



# THE SOCIOTECHNICAL DYNAMICS OF NEGATIVE EMISSIONS, CARBON REMOVAL, AND SOLAR GEOENGINEERING



DEPARTMENT OF BUSINESS DEVELOPMENT  
AND TECHNOLOGY  
AARHUS UNIVERSITY

GENIE PROJECT  
FEBRUARY 23, 2023

PROF. BENJAMIN K. SOVACOOLOO  
PRINCIPAL INVESTIGATOR



# BACKGROUND ON GENIE PROJECT

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GENIE stands for “Geoengineering and Negative Emissions Pathways in Europe”

ERC-Synergy Grant (2021-2027) to Aarhus University, Mercator Research Institute on Global Commons and Climate Change (MCC), International Institute for Applied Systems Analysis (IIASA) as well as University Wisconsin-Madison

Investigate environmental, technical, societal, political, and legal dimensions of 10 negative-emissions and 10 solar-geoengineering technologies in order to identify and develop conditions under which they can be deployed at scale



# THE GENIE TEAM

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Benjamin Sovacool, Aarhus University and Sussex University



Keywan Riahi, International Institute of Applied Systems Analysis (IIASA)



Jan Minx, Mercator Research Institute on Global Commons and Climate Change (MCC)



Gregory Nemet, University of Wisconsin-Madison



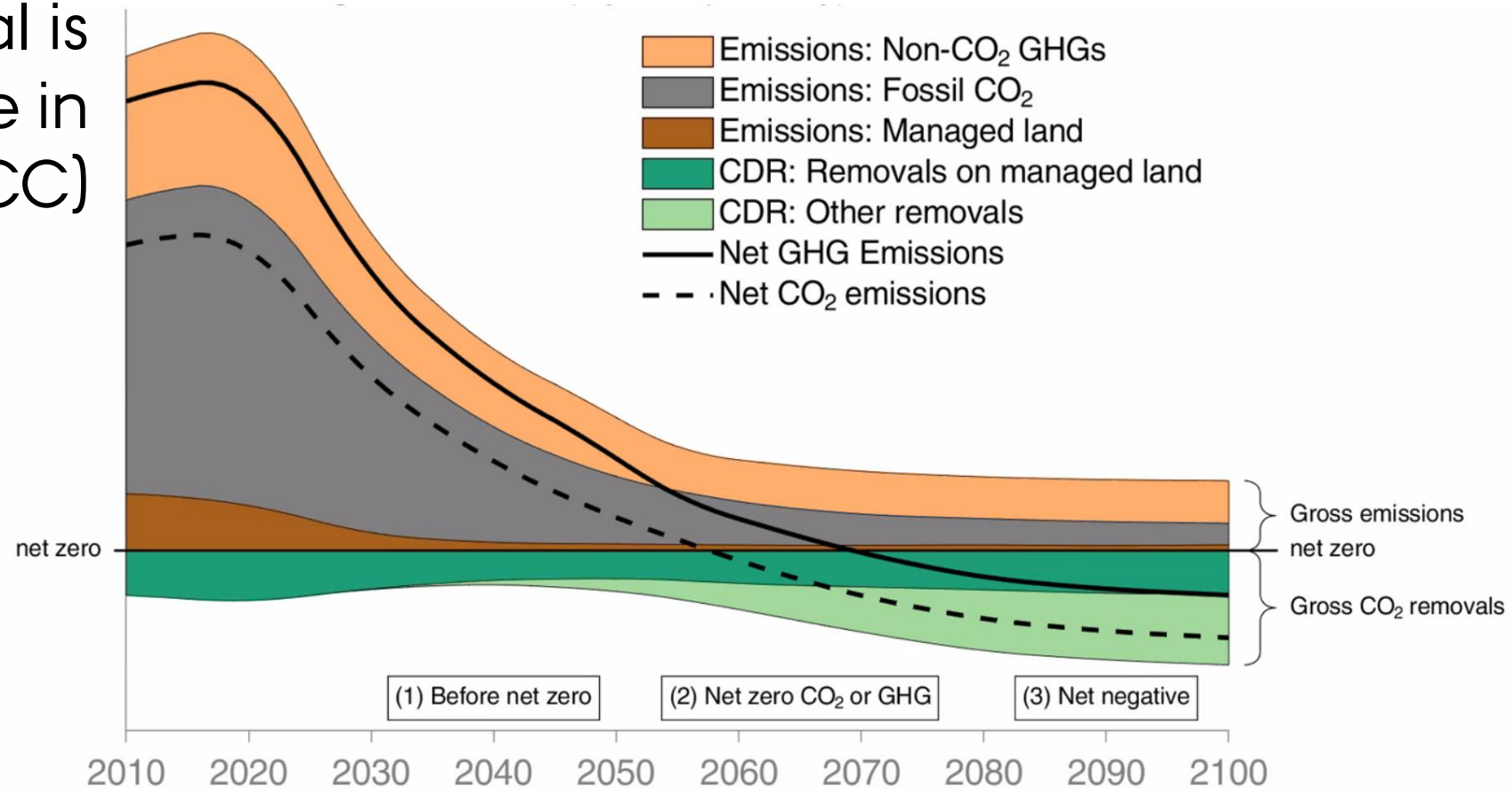
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# STYLIZED PATHWAYS FOR CDR (2010-2100)

Carbon dioxide removal is assigned a growing role in modeling runs (e.g., IPCC)

CDR would need to be scaled up massively by mid-century to remove on gigatonne scale



Source: IPCC 2022

# BACKGROUND

Main Term	Definition	Affiliated terms
<i>Mitigation</i>	An anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases	Carbon abatement, reducing emissions
<i>Adaptation</i>	Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities	Enhancing resilience, adaptive capacity, reducing vulnerability
<i>Geoengineering</i>	Refers to a broad set of methods and technologies that aim to deliberately alter the climate system in order to alleviate the impacts of climate change	Climate engineering, climate remediation, climate modification, climate intervention, planet hacking, GGR, SRM
<i>Greenhouse gas removal (GGR)</i>	Intentional human efforts to remove CO <sub>2</sub> emissions from the atmosphere	Carbon dioxide removal, carbon cycle management, post-emission carbon management, negative emissions
<i>Solar radiation management (SRM)</i>	Controls how much solar energy reaches the surface by manipulating the planet's radiation budget to ameliorate the main effects of greenhouse gases (i.e., warming)	Solar geoengineering, sunlight reflection methods, aerosol injection, solar radiation modification
<i>Carbon sink</i>	Any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol from the atmosphere	Carbon storage, carbon sequestration

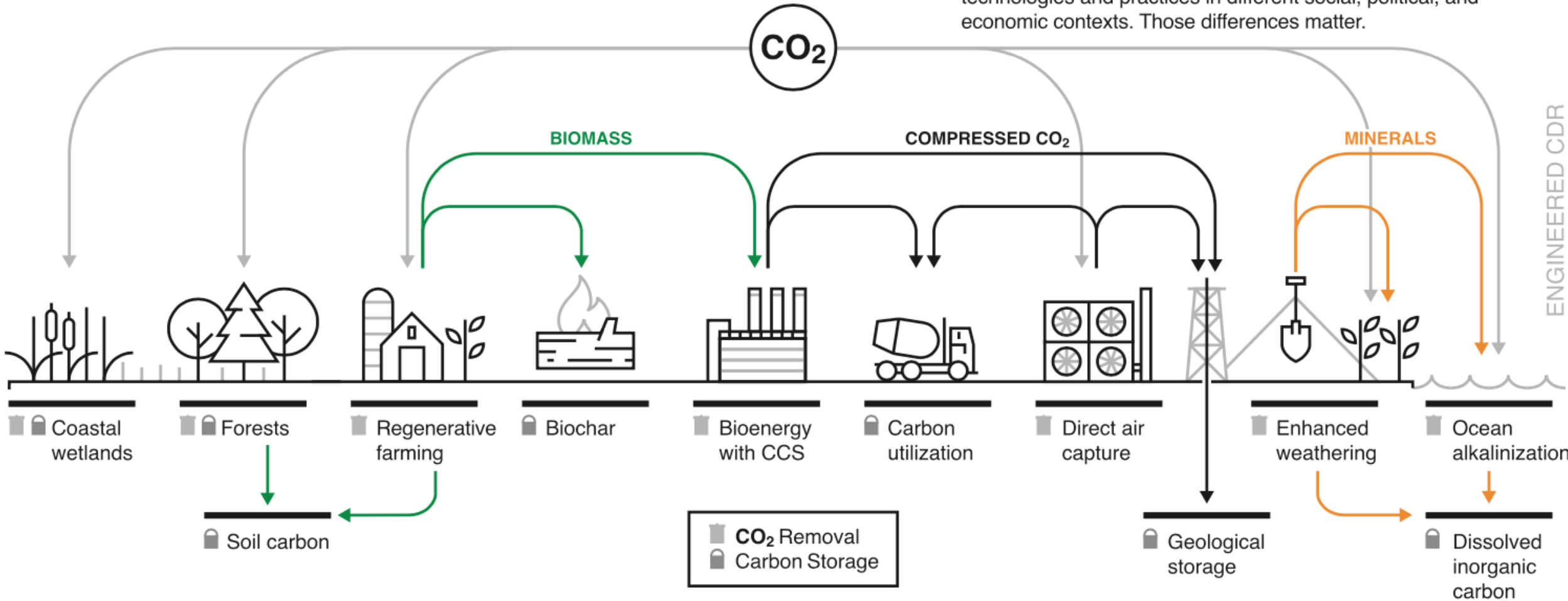
Less costly  
 Closer to deployment  
 More vulnerable to reversal

More costly  
 Greater R&D needs  
 Less vulnerable to reversal

All of these approaches can be implemented using different technologies and practices in different social, political, and economic contexts. Those differences matter.

NATURAL CLIMATE SOLUTIONS

ENGINEERED CDR



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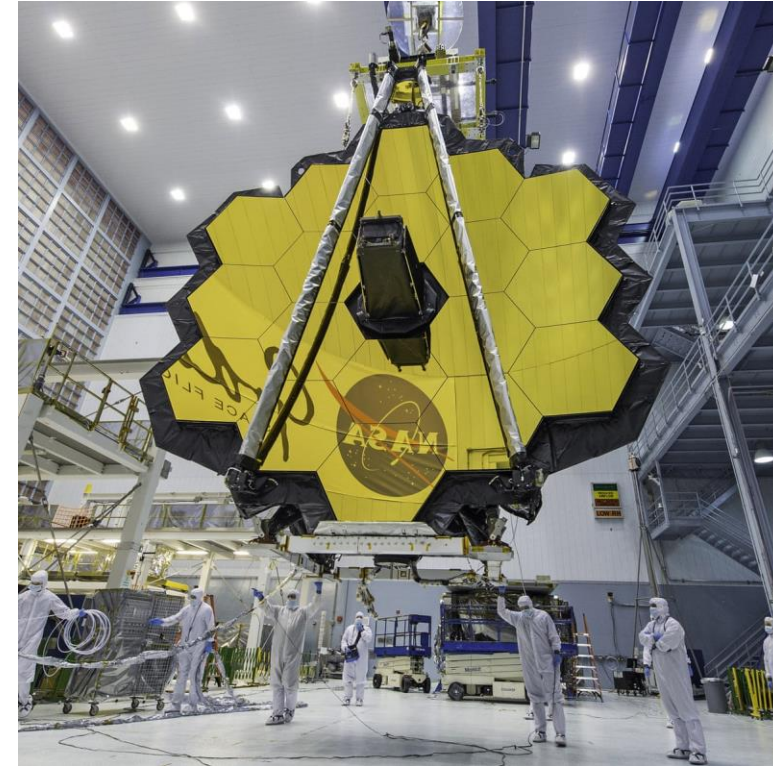


Source: Morrow et al 2020

# THE PROMISE OF SPACE-BASED GEOENGINEERING?

Could have same impact without the risks of impacting the biosphere

Could work in tandem with broader space(faring) initiatives



# Space-based geoengineering

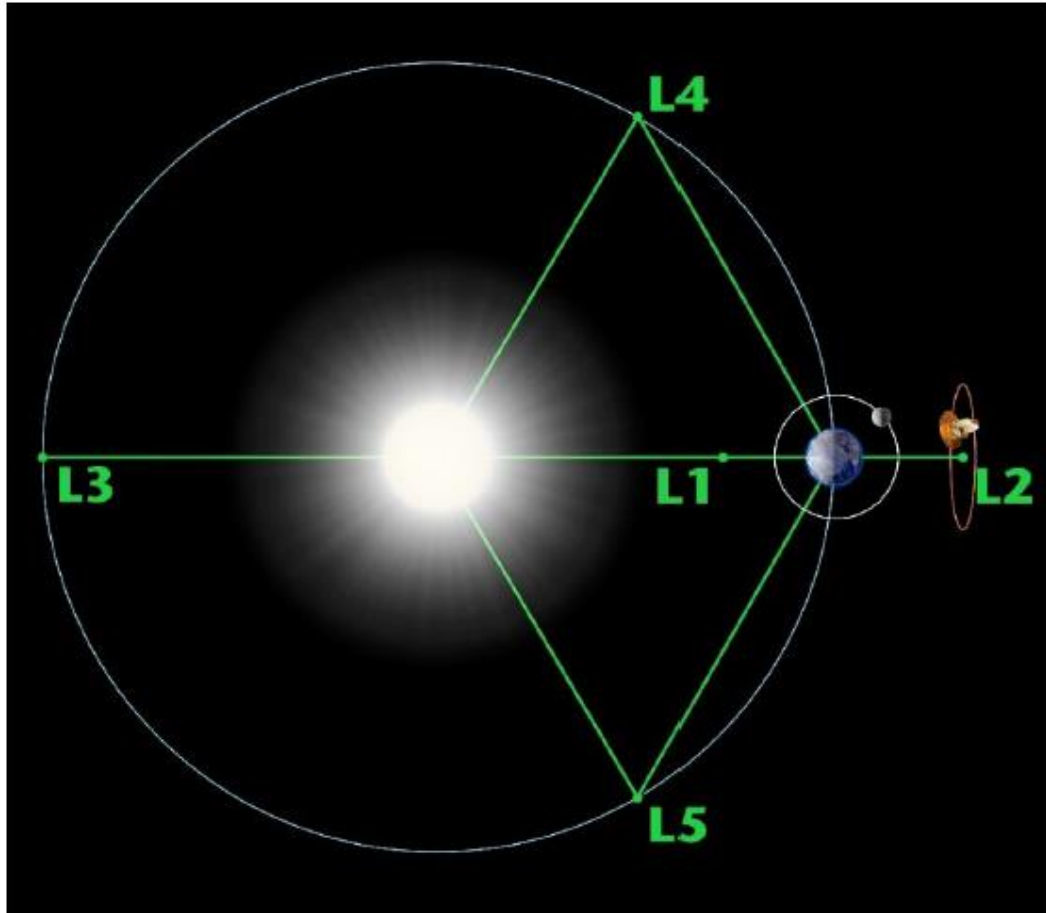
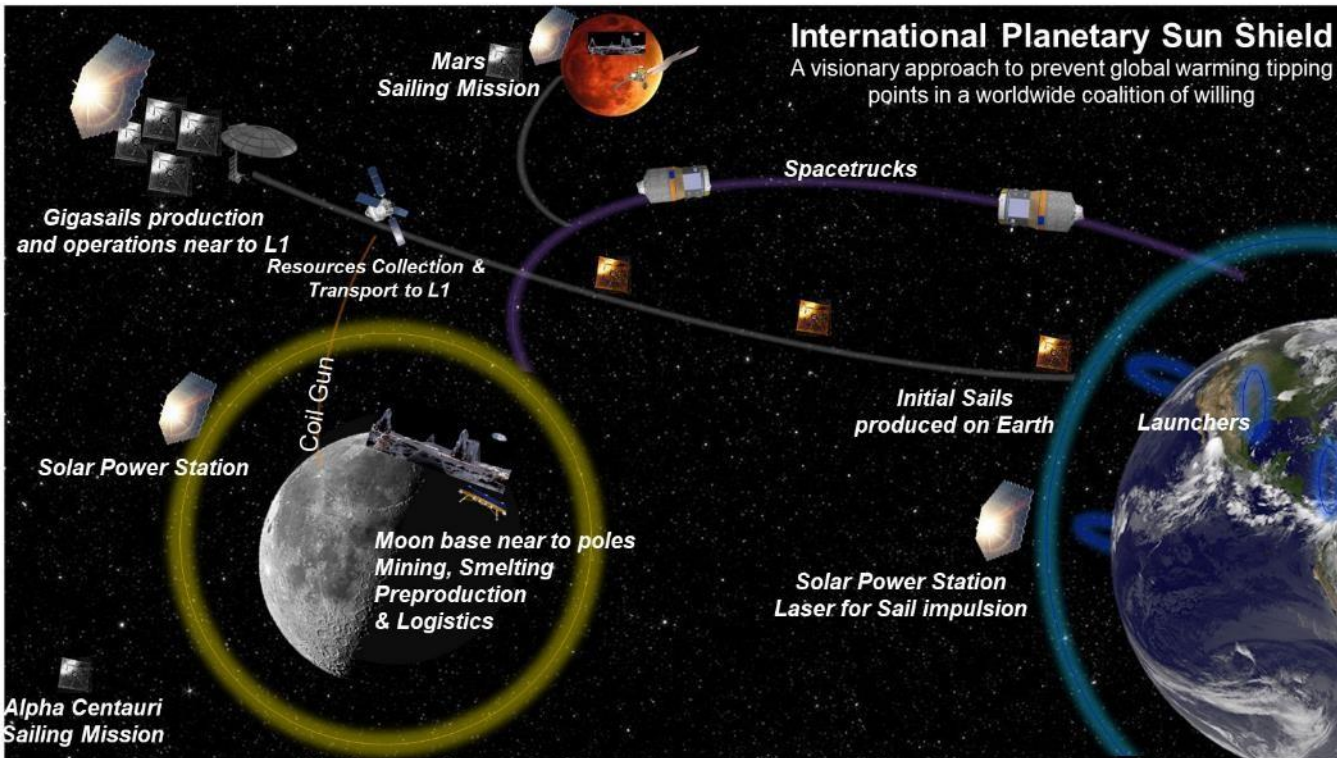


