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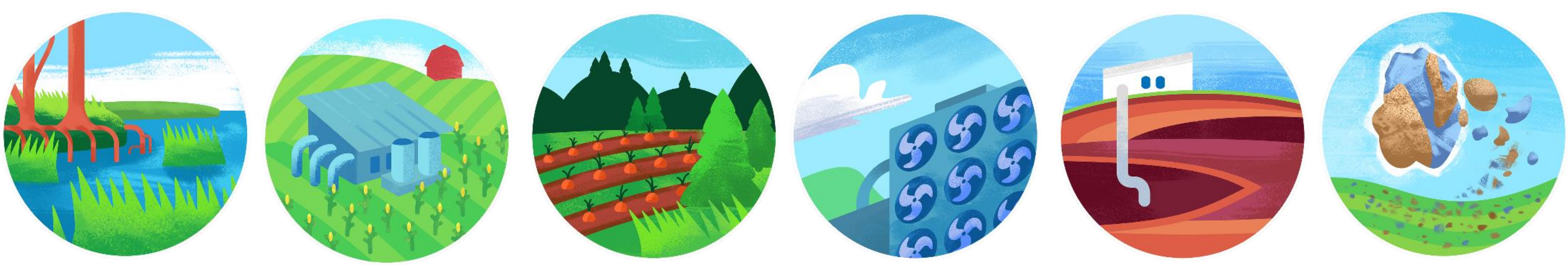
Negative Emissions Technologies and Reliable Sequestration: A Research Agenda



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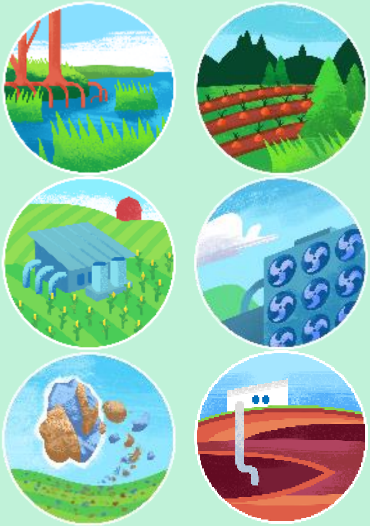
Carbon Mitigation Technologies reduce or eliminate carbon dioxide emissions from fossil fuel use, cement production and land use change.

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

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

Mitigation Portfolio

- NETs
- Energy efficiency
- Low or zero-carbon fuel sources



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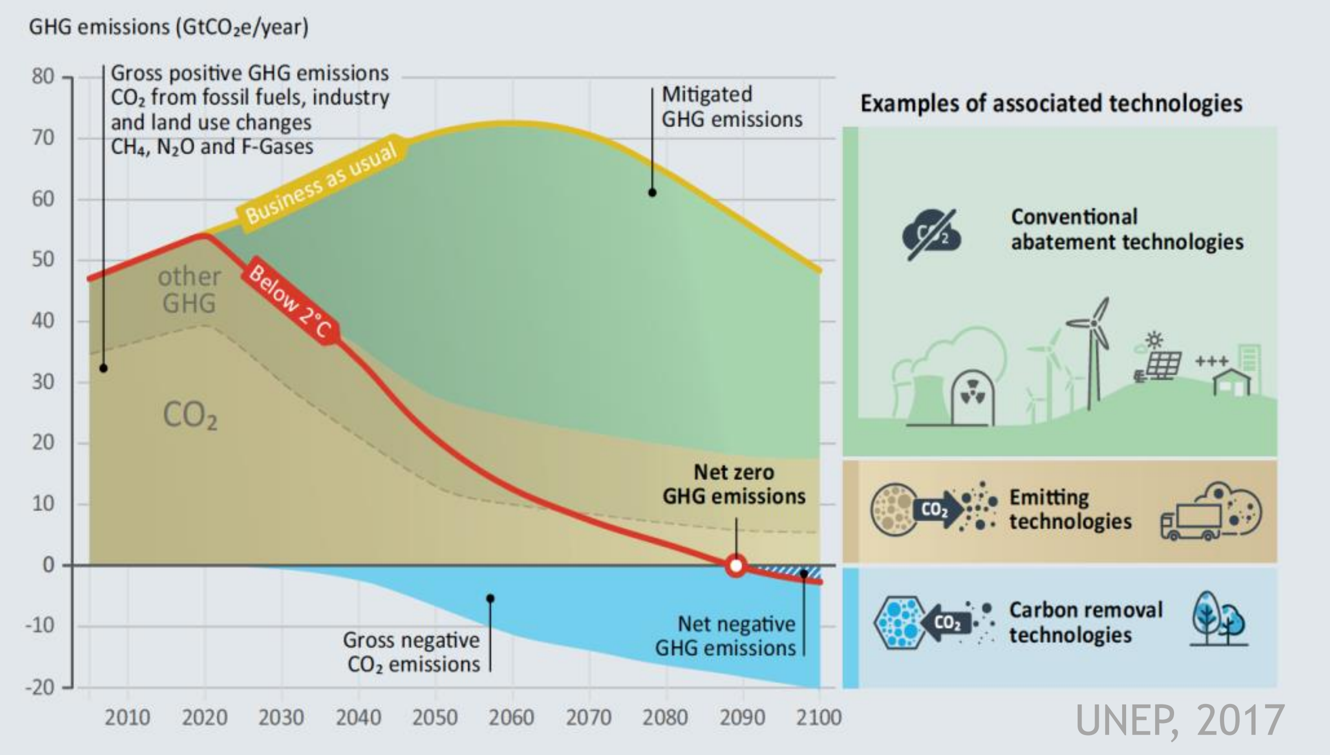
Statement of Task

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

Study Process

- Information gathering workshops
  - Coastal Blue Carbon Approaches (July 2017)
  - Land Management Practices (Sept. 2017)
  - Bioenergy with Carbon Capture and Storage Approaches (Oct. 2017)
  - Direct Air Capture (Oct. 2017)
  - Geologic Sequestration and Mineral Carbonation Approaches (Nov. 2017)
- Additional webinars and presentations
- Committee meetings to develop report
- Extensive external peer review

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



~10 $GtCO_2$/y globally by midcentury

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

Negative Emissions Technologies

Coastal blue carbon

Direct air capture

Terrestrial carbon removal and sequestration

Carbon mineralization

Bioenergy with carbon capture and sequestration (BECCS)

Geologic sequestration

Terrestrial carbon removal and sequestration

- Afforestation/reforestation
- Changes in forest management
- Changes in agricultural practices that enhance soil carbon storage
- Limiting factors:
  - Available land
  - Practical barriers
  - Demand for wood
  - Limited per-hectare rates of carbon uptake

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Bioenergy with carbon capture and sequestration (BECCS)

- Plant biomass used to produce electricity, liquid fuels, heat
- Combined with capture and sequestration of CO_2 produced when using bioenergy and any remaining biomass carbon that is not in liquid fuels
- Limiting factors:
  - Cost
  - Availability of biomass
  - Inability to fully capture waste biomass
  - Fundamental understanding

Four NETs are ready for large-scale deployment:

- afforestation/reforestation
- forest management
- uptake and storage by agricultural soils
- bioenergy with carbon capture and sequestration(BECCS)

However, additional research is likely to further reduce costs, increase efficiency and reduce unwanted impacts.

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Direct air capture

- Chemical processes that capture CO_2 from ambient air and concentrate it
- The captured CO_2 can be injected into a storage reservoir
- Limiting factors:
  - Cost greater than economic demand
  - Practical barriers to pace of scale up

Credit: Climeworks

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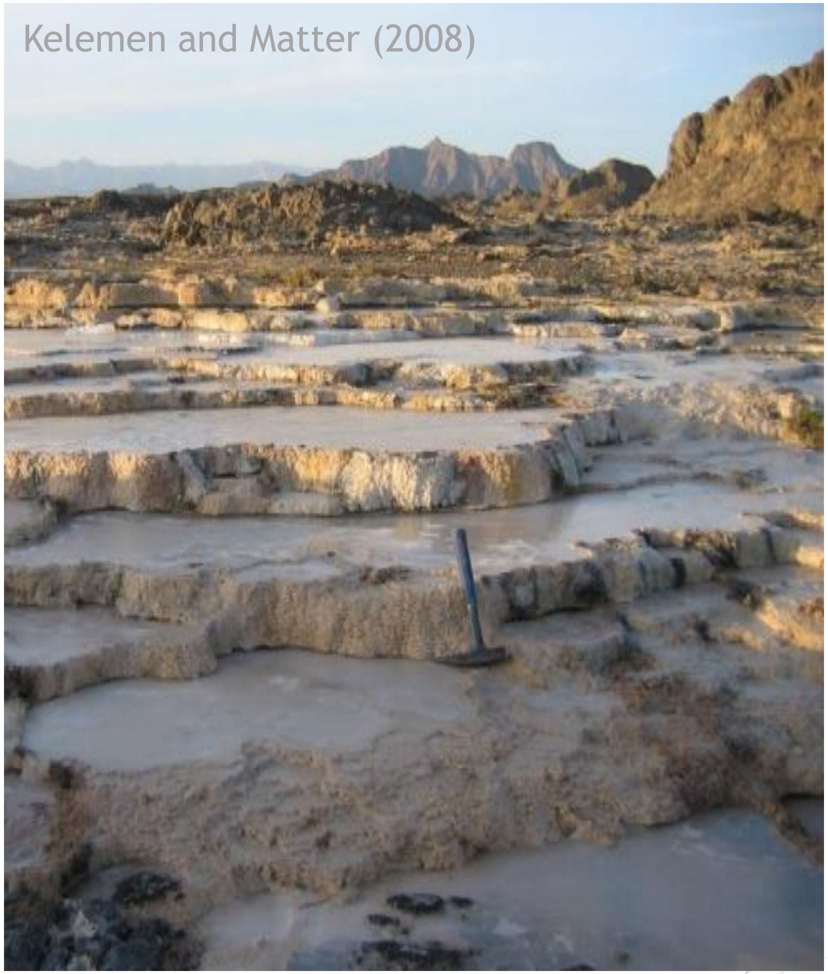
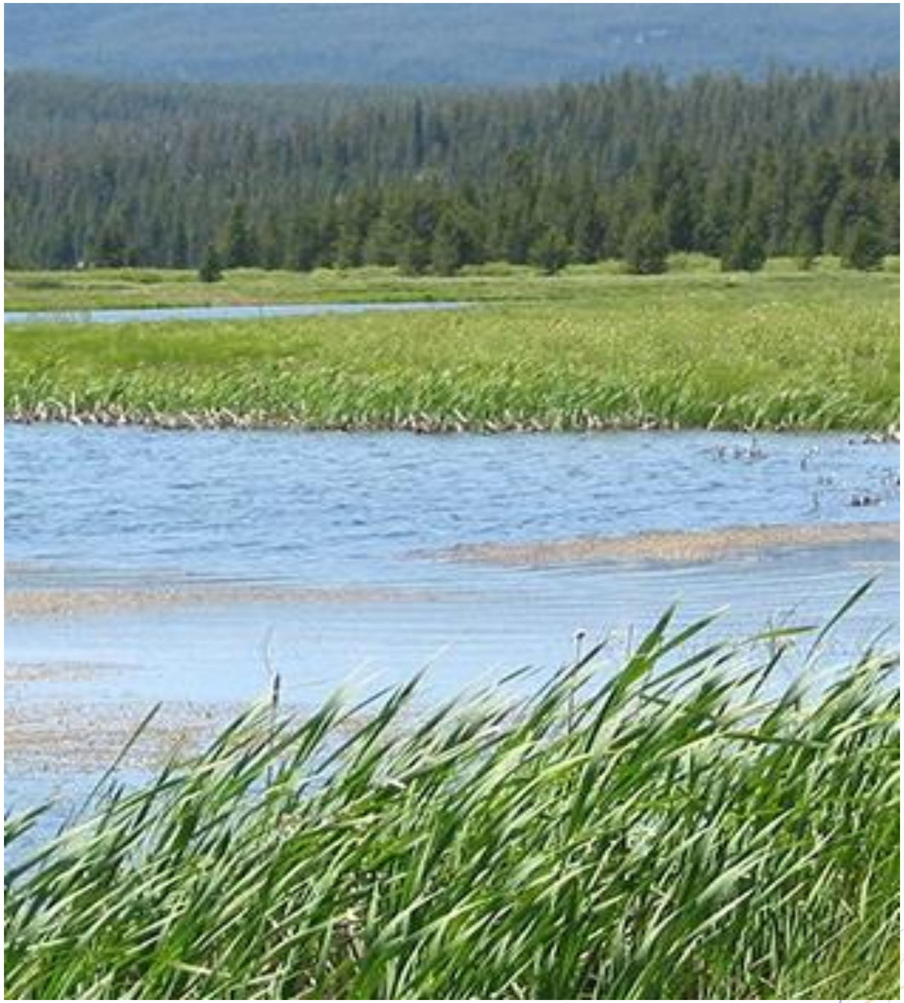
Carbon mineralization

- Accelerated “weathering”
- Atmospheric CO_2 forms a chemical bond with reactive minerals
  - Ex Situ: Occurs at surface where CO_2 in ambient air is mineralized on exposed rock
  - In Situ: Occurs in subsurface where concentrated CO_2 streams are injected into ultramafic and basaltic rocks where it mineralizes in pores
- Primarily limited by lack in fundamental understanding


Kelemen and Matter (2008)

Coastal Blue Carbon

- Practices that increase amount of carbon stored in living plants or sediments in tidal marshlands, seagrass beds, and other tidal or salt-water wetlands
- Limiting factors:
  - Available land given coastal development and land use
  - Understanding of future rates with sea level rise and coastal management



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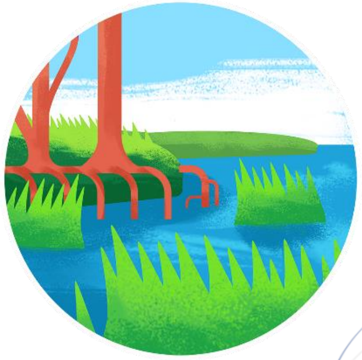
- **Safe and economical direct air capture or carbon mineralization would have essentially unlimited capacity to remove carbon**
  - Direct air capture currently limited by high cost
  - Carbon mineralization currently limited by lack of fundamental understanding

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



Geologic sequestration

- CO_2 captured through BECCS or direct air capture is injected into a geologic formation where it remains in rock pore space for a long time
- Not a NET, rather an option for sequestration component of BECCS or direct air capture
- Practical limits will be set by availability of CO_2, pipelines, regulatory infrastructure and public opinion

Negative Emissions Technology	Estimated Cost ($/t$CO_2$) L = 0-20 M =20-100 H = >100	Upper Bound* for Safe* Potential Rate of CO_2 Removal Possible Given Current Technology and Understanding and at ≤$100/t$CO_2$ (GtCO_2/y)	
		US	Global
Coastal blue carbon	L	0.02	0.13
Afforestation/ Reforestation	L	0.15	1
Forest management	L	0.1	1.5
Agricultural soils	L to M	0.25	3
BECCS	M	0.5	3.5-5.2
Direct air capture	H	0	0
Carbon mineralization	M to H	unknown	unknown
Total		1.02	9.13-10.83

* Upper bound assumes full adoption of agricultural soil conservatio practices, forestry management practices, and waste biomass capture.

