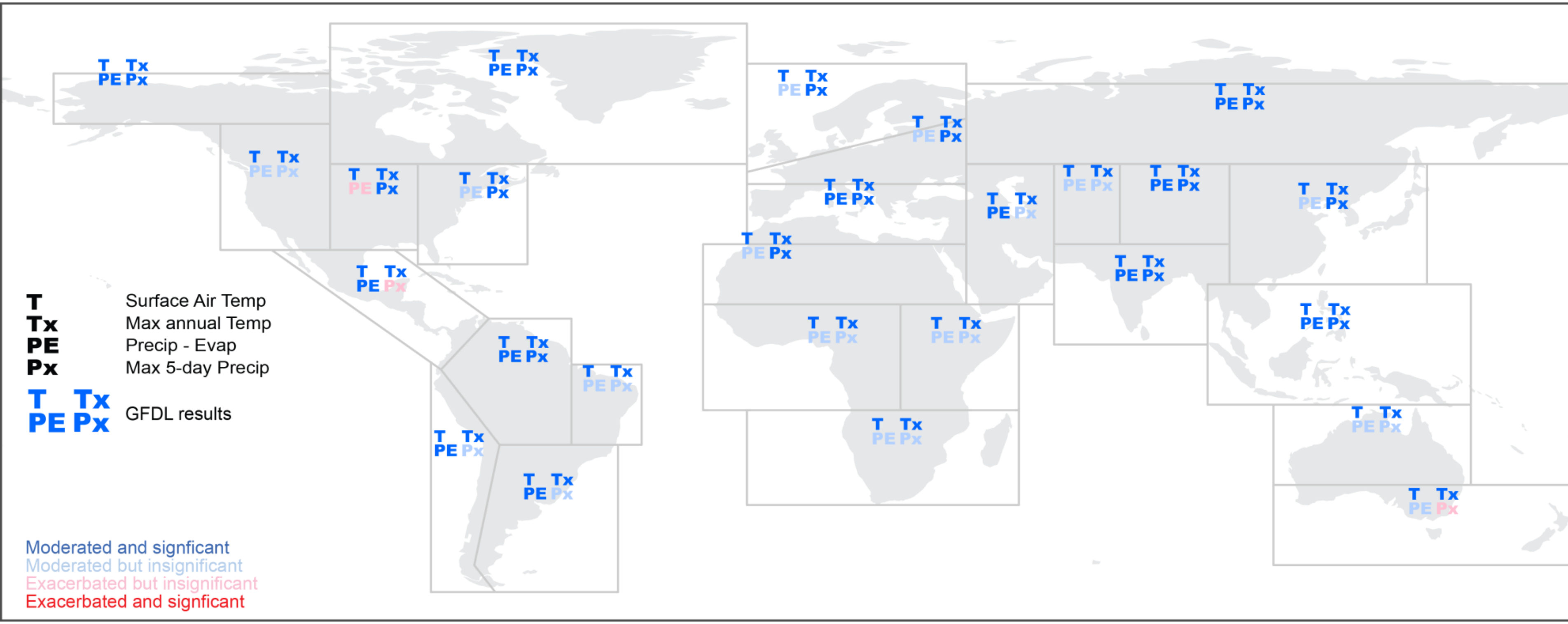
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