Nano4EARTH Kick-off Workshop Highlights

from the Nano4EARTH Kick-off Workshop held on January 23-24, 2023 in Washington, D.C.

NATIONAL NANOTECHNOLOGY COORDINATION OFFICE

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Executive Summary

In October 2022, the White House Office of Science and Technology Policy (OSTP) and the National Nanotechnology Initiative (NNI) announced Nano4EARTH, a National Nanotechnology Challenge to accelerate nanotechnology-enabled innovations that advance the Biden-Harris Administration's commitment to tackling the climate crisis. To energize a broad community and build a foundation for the challenge, the National Nanotechnology Coordination Office (NNCO) organized the Nano4EARTH Kick-off Workshop in January 2023. More than 400 people across sectors, with diverse expertise and perspectives, participated in the event.

Discussions focused on identifying nanotechnologies that are poised to have an impact on climate change effects in the near future (four years or less). Participants shared resources available to overcome barriers to entrepreneurship and technology adoption and identified goals and metrics to ensure momentum and measure success. New connections and networks spanning federal agencies, non-governmental organizations, and industry emerged through proposals for collaborations and events centered on nanotechnology and climate change.

Some common themes included:

- **Battery technology** has seen increased adoption in personal vehicles and long-term energy storage solutions, but further advances in Li-ion, as well as new chemistries and battery architectures, show tremendous potential. It is critical that research directions are well matched with particular use cases.

- **Catalysts** leveraging new understandings of nanoscale materials and phenomena could optimize many industrial processes that currently emit large amounts of greenhouse gases, minimize the need for rare-earth metals, and serve as precursors for alternative energy sources, such as green hydrogen and electrofuels.

- **Coatings and other interface material** innovations could increase the efficiency of nearly any industrial process and lead to more resilient structures and devices, especially in changing and harsh environments. Examples include reflective coatings, corrosion protection, heat management in computing, lubricants and other additives, and membranes for separations. Drop-in solutions that do not require the complete re-engineering of production systems would have more rapid impacts.

- **Capture of greenhouse gases** (GHG) through advanced materials and sorbents (e.g., metal organic frameworks) and nature-mimicking processes (e.g., artificial photosynthesis), especially deployed at the point of production, could measurably reduce climate warming emissions, but deploying at scale still has significant challenges.

Following the workshop, NNCO is convening a series of roundtable discussions that focus on the high-potential nanotechnology areas identified above to pinpoint the specific challenges and opportunities that may be worth increased investigation by members of the federal NNI community. Subject-matter experts across academia, industry, and beyond will be asked to match nanotechnology opportunities to urgent climate change mitigation, with strong consideration of the broader societal needs and impacts. Also, feedback from the kick-off workshop will inform additional activities and events to facilitate conversations and collaborations across this growing community.

Overview

The National Nanotechnology Initiative (NNI) launched the National Nanotechnology Challenge (NNC) mechanism to mobilize the NNI community to address national science and technology priorities. The NNI Federal community – composed of more than 30 Federal agencies, commissions, and departments – identified climate change as the focus of the inaugural NNC. Climate change evaluation, mitigation, and resilience are shared goals across the 30+ NNI participating agencies and departments and top priorities for the Biden-Harris Administration.

The National Nanotechnology Challenge, Nano4EARTH, was launched to leverage recent investments in understanding and controlling matter at the nanoscale to develop technologies and industries that address climate change. **EARTH** is an acronym that stands for **E**valuating, monitoring, and detecting climate change status and trends; **A**verting future greenhouse gas emissions; **R**emoving existing greenhouse gases; **T**raining and educating a highly skilled workforce to harness nanotechnology solutions; and developing **H**igher resilience to – and mitigation of – climate change-induced pressures for improved societal/economic resilience.