*Safe means without without large-scale land-use change that could adversely affect food availability and biodiversity.

Existing options cannot provide amount of negative emissions needed to meet demand/need without unprecedented levels of adoption or changes in land use that could affect food availability and biodiversity

10 $GtCO_2$/y of negative emissions from existing options would require unprecedented rates of adoption of:

- agricultural soil conservation practices
- forestry management practices
- waste biomass capture, processing and distribution

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

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

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

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

Highlights of Research Agenda

- Large “staged” investments to
  - advance high-capacity NETs (direct air capture & carbon mineralization)
  - understand and perhaps soften land constraint facing afforestation/reforestation, forest management, agricultural soils, BECCS
- Many research efforts should be funded by federal agencies, but some would benefit from public-private partnerships
  - e.g., National Air Capture Test Center to support pilot efforts
- Most research topics chosen to pay off within ~10 years
- Some “frontier” research may not pay off fully for ~20 years or more
  - Plant breeding
  - Enhanced weathering in situ in ultramafic rock

Rationale for Research Investment

- States, local governments, corporations, and countries now make or plan large investments in NETs (e.g. ~30% of planned emissions reductions)
  - Advances in NETs will create jobs and benefit US economy, especially if intellectual property is held by US companies
- Unlike wind, solar and unconventional gas, NETs have not yet received public investment at a scale consistent with:
  - need for NETs that can solve substantial fraction of climate problem
  - possible magnitude of return to US economy

NETs Pathway Study

Edinburgh, Scotland
May 22-24th, 2019

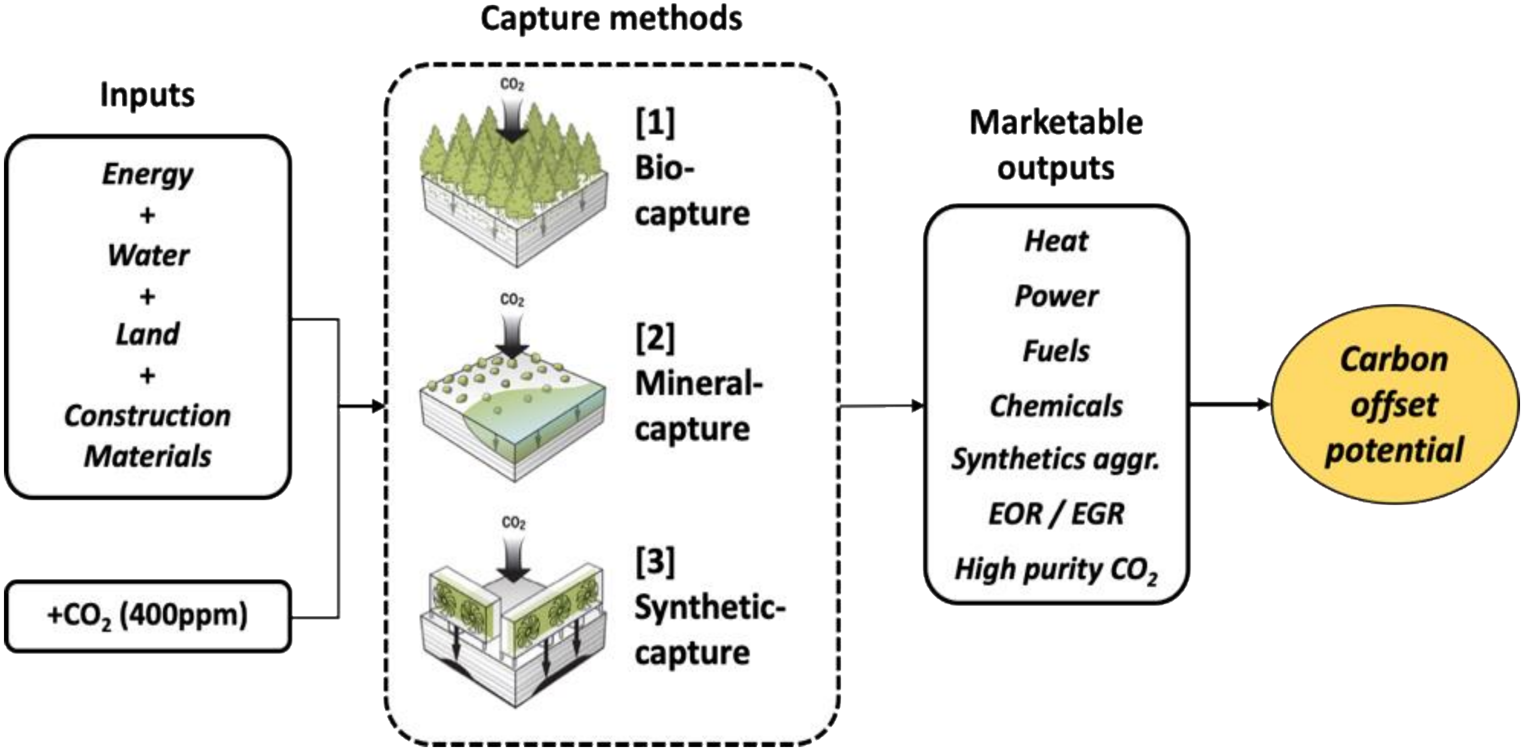
Participants of Study

- Jen Wilcox (and group), Chemical Engineering, WPI
- Florian Kraxner (and group), IIASA
- Phil Renforth (and group), Heriot-Watt University
- Mercedes Maroto-Valer, Heriot-Watt University
- Mijndert van der Spek, ETH, Zurich
- Christoph Beuttler, Climeworks
- Greg Dipple, University of British Columbia
- Peter Kelemen, Columbia University
- Margaret Torn and Grace Wu, UC Berkeley
- Dan Sanchez, UC Berkeley
- Niall Mac Dowell (and group), Imperial College London
- Steve Hamburg, Environmental Defense Fund
- Andrea Ramirez, TU Delft
- Sean McCoy, University of Calgary
- David Heldebrant, Pacific Northwest National Lab
- Michael Matuszewski, DOE
- Sabine Fuss, Humboldt University
- Pete Smith, University of Aberdeen
- Noah Deich and Rory Jacobson, Carbon180
- Dan Plechaty, ClimateWorks Foundation
- Colin McCormick, Valence Strategic, LLC
- Sue Hovorka, UT Austin
- Roger Aines, Lawrence Livermore National Lab
- John Larsen, Rhodium Group

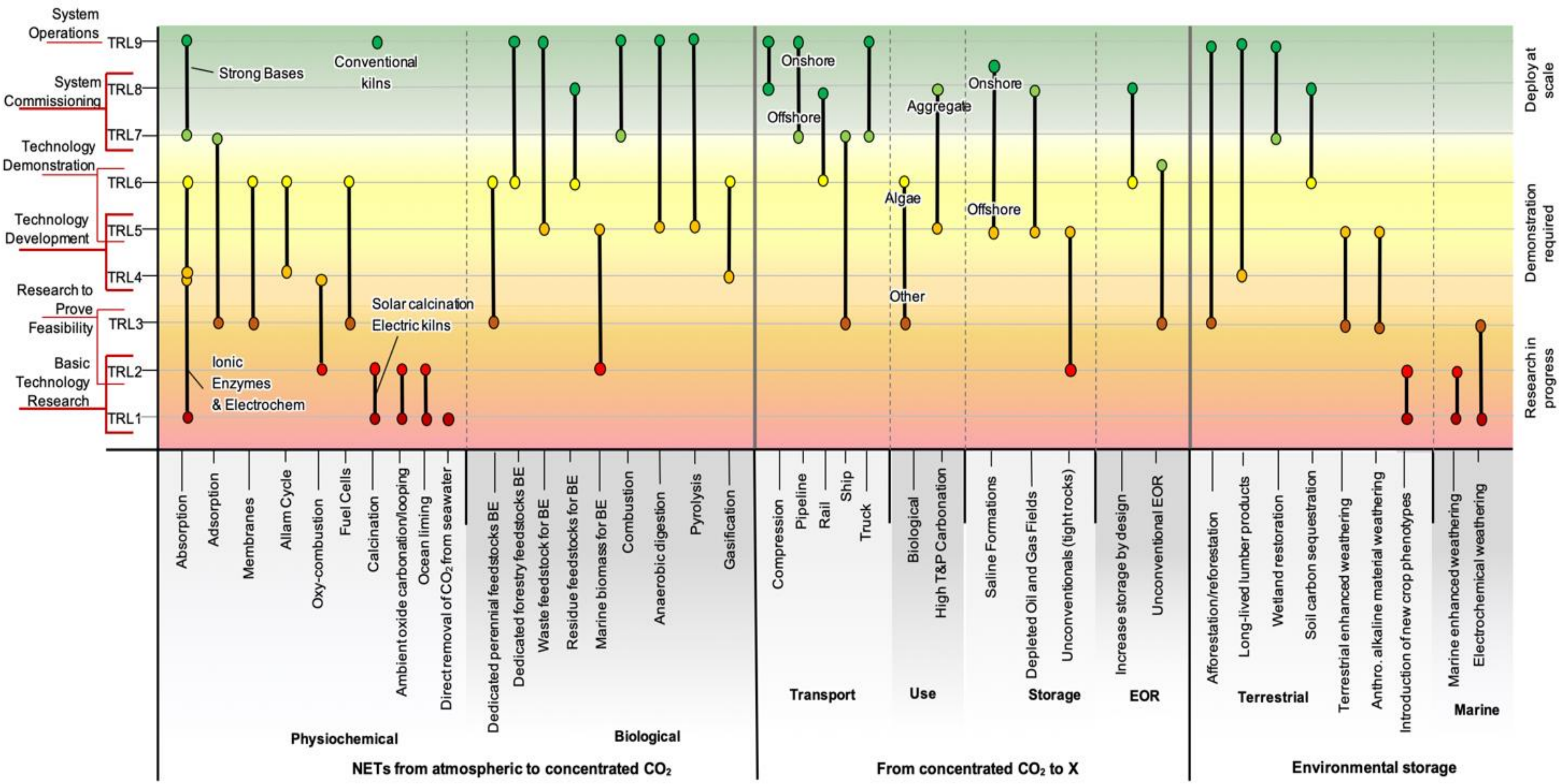
Goals of this Global Negative Emissions Pathway Study

- Bring people together with expertise in the various areas of that comprise negative emissions pathways to develop an international study that helps to define a common framework of this complex emerging field
- Work throughout the year together to outline consistent terminology and boundary conditions of the building blocks of NET pathways/systems
- Develop pathway/system examples of what does and what does **not** result in negative emissions

Utilization May be the Mechanism of Deployment, but …
Not to be confused with Negative Emissions



Building Blocks of NET Pathways/Systems



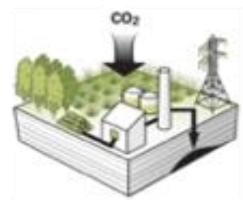
Global Mapping Through International Partnerships

GLOBAL MAPPING

[1]

(FK, MT, RM, KP AS, BC)

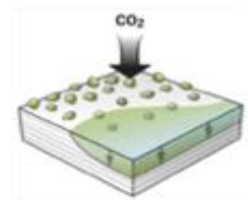
Afforestation-Reforestation-Restoration Opportunities



[2]

(JW, SM, TB, JQ, NK)

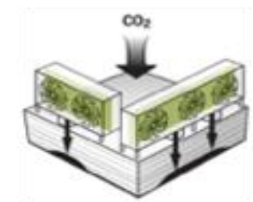
Energy systems combined with CO_2 removal technologies



[3]

(AP, JW, PK, SH, VL)

Mineral-capture & advanced weathering



[4]

(JW, SM, DS)

Siting opportunities for DAC plants

GLOBAL INTEGRATION

[5]

(All)

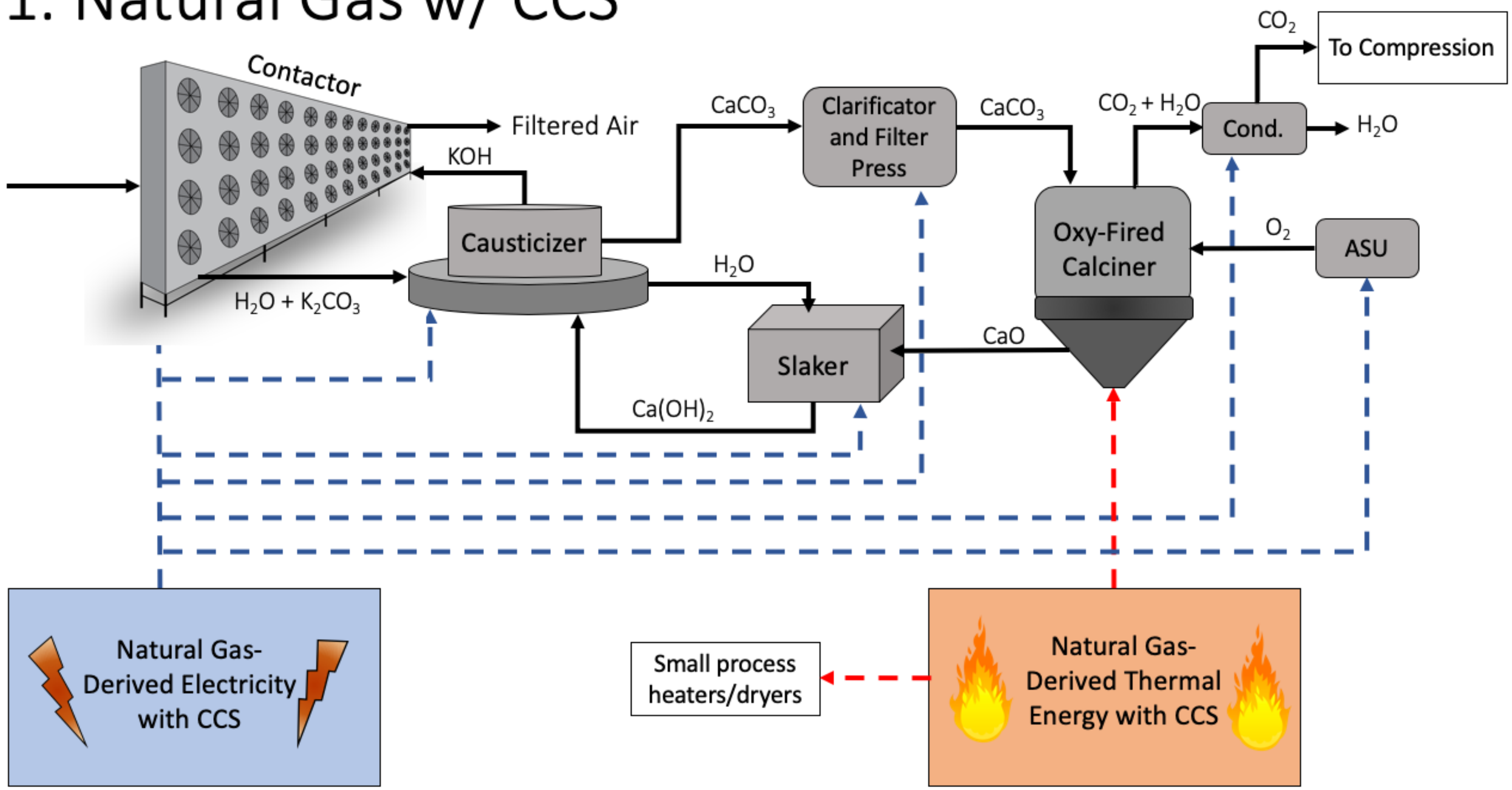
Global mapping results of feasible and sustainable (integrated) NETs deployment scenarios, that maximize carbon removal

Constraints and Boundary Conditions

- What should be included in the building blocks of negative emissions pathways?
- Importance of reporting costs of capture versus cost of net removed CO_2 versus cost of CO_2 produced?
- What are the constraints? Land, water, materials?
- Low-carbon energy – e.g., solar, wind, geothermal, hydro – consider natural gas with carbon capture? Nuclear? Tidal? Others?