Table 1: Overview of Space-Based Geoengineering Proposals

Article	Option	Location	Description
Early [17]	Thin reflecting or refracting glass shield	SEL1	2,000-kilometer-wide, 10µm-thick glass shield to refract sunlight away from Earth
Seifritz [11]	Large mirrors mounted on satellites	SEL1 (or SEL2/3)	Examines general principles for temperature reduction through “satellites bearing large lightweight mirrors”
Mautner and Parks [12]	Fleet of solar screens and deflectors	SEL1, orbit of Sun, or low Earth orbit (LEO)	Aims to reverse 2°C of global warming by intercepting 3% of incoming solar radiation as well as try to mitigate ozone/UV issues
Mautner [13]	Reflective screen of thin film (interwoven with mesh, perhaps)  Dust ring (of lunar or asteroid material) in orbit around Earth	Equatorial ring in LEO	Examines cost and potential to avoid 2-5°C of global warming by intercepting 3-7% of solar radiation, while noting issues with stability and interference with other space activities
Hudson [23]	“Space parasol” using an array of screens	SEL1 (LEO and GEO also considered)	Demonstrates preferability of SEL1 option to those in Earth orbit
Teller et al. [20]	Metallic “small-angle scatterer”	SEL1	Envisions a scattering system of the same area but lower mass than other proposals by being located at SEL1 rather than LEO
Roy [10]	“Solar sail” which is 100,000 square kilometers in length	Unspecified, seems to be SEL1	Particular focus on ability of solar sails to “adjust the earth’s solar constant” through active and intelligent adaptive capabilities
McInnes [24]	Large solar shield	SEL1	Technical study of how to minimize mass of the shield as well as optimize location
McInnes [25]	Large solar reflectors  Large solar absorbers	SEL1	Jointly explores possibility of engineering Earth’s climate through active cooling (to

Baum CM, S Low and BK Sovacool. “Between the Sun and Us: Expert perceptions on the innovation, policy, and deep uncertainties of space-based solar geoengineering,” Renewable and Sustainable Energy Reviews 158 (2022), 112179.

# Space-based geoengineering



Institute of Space Systems (IRS) and Airbus, 2020

*It's a Plan-B climate-airbag solution. It's not meant to stay there more than ten to twenty years... after that it will be removed because, in that time, we need to be able to reduce our climate emissions.*

*All things being equal, I'd prefer for us to be able to do it with space-based measures, because that doesn't involve putting chemicals into the environment. It's a more universal cooling, and it can be tweaked more easily. Except in this world, I prefer it not to be that, because that would cost trillions of dollars.*

*The Dutch building all of the dikes and dams off their coast. That would be my analogue. It is something that they decided to do to preserve their way of life and protect their land.*

*We used to have a saying that before you could build an aircraft, you had to build enough paperwork to fill three times the volume of the aircraft you are building. This would be a different order of magnitude to that, so just the amount of time, the schedule for this thing would be insane, the risk of the timeline.*

*There is this dictum in science fiction: basically, anything big enough to be interesting is also big enough to be oppressive.*

# Or Carbon Removal via Direct Air Capture



# Or Carbon Removal via Direct Air Capture



# GENIE CONSIDERS TWENTY TECHNOLOGIES

Negative emissions and carbon dioxide removal	Solar radiation management and solar geoengineering
Afforestation and reforestation	Stratospheric aerosol injection
Soil carbon sequestration	Marine cloud brightening
Biochar	Cirrus cloud thinning
Bioenergy with carbon capture and storage (BECCS)	Space-based (extra-terrestrial) reflectors
Enhanced weathering	Albedo modification via human settlements
Ocean alkalization or fertilization	Albedo management via grasslands and crops
Blue carbon and seagrass	Albedo management via deserts
Ecosystem restoration	Albedo management via clouds
Direct air capture and storage (DACCS)	Ice protection
Carbon capture utilization and storage (CCUS)	High altitude sunshades

# WITH IN-DEPTH FOCUS ON 10

## Group 1 (SRM)

**Stratospheric Aerosol Injection** – This aims to limit the effects of climate change by using planes or balloons to spray small particles (aerosols) into the upper atmosphere.

The particles would reflect sunlight back into space. This could cool temperatures on Earth. But for this idea to work, we would have to keep doing it continuously. If we stopped, temperatures would rise once again, and probably very quickly. This would not do anything to reduce our greenhouse gas emissions or help with other impacts, such as ocean acidification.



## Marine Cloud Brightening

This aims to limit the effects of climate change by spraying small particles, such as sea salt, into the air over the oceans, to make clouds brighter.

These clouds would reflect sunlight away from the Earth, which could cool temperatures on a local or regional level. Marine cloud brightening might also help to protect ecosystems threatened by climate change. One way to spray the particles would be to use a fleet of ships. But for it to work, we would have to keep doing it continuously. If we stopped, temperatures would rise once again. Also, marine cloud brightening would not do anything to reduce greenhouse gas emissions or help with other impacts, such as ocean acidification.



## Space-based Geoengineering

This aims to limit the effects of climate change by putting a giant mirror or other reflective material in outer space between the Earth and the sun.

Such a space mirror or sunshield would deflect sunlight back into space. This could cool temperatures on Earth. This would avoid direct changes to the land, oceans, or atmosphere of the Earth itself. But for this idea to work, we would need to be able to build and maintain something in space much larger than ever before. A space mirror would also be very costly to build, given that its location would be about four times as far from the Earth as the Moon. Also, it would not do anything to reduce our greenhouse gas emissions or help with other impacts, such as ocean acidification.



## Group 2 (CDR1)

### Afforestation and Reforestation

Both aim to limit the effects of climate change by planting trees.

As trees grow, they absorb carbon dioxide from the atmosphere and store it for decades or longer, as long as the forest is around. But for this idea to work, we would need a lot of land and water. It is therefore likely to compete with agriculture and other uses. Also, if trees were cut down or happen to burn down, then the carbon dioxide would again be released into the atmosphere.



### Soil Carbon Sequestration

This aims to limit the effects of climate change by changing agricultural techniques to store more carbon dioxide in soils.

This could include planting different crops, leaving crop residues on the field, or increasing the number of trees on agricultural lands. By improving soils, it is possible to remove carbon dioxide from the air and store it in soils for decades to centuries. Soil carbon sequestration also requires no additional land and might make soils better for farming. But for it to work, we would need farmers and people in other industries to cooperate and take part. Also, if agricultural practices are not sustained, the carbon dioxide would again be released into the atmosphere.



### Marine Biomass and Blue Carbon

Both aim to limit the effects of climate change by improving how much carbon dioxide is stored in the oceans.

Blue carbon does this by restoring or growing ecosystems such as mangroves, salt marshes, and seagrass meadows. Marine biomass does this by growing seaweeds or macroalgae. All of these absorb carbon dioxide from the atmosphere as they grow. This can then be stored for decades to centuries at the bottom of the ocean. But for this idea to work, we would need many people, especially those in coastal communities, to cooperate and take part. Also, if ecosystems are disturbed or destroyed or the plants are cut down, the carbon dioxide would again be released into the atmosphere.

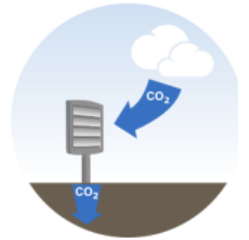


## Group 3 (CDR2)

### Direct Air Capture with Carbon Storage

This aims to limit the effects of climate change by using very large fans to remove carbon dioxide from the air (direct air capture).

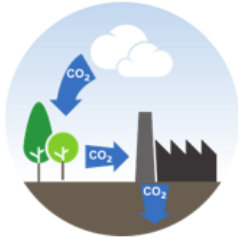
Once pulled into the fans, absorptive liquids convert the carbon dioxide using a chemical process. It can then be stored indefinitely underground (carbon storage). Direct air capture with carbon storage also needs little land. But for it to work, it would require lots of energy along with underground places to store carbon. Direct air capture is also extremely expensive right now and it is not clear if it works at the large scales needed, both of which limit how much it can be used.



### Bioenergy with Carbon Capture and Storage

This aims to limit the effects of climate change by growing and harvesting plants as a source of energy (bioenergy).

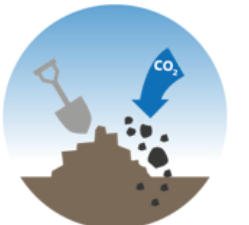
As plants grow, they absorb carbon dioxide from the air. By burning these plants and chemically capturing the carbon dioxide released, bioenergy can provide energy for homes and businesses or be stored underground indefinitely (carbon capture and storage). But for it to work, we would need a lot of land and water (and underground places to store carbon). It is therefore likely to compete with agriculture and other uses. It is also not clear if bioenergy with carbon capture and storage will work at the large scales needed, though some industrial applications do already exist.



### Enhanced Weathering

This aims to limit the effects of climate change by increasing the ability of rocks to absorb carbon dioxide from the atmosphere.

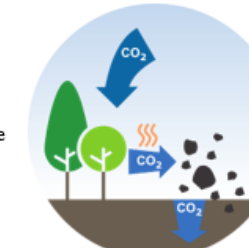
As rocks such as limestone and basalt are exposed in nature to processes like rain, wind, or waves, they are ground down (weathering), which allows them to absorb carbon dioxide. Since this process takes place extremely slowly, enhanced weathering speeds it up by physically or chemically grinding the rocks before placing them onto soils, beaches, or next to rivers. Over time, rocks and their carbon dioxide are ultimately stored in oceans indefinitely. But for it to work, we would need a lot of rocks. This could cause negative ecological and human health impacts (and greater energy use) from more mining and extraction. Also, it is not clear if it will work at the large scales needed, as only limited trials have been done so far.



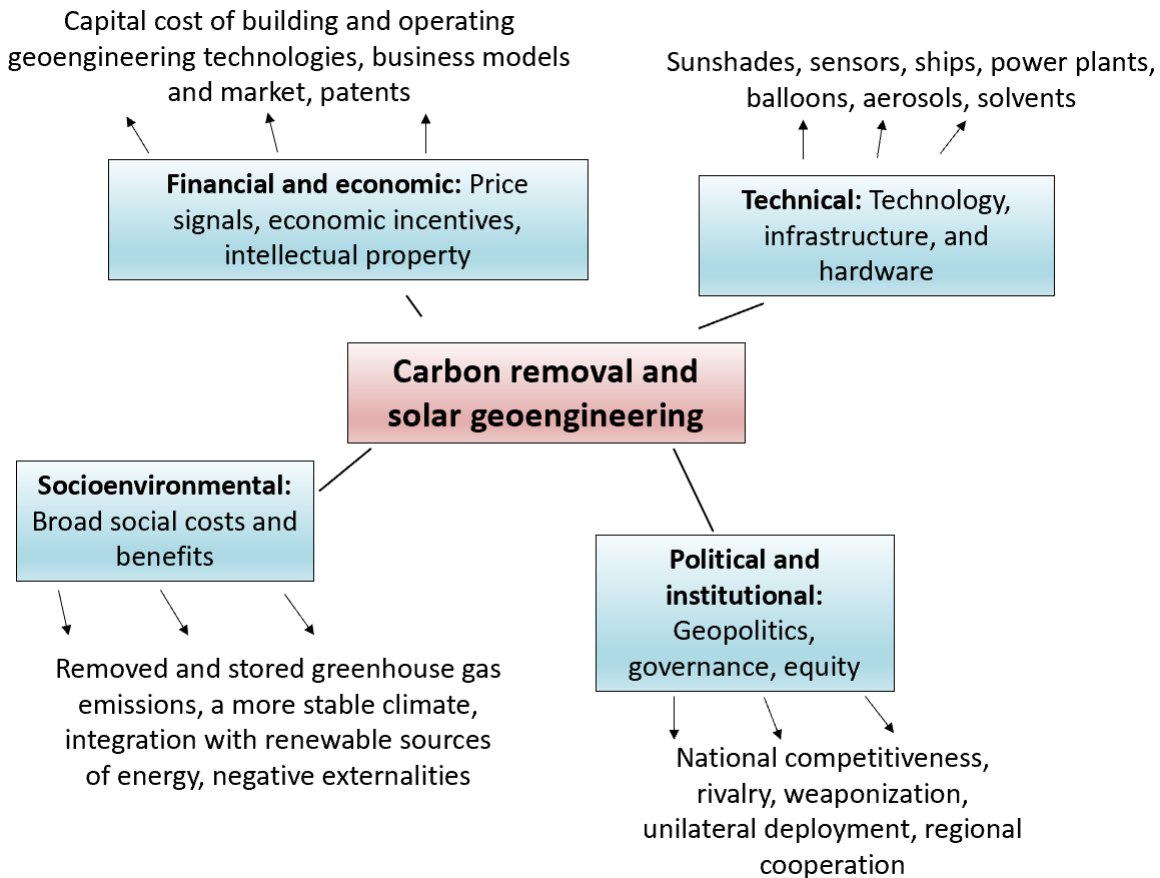
### Biochar

This aims to limit the effects of climate change by heating organic material, such as tree branches and cornstalks, inside a container with no oxygen.

This creates black material very similar to charcoal (biochar). If we grind this up and add it to soil, it is possible to remove carbon dioxide from the air and store it in soils for decades to centuries. Biochar might also make better soils for farming. It could also be added to other things, such as concrete, animal feed, or compost. But for it to work, we would need farmers and people in other industries to take part and, potentially, change how they do things. We would also need a lot of organic material. Biochar is also quite expensive right now, which limits how much it can be used.



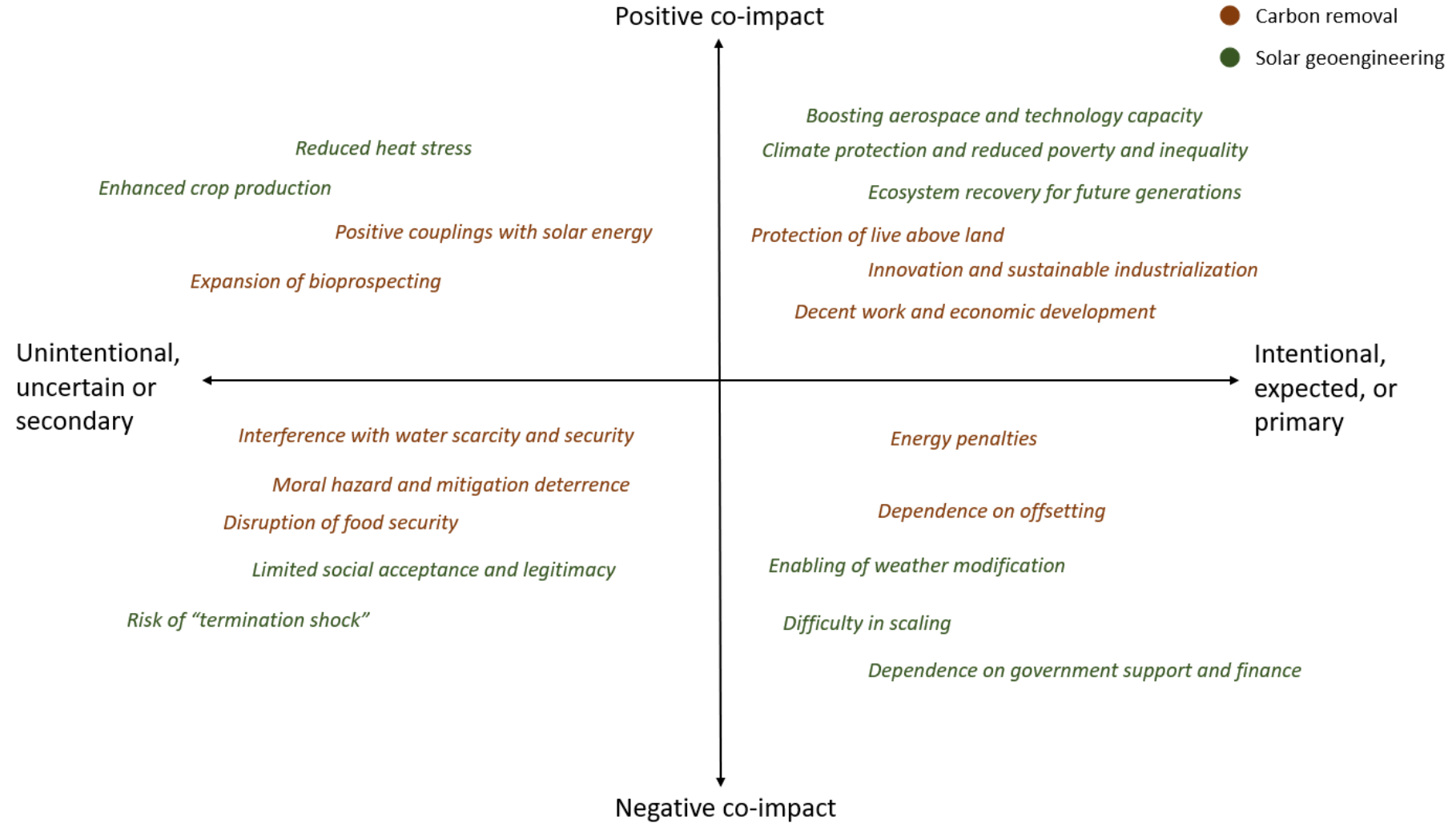
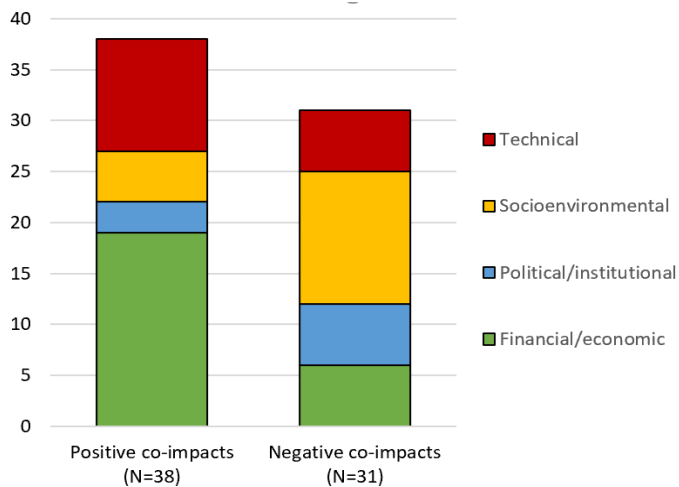
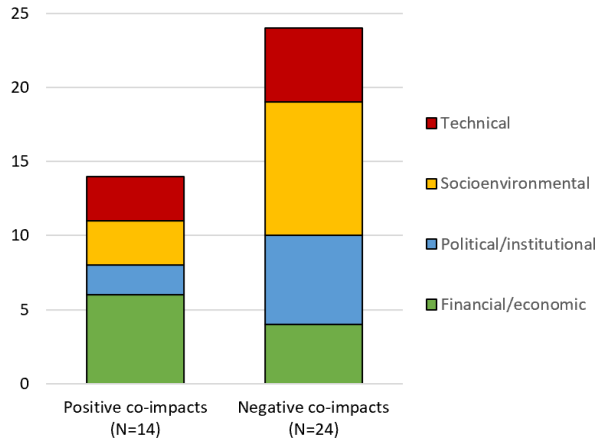
# Finding 1: The prospective co-impacts are immense



- Using a sociotechnical approach, identifies 107 distinct co-impacts related to the deployment of carbon removal and solar geoengineering technologies.
- Slightly less than half (52) were identified as positive co-impacts (38 for carbon removal, 14 for solar geoengineering)
- More than half (55) were identified as negative co-impacts (31 for carbon removal, 24 for solar geoengineering).
- Explores 20 of these co-impacts in more depth

Sovacool, BK, CM Baum and S Low. "Beyond climate stabilization: Exploring the perceived sociotechnical co-impacts of carbon removal and solar geoengineering," *Ecological Economics* (203) (February, 2023), 107648, pp. 1-18.

# Assessing multi-dimensional co-impacts



Sovacool, BK, CM Baum and S Low. "Beyond climate stabilization: Exploring the perceived sociotechnical co-impacts of carbon removal and solar geoengineering," *Ecological Economics* (203) (February, 2023), 107648, pp. 1-18.

# NEGATIVE ONES GERMINATE OPPOSITION

Low, S, CM Baum, and BK Sovacool. Taking it outside: Exploring social opposition to 21 early-stage experiments in radical climate interventions, *Energy Research & Social Science* 90 (2022), 102594.

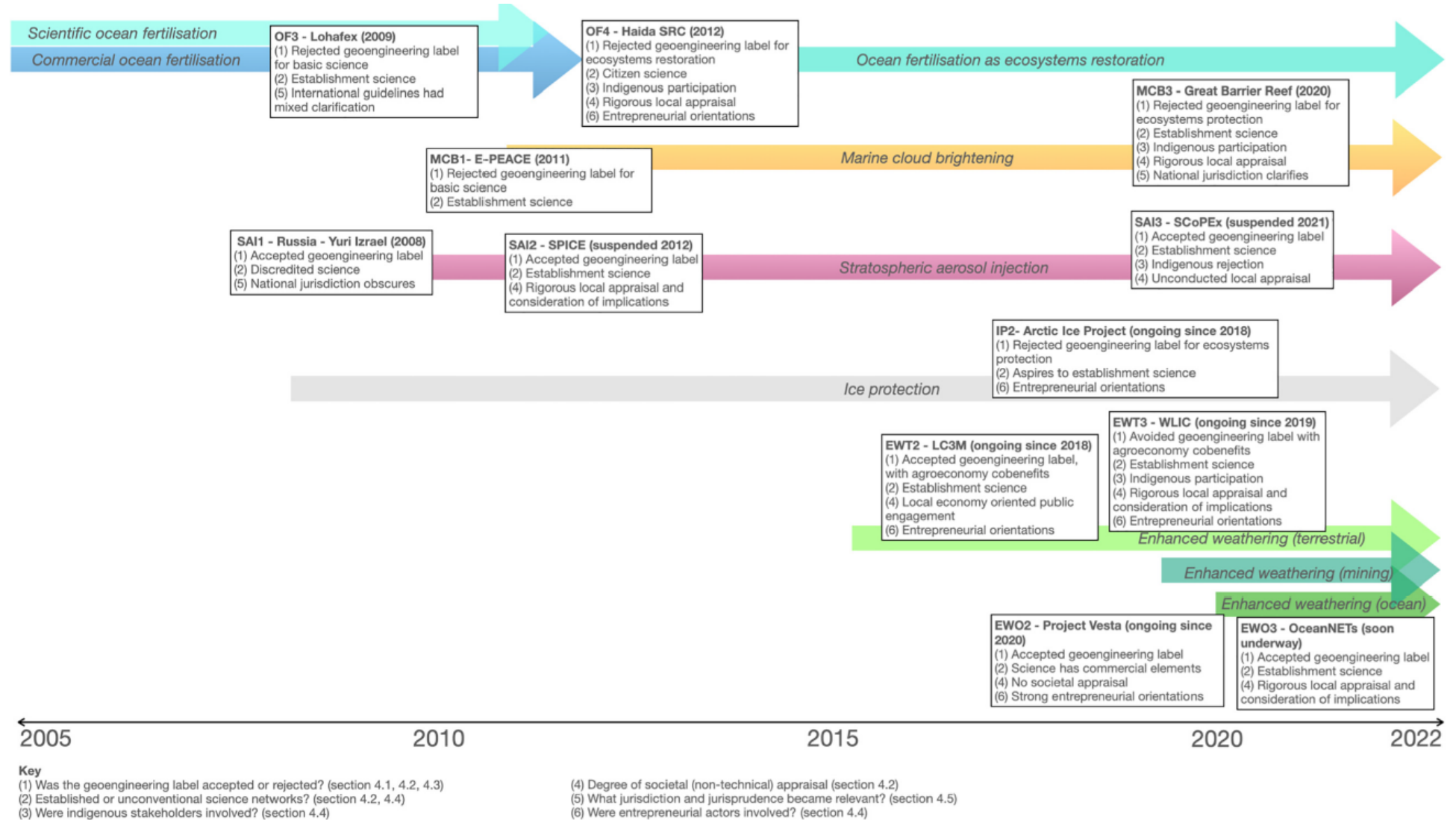


Fig. 2. Themes from selected case studies across technologies and time.

# Social opposition to 21 OF, MCB, SAI, Ice protection, EW experiments

Themes	
<b>Oppositional strategies led by key ENGOS</b>	<ul style="list-style-type: none"> <li>• Modular strategy: Slippery slope towards global-scale climate interventions; Local harms; Lack of consent; Reference to a UN ‘moratorium’; Pressure ‘hosting’ governments</li> <li>• Currently most applied by an environmental NGO network</li> <li>• Many critical scientists advance similar concerns, but do not employ the same tactics</li> </ul>
<b>Strategies supporting experimentation, and societal appraisal</b>	<ul style="list-style-type: none"> <li>• “Scientific” defense: Thresholds and ‘safe zones’; University-/expert-based reviews; calls for the separation of basic science from political and commercial intent</li> <li>• “Societal appraisal” stressed but contested: Critical ‘slow science’ vs. instrumental engagement of more bounded conceptions of risks</li> </ul>
<b>The framing of basic science or co-benefits, and ‘camouflage’</b>	<ul style="list-style-type: none"> <li>• Outside of SAI, experimenters tend to deemphasize ‘geoengineering’</li> <li>• “Camouflage” at work here?: emphasis on early-stage basic science, co-benefits with local economy, and eco-restoration and protection</li> </ul>
<b>Citizen, indigenous, and entrepreneurial involvement</b>	<ul style="list-style-type: none"> <li>• New actors and agendas becoming prominent: citizen science, indigenous actors (as a proxy for deeply localised actors and knowledge), and entrepreneurs, innovation, and industry</li> </ul>
<b>Rules of jurisdiction and jurisprudence</b>	<ul style="list-style-type: none"> <li>• Different norms and law frameworks stipulate different rules for ‘legitimate’ experimentation</li> <li>• Potential for jurisdiction-shopping</li> <li>• Latent or emergent bodies of regulation?</li> </ul>

# FINDING 2: AN EXPERT SURVEY ABOUT POLICY

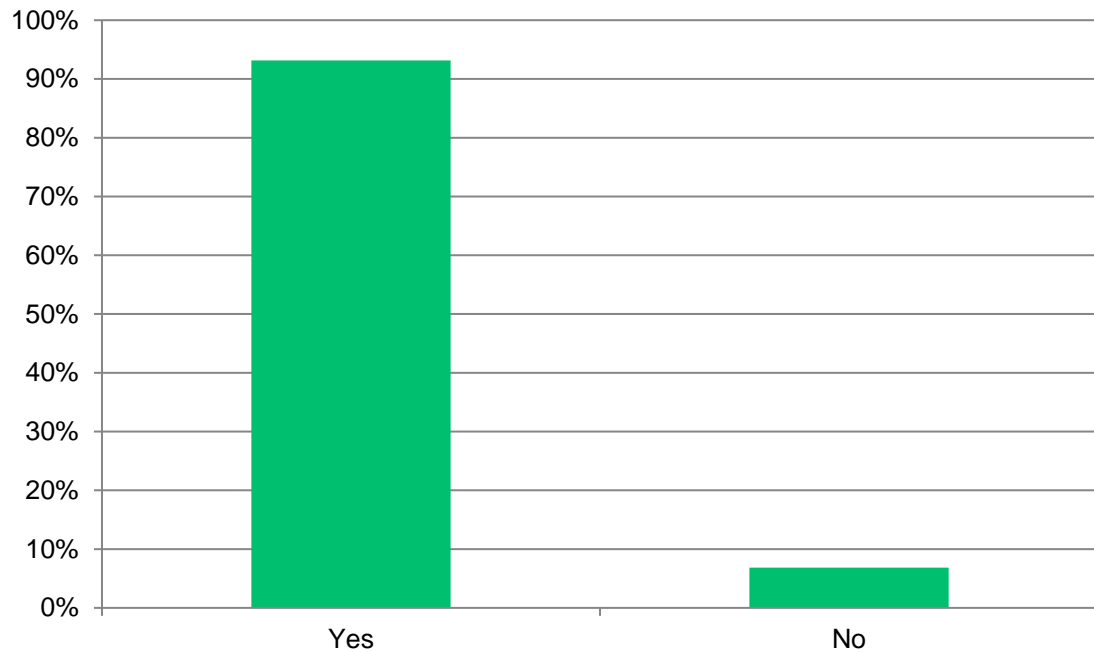
## Summary of the demographics of experts who took part in our survey exercise

Sovacool, BK, CM Baum, and S Low. "Determining our climate future: Expert opinions about negative emissions and solar radiation management pathways," *Mitigation and Adaptation Strategies for Global Change* 27 (58) (October, 2022), pp. 1-50.

