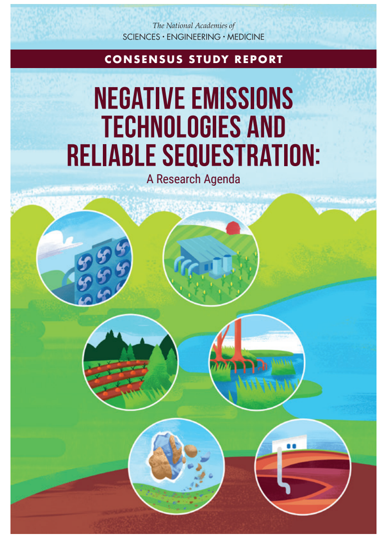
Consensus Study Report

October 2018

HIGHLIGHTS

Negative Emissions Technologies and Reliable Sequestration: A Research Agenda



Negative emissions technologies, which remove carbon dioxide from the atmosphere and sequester it, will be an important part of the portfolio of climate responses. Several land-based negative emissions technologies are ready for large-scale deployment at costs competitive with emissions mitigation strategies. However, these existing options cannot provide the amount of negative emissions needed to meet climate goals without unprecedented changes in land use that could affect food availability and biodiversity. Other negative emissions technologies have high potential capacity but are currently limited by high cost or lack of fundamental understanding. This report proposes a research agenda to overcome these constraints and expand safe and economical negative emissions technology options.

As understanding of the risks and damages of climate change has improved, almost all nations of the world have committed to limit total global warming below two degrees Celsius. Meeting this target is exceedingly challenging; the global mean temperature has already risen about one degree Celsius over the 20th century. Most climate and integrated assessment models project that the concentration of atmospheric carbon dioxide (CO_2) would have to stop increasing (and perhaps start decreasing) by the second half of the century to have a reasonable chance of limiting warming and the dangerous impacts it would bring.

Currently, most climate mitigation efforts focus on reducing emissions of CO_2 to the atmosphere, for example by increasing energy efficiency or switching to low- or zero-carbon fuel sources. However, some emissions sources—such as fossil fuel emissions from air travel and methane emissions associated with agriculture—would be extremely disruptive or expensive to mitigate.

Another strategy for reducing atmospheric concentrations of CO_2 is to deploy negative emissions technologies (NETs), which remove carbon from the atmosphere and reliably sequester it. Removing CO_2 from the atmosphere and storing it has exactly the same impact on the atmosphere and climate as simultaneously preventing an equal amount of CO_2 from being emitted.

In 2015, the National Academies published Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration, which provided an initial assessment of NETs and sequestration technologies. The present report extends this analysis by assessing the benefits, risks, and sustainable scale potential of NETs and sequestration, and defining the essential components of a research, development, demonstration, and deployment program.

MITIGATION IN A NET ZERO EMISSIONS SYSTEM

A common misconception is that NETs would primarily be deployed to reduce atmospheric CO_2 levels only after emissions had been reduced to near zero. However, because emissions reductions become increasingly expensive as emissions drop, it will be less expensive to deploy mitigation and negative emission technologies concurrently (see Figure 1). The central question is: which is least expensive and least disruptive in terms of land and other impacts, an emission reduction or an equivalent amount of negative emission?

Building a broad portfolio of NETs also offers increased resilience to help manage risks of surprises from nature and mitigation actions. Thus, NETs are best viewed as a component of the mitigation portfolio, rather than a way to decrease atmospheric concentrations of CO_2 only after anthropogenic emissions have been eliminated.

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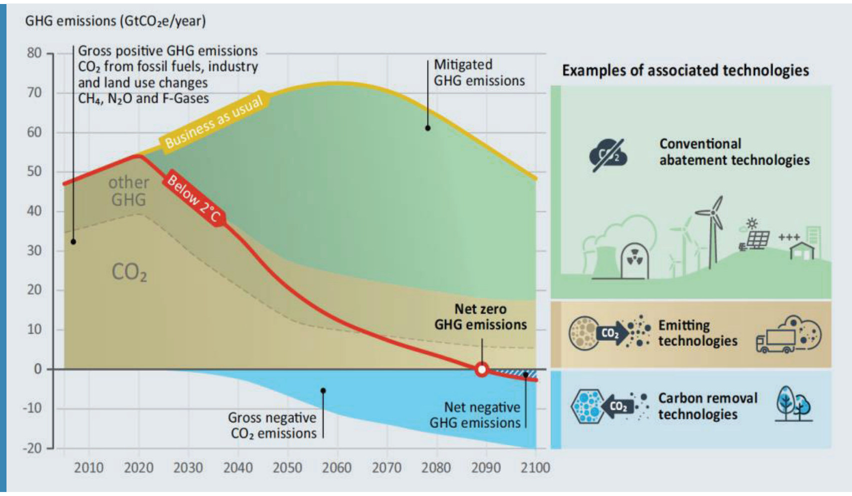
Figure 1. This figure illustrates the potential role of negative emissions technologies in reaching net zero emissions. The chart shows a climate mitigation scenario in which net anthropogenic emissions of all greenhouse gases fall from more than 50 gigatons of CO_2 per year ($GtCO_2/yr$) today to less than 20 $GtCO_2/yr$ at mid century, and to approximately zero by 2100. Approximately 10-20 $GtCO_2/yr$ of gross anthropogenic emissions are from sources that will be very difficult or expensive to eliminate by emissions reductions alone. Most scenarios that limit global warming to two degrees Celsius thus rely on CO_2 removal and storage that ramps up rapidly before midcentury to reach approximately 20 $GtCO_2/yr$ by century's end. Source: UNEP 2017