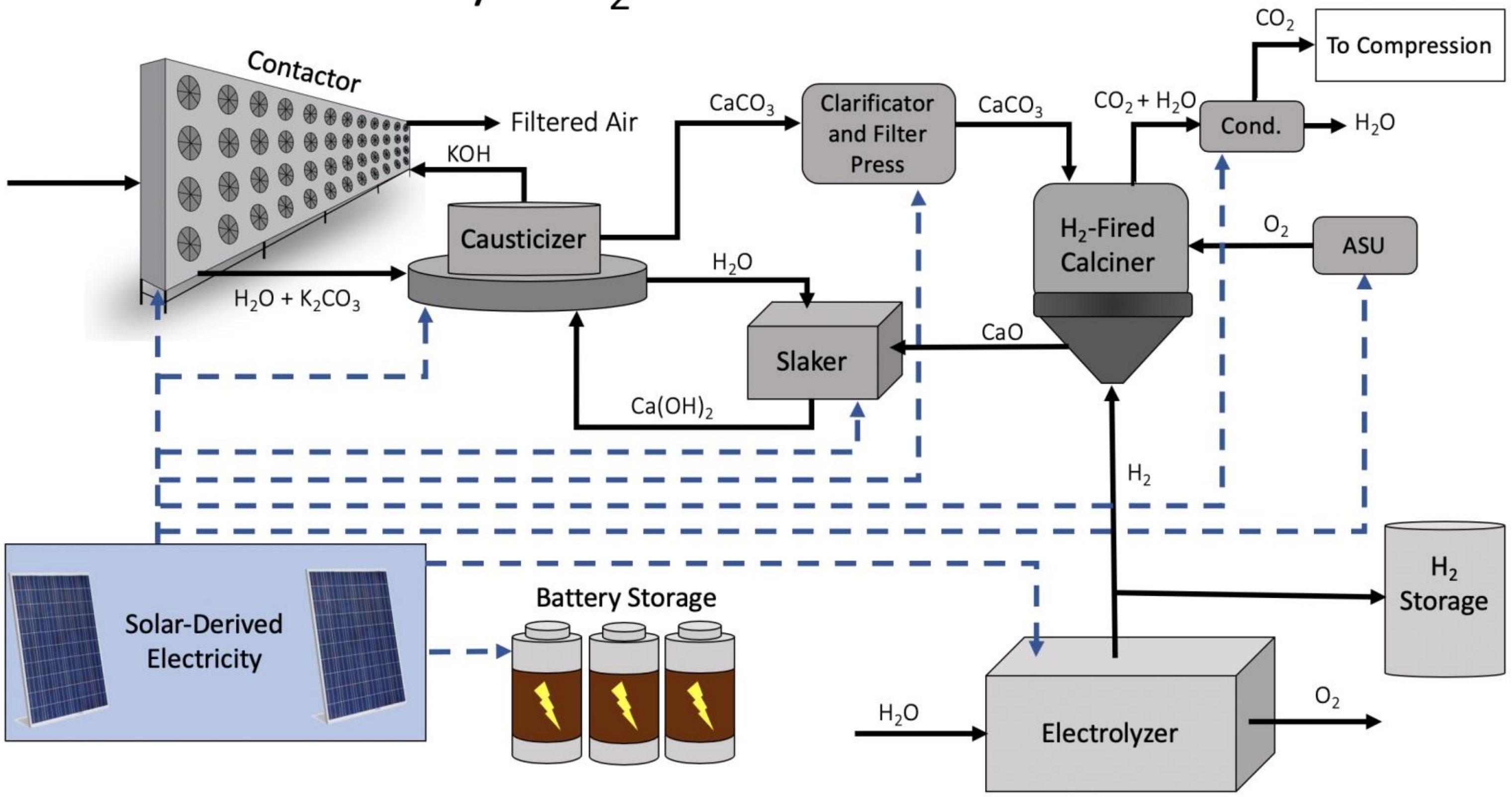
Consider 2 Different Energy System Scenarios

1. Natural Gas w/ CCS

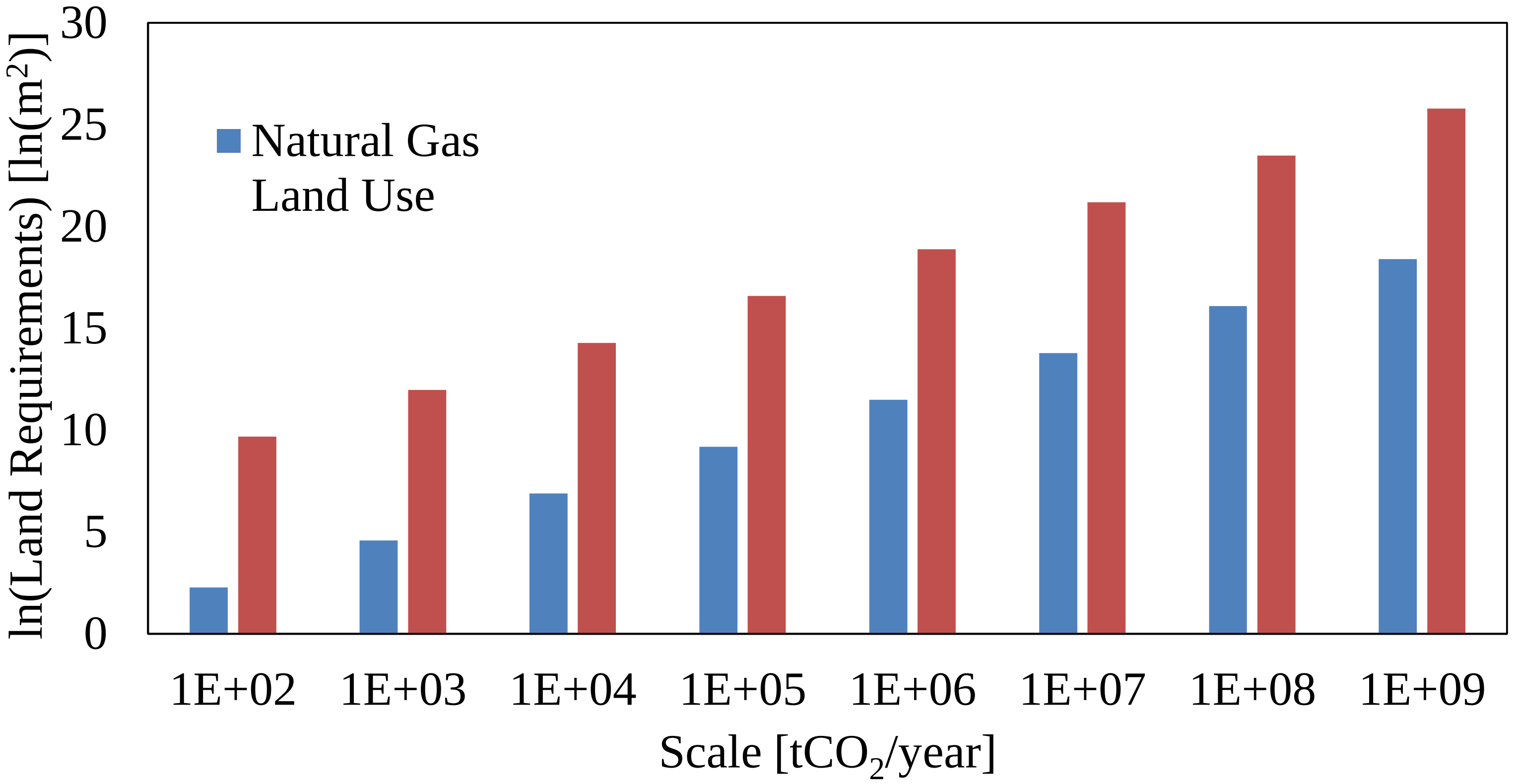


Consider 2 Different Energy System Scenarios

2. Solar Electricity + H_2-Fired Kiln



Natural gas and solar land requirements



Capturing 200 million tonnes from the air?

Powered by natural gas with CCS?

200 DAC plants = 1/2 land area of Washington D.C. roughly 37 mi^2

Powered by solar and H_2?

The size of Maryland roughly 12,400 mi^2

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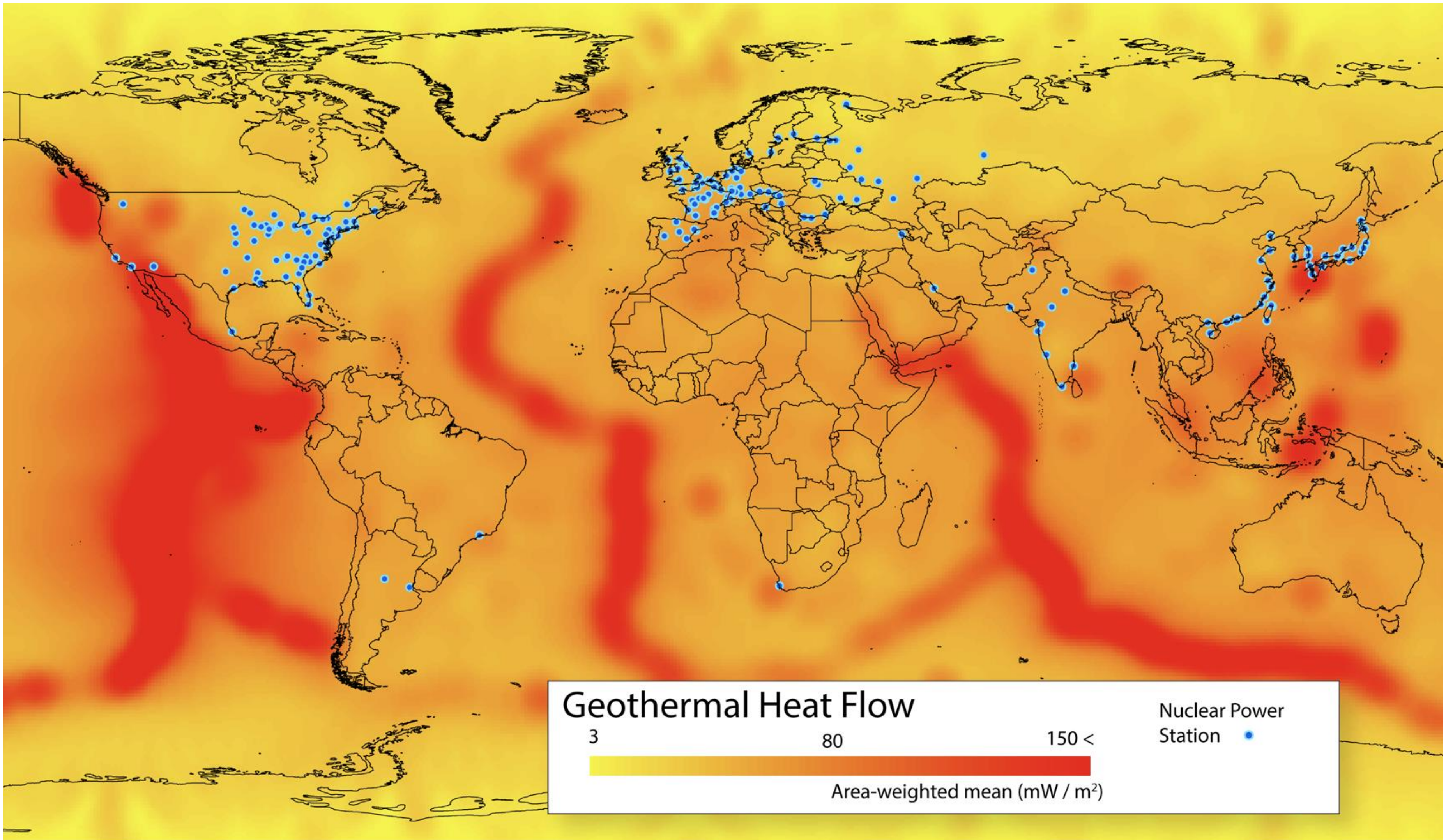
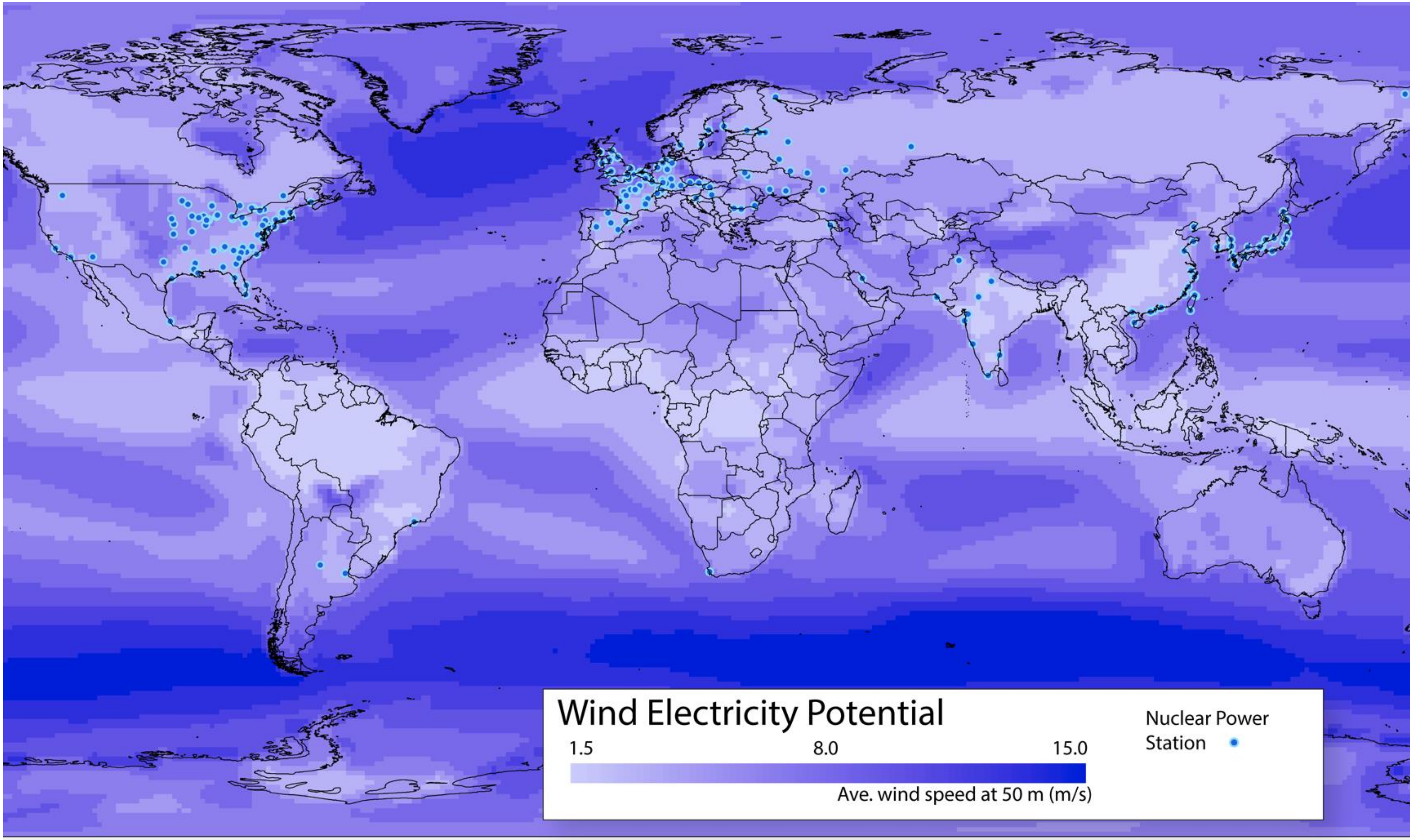
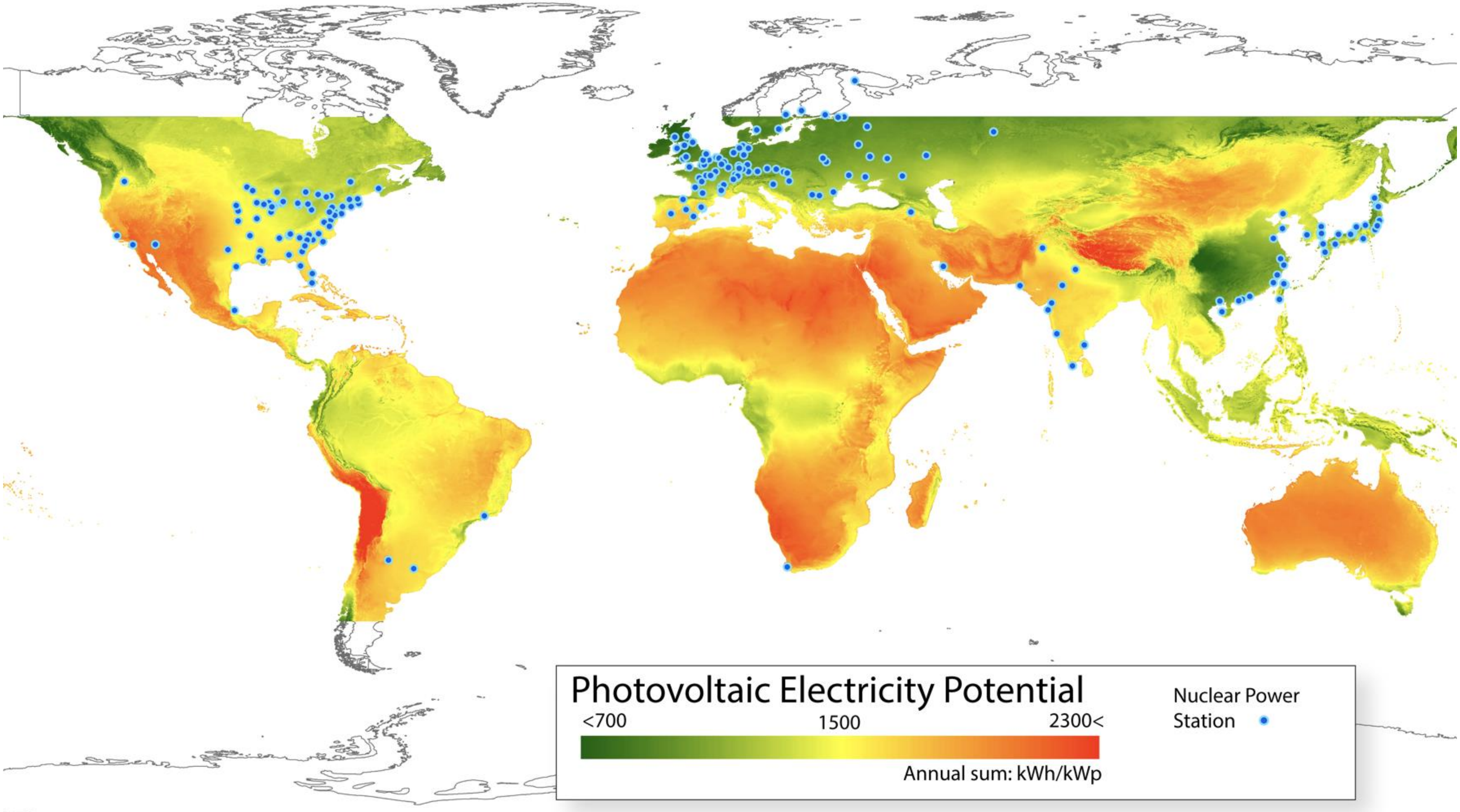
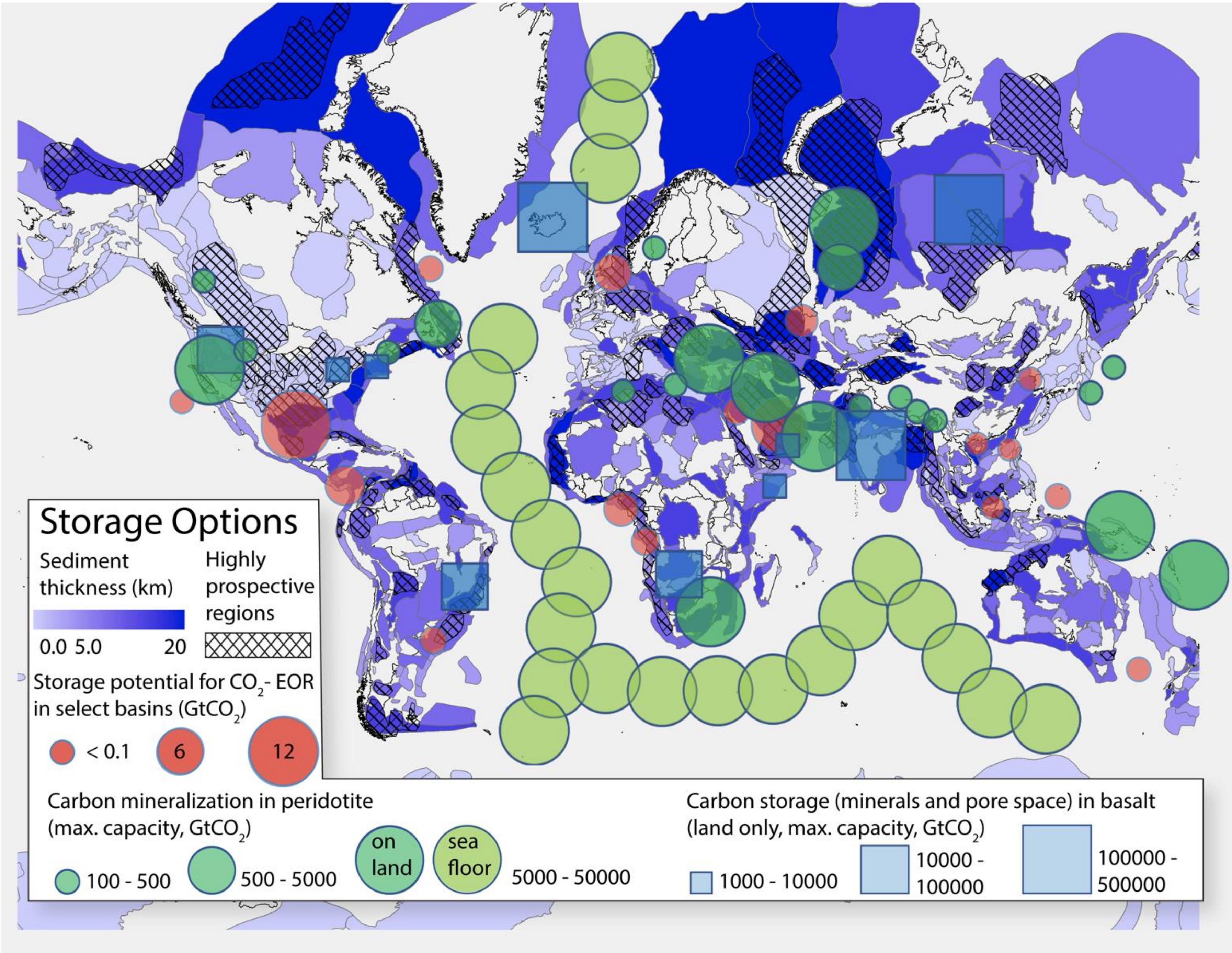
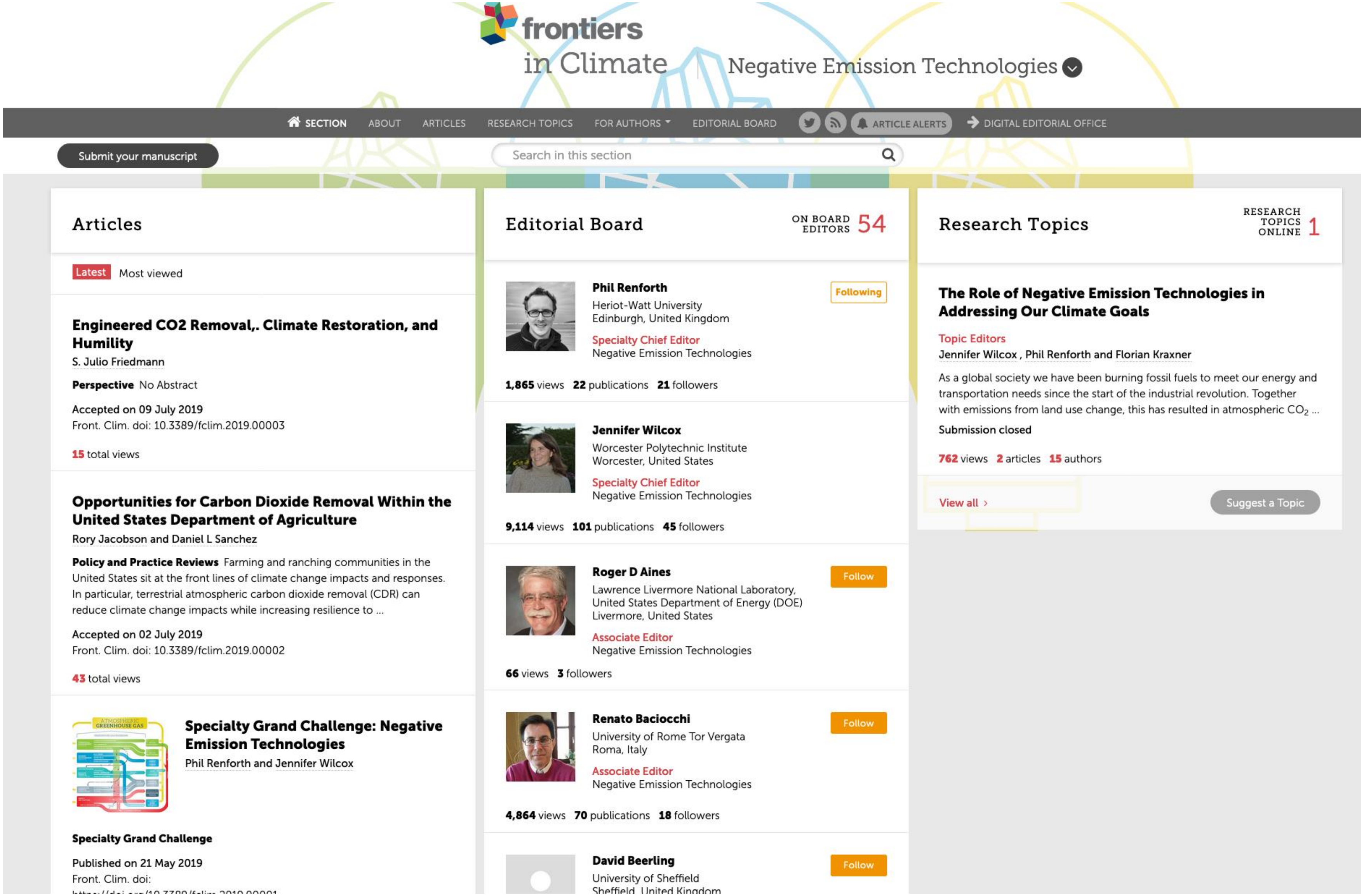