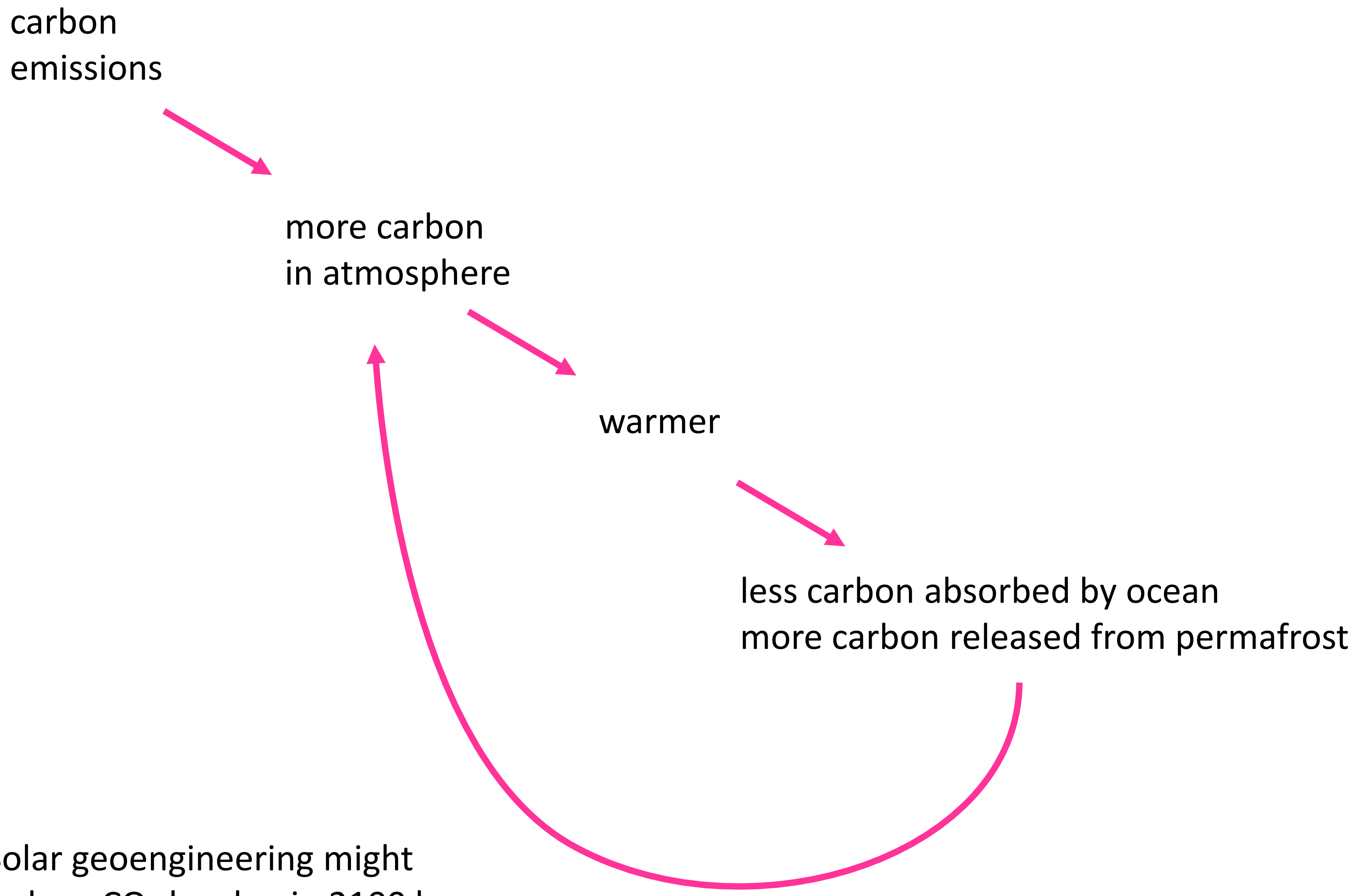
- Reduce sea level rise
- Reduce carbon concentrations and ocean acidification