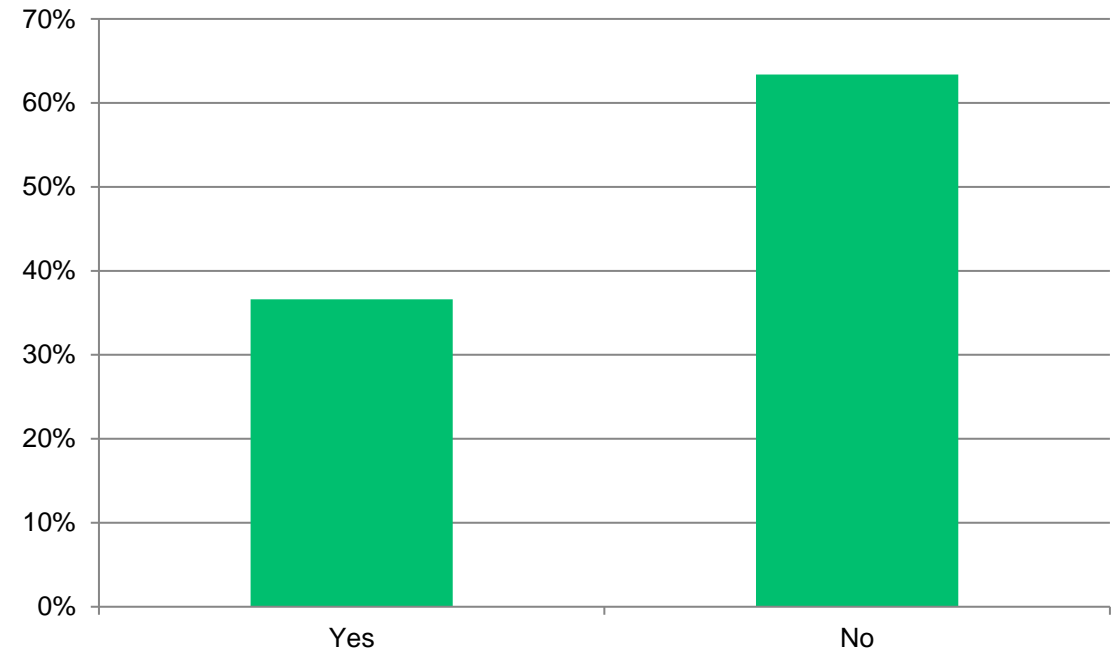
Summary information	No.
No. of experts	74
No. of organizations represented	63
No. of countries represented	15
Cumulative years spent in innovation or research of negative emissions and/or solar geoengineering	810
Average years spent in innovation or research of negative emissions and/or solar geoengineering	6.8
No. of experts whose current position falls into the following areas:	
Civil society and nongovernmental organizations	8
Government and intergovernmental organizations	4
Private sector and industrial associations	6
Universities and research institutes	56

# NECESSITY OF INTERVENTIONS

Sovacool, BK, CM Baum, and S Low. "Determining our climate future: Expert opinions about negative emissions and solar radiation management pathways," *Mitigation and Adaptation Strategies for Global Change* 27 (58) (October, 2022), pp. 1-50.



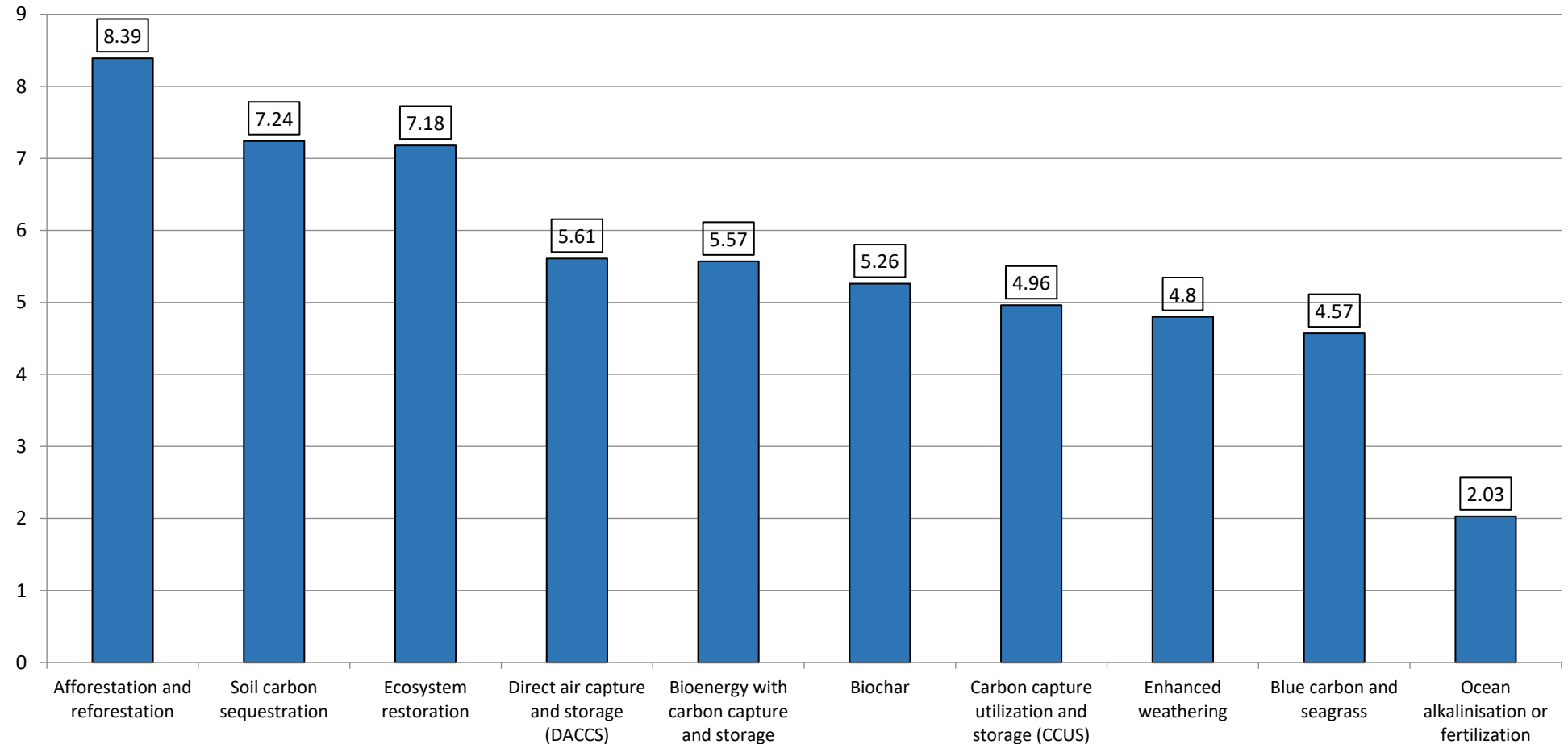
Are NETS necessary?



Is SRM?

# DESIRABILITY AND OPTIMALITY OF OPTIONS

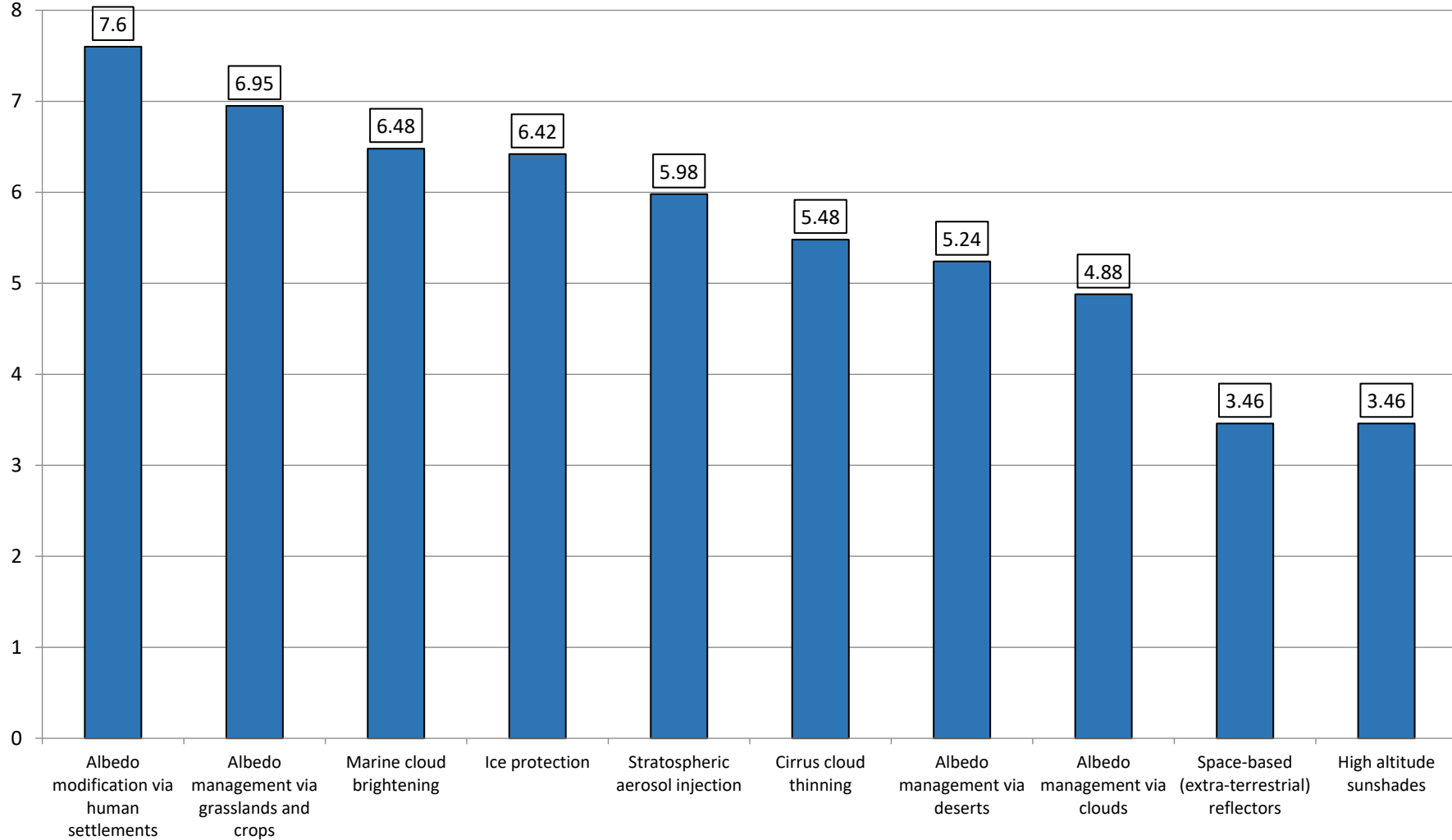
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Negative Emissions Technologies

# DESIRABILITY AND OPTIMALITY OF OPTIONS

Sovacool, BK, CM Baum, and S Low. "Determining our climate future: Expert opinions about negative emissions and solar radiation management pathways," *Mitigation and Adaptation Strategies for Global Change* 27 (58) (October, 2022), pp. 1-50.



Solar Geoengineering Technologies



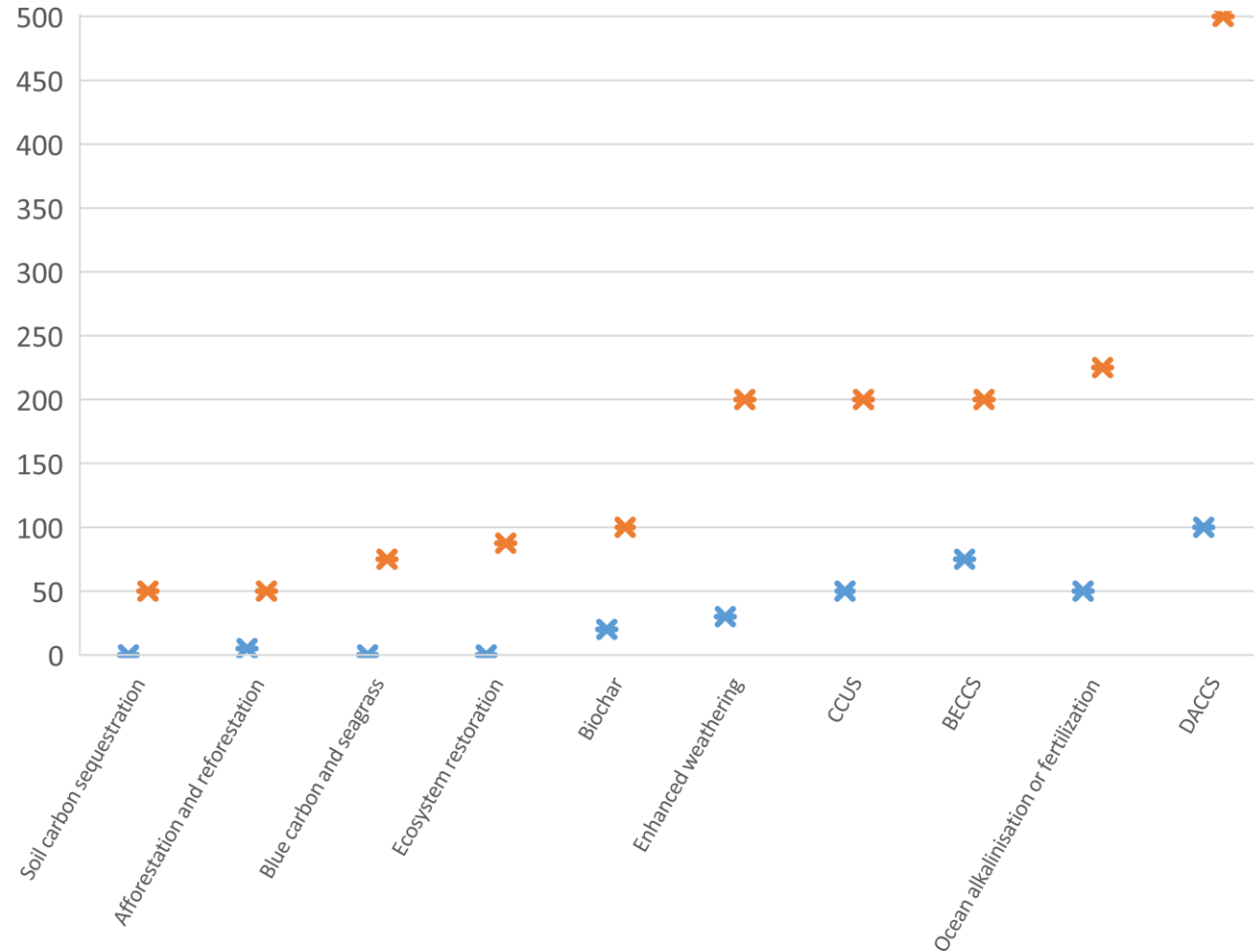
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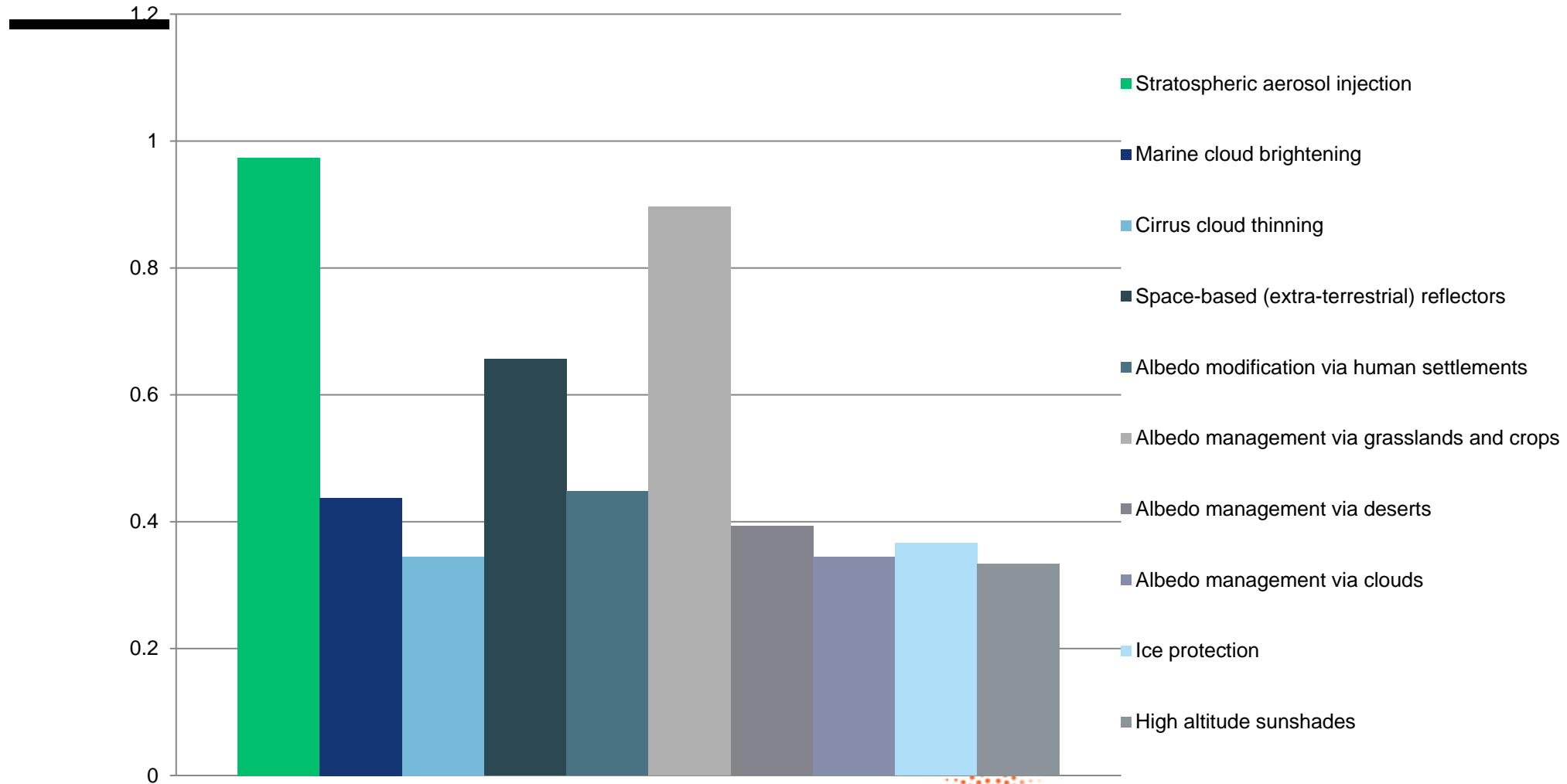
# EXPERT PERCEPTIONS ON EFFICACY / COST

■ Minimum cost per tCO2 (US\$) ■ Maximum cost per tCO2 (US\$)

Sovacool, BK, CM Baum, and S Low. "Determining our climate future: Expert opinions about negative emissions and solar radiation management pathways," *Mitigation and Adaptation Strategies for Global Change* 27 (58) (October, 2022), pp. 1-50.