Geothermal Heat Flow
3
80
150 <
Area-weighted mean (mW / m2)
Nuclear Power Station


Wind Electricity Potential
1.5
8.0
15.0
Ave. wind speed at 50 m (m/s)
Nuclear Power
Station


Photovoltaic Electricity Potential
<700
1500
2300<
Annual sum: kWh/kWp
Nuclear Power Station


Storage Options
Sediment thickness (km)
0.0 5.0 20
Highly prospective regions
Storage potential for CO_2- EOR in select basins ($GtCO_2$)
< 0.1
6
12
Carbon mineralization in peridotite (max. capacity, $GtCO_2$)
100 - 500
500 - 5000
on land
sea floor
5000 - 50000
Carbon storage (minerals and pore space) in basalt (land only, max. capacity, $GtCO_2$)
1000 - 10000
10000 - 100000
100000 - 500000

Study will be published in New Journal on NETs – Open-Access



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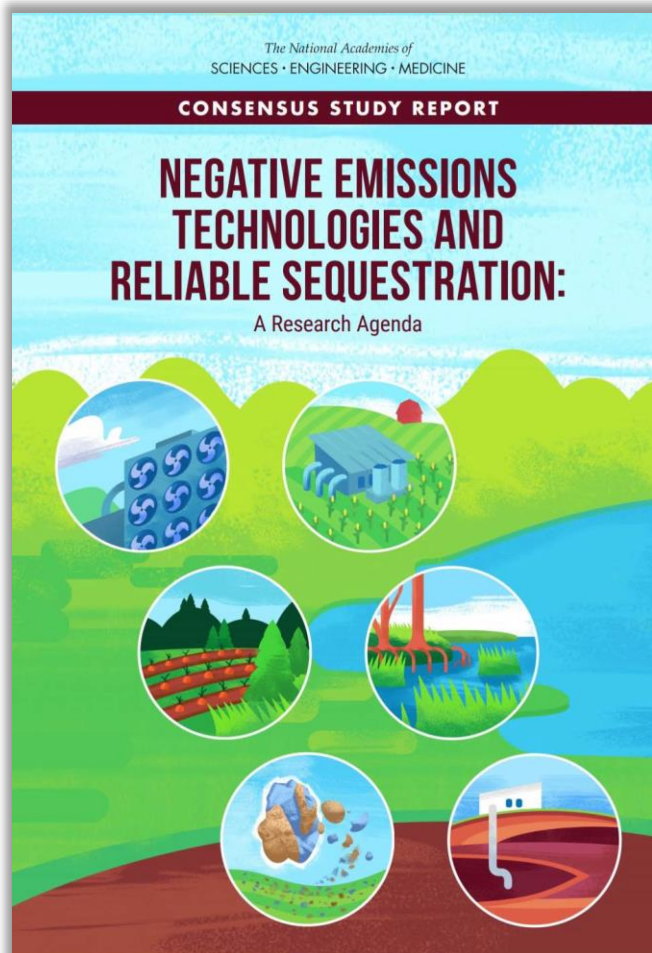

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