Carbon cycle feedbacks

Solar geoengineering might reduce CO_2 burden in 2100 by 5-25% at a cost of <0.5 $\$/tCO_2$

Solar geoengineering reduces atmospheric carbon burden, Keith, Wagner, and Zabel, *Nature Climate Change,* 2017

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- 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?

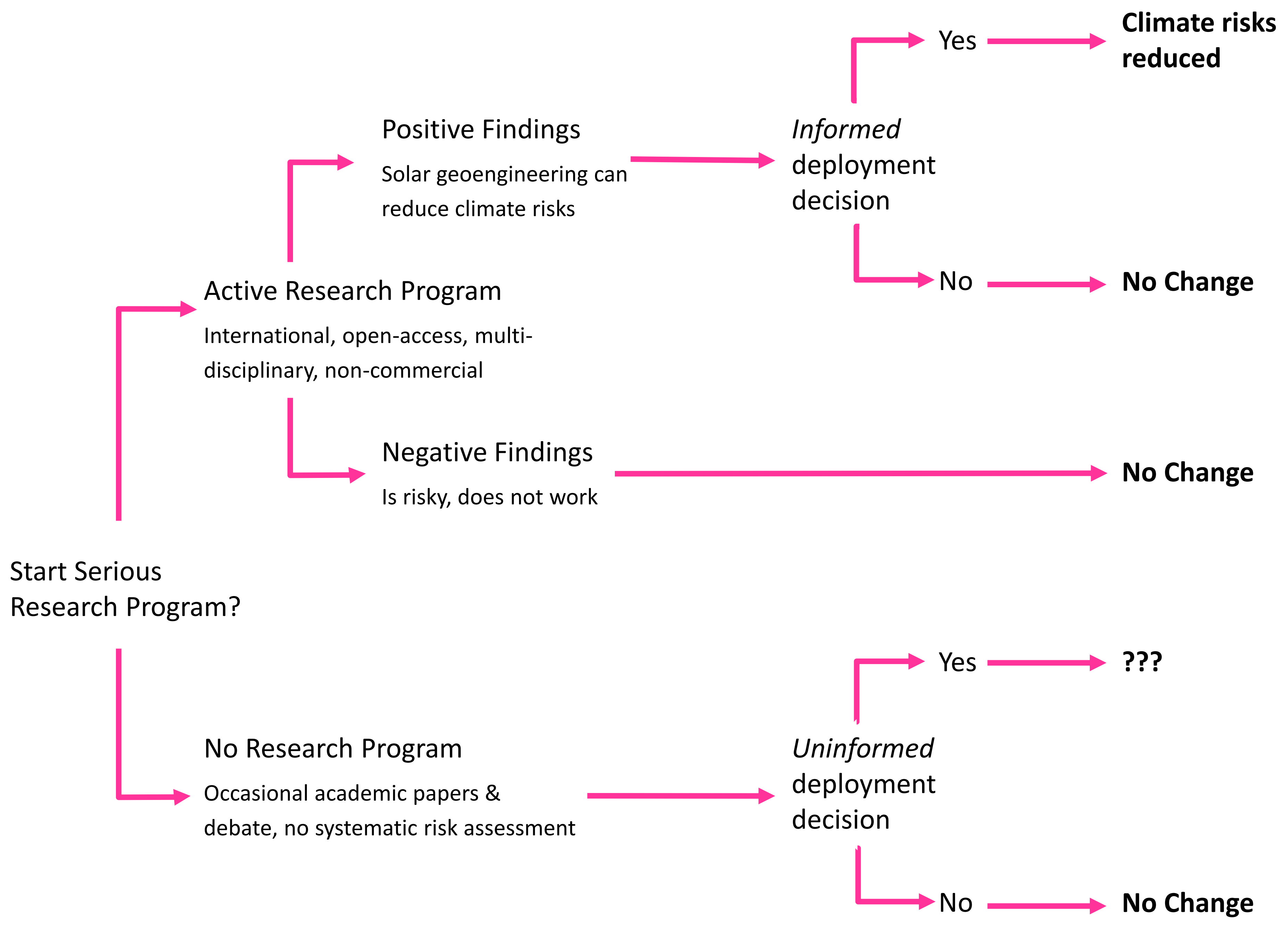
Evidence

- Models of dynamics and aerosol microphysics ←→ observations of aerosols and tracers
- Feedback experiments & control theory → 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