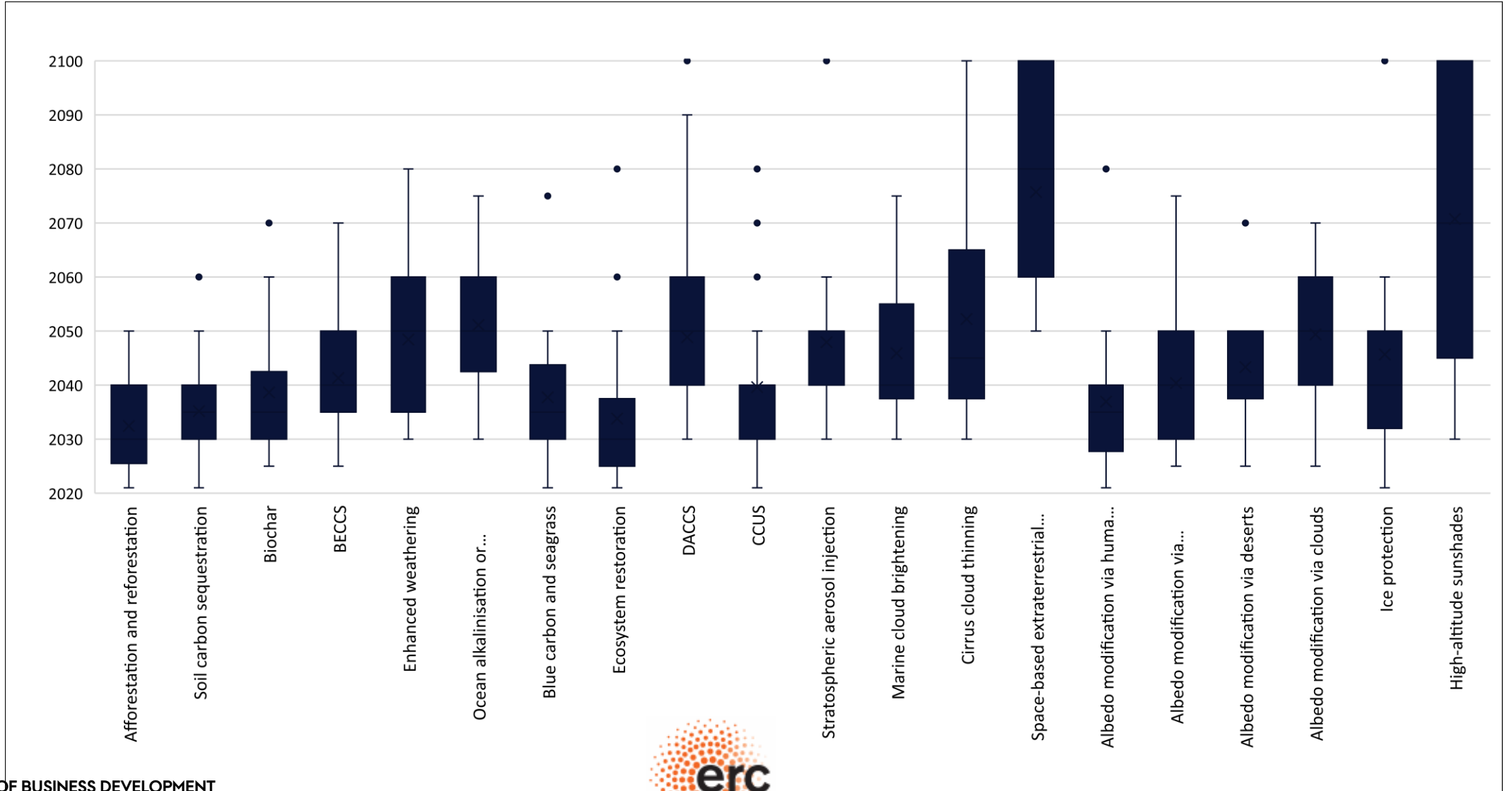
# ESTIMATIONS OF EFFICACY



Sovacool, BK, CM Baum, and S Low. "Determining our climate future: Expert opinions about negative emissions and solar radiation management pathways," *Mitigation and Adaptation Strategies for Global Change* 27 (58) (October, 2022), pp. 1-50.

# SCALING AND DEPLOYMENT

Sovacool, BK, CM Baum, and S Low. "Determining our climate future: Expert opinions about negative emissions and solar radiation management pathways," *Mitigation and Adaptation Strategies for Global Change* 27 (58) (October, 2022), pp. 1-50.



# SCALING AND DEPLOYMENT

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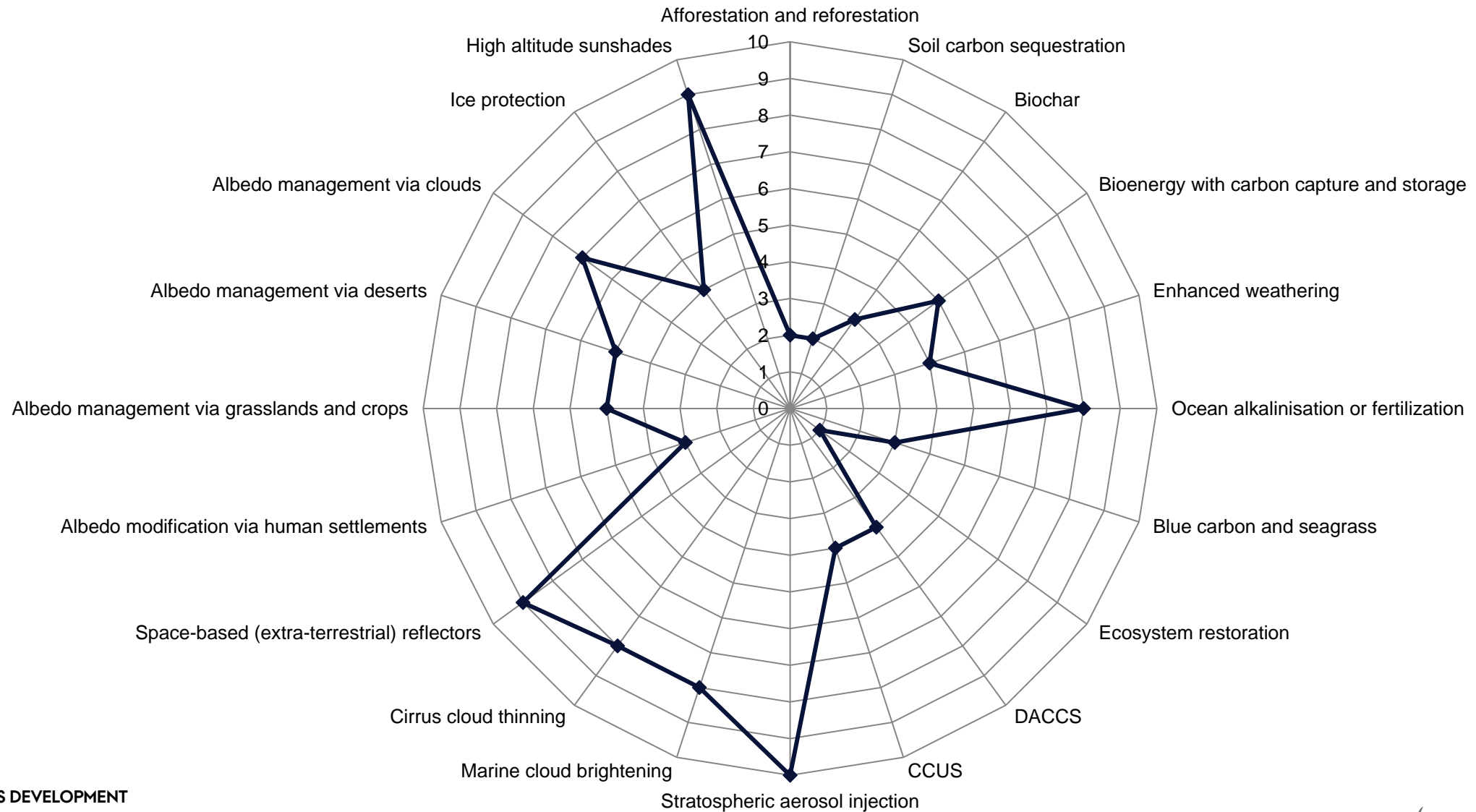
Expert elicitations for “never” achieving deployment were much higher for a fairly large number of options, each with 50% or more of respondents suggesting “never”:

- Albedo modification from human settlements (51.2%);
- Ice protection (54.8%);
- Stratospheric aerosol injection (65.3%);
- Marine cloud brightening (63.8%);
- Albedo modification by grasslands (68.3%);
- Albedo modification by deserts (78.0%);
- Cirrus cloud thinning (79.1%);
- Albedo modification by clouds (79.5%);
- Ocean alkalization or fertilization (80.9%);
- High-altitude sunshades (82.9%);
- Space-based reflectors (84.4%).

Sovacool, BK, CM Baum, and S Low. “Determining our climate future: Expert opinions about negative emissions and solar radiation management pathways,” *Mitigation and Adaptation Strategies for Global Change* 27 (58) (October, 2022), pp. 1-50.

# EXPERT PERCEPTIONS ON COMPOSITE RISKS

Sovacool, BK, CM  
Baum, and S Low.  
“Determining our  
climate future: Expert  
opinions about  
negative emissions  
and solar radiation  
management  
pathways,”  
*Mitigation and  
Adaptation  
Strategies for Global  
Change* 27 (58)  
(October, 2022), pp.  
1-50.



# EXPERT PERCEPTIONS ON BARRIERS

	Technology upscaling and readiness	Storage and disposal constraints	Public perception and social acceptance	Legal and regulatory obstacles	Challenges to system integration	Financing	Market demand	Environmental or planetary risks	Other factors
<i>Afforestation and reforestation</i>	1.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00	4.00
<i>Soil carbon sequestration</i>	2.00	1.50	1.00	1.50	2.00	2.00	2.00	1.00	1.50
<i>Biochar</i>	2.00	2.00	1.50	2.00	2.00	2.00	2.00	2.00	1.50
<i>BECCS</i>	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
<i>Enhanced weathering</i>	3.00	2.00	3.00	3.00	2.00	3.00	3.00	2.00	1.00
<i>Ocean alkalization or fertilization</i>	4.00	2.00	4.00	4.00	3.00	3.00	4.00	5.00	3.00
<i>Blue carbon and seagrass</i>	2.00	2.00	1.00	2.00	2.00	3.00	3.00	2.00	1.00
<i>Ecosystem restoration</i>	1.00	2.00	1.00	2.00	2.00	3.00	2.00	1.00	1.00
<i>DACCS</i>	4.00	3.00	3.00	2.00	3.00	4.00	3.00	2.00	3.00
<i>CCUS</i>	3.00	4.00	3.00	2.00	3.00	3.00	2.00	2.00	3.00
<i>Stratospheric aerosol injection</i>	4.00	1.00	5.00	5.00	4.00	3.00	4.00	5.00	4.00
<i>Marine cloud brightening</i>	4.00	1.00	4.00	4.00	3.50	3.00	4.00	4.00	3.00
<i>Cirrus cloud thinning</i>	5.00	2.00	4.00	4.50	4.00	4.00	4.00	5.00	3.50
<i>Space-based (extra-terrestrial) reflectors</i>	5.00	3.00	5.00	5.00	4.00	5.00	4.00	5.00	5.00
<i>Albedo modification via human settlements</i>	2.00	1.00	2.00	2.00	1.50	2.50	2.00	1.00	1.50
<i>Albedo management via grasslands and crops</i>	3.00	2.50	2.50	2.00	3.00	3.00	3.00	2.00	2.00
<i>Albedo management via deserts</i>	3.00	2.50	3.00	3.00	3.00	3.00	3.00	3.00	3.00
<i>Albedo management via clouds</i>	4.00	3.00	4.00	4.00	3.00	3.00	4.00	4.00	2.00
<i>Ice protection</i>	4.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	1.00
<i>High altitude sunshades</i>	5.00	3.00	5.00	4.00	3.00	5.00	5.00	4.00	4.00



# EXPERT PERCEPTIONS ON BARRIERS

	Technology upscaling and readiness	Storage and disposal constraints	Public perception and social acceptance	Legal and regulatory obstacles	Challenges to system integration	Financing	Market demand	Environmental or planetary risks	Other factors
<i>Afforestation and reforestation</i>	1.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00	4.00
<i>Soil carbon sequestration</i>	2.00	1.50	1.00	1.50	2.00	2.00	2.00	1.00	1.50
<i>Biochar</i>	2.00	2.00	1.50	2.00	2.00	2.00	2.00	2.00	1.50
<i>BECCS</i>	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
<i>Enhanced weathering</i>	3.00	2.00	3.00	3.00	2.00	3.00	3.00	2.00	1.00
<i>Ocean alkalization or fertilization</i>	4.00	2.00	4.00	4.00	3.00	3.00	4.00	5.00	3.00
<i>Blue carbon and seagrass</i>	2.00	2.00	1.00	2.00	2.00	3.00	3.00	2.00	1.00
<i>Ecosystem restoration</i>	1.00	2.00	1.00	2.00	2.00	3.00	2.00	1.00	1.00
<i>DACCS</i>	4.00	3.00	3.00	2.00	3.00	4.00	3.00	2.00	3.00
<i>CCUS</i>	3.00	4.00	3.00	2.00	3.00	3.00	2.00	2.00	3.00

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<i>Biochar</i>	2.00	2.00	1.50	2.00	2.00	2.00	2.00	2.00	1.50
<i>BECCS</i>	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
<i>Enhanced weathering</i>	3.00	2.00	3.00	3.00	2.00	3.00	3.00	2.00	1.00
<i>Ocean alkalization or fertilization</i>	4.00	2.00	4.00	4.00	3.00	3.00	4.00	5.00	3.00
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<i>DACCS</i>	4.00	3.00	3.00	2.00	3.00	4.00	3.00	2.00	3.00
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<i>Biochar</i>	2.00	2.00	1.50	2.00	2.00	2.00	2.00	2.00	1.50
<i>BECCS</i>	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
<i>Enhanced weathering</i>	3.00	2.00	3.00	3.00	2.00	3.00	3.00	2.00	1.00
<i>Ocean alkalization or fertilization</i>	4.00	2.00	4.00	4.00	3.00	3.00	4.00	5.00	3.00
<i>Blue carbon and seagrass</i>	2.00	2.00	1.00	2.00	2.00	3.00	3.00	2.00	1.00
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<i>DACCS</i>	4.00	3.00	3.00	2.00	3.00	4.00	3.00	2.00	3.00
<i>CCUS</i>	3.00	4.00	3.00	2.00	3.00	3.00	2.00	2.00	3.00

