US Academies call for research agenda on *Negative Emissions Technologies and Reliable Sequestration*

Climate change has long been a topic of significant scientific and political discussion. Scientific evidence and predictions of the impact of climate change have served to galvanize international political action and treaties that have garnered varying levels of support. The 1992 United Nations Framework Convention on Climate Change (UNFCCC) was the first treaty to set goals for international cooperation to mitigate climate change, which was followed by the Kyoto Protocol in 1997 and the Paris Agreement in 2015. The Paris Agreement set a target to limit the increase in global average temperature this century well below 2°C above preindustrial levels.

While recognition of the danger of climate change is globally very high, a report commissioned under the Paris Agreement and conducted by the United Nations Intergovernmental Panel on Climate Change (IPCC) raises new concerns. The report, released in October 2018, examined the effects of a 1.5°C average temperature rise above preindustrial levels and concluded that without aggressive global action, many of the most severe effects of climate change—worsening food shortages, increasing wildfires, mass die-off of coral reefs, and intensifying droughts—will likely arrive by 2040 rather than decades later as originally predicted.

There are many technological solutions to address climate change, but unfortunately, there is no silver bullet. To date, most of the focus has been on developing and deploying technologies that essentially slow down the rate of fossil fuel use. This has been accomplished by replacing some fossil-fuel-based power generation with lower carbon or renewable energy sources by increasing energy efficiency and by capturing and storing emissions from fossil-fuel-based power plants. These solutions have already made an impact, but most climate models predict that reducing emissions alone (even nearing net-zero emissions, which is unlikely due to cost considerations and difficulty in eliminating some emission sources like methane associated with agriculture) will not limit total global warming below the targeted 2°C.

Another strategy for addressing climate change is to reduce the atmospheric concentration of carbon dioxide—the primary greenhouse gas responsible for climate change—by putting it back into geologic reservoirs and terrestrial ecosystems. This is the topic of a study released by the US National Academies of Sciences, Engineering, and Medicine (Academies) in October 2018. The consensus report,

International Cooperation Efforts to Mitigate Climate Change

United Nations Framework Convention on Climate Change (UNFCCC)
This was the first international environmental treaty addressing climate change. It was adopted on May 9, 1992, signed by 197 parties, including all United Nations member states, and entered into force on March 21, 1994. This treaty set up a framework of non-binding limits on greenhouse gas emissions for individual countries, with a goal of "preventing dangerous anthropogenic interference with Earth's climate system."

Kyoto Protocol
This treaty extends the commitment to reduce greenhouse gas emissions established by the UNFCCC and acknowledges the scientific consensus both that global warming is occurring and that it is extremely likely that human-made CO_2 emissions have been a predominant cause. The protocol established binding targets for greenhouse gas emissions reductions for industrialized countries based on the treaty's acknowledgment that economically developed nations are both more capable of combating climate change and historically responsible for the levels of greenhouse gases in the atmosphere at the time. It was adopted on December 11, 1997, and came into force on February 16, 2005. The United States signed but never ratified the Kyoto Protocol because it lacked political support due to the treaty's differing requirements for emissions reduction for industrialized versus developing countries. The European Economic Community (a regional economic organization) and 191 countries eventually ratified the treaty, but Canada renounced it and withdrew in December 2012.

Paris Agreement
The Paris Agreement is the latest climate treaty, and its long-term goal is to keep the increase in global average temperature this century well below 2°C (above preindustrial levels) and to pursue an even more aggressive goal to limit the rise to 1.5°C. The agreement requires each nation to determine and report on its own plan to mitigate climate change and encourages setting increasingly stringent targets but includes no mechanism to force compliance. It was adopted on December 12, 2015, signed by 195 UNFCCC members, and went into force on November 4, 2016. In June 2017, US President Trump announced his intention to withdraw the United States from the Paris Agreement. (Under the Agreement, the United States cannot officially withdraw until November 2020.)

titled *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, posits that negative emissions technologies (NETs), which take CO_2 from the atmosphere and store it, will be an important piece of the overall portfolio of climate mitigation efforts. "We are now in a position that if we want to limit warming to 2°C by 2100, [both] the direct removal of CO_2 from the atmosphere, in addition to avoiding it in the first place, will be required," says Jennifer Wilcox, James H. Manning Chair and Professor of Chemical Engineering at Worcester Polytechnic Institute. Wilcox, a committee member for the Academies study, added, "Carbon dioxide removal should not be seen as a replacement to mitigation, but rather as an additional measure."