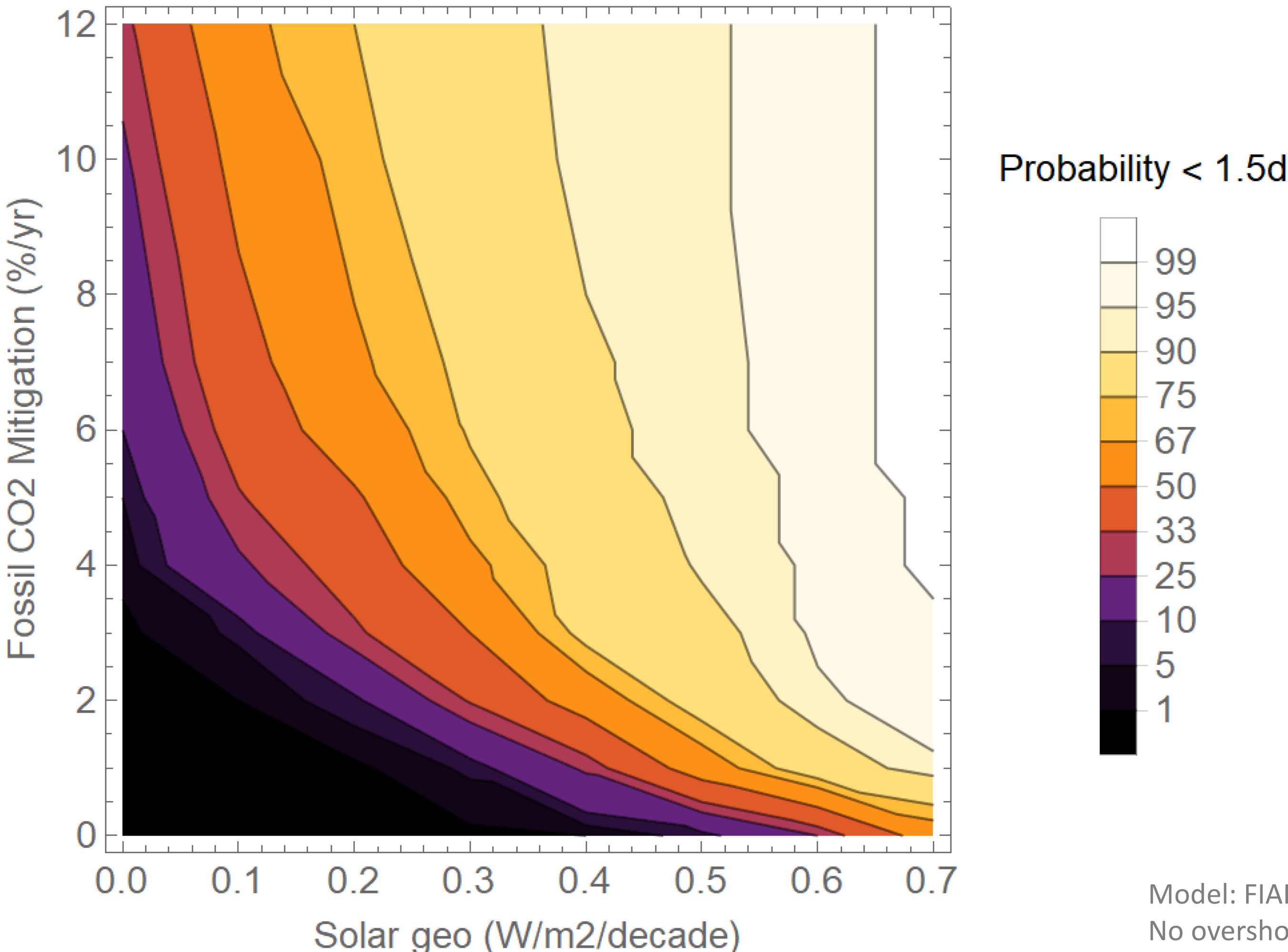
Caveats

- 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 procees

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


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

Probability of <1.5: trade off between rate of decarbonization & ramp solar geoengineering



Model: FIAR v1.3
No overshoot
CO_2 linear fit to last 3 decades
Exponential decline starts in 2020