# FINDINGS

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- Unlike other elicitation processes where experts are more positive or have high expectations about novel options, our results are more critical and cautionary, esp. for solar geoengineering
- When put portfolios organized by a forced hierarchy of prioritization, our experts supported **afforestation and reforestation, ecosystem restoration, and soil carbon sequestration** as the most optimal negative emissions options and **albedo modification via human settlements, albedo management via grasslands and crops and marine cloud brightening** as the most desirable solar geoengineering options
- This thinking partly aligns with the expected potential these options have by our experts, with **afforestation and reforestation, ocean alkalization or fertilization, and bioenergy with carbon capture and storage** expected to achieve the most substantial emissions reductions by 2050 (a collective 165.85 GtCo<sub>2</sub>)
- **Stratospheric aerosol injection, albedo management via crops, and space-based reflectors** are identified with a mean potential to reduce a combined 2.5 C degree temperature change

# FINDINGS

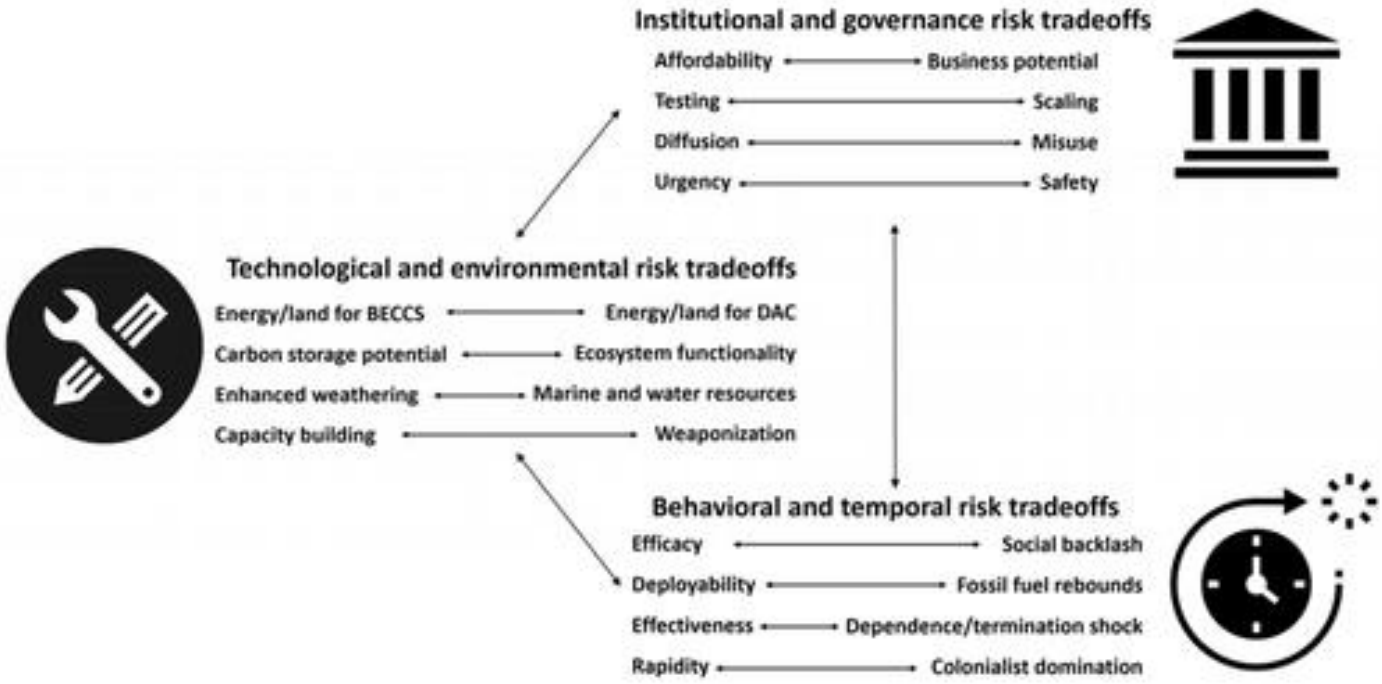
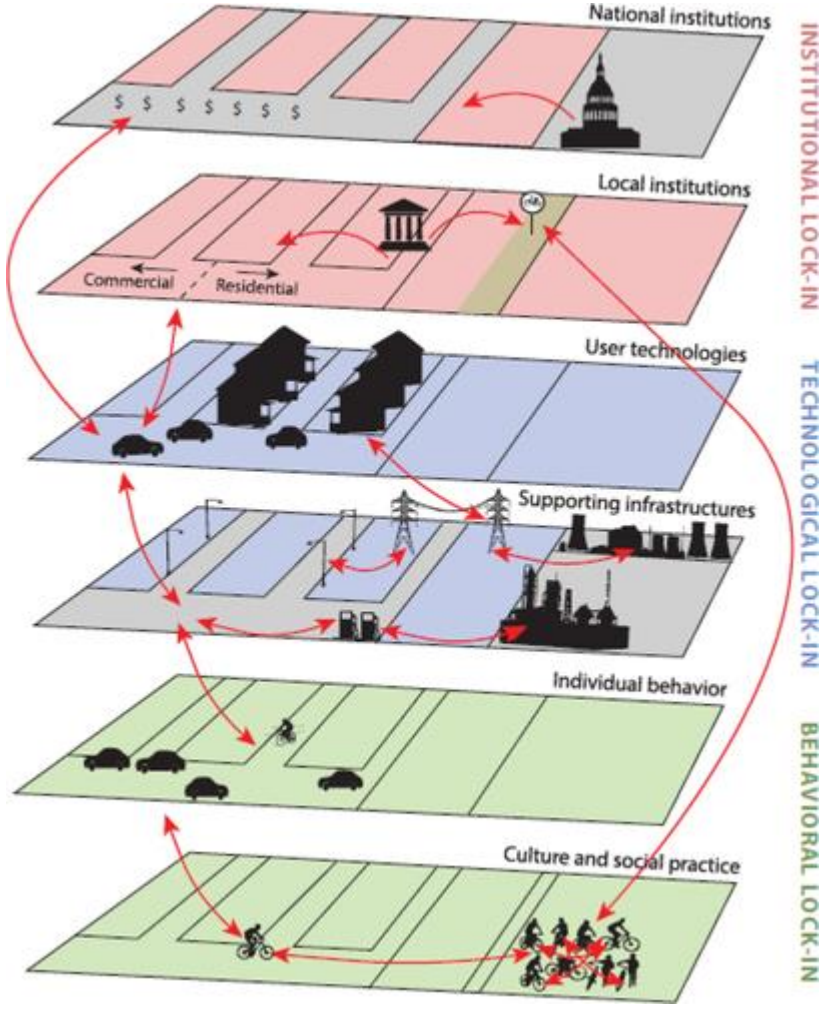
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- The **comparative efficacy** of the more affordable options becomes striking when compared to the others: per ton of carbon displaced, soil carbon management would be about 60 times more cost effective than bioenergy with carbon capture and storage.
- **Ecosystem restoration** would be about 18 times more cost effective than **carbon capture utilization and storage**, and **blue carbon and seagrass** to be about 35 times more cost effective than **direct air capture**.
- Only the options of **afforestation and reforestation** (2032) and **soil carbon sequestration** (2035) were expected to be widely deployed (e.g., surpassing a 20% market share) before 2035.
- Much-discussed options such as **carbon capture utilization and storage**, **direct air capture**, **bioenergy with carbon capture and storage**, and virtually all **solar geoengineering options** are not expected to achieve deployment until at least 2040. Some options were identified as not reaching deployment until well after **2050** or even **2070** at the earliest. This places a preponderance of options as out of reach and **unavailable for use within the next two decades**.
- A majority of experts even suggested that some options—especially albedo modification by deserts, cirrus cloud thinning, albedo modification by clouds, ocean alkalization or fertilization, high-altitude sunshades, and space-based reflectors—would **never reach commercialization**.

# FINDING 3: RISK-RISK TRADEOFFS

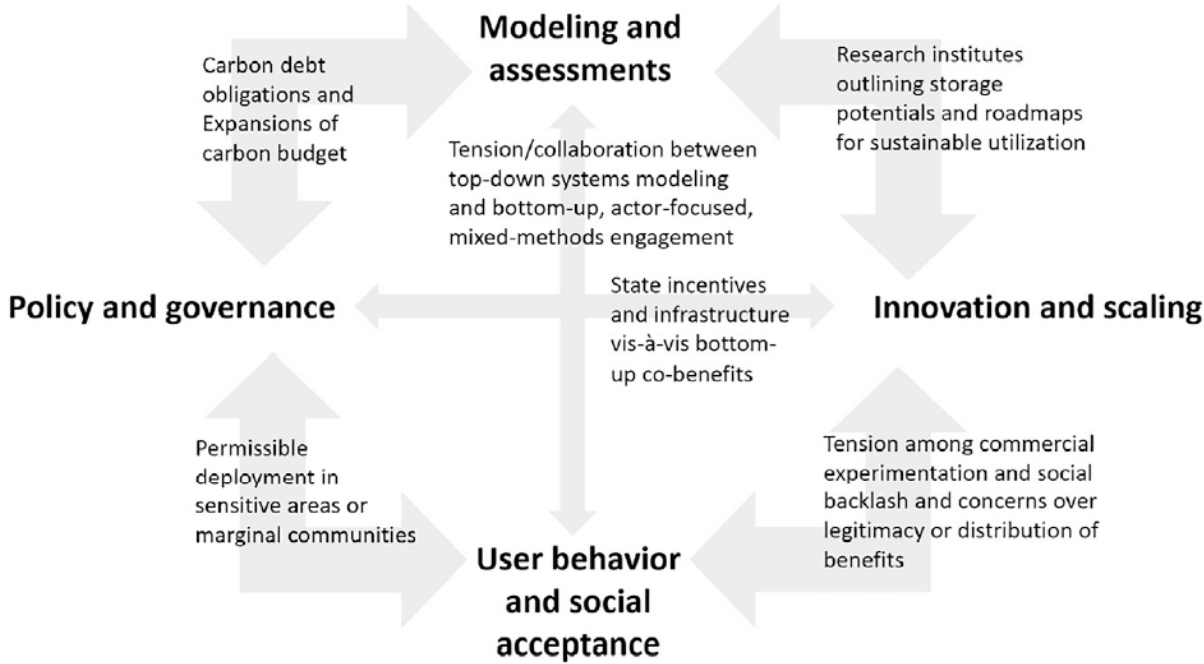
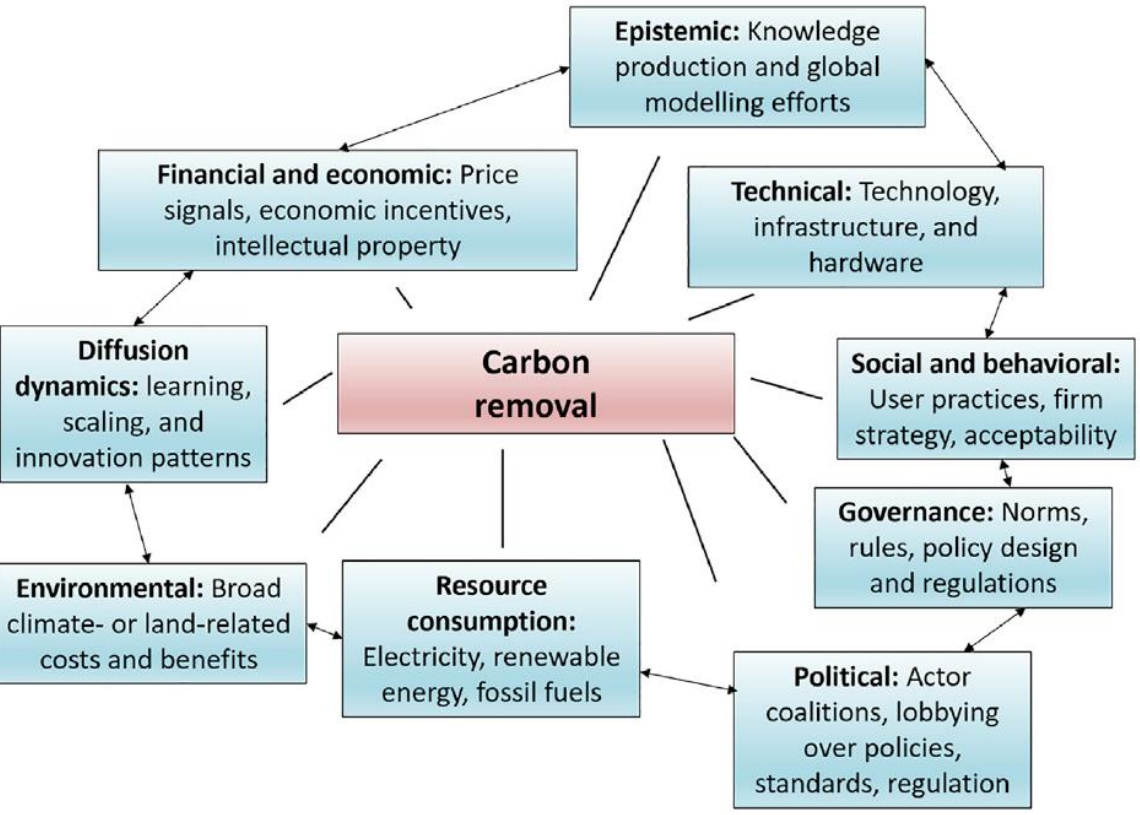
	<i>Promising prospective benefits</i>	<i>Perilous potential costs</i>
<b>Technical dimension</b>	Offers rapid climate change abatement in a world where neither mitigation or adaptation can adequately address climate change	Would not address all fundamental changes in climate or threats such as ocean acidification
	Some options (e.g., stratospheric aerosol injection) could be done with today's technology and deployed in a matter of a few years	Only a few options ready for deployment, most would be years to even many decades away; and even then, would need to be deployed in perpetuity for hundreds if not thousands of years
<b>Financial dimension</b>	Portfolios using some options (aerosols) could be deployed at the cost of only a few hundred million dollars to \$25 to \$30 billion, compared to the need to invest trillions of dollars in climate mitigation efforts, other options (DACCS) already cost-competitive with carbon prices in the European Union	Some options (e.g., enhanced weathering) could cost as much as \$600 trillion alone; some NETS would require prices as high as \$4000/ton of carbon by the year 2100
	Some options (e.g., afforestation, reforestation, soil recycling, BECCS) could contribute to local improvements in the environment and also generate much needed revenue for farms and otherwise deprived rural areas	Anticompetitive patent behavior, including patent thickets and overly broad patents, could deter and slow innovation trends or consolidate benefits among only a few large firms
<b>Socioenvironmental dimension</b>	Can deliver extremely large emissions reductions on par with the Paris Accords and consistent with a 1.5 to 2 degree temperature pathway	Many options are themselves energy intensive and could come to consume very large amounts of energy themselves (e.g. up to 10 GJ of energy per ton captured and stored, or up to 19.4% of global energy consumption or 53-83% of global gas use)
	Could bolster investments in other coupled sociotechnical systems (e.g., renewable electricity, carbon capture and storage, nuclear power, bioenergy, hydrogen)	Can reduce efforts at climate mitigation and promote "mitigation deterrence," as well as resulting in their own waste streams as well as a host of environmental calamities to land, water, climatic change, and local habitats and forests including the species that depend on them
<b>Political dimension</b>	Can expedite and facilitate future technological innovations that enhance the economic competitiveness of supporting nations	Weak governance structures and lack of monitoring and verification could give rise to misuse and even weaponization of the technologies
	Does not necessarily rely on multilateral governance initiatives, and can instead be deployed quickly by single nation states and even sub-national actors (i.e., it is not prone to the tragedy of the commons). That said, could also stimulate regional cooperation and different geopolitical clubs and coalitions of countries with aligned geoengineering interests	Raises concerns of colonialism, piracy and dependence on large firms or actors in the Global North, at the expense of the Global South

# RISK-RISK TRADEOFFS ACROSS THE SOCIOTECHNICAL SYSTEM



Sovacool, BK, C Baum, and SJ Low. "Risk-risk governance in a low-carbon future: Exploring institutional, technological, and behavioral tradeoffs in climate geoengineering pathways," *Risk Analysis* (in press)

# RISK-RISK TRADEOFFS ACROSS THE SOCIOTECHNICAL SYSTEM



Sovacool, BK, CM Baum, and S Low. "Reviewing the sociotechnical dynamics of carbon removal," *Joule* 7(1) (January 2023), pp. 57-82.