The report examined the state of current R&D for NETs and geological sequestration. The limiting factors and existing areas of knowledge gap were identified for each technology, and the potential of each NET for positive impact on the climate was estimated. The analysis included data on the potential rates of CO_2 removal and sequestration that could be safely achieved (without triggering large adverse societal, economic, or environmental impacts) with each NET. Furthermore, the report estimated that to achieve economic viability, NETs must be able to remove and store CO_2 at a cost of less than $100 per ton of CO_2 removed, and rated each NET on its current ability or future potential to meet these criteria.

The report concludes that in order to meet the climate goals of the future, a concerted and immediate research agenda to address the gaps in knowledge and bring NETs to scale should be implemented. And it is within the research arena that materials researchers will likely play a role in addressing the climate change issue. "The three most scalable technological approaches to NETs all rely on functional materials," says Christopher Jones, William R. McLain Chair and Professor of Chemical Engineering at the Georgia Institute of Technology. Jones, another committee member for the Academies study, further explains, "For direct air capture, materials that are engineered to bind CO_2 under ultra-dilute conditions and then liberate concentrated CO_2 on demand with an appropriate low energy trigger—like a temperature or vacuum swing—are needed. For BECCS, [biomass energy with carbon capture and storage] related CO_2-sorbing materials are also used for post-combustion CO_2 capture. And for mineral carbonation, the fundamental kinetic and thermodynamic properties of various natural minerals that can react with CO_2 in various concentrations remain to be fully elucidated."

Development of Negative Emissions Technologies (NETs)

Costal Blue Carbon

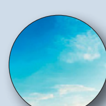
Methods that increase carbon storage in living plants or sediments in coastal ecosystems. Although this NET has a limited potential to remove carbon due to the relatively small coastal landmass, its cost is low or zero because it is rolled into existing coastal projects (i.e., coastal adaptation), and further research to understand the future impact on carbon uptake rates from sea-level rise and other climate impacts is necessary.

Terrestrial Carbon Removal and Sequestration

Methods include afforestation/reforestation, forest management, and agricultural soils (changing agricultural practices to enhance carbon storage in the soil)—all methods are means to enhance carbon storage in terrestrial ecosystems. These NETs are already cost-competitive with existing emissions mitigation strategies and are ready for large-scale deployment, but carbon removal is limited by available land (food availability or biodiversity could be impacted if substantial amounts of land were repurposed). Research on these NETs should address land issues by developing plants or methods that are more efficient in sequestering carbon in terrestrial ecosystems.

Biomass Energy with Carbon Capture and Sequestration (BECCS)

Method where crops are specifically cultivated to take up CO_2 as they grow and are then used to produce electricity, liquid fuels, and/or heat. Similar to terrestrial methods, this NET is cost-competitive with current emissions mitigation strategies, is limited by available land, and requires research to address the land constraint. In addition, to qualify as a NET, BECCS requires capture and storage of the CO_2 generated with consumption of the feedstock, likely in the form of geological sequestration.

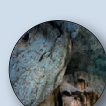


Direct Air Capture (DAC)

Method uses a filtering process to capture CO_2 directly from ambient air and then concentrates it and stores it, likely in geological sequestration like BECCS. DAC has a very high potential capacity to remove carbon from the atmosphere, but it is limited by current high costs (there is no economic driving force for DAC), and research is necessary to develop low-cost methods. Development of technologies and markets that recycle CO_2 may be another area where materials research is necessary and could provide a cost offset for DAC; however, reuse of the CO_2 would ultimately mean it will eventually be released back into the atmosphere rather than sequestered.