David Keith, Kate Rickie, Oliver Morton -- Draft

Risk and efficacy

Forcing

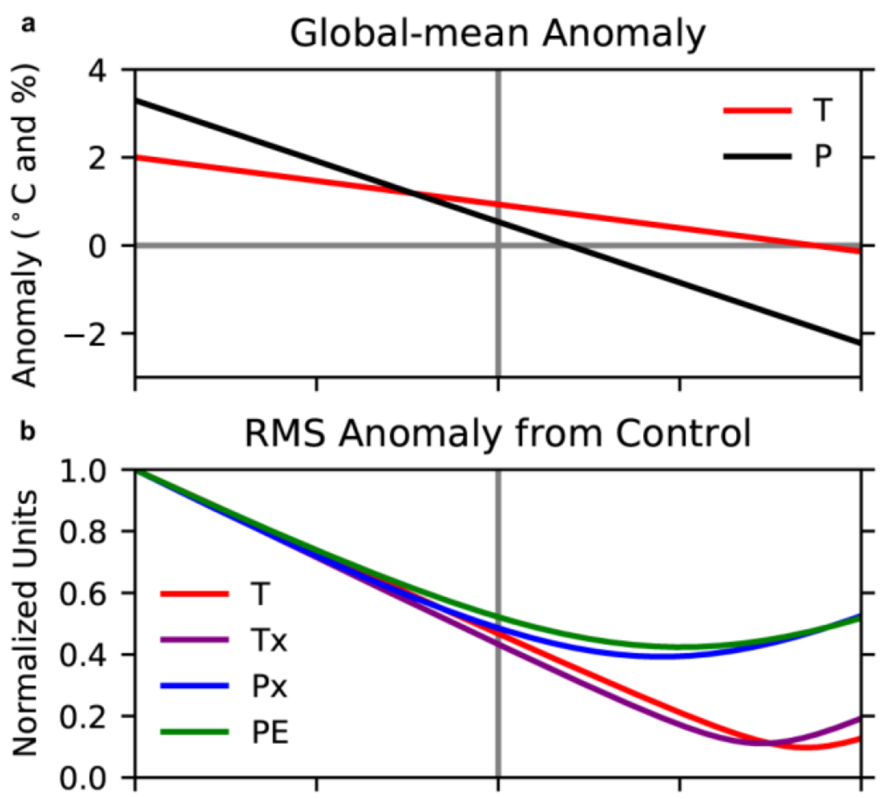
Risks (of stratospheric sulfates)

- 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



Peter Irvine, Kerry Emanuel, Jie He, Larry W. Horowitz, Gabriel Vecchi, David Keith,
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.

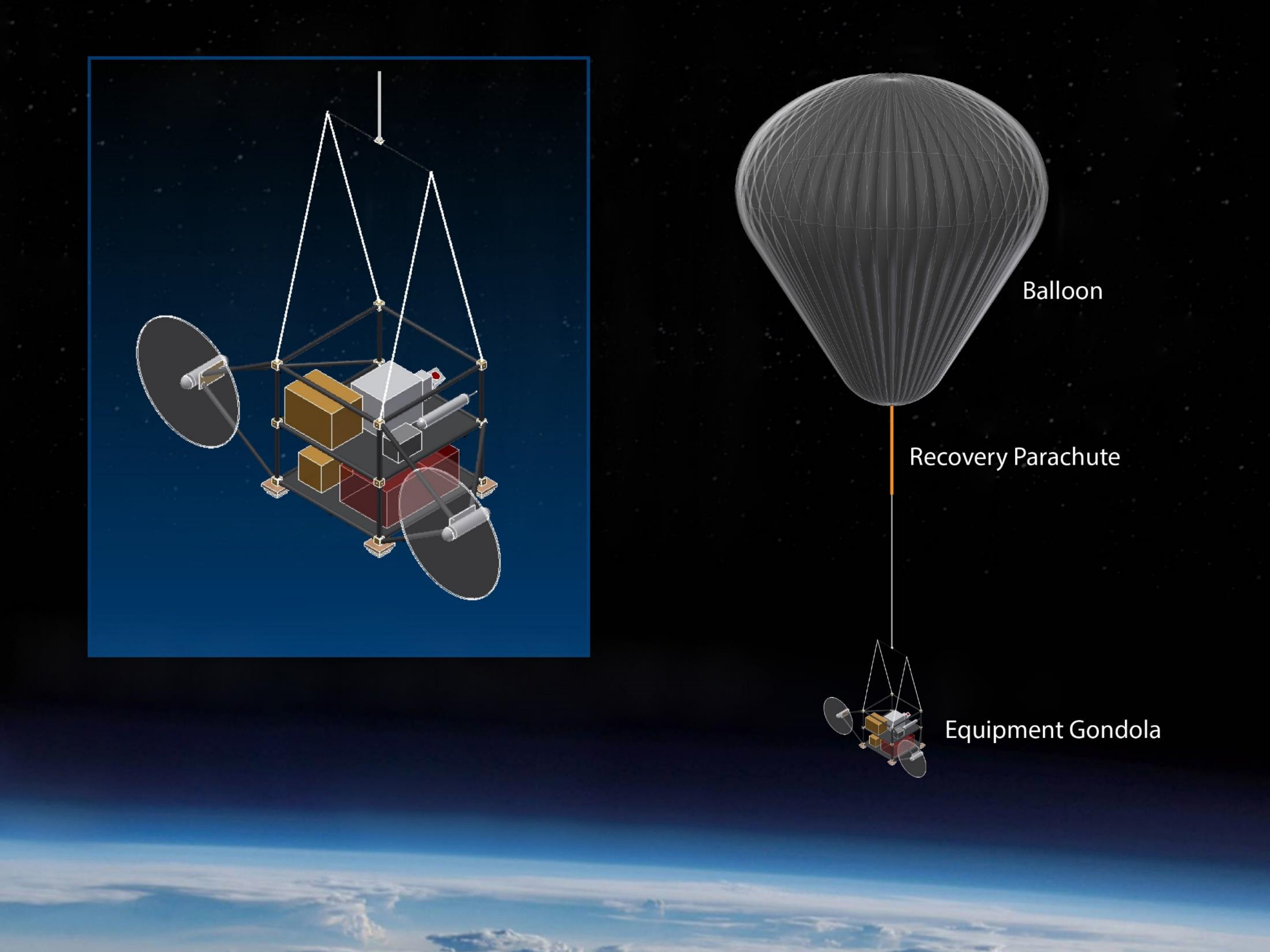
SCoPEx: Basic design and concept of operations