Figure 1. Visualizing carbon removal as a sociotechnical system

# FINDING 4: JUSTICE AND EQUITY IMPACTS

Total number: 125 experts

10 carbon removal and 10 solar geoengineering technologies

Over 100 with expertise in both as novel climate strategies

Mostly from universities and research institutes

Just under 10% from Global South

<i>Summary information</i>	<i>No.</i>
No. of experts	125
No. of organizations represented	104
No. of countries represented	21
No. of academic disciplines represented	34
Cumulative years spent in the geoengineering industry or research community	881
Average years spent in the geoengineering industry or research community	7.8
No. of experts whose current position falls into the following areas:	
Civil society and NGOs	12
Government and intergovernmental organizations	8
Private sector and industrial associations	12
Universities and research institutes	94
No. of experts from the Global South	12

# EXPERT-INTERVIEW EXERCISE

- “A whole systems energy justice mapping of twenty negative emissions and solar geoengineering pathways”
- What equity and justice concerns arise with these 20 negative emissions or solar geoengineering options?
- What particular vulnerable groups could be affected?
- What risks do these options entail for communities or the climate?

<b>1. Innovation</b>	Which particular options have high or low innovation potential in technical, communication, societal appraisal, and policy dimensions?
<b>2. Coupling</b>	What energy systems or other sociotechnical systems could or should be coupled to carbon removal?
<b>3. Business models</b>	What business models and markets could carbon removal create or disrupt?
<b>4. Risks</b>	Which serious risks (e.g., social, political, military, ethical, environmental) may arise?
<b>5. Sustainability</b>	What are the synergies and trade-offs of deployment for the Sustainable Development Goals and other societal objectives?
<b>6. Justice</b>	What vulnerable groups could be affected, positively or negatively?
<b>7. Actors</b>	Who are the relevant (or most important) actors (or stakeholders / networks), e.g. for commercialization, development, and/or acceptability?

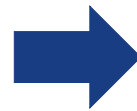
# JUSTICE IN CDR AND SRM LITERATURE

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Procedural justice: lack of engagement of (vulnerable) groups or centering of decisions in Global North

Mitigation deterrence: potential as solutions could undercut necessary urgency for climate mitigation

Distributional justice: unfair distribution of risks and benefits, within and across countries



Focus on distributional (perhaps procedural) justice, germane to deployment and policymaking

Certain technologies (afforestation) but very little on direct air capture, enhanced weathering, etc.

Framed in local “NIMBY” terms, other scales and temporalities neglected

Sovacool, BK, C Baum, and S Low. “Climate protection or privilege? A whole systems justice milieu of twenty negative emissions and solar geoengineering technologies” *Political Geography* 97 (August, 2022), 102702, pp. 1-21..

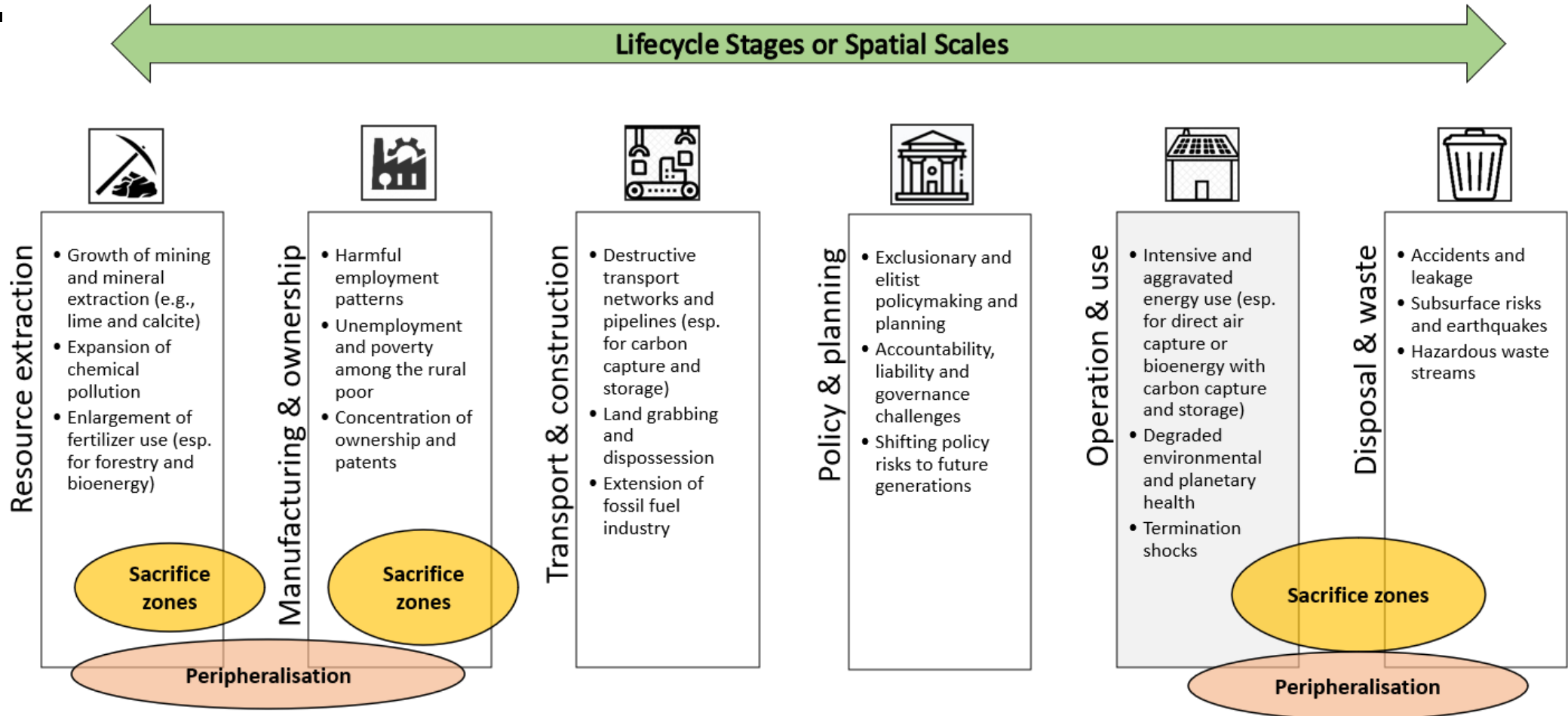
# WHOLE-SYSTEMS JUSTICE AND CDR/SRM

- **Resource extraction**, including mineral, chemical, and extractive industries, which often involve the displacement of workers or generate community hazards;
- **Manufacturing, labor, and ownership**, which can involve occupational hazards and impacts on labor and employment and concentrations of ownership and intellectual property;
- **Transport and construction**, including accidents during the building of systems as well as embodied environmental footprints of materials or the grabbing of land needed to build facilities;
- **Policymaking and planning**, including licensing, permitting, standards and regulation;
- **Operation and use**, including provision of energy services (or in this case, e.g., capture and storage of carbon dioxide) or the risk of onsite accidents;
- **Disposal and waste**, including issues of recycling, waste incineration and electronic waste flows as well as accidents at storage facilities.

Sovacool, BK, C Baum, and S Low. "Climate protection or privilege? A whole systems justice milieu of twenty negative emissions and solar geoengineering technologies" *Political Geography* 97 (August,

2022), | 102702 pp. 1-21..

# WHOLE-SYSTEMS JUSTICE AND CDR/SRM



Sovacool, BK, C Baum, and S Low. "Climate protection or privilege? A whole systems justice milieu of twenty negative emissions and solar geoengineering technologies" *Political Geography* 97 (August, 2022), 102702, pp. 1-21..

# “TRANSPORTATION AND CONSTRUCTION”

*“For negative emissions to reach the scale required for climate stabilization, we will need very super continental-scale managed plantations that are harvested on a short rotation cycle, and this would need catchment areas of thousands of square kilometers. Transport alone would be daunting, even if you build monorails in the forests to transport trees to the unit, or micro-CDR or storage units to bring to the forest or invent CCS units on wheels or drones, it becomes almost impossible.” (R081)*

*“There won’t be any trust for deployment of these options in tribal lands, people will doubt that it will help them ... These options could even be seen as a colonial enterprise to displace local groups from their assets.” (R007)*

*“If you were to actually roll out carbon capture and sequestration, you'd be able to maintain the current distribution of fossil plants. The communities that have been built around coal and gas plants would be able to continue to prosper, but it would also imply continued or even additional use of fossil fuels.” (R079)*

# WHOLE-SYSTEMS JUSTICE

	Resource extraction, chemicals, and fertilizers	Manufacturing, labor and ownership	Transportation, construction and land grabbing	Policymaking and planning	Deployment, operation and use	Disposal and waste
<b>Nature-based carbon dioxide removal (e.g., soil carbon sequestration, biochar, afforestation and reforestation, blue carbon and seagrass)</b>	Possible dependence on fertilizers or pesticides or monoculture plantations	Resource-curse risks for workers and communities	Extensive transport networks needed harvest forest outputs, competition with other land-uses	Climate colonialism, poor monitoring, verification, and accounting, loss of freedom for future generations	Pollution of agricultural land or food, hidden or unknown environmental risks, impermanence and reversibility of carbon storage	Generation of agricultural residues and biomass wastes
<b>Engineered carbon dioxide removal (e.g., CCUS, DAC, BECCS, OIF, enhanced weathering)</b>	Large-scale mining operations, chemical pollution from solvents and treatments, dependence on fertilizers	Resource-curse risks for workers and communities, creation of sacrifice zones near deployment, strengthening of fossil-fuel incumbents	Extensive transport networks needed to deliver energy crops or residues, creation of pipelines and storage reservoirs, fleets of ships for ocean iron fertilization, competition with other land-uses, displacement of vulnerable groups, increases in fossil fuel consumption	Irresponsible distribution of risks between Global North and Global South, a “Pandora’s Box” of liability concerns over stored carbon, loss of freedom for future generations	Immediate increases in energy consumption, risk of sudden termination shocks or effects	Accidents at storage sites including suffocation of host communities, impermanence of long-term storage, earthquakes, energy penalties and increased resource waste

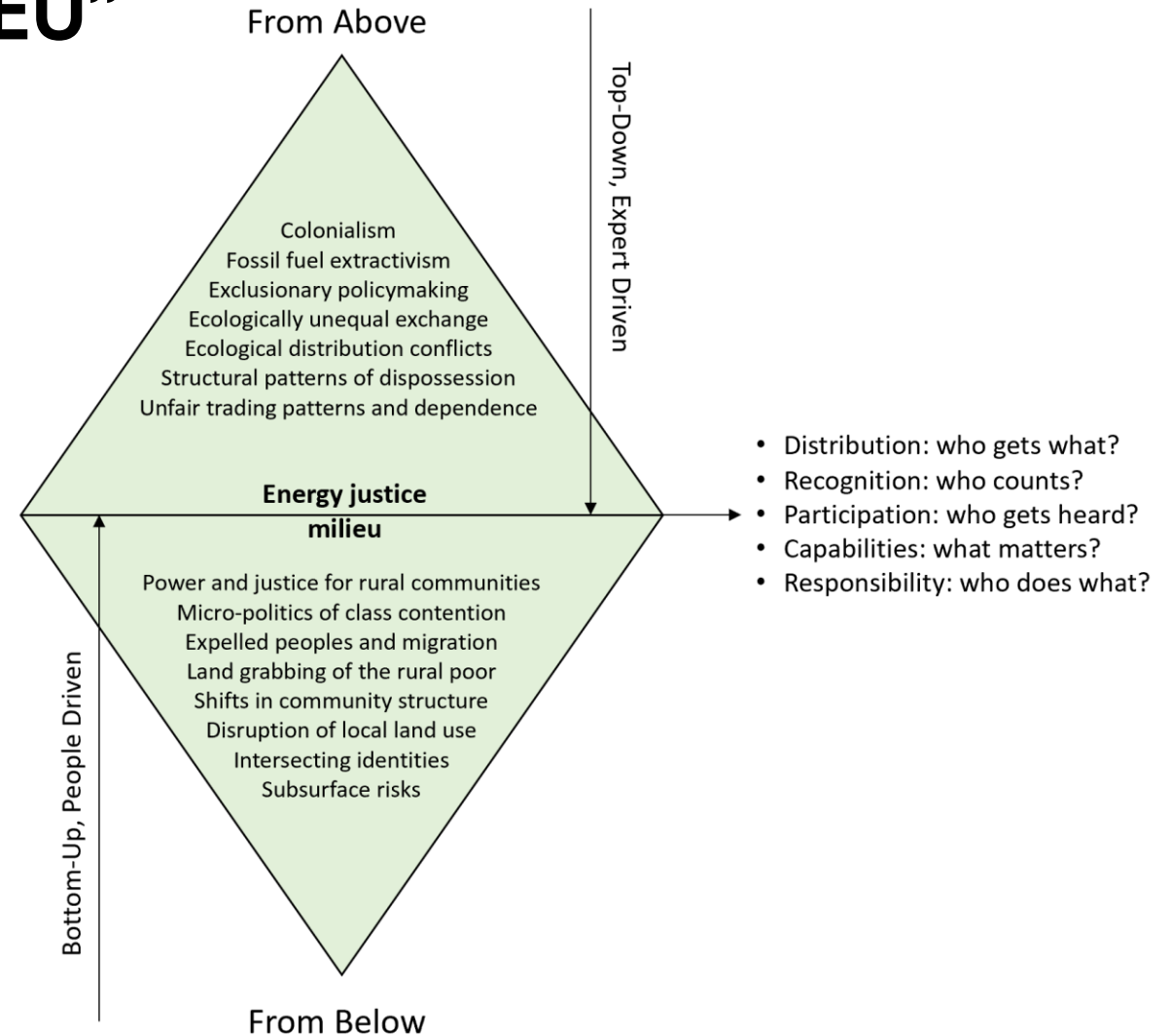
# “WHOLE-SYSTEMS JUSTICE MILIEU”

“Milieu” highlights that “justice” is emergent, evolving, and relational

Capture injustices from below or bottom-up (land use/grabbing, community impacts) and from above or top-down (exclusionary policymaking, colonialism)

“Bottom-up” offers people-driven approach capturing localized narratives, meanings, perceptions, values