The Nano4EARTH challenge was announced by the White House Office of Science and Technology Policy (OSTP) and the NNI on National Nanotechnology Day, October 9, 2022, and the Nano4EARTH Kick-off Workshop was held on January 24–25, 2023. The goal of the workshop was to convene the broad NNI community and discuss areas of potential impact. More than 400 people, representing more than 180 organizations, participated in-person and online. The participants represented NNI community members across diverse disciplines and backgrounds, such as academic and research institutions, industry and technology development, K–12 education, nonprofit and philanthropic organizations, and the federal and state governments.

The workshop was organized around two keynotes, three panel discussions, and one all-hands strategic planning discussion (see Appendix for a detailed agenda). The keynote speakers were tasked with identifying success stories, current needs, and resources in the nanotechnology and climate change arena from perspectives both within and independent of the Federal government. The three panel discussions focused on identifying promising nanotechnologies, resources and needs for climate entrepreneurs, and metrics and goals for the challenge. The final session explored and grouped technologies that garnered the most interest and excitement throughout the workshop and during the workshop's pre-work.

This document provides an overview of the conversations at the workshop and highlights recurring themes discussed. The document is divided into three overall highlights: technical areas and themes; accelerating technology scale-up and adoption; and entrepreneurship, workforce, and education. The workshop agenda is included as an appendix, and the recordings are available here.

Technology areas and themes

Overview and highlighted needs

Climate leaders at the workshop identified technical needs and referenced past climate change mitigation reports and goals throughout the discussions (e.g., International Energy Agency's Net-Zero by 2050 and U.S. Innovation to Meet 2050 Climate Goals reports). Areas of technical needs listed in these reports include carbon capture; carbon transport and storage; biofuels; and metals production and use (e.g., iron, steel, and aluminum). Another area of need is biodegradable plastics. Plastic waste can be found everywhere, but only 9% of it is recycled worldwide, and most compostable plastics do not degrade in marine and soil environments. Solar geoengineering and optimizing energy distribution were also discussed. According to climate leaders, approximately 50% of the technologies needed to meet the 2050 climate goals are in the demonstration stages.

The five areas of technical needs identified by the U.S. Innovation to Meet 2050 Climate Goals report as having the highest potential for impact are: zero-emission grid and electrification; zero-emission heating, ventilation, and air conditioning; net-zero aviation; industrial products and fuels; and fusion energy. Nanotechnology can play a role in addressing all five technical needs. Drop-in versions of technologies discussed – solutions that could be absorbed into current infrastructures and supply chains – were highlighted throughout the discussion as important for short-term impact. Scale-up and adoption are common challenges for these technical themes.

Many promising nanotechnologies were discussed throughout the workshop. To facilitate follow-on discussions and other activities, most of the nanotechnologies discussed were grouped into four general themes (discussed below) that represent what the workshop participants highlighted more frequently. These nanotechnologies can be used to address the technical needs identified by the reports discussed above. For a complete list of nanotechnologies discussed, please refer to the workshop's recordings.

Coatings, membranes, lubricants, and other interface technologies

Close to 20% of global energy consumption is used to overcome friction at interfaces – junctions between different materials or components. Overcoming friction at these interfaces can significantly reduce mechanical, electrical, and thermal energy inefficiency. Nanotechnology-enabled interface solutions provide an advantage over other interfaces because they can reach nanoscale crevices in materials, reducing energy loss without the need for additional material. Coatings, lubricants, membranes, and other interface nanotechnologies thus have the potential to reduce energy consumption and, overall, decrease greenhouse gas (GHG) emissions.

For example, buildings generate close to 40% of global CO_2 emissions, and nanotechnologies, such as "smart windows," offer potential solutions. Smart windows could be made with a variety of advanced nanomaterials, such as thermochromic and/or electrochromic glass. These technologies allow natural light to enter a building while deflecting heat. Another emerging technology of interest is perovskite photovoltaics. Perovskites can be deposited on any surface, are flexible, lightweight, cheap, and as efficient as silicon, but they quickly degrade. New research shows that capping materials, a coating layer to protect the solar cell from environmental stressors, can improve the lifetime of perovskites by more than five years.

Membranes, sorbents, and other separation and purification technologies have a high potential to increase energy efficiency throughout industrial processes. Chemical separation is currently done mostly by thermal distillation (boiling), which represents 12% of U.S. energy expenditures. Nanoscale membranes and sorbents can provide more efficient separation of materials. For example, nanofiltration membranes made of graphene oxide, metal oxides, nanofibers, and carbon nanotubes could be used as alternatives to thermal distillation, saving up to 90% in energy expenditures. A forward-looking strategy should identify where developments in one sector can be repurposed for innovations in others. For example, membrane technologies developed by the petrochemical sector, such as zeolites, have uses for CO_2 separation from air.

Increased efficiency in computing arising from optimized interfaces was a recurring topic during the workshop. Interface nanomaterials are increasing computational energy efficiency and power. For example, in semiconductors, the current "7 nm" transistor technology node is 10 million times smaller than the original transistor, which was created 75 years ago. This advance has greatly reduced the cost, increased the energy efficiency of computation, and allowed computation to be applied to new industries, such as agriculture. For example, nanosensors and artificial intelligence are being used to produce autonomous tractors, increasing efficiency for food production. While computation power can increase computation efficiency and save resources, it increases electricity demand, therefore renewable sources of energy and energy storage are even more important. As computational needs increase, thermal management at interfaces is another topic of importance to achieve increased energy efficiency.

Batteries and energy storage

The commercialization of battery and energy storage research has made remarkable progress, but more innovation is needed to reach current electrification goals, particularly in transportation and grid storage. The electric vehicle market is driving the development of ground transportation batteries. Batteries for light-duty vehicles have dropped in price by a factor of 10 in the past decade, but innovations to electrify other transportation sectors, such as heavy-duty transport, rail, shipping, and aviation, are still needed. Nanotechnology additives at the electrode interface can help batteries become more efficient and increase their shelf lives. For example, nanotechnology researchers are working on selective polymer membranes with built-in molecular cages to allow higher-power batteries. Others are developing a new class of solid electrolytes from polymers and ceramics for lithium-metal batteries. There is a strong need and interest for high-density solid-state electrolytes, but this technology is still not mature.

Nanotechnology could also contribute to research in non-traditional battery areas, such as gravity-based storage, lightweight materials, and magnets. Other promising areas include cathodes, anodes, and corrosion- and fire- resistant materials. For example, silicon anodes for lithium-ion batteries can help store more store eight times more lithium ions than graphite anodes, but lithium can cause strain fractures on silicon. A company was able to solve that issue using nanoscale silicon. It is more flexible and can withstand strain. The technology is being used in cell phone batteries. Similar innovations are needed in grid-scale energy storage to allow intermittent networks (e.g., solar and wind) to be used on the grid.

Improved grid energy storage (short- and long-duration) is needed to tie renewable energy production to the energy demand cycles and expand access to clean energy. Effective long-duration energy-storage technologies will need to store energy for weeks, and even across seasons. Grid batteries need to be resilient to withstand emergencies and climate-related weather extremes. Thus, battery-economics considerations differ by application. For example, a car battery can be expensive but needs to be lightweight. On the other hand, for grid storage, a battery needs to be less expensive, because the energy produced needs to compete at pennies per kWh.

Capture of greenhouse gases (GHGs)

Every climate-mitigation model suggests we need significant carbon capture from the atmosphere to reach climate goals. To achieve this, the timeline of GHG capture innovations needs to be accelerated. Capture technologies are currently very inefficient and need more than 6- to 10-fold improvements in energy efficiency to become viable solutions. New nanomaterials and processes can help. The amount of energy needed to capture CO_2 is currently very high, because the main technologies depend on water-based solvents. These solvents absorb CO_2 at low temperatures and then need to be heated to release CO_2. This process requires raising the water temperature to the boiling point in every cycle.