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.

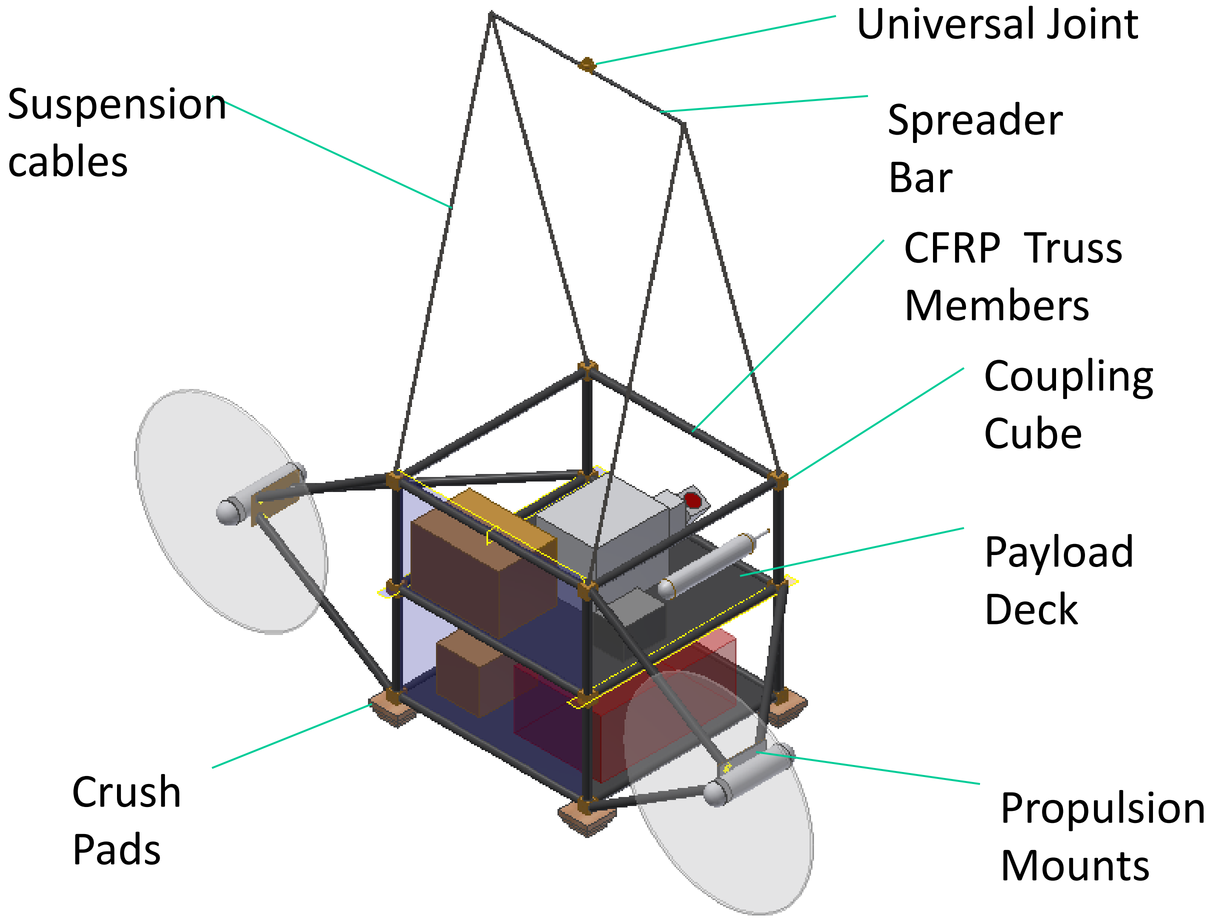
SCoPEx will used a propelled balloon gondola containing all instruments and drive system.