FOUR NEGATIVE EMISSION TECHNOLOGIES ARE READY TO BE DEPLOYED, BUT ARE INSUFFICIENT TO MEET CLIMATE GOALS

The report's authoring committee reviewed current knowledge and technical development of NETs (see Table 1). They identified the potential rates of CO_2 removal and sequestration that could be achieved safely (without causing large adverse social, economic, and environmental impacts), and economically (incurring direct costs below $100 per ton of CO_2).

Box 1. Negative Emissions Technologies and Sequestration Approaches

Coastal Blue Carbon—Practices that increase the amount of carbon stored in living plants or sediments in tidal marshlands, seagrass beds, and other tidal or salt-water wetlands.

Terrestrial Carbon Removal and Sequestration—Changes in forest management and agricultural practices that enhance soil carbon storage.

Bioenergy with Carbon Capture and Sequestration (BECCS)—The cultivation of crops which take up CO_2 as they grow and are used to produce electricity, liquid fuels, and/or heat. The CO_2 generated is captured and sequestered underground.

Direct Air Capture—Filtering processes that capture CO_2 from ambient air and sequester it underground.

Carbon Mineralization—The use of reactive minerals (particularly mantle peridotite, basaltic lava, and other reactive rocks) to form chemical bonds with CO_2.

Geological Sequestration—CO_2 captured through BECCS or direct air capture is injected into a geologic formation, such as a saline aquifer, where it remains in the pore space of the rock for a long time. This is not a NET, but rather an option for the sequestration component of BECCS or direct air capture.

With current technology, and using all available land and waste biomass, four NETs—afforestation/reforestation, changes in forest management, uptake and storage by agricultural soils, and biomass energy with carbon capture and storage (BECCS)—could be scaled up to capture and store substantial amounts of carbon: ~1 $GtCO_2/yr$ in the United States and ~10 $GtCO_2/yr$ globally. However, attaining these levels would require unprecedented rates of adoption of agricultural soil conservation practices, forestry management practices, and waste biomass capture. Practically achievable limits are likely substantially less, perhaps half the 1 $GtCO_2/yr$ in the US and 10 $GtCO_2/yr$ globally.

Further, the potential global uptake from current NETs is substantially lower than the negative emissions in most scenarios that would produce less than 2 degrees Celsius of warming. In order to play a large role in mitigating climate change, NETs will likely need to ramp up rapidly before mid-century to remove up to 20 $GtCO_2/yr$ globally by century's end (see Figure 1).

COMPETITION FOR LAND LIMITS THE EXPANSION OF SOME TERRESTRIAL-BASED NEGATIVE EMISSIONS TECHNOLOGIES

Extending afforestation/reforestation and BECCS to deliver more than 10 $GtCO_2/yr$ of negative emissions would require hundreds of millions of hectares of arable land. However, with demands for food expected to double by mid-century, such a repurposing of land would likely disrupt food supply, unless there is a breakthrough in agricultural productivity, revolutionary changes in diets, and other measures such as reduced food waste. There are also environmental constraints: repurposing land could involve the clearing of tropical forests, threatening biodiversity.

Research efforts could identify ways to increase CO_2 removal and soften the land constraint, for example by developing crop varieties that absorb and sequester CO_2 more efficiently. However, such efforts likely will take decades to deliver results, demonstrating an urgent need to advance high-capacity NET alternatives.

TABLE 1. Cost, Limiting Factors, and Impact Potential of NETs with Current Technology and Understanding. "Safe" rate of CO_2 removal means that the deployment would not cause large potential adverse societal, economic, and environmental impacts. Estimated rates assume full adoption of agricultural soil conservation practices, forestry management practices, and waste biomass capture.