There is a need for materials that can absorb CO_2 or other GHGs without requiring as much energy to release it. Currently, researchers are working on solid-phase sorbents, such as metal-organic frameworks (MOFs). MOFs are solid “sponges” that can selectively absorb CO_2 or other gases and can then release it through a phase change with small energy costs. But the technology is not mature enough for commercial deployment.

Large demonstration projects are needed to solve scaling-up challenges. Federal R&D programs and private companies are working to scale up GHG capture technologies, and new demonstration facilities are being built around the country, as scale-up is still a key challenge for all GHG capture technologies. In addition to long-term geologic and/or biologic storage, the CO_2 captured could be used to create value-added products such as electrofuels. Electrofuels can be synthesized by combining carbon captured from the environment with hydrogen. Other potential nanomaterial-based solutions could include a multimaterial system to target different GHGs.

Another growth area is overall GHG reduction at point of production, because capture technologies are not yet ready for large deployment. Some refrigerants are powerful producers of GHGs. An alternative to current refrigerants is solid-state refrigerants. For example, researchers have developed a solid-state refrigerant based on 2D perovskite layers modified with metal ions or long-chain polymers with amine groups. This technology could potentially eliminate 43 GT of CO_2 over 30 years – like the impact photovoltaics adoption has on GHGs. Other high-GHG-emitting products and materials include steel and cement, and nanotechnology-enabled alternatives could offer solutions.

Catalysts

The larger surface-to-volume ratio of nanocatalysts provides an advantage compared to traditional catalysts. Nanocatalysts can be used to create high-energy-density liquids, such as electrofuels, and other commodities normally made with fossil fuels, displacing the need for extracting new fossil fuels, and promoting circularity of captured CO_2. For example, net-zero aviation is one of the goals to achieve the country's net-zero goals by 2050. A start-up is currently building the first U.S. factory to produce jet fuel from captured CO_2 using a proprietary metal nanocatalyst, green electricity, and water. This jet fuel is a drop-in replacement to traditional petrochemical alternatives. As the field of CO_2 capture matures, more processes that create value-added products from the captured CO_2 are needed.

One of the key needs identified during the workshop discussions is that catalysts should be made with earth-abundant materials – even if using such materials decreases performance – because access and sustainability of more abundant materials will play a role in their cost and ease of adoption. Also, existing nanocatalysts could be adopted in new industries. For example, zeolites are commonly used in the petrochemical industry, and their catalytic and sorbent properties could be used in other less mature industries. Nanocatalysts that can be used as part of a drop-in technology into existing infrastructure – so they don't disrupt the entire supply chain – could have an impact in the short term.

Accelerating technology scale-up and adoption

To prevent crucial climate tipping points, the innovation cycle for climate nanotechnologies needs to be compressed from 20–30 years to 5–10 years. While many promising novel nanomaterials have been synthesized in the past decades, the focus needs to be shifted from creating new materials to increasing production of existing nanomaterials. Increasing efficiency in current industrial practices is another short-term, impactful goal. The petrochemical industry is an example of a potential benchmark for efficiency. Risks could be minimized by using established technologies to increase efficiencies in industrial processes and by developing drop-in technologies that do not disturb existing markets, systems, and supply chains. The NNI agencies could help bridge the gap between academia and industry and among industrial sectors, so that advances in drop-in technology can be adopted quicker.

Furthermore, predictability of performance – understanding the behaviors and properties of materials and devices under various conditions – could help compress the innovation cycle. Experimentation under many conditions takes time and resources. Predictability could be aided by digital tools, such as detailed models or "digital twins,'' which enable high-throughput testing without the need to repeat physical tests. An immediate need is to create digital twins for chemical-conversion devices based on multiphysics and multiscale devices. Nanotechnology can learn from what the fusion field has done with simulations and predictability models.

A wealth of initiatives, infrastructure, and programs that support technology translation at the federal level could help climate nanotechnologies reach their full potential. Most programs discussed are not specific to climate or nanotechnology, but awareness of these programs could help future climate entrepreneurs. The recent *Inflation Reduction Act* and the *Bipartisan Infrastructure Law* are major components of a new wave of the federal government's support of commercialization efforts. Because of recent investments, federal agencies are now able to expand their entrepreneurial support programs. The national laboratories are also equipped to discuss IP and other commercialization issues.

Financial support, infrastructure, mentorship, and needs

Financial resources

The federal government has established many programs to provide financial and business development resources for technological innovation. Knowing how to navigate those programs is an important skill for climate entrepreneurs. These programs could provide initial support for climate entrepreneurs and could help identify and address initial roadblock to scale-up and commercialization.

Here are selected examples:

- The Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs.
    - The NSF-funded SBIR/STTR program is a valuable entry point to government resources; it provides funds and know-how to develop potential business ideas. People who receive an NSF-funded SBIR/STTR grant can later receive awards from other SBIR/STTR-granting agencies that tend to focus on specific applications of a given technology.
    - The SBIR/STTR program provides access to business development mentors who can support the entrepreneur through the different administrative processes. The program also provides money up front to hire administrative and accounting support, a key barrier for growth discussed at the workshop.
    - Some universities offer classes and boot camps dedicated to discussing the SBIR process. Expanding access to those classes could make the process more accessible.
- The I-Corps program is another resource that helps with techno-economic analyses and customer discovery.
    - Different federal agencies, such as DOE, NIH, and NSF, offer I-Corps programs.
- Manufacturing USA and ARPA-E are other examples of technology acceleration and commercialization support programs across the federal government.
- National lab-embedded entrepreneurship programs funded by DOE.
    - The national lab-embedded entrepreneurship programs provide a two-year window of funding to de-risk technologies and enable pivoting, while providing a support community among entrepreneurs. For example, Chain Reaction Innovations, at Argonne National Laboratory, is a program that supports researchers to de-risk innovations. Through this effort, 35 companies have raised more than $580 million and created 600 jobs. There are similar programs at other DOE National Laboratories (e.g., Innovation Crossroads at Oak Ridge National Lab, Cyclotron Road at Lawrence Berkeley National Laboratory, and West Gate at the National Renewable Energy Laboratory).
- The ACTIVATE fellowship.
    - The fellowship helps turn an idea into a product in two years. This fellowship program is similar to the lab-embedded entrepreneurship program.
    - The fellowship is supported by a coalition of federal agencies and philanthropic organizations.
- Internal government programs to support staff to become “intrapreneurs.”
    - For example, the NIST Technology Partnerships Office provides intrapreneurship support, and the model could be expanded to other agencies.

Infrastructure resources

Federally funded facilities and programs are another great resource for entrepreneurs. The workshop included a discussion of many programs that are representative of efforts across many federal agencies, DOE often being used as an example (from the keynote talk). These facilities support innovators and democratize access to specialized and expensive tools.

Here are selected examples of facilities, consortia, and pathways to collaborate with these resources:

- The DOE-funded Nanoscale Research Centers (NSRCs)
    - At the five DOE NSRCs, 35% of users in 2022 conducted research in Nano4EARTH-related topics.
- The NSF-funded National Nanotechnology Coordinated Infrastructure (NNCI)

- Federal Laboratory Consortium
    - A network of more than 300 labs with resources, such as IP for licensing; equipment for use; and experienced scientific staff with whom to collaborate.
- Cooperative Research and Development Agreements (CRADAs)
    - CRADAs are a potential avenue for collaboration with national labs and other government entities.
    - CRADAs make government facilities, IP, and expertise available for collaborative interactions. It is an important resource that allows private companies to interact with thousands of researchers at national labs and government entities.
- Manufacturing USA
    - Manufacturing USA is a public-private partnership consisting of manufacturing institutes, infrastructure, and expertise.
    - The Rapid Advancement in Process Intensification Deployment Institute (RAPID) Manufacturing Institute is an example of a Manufacturing USA institute that supports the development of climate technologies.
- Technology demonstration facilities
    - DOE's new Office of Clean Energy Demonstration is dedicated to technology demonstration. DOE will also establish innovation hubs around climate change-related research topics, such as carbon capture.
    - DOD announced that some bases will be made available for climate testbeds.

Other non-federal resources

Individual states have their own resources and initiatives. For example, Virginia has the Manufacturing Extension Partnership (MEP) Genedge (https://genedge.org/). The MEP is an example of a public-private partnership helping small businesses with their manufacturing needs. Another state-specific example is the California Energy Commission, which provides funding to national labs and university campuses to work with entrepreneurs. Finally, local universities (especially commercialization or technology transfer offices), national labs, and industrial parks can help connect entrepreneurs with technical and business experts (e.g., accountants and legal professionals).

Entrepreneurship, workforce, and education needs

Opportunities to increase access for climate entrepreneurs

The Brookings Institute reports that startup rates have been declining in the United States. Student loan debt and lack of support for founders from under-represented groups are reported as barriers for innovation. Entrepreneurship is a skill that needs to be cultivated and introduced as a potential path to scientists and engineers early in their careers, and researchers need to learn how to de-risk their technologies. For example, NNCI provides entrepreneurship training across the network, and this training facilitates a nanotechnology entrepreneurship challenge (NTECH). NTECH provides the foundation to apply to other programs, such as I-Corps. NNCI also hosts a Research and Entrepreneurship Experience for Undergraduates (REEU) program, adding elements of entrepreneurship to the traditional NSF REU program.

The academic community needs more opportunities for exposure to industrial problems (e.g., internships) and to potential collaborators across fields and sectors. Funding calls could emphasize the need for such opportunities. For example, NSF award recipients can receive a supplement award for their graduate students, so they can become interns in the private sector through the new NSF convergence accelerator. Collaborations can also help scientific research institutions and companies share expertise and resources. Such collaborations also are a great way to explore new use cases.

A personal financial risk is associated with any entrepreneurship activity, but for nanotechnology specifically, very expensive equipment is needed. To help accelerate progress, building a whole ecosystem (including salaries) around those resources and equipment is needed. Personal risk should be identified and mitigated. Currently, innovators combine different Small Business Administration (SBA) and Service Corps of Retired Executives (SCORE) programs to patch together funding for a couple of years. Expanding baseline funding to 3–5 years could help increase the TRL of the technology. Explaining the business world to researchers (e.g., what to do with stock options?) and information on how to navigate conflicts of interest (given that entrepreneurs are usually already employed) is needed. Public-private partnerships need to sort out IP issues in advance, as IP agreements may also disrupt and delay the innovation cycle.

How the NNI can facilitate entrepreneurship, scale-up, and adoption

Federally funded infrastructure provides a way to amplify and accelerate the impact of nanotechnology-enabled climate innovations. However, reinvestment is needed. The current infrastructure is aging, and expensive tools are going offline. Expanding current facilities to include testbeds would also greatly benefit entrepreneurs.

Coalitions, public-private partnerships, and other mechanisms that facilitate meaningful interactions between research and industry are needed to accelerate the exchange of ideas and feedback. Climate scientists and nanoscientists can learn from each other. The NNI could help build communities of interest/practice and convene climate scientists and nanoscientists to develop research pathways. If a cohesive community is established, learning can be transferred quickly among participants, which can help identify and prioritize problems/areas of greatest need. The NNI could also help create spaces for big companies and startups to exchange ideas. Startups have a lot of ideas/solutions that big companies are looking for. The NNI could help companies understand permitting requirements, anticipate challenges, and streamline market deployment.

It is also important to assess the health of the nanotechnology-enabled climate innovation ecosystem – how many ideas are finding a technology development pathway and what might be missing. The NNI could help develop feedback loops connecting experience and lessons learned from demonstration projects back to the innovation cycle. The NNI could also help develop seamless ways to provide steady support throughout the innovation cycle. For example, expanding translational user facilities, such as the NSRCs and the NNCI sites, could help entrepreneurs produce materials at scale that would be incorporated into prototype devices, enable them access to machines to build next-generation batteries, and provide affordable access to testing equipment.

Economic and workforce needs to facilitate scale-up and adoption of nanotechnology-enabled solutions

Economic evaluation is needed to accelerate scale-up. For example, some nanomaterials for catalysis can be perceived as expensive; however, an evaluation may reveal that the amount of materials needed is small, indicating that processes using such materials may be economically feasible. It is challenging for companies to make major technology changes, because many previous investments are at stake.

Solutions can include focusing on emerging economies, in which those investments are not already embedded, and focusing on drop-in technologies for established processes.

Another important consideration for scale-up is the availability of critical minerals. Currently, a strong focus on maximal device performance drives the selection of rare and costly materials. The supply chain, security, and environmental risks of mining those materials are important considerations. Recyclable and earth-abundant materials should be prioritized for products that need to be mass-produced, even when they slightly decrease performance.

Adoption is key to making innovations impactful, but there are many steps beyond the lab, such as acceleration to market, workforce development, and early engagement of society, which are needed to achieve widespread adoption to reduce negative impacts on the environment. The average time from lab to market for nanotechnologies is more than 20 years. For example, it took 60 years for solar photovoltaics (PVs) to achieve widespread adoption. The initial cost of PVs was very high through the 1970s, while fossil fuels were comparatively inexpensive. But in 2011, PVs achieved grid cost parity – their cost became equal to or less than the cost of conventional fossil fuels. The space program served as a stepping-stone market to test and pioneer PVs. Finding high-value initial markets for other climate technologies could help accelerate commercialization.

One way to accelerate the innovation timeline is energizing the workforce by providing meaningful and lucrative careers; designing specific curricula that teach about global challenges and emerging technologies; promoting entrepreneurship; increasing diversity in the field; and fostering international collaboration. Promoting research questions focusing on tomorrow's needs – including resilience and resilience preparedness – is also important to accelerate innovation. Prize competitions can also serve as a mechanism to accelerate innovation by soliciting creative ideas from diverse expertise and backgrounds.

Education

Education is an undertapped resource for climate resilience and a key metric that could be used to track progress of Nano4EARTH efforts. Education could be measured as increased awareness through formal curriculum development and informal education opportunities that address the climate crisis and highlight solutions-based learning using nanotechnology. K–12 curriculum development on nanotechnology and climate change exists, but expansion and widespread coordinated efforts are needed.

Educators need support to simplify the complexity of climate change. Curricula could help to link science, engineering, and actionable community targets. Teachers could use nanotechnology to inspire students to imagine the possibilities for the future, as climate change is relevant to many subjects (e.g. science, history, ecology, biology, etc.). Discussing these topics in the classroom could motivate students to seek careers in nanotechnology to solve the climate crisis.

The development of informal educational opportunities is another potential metric. These opportunities include discussing research and technology innovation with its potential users through partnerships with science museums, media content creators, professional societies, and public webinars. Making information generated more accessible is needed, especially to people impacted by climate change who live in underserved communities.

Next steps

As new climate solutions are developed, it is important to keep environmental, health, and safety (EHS) issues at the forefront of the innovation process. The nanotechnology community has a long history of proactive nanoEHS involvement, and successes and lessons learned can be applied to climate nanotechnologies. Early engagement of communities and standards development organizations (e.g., International Organization for Standardization (ISO), ASTM International, IEEE) which study the impact of technologies/materials used is important. Standards have implications for economic competitiveness and for EHS. Standards facilitate the ease of global commerce by opening markets and accelerating adoption of emerging technologies. The United States has the opportunity to develop a strategy to ensure standards are well thought out and engage wide participation.