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.


Balloon
Recovery Parachute
Equipment Gondola

SCoPEx payload structure concept



- 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

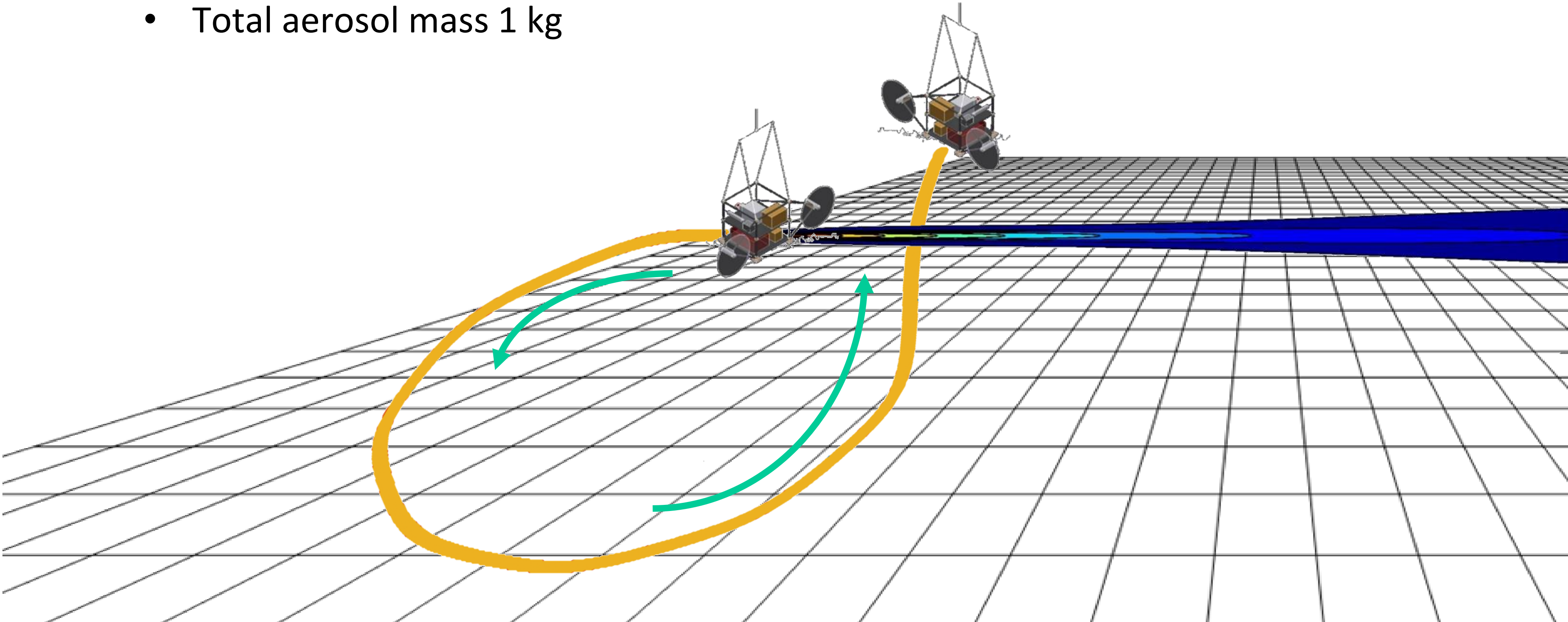
Commercially available materials and demonstrated designs allow for parametric payload design.

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.