“Top-down” emphasizes role of structural factors and how they constrain behavior



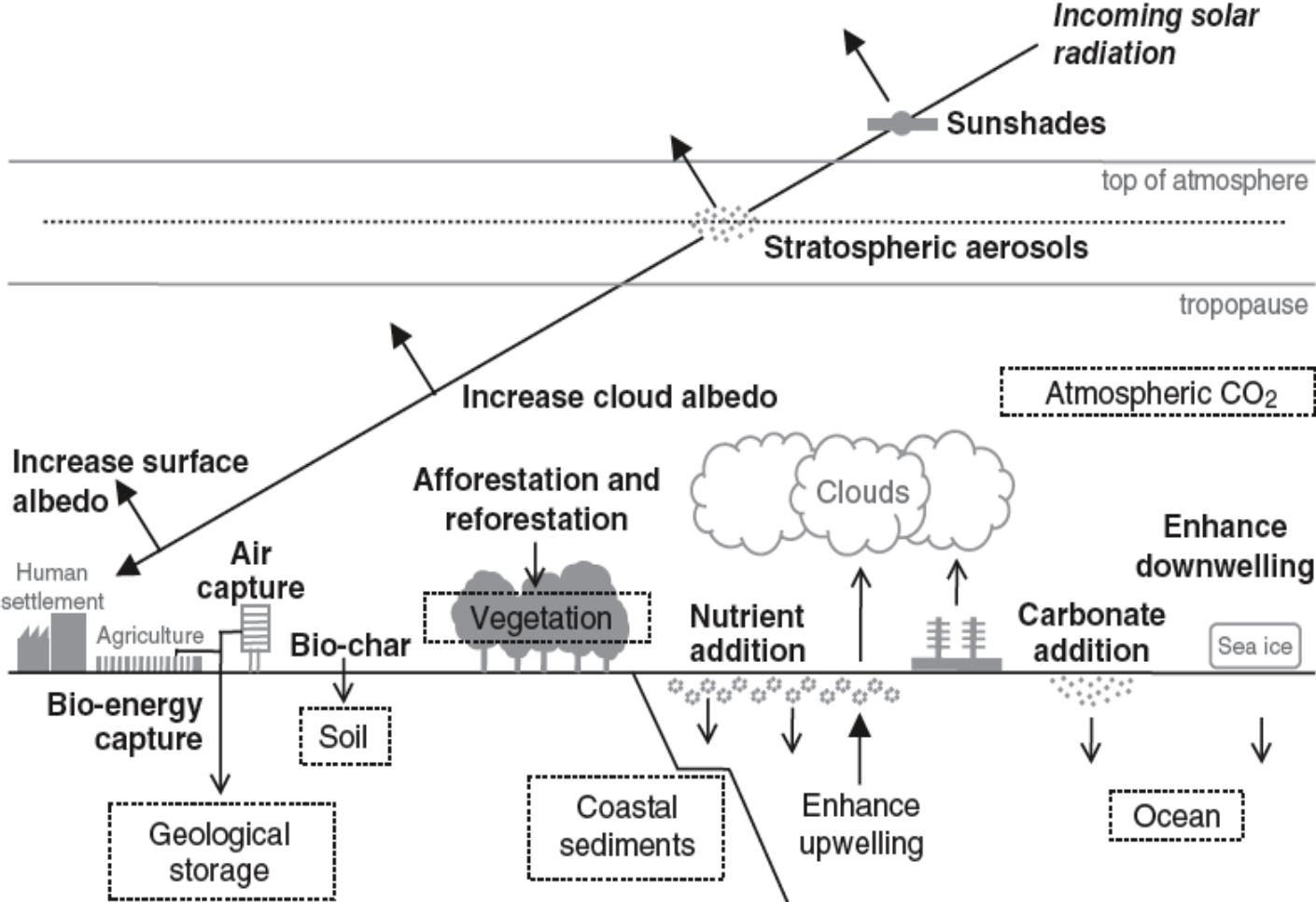
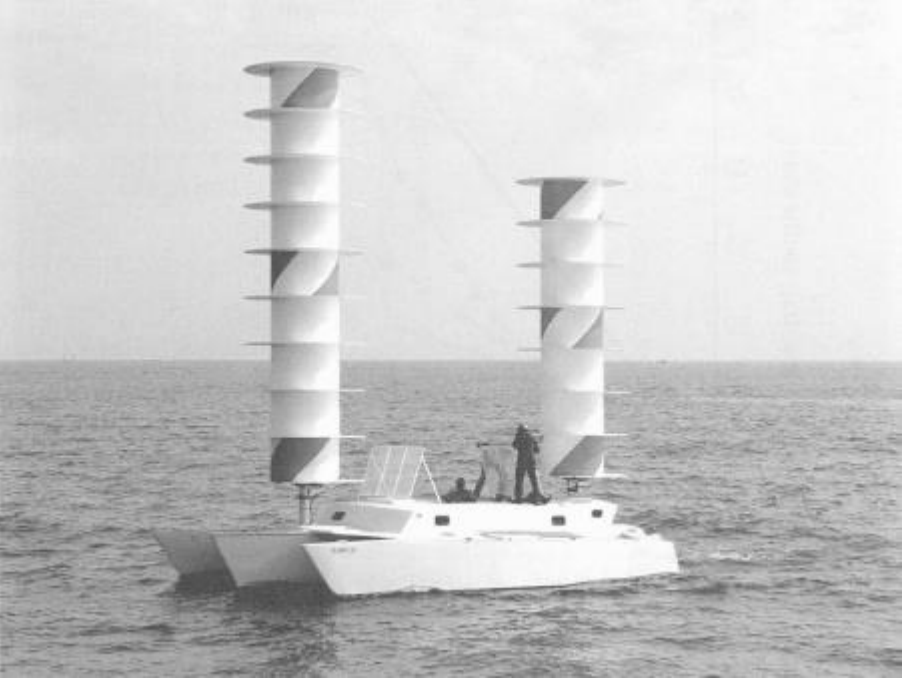
# WHOLE-SYSTEMS JUSTICE MILIEU

Tenet of justice	Burdens related to negative emissions and solar geoengineering technologies
<i>Distribution</i>	<ul style="list-style-type: none"> <li>• Land use impacts among communities hosting infrastructure</li> <li>• Shifting pollution flows from fertilizers for new energy crops</li> <li>• Uneven climatic protection from aerosol injection or cloud brightening</li> <li>• Creation of “pollution havens” near mining or disposal sites and “sacrifice zones” among the world’s poor</li> <li>• Hidden future and unknown risks</li> </ul>
<i>Recognition</i>	<ul style="list-style-type: none"> <li>• Increased vulnerability among demographic or cultural groups (rural farmers, indigenous peoples) near infrastructure</li> <li>• Entrenchment of preexisting patterns of spatial, economic, or political peripheralization</li> <li>• Impacts on non-human species (forest loss, water use, habitat change, land degradation)</li> <li>• Threat of real or potential termination shocks and risks to future generations</li> </ul>
<i>Participation</i>	<ul style="list-style-type: none"> <li>• Inadequate attention to and respect for social acceptance and community well-being, lack of adequate compensation for benefits</li> <li>• Unfair or non-representative energy or climate planning and policymaking at local, national, and global levels</li> </ul>
<i>Responsibility</i>	<ul style="list-style-type: none"> <li>• Threat of “mitigation deterrence” and rebounds in fossil fuel consumption and profiteering that interfere with decarbonization</li> <li>• Perpetual risk of accidents or carbon leakage</li> <li>• Creating a “Pandora’s Box” of liability</li> </ul>
<i>Capabilities</i>	<ul style="list-style-type: none"> <li>• Concentration of profits, wealth, resources or intellectual property among elites with risks distributed to communities</li> <li>• Constraints arising from deployment related to local employment, capacity building, gender equality, or other Sustainable Development Goals</li> </ul>

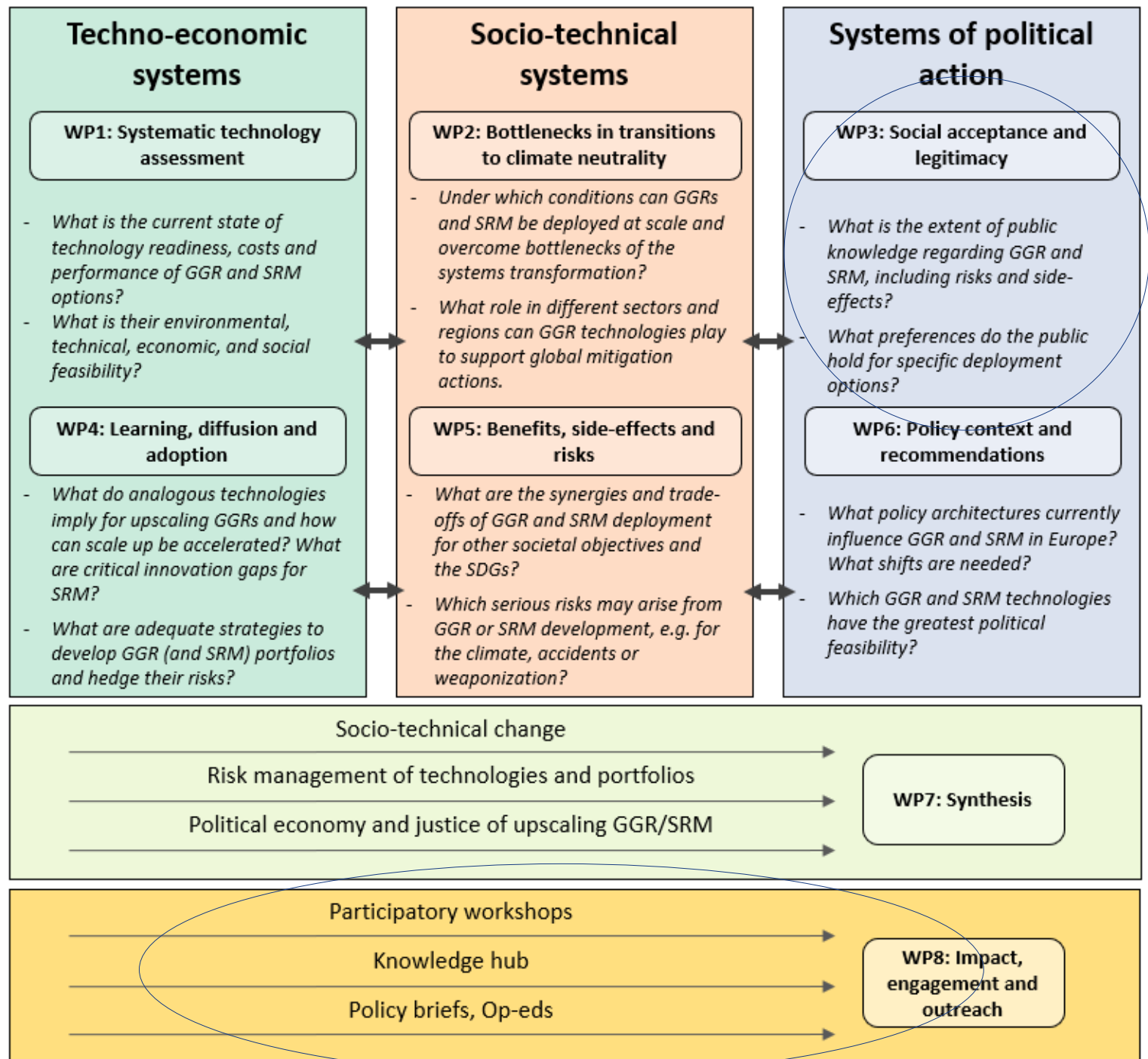
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# CONCLUSION AND THREE FUTURE RESEARCH DIRECTIONS

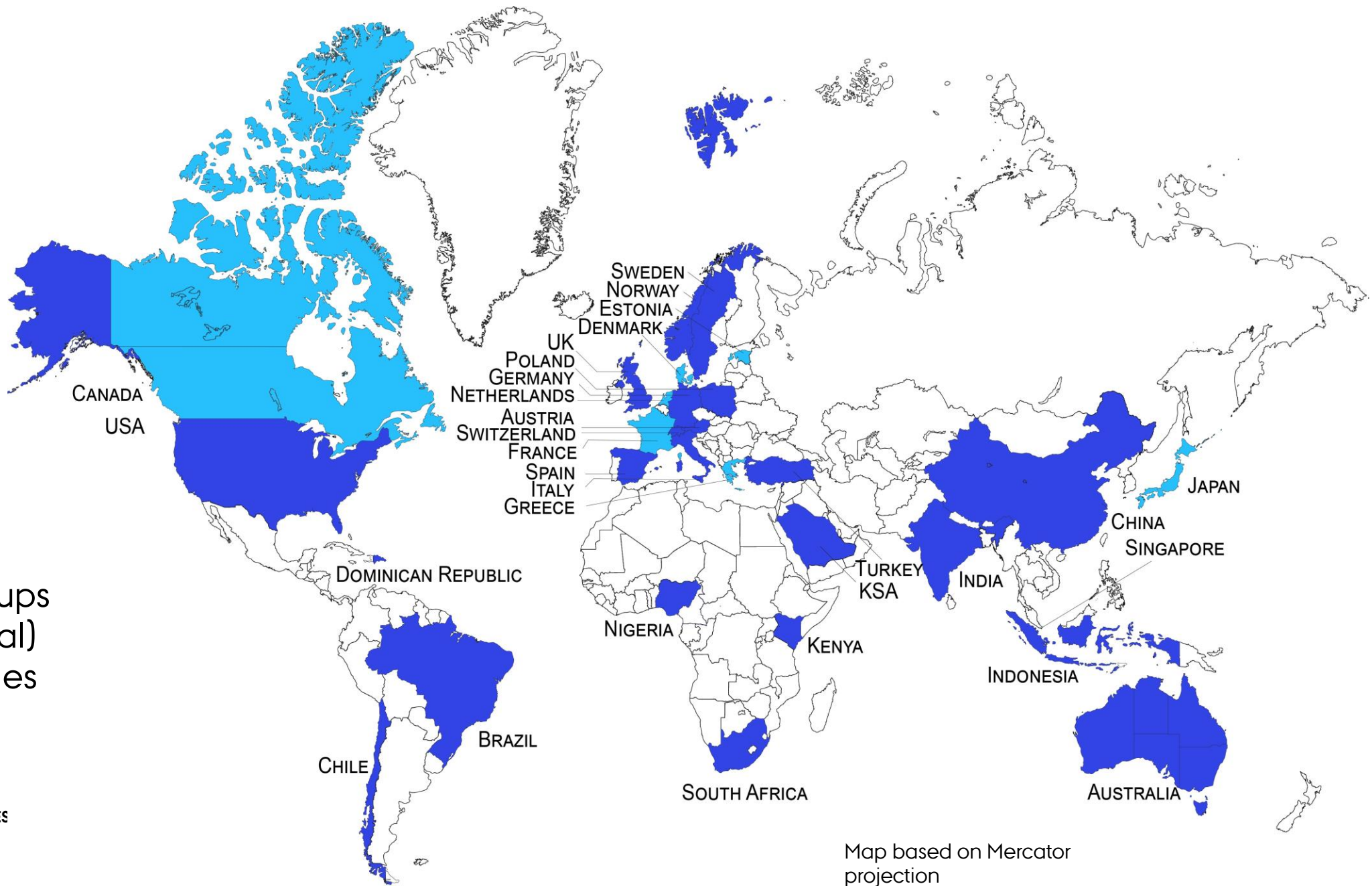
# COCKTAILS AND PORTFOLIOS



# SURVEYS, FOCUS GROUPS AND KNOWLEDGE EXCHANGE



# SCOPE



- Survey in 30 countries
- 2 Focus Groups (urban & rural) in 22 countries

# SURVEY DESIGN



Introduction to technologies  
Familiarity with particular technologies

Randomized assignment to technology grouping: Solar Radiation Management, Carbon Dioxide Removal 1 (“nature-based”), Carbon Dioxide Removal 2 (“engineered”); 4 familiarity items & comprehension checks

Perceptions of risks and benefits

4 risks & benefits items per technology (adapted from Jobin & Siegrist 2020, Wright et al. 2014);  
Weighing risks & benefits – 1 per technology (adapted from Pidgeon & Spence 2017)

Assessment of support for technology

1 one R&D, 1 on small scale field trials, 1 on broad deployment (adapted from Pidgeon & Spence 2017, Jobin & Siegrist 2020)

Assessment of policy options

Selection of up to 7 policy option at national & international scale

Assessment of potential covariates

Value orientations and tampering with nature; trust in institutions and science; perceptions and experience of climate change; ownership of green technologies (all items based on previously used scales)

Demographics

Age, gender, occupation, income, political views, religiosity, member of minority or indigenous groups



# FOCUS GROUP DESIGN



## Warm-up & Introduction

- Perceptions of climate change
- First reactions to the approaches introduced in the reading material

## Risks and benefits

- What benefits / risks?
- Who benefits/is negatively affected?

## Governance: actors and actions

- Who should take decisions?
- Which actions should be taken before considering or when implementing?
- Which role do participants see for the public/themselves?

## Imagined futures

- Creating headline about a chosen approach in the year 2030



**Separate  
discussion on SRM  
& CDR  
approaches**



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