Negative Emissions Technology	**Estimated Cost** ($/t$CO_2$) L = 0- 20 M =20 -100 H = >100	**Safe Potential Rate of CO_2 Removal Possible Given Current Technology and Understanding and at ≤$100/t$CO_2$** (Gt$CO_2$/y)		**Primary Current Limiting Factors**
		US	Global	
Coastal blue carbon	L	0.02	0.13	• Land • Scientific/technical understanding
Afforestation/ Reforestation	L	0.15	1	• Land • Practical barriers
Forest management	L	0.1	1.5	• Demand for wood • Practical barriers
Agricultural soils	L to M	0.25	3	• Limited rates of carbon uptake • Practical barriers
Biomass energy with carbon capture and sequestration (BECCS)	M	0.5	3.5-5.2	• Cost • Availability of biomass • Practical barriers • Fundamental understanding
Direct air capture	H	0	0	• Current cost is above $100/t$CO_2$ • Practical barriers
Carbon mineralization	M to H	unknown	unknown	• Fundamental understanding
Total		1.02	9.13-10.83	

DIRECT AIR CAPTURE AND CARBON MINERALIZATION HAVE HIGH POTENTIAL BUT STILL NEED SIGNIFICANT RESEARCH

Direct air capture or carbon mineralization could be revolutionary, because the potential capacity for CO_2 removal of each of these options is larger than the need.

The primary impediment to direct air capture is high cost—Climeworks, which operates the only commercial direct air capture machine reports a cost of $600 per ton of CO_2. There is no commercial driving force for developing direct air capture technologies, in contrast to other NETs such as afforestation/reforestation, BECCS-to-fuels, and coastal blue carbon, which bring economic and other benefits unrelated to their climate impacts. Therefore, developing a low-cost direct air capture option will require sustained government investment. Cooperating and competing researchers and start-ups could explore options and advance many dimensions of the technology at once.

Carbon mineralization is limited by many scientific and technical unknowns, including a lack of understanding of the kinetics of CO_2 uptake, and insufficient technical expertise to manage tailings piles so that they effectively take up CO_2. There are also potential environmental impacts. Mining or otherwise exposing minerals that spontaneously bind CO_2 would create enormous volumes of waste rock, possibly containing substances that could contaminate water, air, or both.

COASTAL BLUE CARBON APPROACHES HAVE RELATIVELY LOW CAPACITY, BUT ARE LOW COST

Although their potential for removing carbon is lower than other NETs, coastal blue carbon approaches warrant continued exploration and support. The cost of this NET is low or zero, because investments in many coastal blue carbon projects bring other benefits, such as coastal adaptation. At zero cost, even low rates of CO_2 removal justify spending on research. Priorities include advancing understanding of how sea-level rise, coastal management, and other climate impacts will affect future uptake rates.

RESEARCH NEEDED TO OVERCOME CONSTRAINTS

Scaling the capacity of NETs to meet expected needs for carbon removal will require a concerted research effort to address the constraints that currently limit deployment. The research agenda proposed in this report addresses gaps in scientific and technical understanding, and research needed for bringing NETs up to scale, including cost reductions, deployment, and monitoring and verification.

The federal government has many other research priorities, including others in mitigation and adaptation to climate change. However, there are multiple reasons to pursue research on NETs. First, states, local governments, corporations, and countries around the world are now making substantial investments to reduce net carbon emissions, including efforts to advance negative emissions. If the intellectual property is held by U.S. companies, advances in NETs will benefit the U.S. economy. Second, as climate damages mount, the U.S. will inevitably take increased action to limit future climate change. Third, the U.S. is already making a substantial effort for capture and storage, including the new tax credit of $50 per ton of CO_2 which would leverage the value of new investments in NET research. Thus, though climate mitigation remains the motivation for global investments in NETs, intellectual property and economic benefits will likely accrue to the nations that develop the best technology.

Recommendation: The nation should launch a substantial research initiative to advance negative emissions technologies (NETs) as soon as practicable. A substantial investment would (1) improve existing NETs (i.e., coastal blue carbon, afforestation/reforestation, changes in forest management, uptake and storage by agricultural soils, and biomass energy with carbon capture and sequestration) to increase the capacity and to reduce their 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 the high costs and many unknowns could be overcome; and (3) advance NET-enabling research on biofuels and CO_2 sequestration that should be undertaken anyway as part of an emissions mitigation research portfolio.

COMMITTEE ON DEVELOPING A RESEARCH AGENDA FOR CARBON DIOXIDE REMOVAL AND RELIABLE SEQUESTRATION

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For More Information . . . This Consensus Study Report Highlights was prepared by the National Academies of Sciences, Engineering, and Medicine based on the Consensus Study Report *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (2018). The study was sponsored by the U.S. Department of Energy, the National Oceanic and Atmospheric Administration, the Environmental Protection Agency, the United States Geological Survey, the V. Kann Rasmussen Foundation, the Linden Trust for Conservation, and Incite Labs, with support from the National Academy of Sciences' Arthur L. Day Fund. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any organization or agency that provided support for the project. Copies of the Consensus Study Report are available from the National Academies Press, (800) 624-6242; http://www.nap.edu or via the Board on Atmospheric Sciences and Climate web page at http://www.nationalacademies.org/basc.

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