The workshop connected a diverse set of practitioners and interest groups and sparked plans for new collaborations and community-led events. NNCO will follow up the workshop with a series of roundtable discussions on the four recurring themes from the workshop: interfacial nanotechnologies; batteries and energy storage; GHG-capture technologies; and catalysis. NNCO will continue to facilitate interactions between the broader NNI community and the climate community to help accelerate responsible development and cross pollination of ideas and technology adoption throughout different sectors. Examples of such events include sessions at professional conferences to connect entrepreneurs with federal resources – for example, available tools and infrastructure – and to provide financial support and training. Furthermore, the NNI is facilitating educational activities and developing resources to highlight the role nanotechnology could play in inspiring solutions for climate change in and outside of the classroom.

Appendix

Workshop agenda

Location: Hilton Washington DC National Mall The Wharf, L’Enfant (Ballroom) Salon A, 480 L’Enfant Plaza SW, Washington, DC 20024

January 24, 2023 (Eastern Standard Time)

- 9:00 am | Introduction of Nano4EARTH by NNCO Director Dr. Branden Brough
- 9:10 am | Keynote speaker: Dr. Asmeret Asefaw Berhe, Director, Office of Science, U.S. Department of Energy
- 10:10 am | Break
- 10:30 am | Panel 1: Identifying nanotechnology-enabled solutions for addressing climate change
    - Moderator: Dr. Mark Griep, Materials Engineer, U.S. Army Research Laboratory
    - Panelists:
        - Dr. Sally Benson, Deputy Director for Energy and Chief Strategist for the Energy Transition, Office of Science and Technology Policy, Executive Office of the President
        - Dr. Michele Ostraat, Chief Scientist, Pajarito Powder
        - Dr. Lloyd Whitman, Senior Director, GeoTech Center, Atlantic Council
- 12:00 pm | Lunch break

- 12:30 pm | Panel 2: Climate Entrepreneurs: Resources, successes, and shortcomings
    - Moderator: Dr. Christie Canaria, Interagency Policy Specialist, National Institute of Standards and Technology
    - Panelists:
        - Dr. Nichole Cates, Senior Research Scientist, Smart Material Solutions
        - Dr. Etosha Cave, Co-Founder and Chief Scientific Officer, Twelve
        - Dr. Dick T. Co, Director, Chain Reaction Innovations, Argonne National Laboratory
        - Dr. Matthew Hull, Director, Nanoscale Characterization and Fabrication Laboratory, NanoEarth, Virginia Tech
- 2:00 pm | Summary
- 2:05 pm | Adjourn
- 2:05- 3:00 pm | In-person-only networking session

January 25, 2023 (Eastern Standard Time)

- 9:00 am | Welcome remarks by NNCO Director Dr. Branden Brough
- 9:05 am | Keynote speaker: Dr. Cynthia Friend, President, Kavli Foundation
- 10:05 am | Break
- 10:15 am | Panel 3: Measuring the impact and influence of Nano4EARTH
    - Moderator: Dr. Nora Savage, Program Director, National Science Foundation
    - Panelists:
        - Dr. Mike Kuperberg, Executive Director, U.S. Global Change Research Program
        - Dr. Kelley Lê, Executive Director of Environmental and Climate Change Literacy Projects, University of California, Irvine
        - Dr. Gavin A. Schmidt, Director, Goddard Institute for Space Studies, NASA
- 11:45 am | Lunch break
- 12:15 pm | Strategic planning exercise
    - Moderators: Dr. Branden Brough, Director, National Nanotechnology Coordination Office and Dr. Quinn Spadola, Deputy Director, National Nanotechnology Coordination Office. The goal of this session was to distill the discussions from the workshop and identify priority nanotechnologies, barriers to commercialization, and metrics to track progress and impact.
- 1:45 pm | Closing remarks and summary
- 2:00 pm | Adjourn