Carbon Mineralization

Method uses reactive minerals to form chemical bonds with CO_2 to effectively capture and sequester CO_2. This NET has a very high potential capacity to remove carbon from the atmosphere, but is limited by lack of fundamental understanding of the process and requires research to find effective functional materials and economically feasible reaction routes.



Geological Sequestration

Method by which captured CO_2 can be injected into geological formations for long-term underground storage. This is not a NET, but an option for the necessary sequestration component of BECCS, DAC, or other CO_2-capturing technologies.

Press center during the 21st session of the UN Conference on Climate Change, Paris, France, November 30, 2015. Photo credit: Shutterstock.

While the Academies' study calls for the launch of what it terms a "substantial" research initiative on NETs and sequestration as soon as practicable, Jones and Wilcox point out two significant hurdles. "The biggest hurdle has always been political will," Jones says, and Wilcox readily agrees. But Jones also expresses optimism that society may be reaching a turning point where research on NETs and sequestration could be a win for both major political parties in the United States:

> *For the longest time, policymakers viewed climate change and emissions reduction technologies as a political issue that they and their constituents found themselves on one side of or another. However, in 2018, several key things have changed…. Even if some people in the US do not feel that climate change is a perilous threat, there is no denying that the rest of the world will work toward emission reductions, creating a massive market for NETs. Furthermore, many hydrocarbon producers are also the same firms with expertise in gas separation technologies, which are key components of NETs. Therefore, we are at a point in history where they may realize it is in their best interest to develop and help deploy NETs, as it can potentially prolong the safe use of hydrocarbons and they may generate valuable intellectual property and technology position as well. Given the desire on one side to stabilize the climate, and the desire on the other side to develop [US] business, we may now be at a point where we can collectively move forward to develop NETs with the goal of developing [a US] position of technological prominence, keeping jobs and infrastructure processing hydrocarbon resources, while also fighting climate change. At no point in recent history has a scenario such as this evolved where both political sides can come out as winners.*

In fact, Jones points to the 45Q tax credit and the potential for carbon capture and storage (CCS) to be incorporated into California's low carbon fuel standard (LCFS) as evidence that the political scales are already starting to tip in favor of NETs. Passed in early 2018 as part of the budget deal, the 45Q tax credit increased tax credits from \$35 to \$50 per ton of CO_2 captured and stored in secured geological storage for CCS projects constructed over the next six years. This credit makes CCS projects more economically viable, and the Academies' report points out it will also "leverage the value of new investments in NET research." The incorporation of CCS into California's LCFS is important because it would create the first market for CCS in the United States and provide a driving force to develop NETs and sequestration technologies.

The second significant hurdle that NETs face involving sequestration is lack of public understanding and support. "Ultimately, the CO_2 needs to be put back in the Earth where it came from to begin with, if we are to meet our climate goals," says Wilcox, and to accomplish that she says, "we need 1000x more demonstration-scale projects associated with geologic storage." As we have seen with a variety of climate mitigation technologies from alternative energy to electric cars, demonstration of the technology can garner public acceptance and support, which can also be a driving force for further R&D. This is exactly what Wilcox believes is needed for geological sequestration—demonstration and education "so that we can get society's acceptance. Without geological sequestration, a requisite part of some of the most promising NETs and CO_2 mitigation strategies, it will not be possible to address our climate goals," she says.

While the issue of climate change is still far from settled, the Academies' call for a concerted research agenda on NETs and sequestration may be tenable. Whether seen as part of an "all of the above" approach to addressing climate change, or as a means of securing intellectual property and economic dominance in a growing market, support for negative emissions technologies appears to be growing on both sides of the aisle. Given the key role of research in advancing these technologies, the materials community may have an unparalleled opportunity to both help shape the proposed research agenda and to positively impact climate change.

Jennifer A. Nekuda Malik

Additional Information

IPCC report on climate change
www.ipcc.ch/report/sr15

Academies' report on NETs and reliable sequestration
www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda