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Positioning nanotechnology to address climate change

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Abstract
One of society's most pressing challenges in the twenty-first century is that of climate change. In fact, climate change is seen as the most defining issue of our time as we are witness to an anthropogenic perturbation in geology and earth sciences of global scale. To move forward in this new era, solutions will be sought to both mitigate the effects of climate change (e.g., reduce greenhouse gasses) as well as adapt and build resilience (e.g., improve infrastructure and agriculture to resist damage from extreme weather or floods). The immediacy of the needed solutions dictates that the response must use the full force of society's current knowledge base, science, technology, and innovation. Nanotechnology, an enabling technology that has matured over the past few decades and now considered for general-purpose and mass use, is ideal for addressing climate change and its impacts. To position nanotechnology to address such complex challenges, this Perspective integrates collective insights from a broad range of viewpoints and presents recommendations for how research can be motivated and scoped, organized, and implemented to achieve beneficial outcomes and innovations in the most efficient ways. While this Perspective was created with a focus on the research landscape within the United States, the findings are also relevant in other international contexts. Research that can effectively advance nanotechnology solutions will be use-inspired basic research, incorporate systems-level thinking, apply a convergence research approach, engage stakeholders, and require advanced nanotechnology infrastructure. By illuminating this compelling and complex research topic, this Perspective aims to direct, inform, and accelerate needed actions in the research community to advance nanotechnology solutions for addressing climate change.

Keywords Nanotechnology · Convergence research · Climate change · Infrastructure · Basic research

1 Introduction

It is becoming abundantly clear that solutions to address climate change are urgently needed. While climate change science and mitigation strategies have been studied for decades, meaningful progress to limit global emissions has been very limited (e.g., Stoddard et al. 2021; United Nations Climate Change 2022) and atmospheric CO_2 concentrations continue to rise with a corresponding increase in global temperatures and other significant pressures on various ecological systems (NOAA 2022, 2023). In fact, it was recently reported that six of the nine so-called planetary boundaries have been exceeded and more will be exceeded soon, which is graphically represented in Fig. 1 (Richardson et al. 2023). In addition to exceeding these safe operating boundaries, human activity has fundamentally changed Earth's geology, as evidenced in our sediments and ice (Waters et al. 2016). These changes manifest the emergence of a new "Anthropocene epoch"—a global

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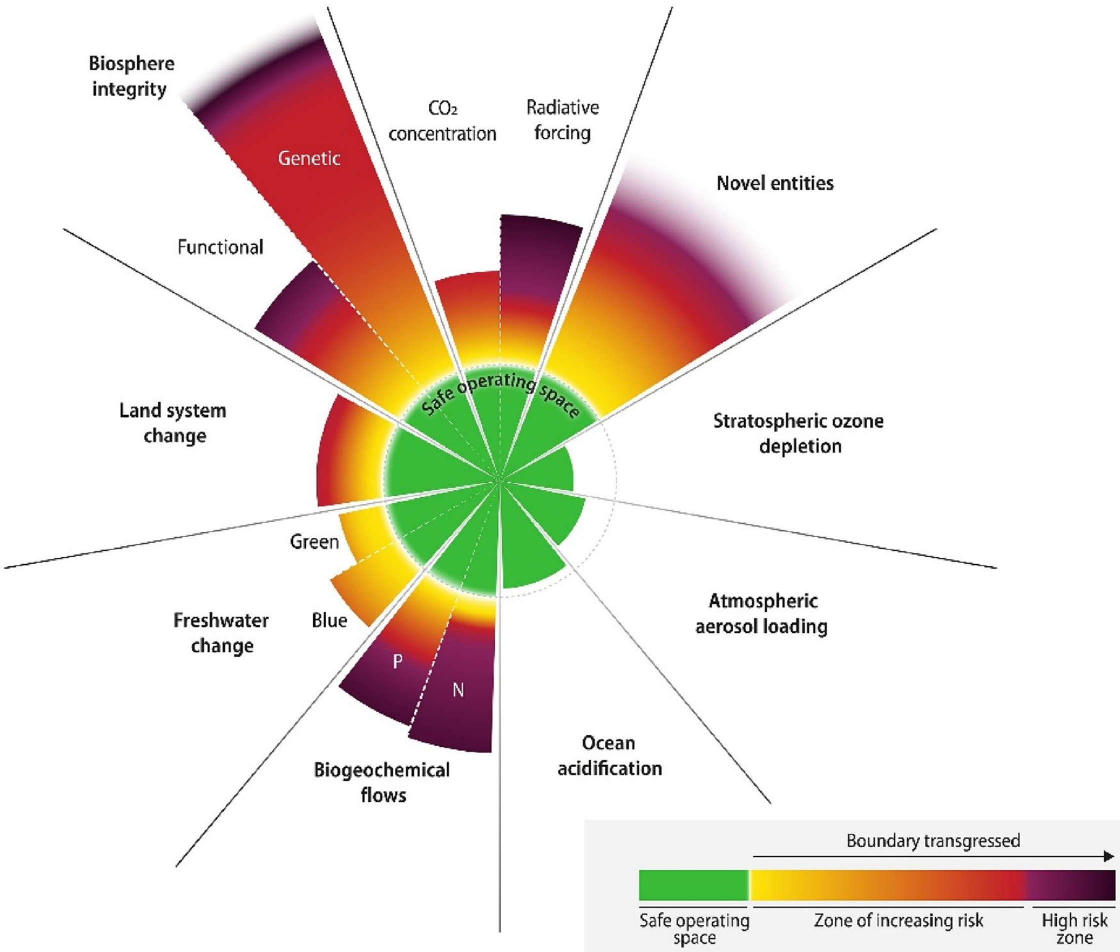

Fig. 1 In the planetary boundaries framework, six of the nine boundaries are transgressed, illustrating significant anthropogenic impacts on the Earth. Reprinted from Richardson et al. (2023), which was distributed under a Creative Commons Attribution Non-Commercial License 4.0 (CC BY-NC), https://creativecommons.org/licenses/by-nc/4.0/

anthropogenic perturbation that reflects a transition from a relatively stable, 10,000-year Holocene period to an era in which humans have affected climatic, biological, and geochemical signatures of Earth.

The most recent Synthesis Report from the Intergovernmental Panel on Climate Change details the human-induced changes to our atmosphere, oceans, cryosphere, and biosphere and how such changes are seen across every region of the world, leading to widespread adverse impacts such as losses and damages to people and our environment. These impacts have furthermore disproportionately affected vulnerable communities (IPCC 2023). Everywhere in the world, the human experience is changing, including extreme temperature fluctuations, wildfires, increased storm intensity, and the occurrence of hurricanes in the Pacific Ocean. In some areas of the world, there are severe droughts and loss of groundwater supplies (e.g., Southwest United States (U.S.)), while flooding is being seen with more frequency in others (e.g., New York City, U.S. and Sydney, Australia).

To accelerate our resilience against climate change, we must leverage the full force of society's knowledge base, science, technology, and innovation to advance both sustained mitigation strategies as well as implement adaptation measures. Among other key enabling technologies, nanotechnology, developed with major financial and intellectual investments as an interdisciplinary research area over the past several decades, can offer opportunities to address key climate change mitigation and adaptation challenges, helping to reduce substantial losses and damages in the future. For example, nanotechnology has the potential to contribute to stronger, lightweight materials used in vehicle and transport, enable more energy-efficient coatings for surfaces, contribute further to renewable energy infrastructure such as that provided by solar and wind, and improve efficiency of batteries for energy storage.

Over the past 20+years, the U.S. invested in nanotechnology through a concerted, multi-agency National Nanotechnology Initiative (NNI). Starting in 2000, the genesis of the NNI catalyzed organizations and individuals from academia, industry, and government to develop new foundational knowledge of nanoscale phenomenon and materials and develop novel and economic applications for nanotechnology. Moreover, an important goal from the outset of the NNI was to support the responsible development of nanotechnology, e.g., by considering the environmental, health, and societal implications of the technologies themselves and their applications. Since that time, over $40B USD has been invested to advance our "*fundamental understanding of and ability to control matter at the nanoscale*" (NNI 2023a) and we now have nationally supported nanotechnology infrastructure centers sponsored by many federal agencies including the Department of Energy (e.g., Nanoscale Science Research Centers, or NSRCs) and the National Science Foundation (e.g., the National Nanotechnology Coordinated Infrastructure Sites, or NNCI Sites). The time, investment, and successes were so substantial that Roco said nanotechnology is now for "*general-purpose and mass use*" (Roco 2020).

More recently, nanotechnology and its associated disciplines have been more strongly connected to climate change at national and global levels. In early 2021, U.S. President Biden elevated climate change in the U.S. national agenda at the beginning of his term (The White House 2021). Later, in 2022, the U.S. White House Office of Science and Technology Policy (OSTP) released 37 "Net-Zero Game Changer Opportunities," physical science and engineering challenges that could help transform our energy system and infrastructure, seeking to motivate and direct the full potential of the U.S. public and private innovation ecosystems (The White House 2022). Soon thereafter, the Engineering Research Visioning Alliance (ERVA), a project sponsored by the U.S. National Science Foundation (NSF), published a workshop report that identified specific opportunities in science, engineering, and technology that are necessary to advance solutions to addressing climate change (ERVA 2022). These opportunities became grouped topically into four categories: (i) energy storage, transmission, and critical materials, (ii) greenhouse gas (GHG) capture and elimination, (iii) resilient, energy-efficient, and healthful infrastructure, and iv) water, ecosystems, and geoengineering assessment (ERVA 2022). The ERVA report emphasized the importance of engineering tools that require significant and sustained investment, some of which are the tools and facilities supported under the NNI, e.g., currently available NSRCs and NNCI Sites. Nanotechnology, now poised as a general-purpose and mass use technology within these open-access facilities, presents opportunities to address challenges in all four of these research categories.

The identification of nanotechnology as an opportunity to address climate change mitigation and adaptation challenges was further solidified in 2023, when the National Nanotechnology Coordination Office (NNCO) issued a "Nano4EARTH Challenge." Nano4EARTH is motivated by a need to act quickly, with matured science and technologies, to advance compelling nanotechnology commercialization opportunities for climate change mitigation and adaptation (NNI 2023b). In an inaugural convening event for Nano4EARTH (in which many of the authors of this Perspective participated), the NNCO brought together hundreds of stakeholders in hybrid modality to identify the most impactful research opportunities for nanotechnology to help address climate change and to identify technologies that were ripe for translation into the market. Common themes that emerged involved immediate opportunities in battery technologies, catalysts and advanced materials and sorbents for addressing greenhouse gas emission and capture, and coatings and other material innovations for increased efficiency in industrial processes (The White House 2023). Specific and immediate research topics are elaborated upon in a recent publication by the NNCO (Campa et al. 2024) as well as the ERVA report (ERVA 2022).

While these efforts address certain immediate commercialization opportunities of mature technologies, there remain other relevant questions around how the nation's basic research activities and infrastructure in nanotechnology, which was built up and maintained through decades of national investments, can *evolve* to help support both commercialization and basic research underpinning nanotechnology for addressing climate change. Moreover, it is critical to achieve this evolution in a way that is responsible, sustainable, does not introduce new or alternative risks, is inclusive, and provides equitable solutions. To fill this information gap in the general approach to the research process itself, this Perspective aims to identify key needs in the process and infrastructure to advance climate change solutions in the longer term.

This Perspective was developed by a small working group associated with the U.S. NNCI that convened a range of stakeholders from research, industry, and government and from disciplines across the physical, life, social, and economic sciences to discuss key questions about the future needs and opportunities at the intersection of nanotechnology and climate change. To convene stakeholder participants, an open, online workshop was organized and held in February of 2023. After the workshop, the working group and select participants met monthly to further elaborate and prioritize key needs. The working group synthesized the input gathered during the workshop and subsequent working group discussions and the resulting opinions are shared in this Perspective.

From the workshop and synthesis discussions emerged five high-level characteristics of future research that can most effectively advance nanotechnology solutions to address climate change within the U.S.-based context, although many aspects are relevant for other regions as well:

1. Long-term basic research in nanotechnology needs use-inspiration, i.e., connection to specific solution spaces in climate change needs.
2. Systems-level thinking is a necessary framework to create new discoveries and effective nanoscale innovations that are sustainable and can ultimately be adopted by society as solutions.
3. The research process needs the practice of convergence research to integrate diverse disciplines on specific and compelling topics of appropriate scope.
4. Stakeholders must be involved in guiding the prioritization of nanotechnology research effort and the design of research projects, also ensuring sustainability.
5. Nanotechnology infrastructure, e.g., equipment, personnel, and facilities, needs to be designed or adapted to a different and evolving user base which is increasingly interdisciplinary and is composed of individuals working on increasingly complex systems.

Each of these five characteristics is elaborated upon in subsequent sections. The five characteristics are themselves distinct yet also highly complementary. For example, higher level constructs such as Convergence Research can capture most, if not all, of these characteristics.

In parallel to research and innovation that advances nanotechnology to address climate change, we also recognize that nano-safety and risk governance research needs to advance simultaneously to ensure the responsible and sustainable use of nanotechnology following best practices. Such research could include, among other things, investigation on potential impacts on the environment, health, and society across life cycle stages as well as iterative engagement strategies to understand and incorporate diverse stakeholder perspectives in research and innovation cycles (Grieger et al. 2019b, 2022; Kokotovich et al. 2021).

This Perspective may be useful to many different categories of readers. For researchers and scholars, the content could be used to determine impactful research areas, inform the best approaches toward research in this area, and adapt curricula toward sustainability. For those who work within funding agencies, we anticipate the content is useful to consider when prioritizing areas of investment. Entrepreneurs may also use this information to wisely focus time and resources to scale technologies that are most likely to be adopted by society and effectively advance climate change solutions. Moreover, given the urgency of needed solutions, we anticipate that identifying and communicating these research characteristics will accelerate both consensus-building and actions in the research community, both in the U.S. as well as internationally.

2 Use-inspired basic research in nanotechnology

To accelerate actionable climate change solutions based on new fundamental knowledge and discoveries, investments in nanotechnology research require consideration that new technical innovations are discovered and developed within the context of complex societal and ecological systems. Such efforts are necessarily long term in nature (5–10 years or longer) such that they can focus on foundational science and tools, human scale interventions for adaptation to maintain and enhance quality of life, and earth scale assessment and mitigation to preserve planetary systems. Such long-term efforts can typically be categorized as fundamental or basic research.

A useful construct to place nanotechnology in the context of vexing societal challenges like climate change is the Stokes research classification system, reproduced in Fig. 2 (Stokes 1997). This influential framework locates different types of research activities according to two orthogonal dimensions: (i) whether the research is seeking new fundamental understanding, and (ii) whether the research is guided by specific uses or applications. The framework was developed in response to a prevailing understanding at the time and still persistent today that "basic research" and "applied research" are distinct activities. The quadrant marked as Pasteur in the Stokes diagram is shown to capture so-called "use-inspired basic research," which is research seeking new fundamental understanding while also being guided by specific applications. In the 21st Century, according to Stokes and others, a significant amount of research can be categorized in the Pasteur quadrant. Take, for example, the work of quantum physicists who are seeking new fundamental understanding of quantum effects with the aim to develop quantum computing and related technologies or medical scientists seeking to cure a specific disease. Thus, scientists who seek fundamental understanding through basic research activities

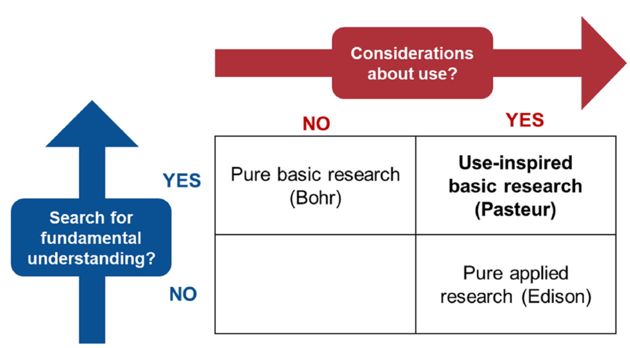

Fig. 2 The Stokes research classification system, drawn after (Stokes 1997)

can do so while also conscientiously choosing problems of interest based on societal needs. The Stokes research classification system is therefore a framework that resolves tensions over basic versus applied research and, equally, can accelerate the advancement of technologies and solutions needed by society.

With nanotechnology now positioned for general-purpose and mass use, it is necessary to scope its application to specific use cases, i.e., giving nanotechnology use-inspiration. An engineering-specific literature review commissioned by ERVA (ERVA 2021) provides insights into how engineering contributes to various specific use applications. The report also well reflects the categories of potential influence for nanotechnology. The ERVA-commissioned report shows strong engineering contributions in the areas of energy storage, solar and renewable energy, decarbonizing industries, and carbon sequestration. However, engineering is less well represented in other areas such as resilient infrastructure and geoengineering and is identified in 20% or less publications in the areas of ecosystems and agriculture, and health and climate change. Even though a small percentage, there are many examples of nanotechnology contributions in these spaces, e.g., a 2020 review article in Nature Food that assessed the technology readiness level (TRL) of various nanotechnologies in plant agriculture, their potential impact, and barriers to implementation (Hofmann et al. 2020). Areas of most significant promise were related to smart-delivery pesticides, RNA interference for pest management, and efficient fertilizers. Nevertheless, the dearth of engineering contributions to certain areas of climate change research evidences the opportunities to grow convergent research across disciplines—including and beyond nanotechnology—to create effective innovations to address climate change. In other words, it is apparent that nanotechnology and engineering only nascently contribute in a small fraction to overall climate change research and could contribute more.

Ultimately, ERVA identified four specific categories of research needs which were adopted for the purpose of our project to discuss nanotechnology research needs. These categories are listed below, and specific, exemplary nanotechnology opportunities are elaborated upon within each:

Energy storage, transmission, and critical materials: Nanotechnology is ubiquitous in this space and poised to contribute solutions that can be demonstrated and scaled. Thousands of studies have been published at an increasing rate over the last 20 years and many of these technologies have been licensed and commercialized. Continued advances are required to address needs for nanoengineered materials to enable various aspects including separation processes across the life cycle for critical minerals and energy generating systems; non-traditional energy storage and extraction technologies; and energy infrastructure designed to operate under extreme conditions (ERVA 2022). From our workshop and project, additional gaps specific to nanotechnology were identified, and ranged from strategies for reusing dissipative energy to using earth-abundant elements to make robust energy storage materials with tunable properties. To meet these needs, nanotechnology facilities, equipment, and convergence expertise are required to translate and scale promising solutions from the lab to the market. Methods are needed for studying materials at nanoscale resolution in situ during use. At the same time, needs for nanotechnology to enable a modern society without additional climate burden include electrochemical systems tunable to a variety of applications, new sources of energy for the Internet-of-Things (IoT) and autonomous nanodevices, and Artificial Intelligence/Machine Learning (AI/ML) integration to optimize solutions. In addition, application of best practices in social science is needed to enable understanding of economic imperatives, as well as to engage communities affected by sourcing of energy storage and critical materials.

Water, ecosystems, and geoengineering assessment: This emerging area shows strong promise for robust advances with strategic investments in nanotechnology. Use-inspired research is needed to advance sensors and monitoring systems, e.g., to help mitigate losses of treated water in aging distributions systems, and that can be deployed at scale to analyze and forecast watershed fluctuations associated with extreme and severe weather conditions. Research is also required to enable monitoring and verification of CO_2 removal technologies and systems as these are demonstrated and implemented (ERVA 2022). There are opportunities in specific geographies to use nanotechnology to address challenges in providing safe water and food to drought-stricken areas. There are needs for research in monitoring and removing contaminants from, and desalination for, drinking water supplies as well as for nanotechnology to improve crop yields in agriculture amidst changing real-world conditions. At the same time, the need for holistic evaluation of nano-enabled solutions to anticipate unintended consequences across the life cycle is vital. Key societal considerations include the fate of nanomaterials in water supplies and long-term consequences of geoengineering approaches. Approaches for scoping priority problems and solutions with input from those most at risk of impacts to climate change and to consequences of mitigation technologies are also crucial.

Resilient, energy-efficient and healthful infrastructure: The potential for nanotechnology to contribute to solutions that facilitate adaptation to climate change is only just being recognized. Nanotechnology will need to continue to play a leading role in the design and engineering of renewable energy infrastructure to reduce transportation, industrial, and powerplant emissions. Promising opportunities for additional investment include nano-enabled solutions to advance a built environment that has a reduced carbon footprint and supports climate adaptation. Example research areas include cost-effective technologies for retrofitting existing structures to minimize use of energy and water, as well as to reduce impacts of extreme heat, wind, and flooding (ERVA 2022). Specific examples include self-healing structures and concrete, as well as integrated sensors for truly smart buildings and infrastructure. Optimizing solutions will require tools for materials life cycle analyses that characterize impacts of new materials and infrastructure. Sustainable solutions will also require acknowledgment that ecological and societal systems are interconnected and developed infrastructure should foster biodiversity while also caring for people and communities.

Enabling greenhouse gas (GHG) capture and elimination: This nascent area has been gaining traction in the nanotechnology research community. As planetary boundaries are exceeded, the necessity of removing CO_2 from the atmosphere is being recognized as paramount (Arehart et al. 2021; The Economist 2023). In fact, this area presents the ultimate case for use-inspired research requiring significant investments. Overall, materials and processes are required to capture and eliminate or store GHGs sustainably. Further, technologies that target methane and nitrous oxide are needed in addition to those focused on CO_2. Research is also needed that focuses on enhancing natural processes and on solutions for high emission sites (ERVA 2022). In this research category, the convergence of nanotechnology with agriculture, plant sciences, and marine sciences is critical as well as research to support scalable solutions and inform economic policy to drive implementation of technical innovations. Proximate communities that will be directly impacted will need to be involved early as infrastructure for removing CO_2 is constructed.

3 The necessity of systems-level thinking

Advancing the development of nanotechnology-based solutions to address climate change requires the broadest systems-level thinking because such nanotechnology solutions need to be accepted by and adopted within broader socioeconomic, cultural, and political contexts. In earlier work in the related area of environmental protection, the National Academies emphasized the need for systems-level thinking, saying "*The challenges associated with environmental protection today are multifaceted and affected by many interacting factors. The challenges operate on various, often large, spatial scales, unfold on long temporal scales, and usually have global implications (for example, carbon dynamics, nutrient cycles, and ocean acidification). Dealing with these problems will require systems thinking and integrated multidisciplinary science*" (National Research Council 2012).

Today, systems-level thinking is introduced in many different disciplines and applications, yet taking on somewhat disparate definitions. Here, we define systems-level thinking as a "*framework for seeing interrelationships rather than things, for seeing patterns of change rather than static 'snapshots'*" (Senge 2006). This definition contains two key elements to systems thinking: interrelationships and their changes with time. Importantly, systems thinking is a tool to help make decisions while being able to understand multiple causal roots and possible outcomes. Emphasizing systems thinking as a tool, Crawley said that systems-level thinking is a method to "*simplify complexity, recognize patterns, and create effective solutions*" (MIT Open Learning 2022).

In his book, *The Fifth Discipline*, Peter Senge proposes 11 laws of systems-level thinking that are relevant for research contexts pertaining to climate change solutions (Senge 2006). For example, the first law "Today's problems come from yesterday's 'solutions'," could very clearly represent, for instance, excessive greenhouse gas emissions initiated by the industrial revolution or forest degradation to expand agricultural lands and raise livestock. Further, the 11th law, "There is no blame" points toward the complex, intertwined, and cross-sectional nature of many of our wicked problems, including climate change. Overall, Senge's laws and the associated examples reinforce the need to understand systems at a high level and consider all aspects of technology introduction, e.g., from sourcing materials, to manufacturing, to consumer adoption, to downstream consequences of use, as well as the associated changes to society and to the environment in both space and time.

Systems-level thinking has been applied to countless applications ranging from organization and management to human health and environmental science. In all of these application spaces, the objects in the system include humans (either as subjects or decision makers), scientific principles, technologies, and the environment (however that is defined in any specific example). We emphasize here the necessity of all of these different types of components in systems (e.g., humans, scientific principles, technologies, the environment), especially in any area related to climate change. Such components are likely to span international contexts and require international collaboration and cooperation for effective technology development, commercialization, and adoption. For example, one cannot consider advances in batteries or solar cells without considering the upstream sourcing of the component materials (which likely spans nations and international regulatory structures) and those associated impacts on local communities (often captured under preemptive life cycle analysis, e.g., as in Horgan et al. 2023) as well as adoption by consumers and even the potential influence of public policy. Such contention is evident in a recent discovery of a large U.S. source of lithium-containing rocks in Maine, where State regulations intended to protect the environment inhibit its availability (Semuels and Cough 2023).

One of the largest systems of relevance in climate change studies is the Earth itself. The interrelatedness of Earth's planetary boundaries, represented in Fig. 1 (Richardson et al. 2023), demonstrates the value of recognizing it as a system. For example, the co-use of phosphorus and nitrogen in agriculture as fertilizers and the relation of both to greenhouse gas emissions, e.g., CO_2 from the energy required to produce nitrogen-based fertilizers and CH_4 from harmful algal blooms associated with phosphorus runoff. Addressing just one of these issues may have unexpected consequences for the others, thus reinforcing the need for systems-level thinking. In fact, given the very large size of the Earth and the interrelatedness of many challenges, a systems-of-systems (SoS) framework is being developed by Little et al. to "*integrate fragmented data and disconnected knowledge into new understanding*" (Little et al. 2023).

Importantly, systems-level thinking enables the prioritization of effort and identification of suitable evaluation and success metrics. Given the finite resources available to science, society must be purposefully motivated and invest wisely. For example, using Fig. 1, the extent of which each planetary boundary passes Earth's safe operating limit aids in its justification for prioritization. Society could invest immediate attention in areas of critical need (e.g., biosphere integrity) while making longer-term investments in use-inspired basic research in other areas (e.g., atmospheric aerosol loading), pointing to the value of both shorter and longer-term runways for research and technology investments.

Evaluation and success metrics can also be better defined within the contexts of systems. In traditional basic and applied research, economic impact is often the preferred measure of research project success, i.e., through economic benefits such as job creation or the manufactured products. Economic impact analysis can indeed be used to demonstrate the scaling of nanotechnologies to address climate change, and we emphasize the value of innovation and entrepreneurship programs to catalyze these outcomes. However, in topics of environmental significance, researchers also need to consider the impacts to the environment, e.g., through studies in environmental and natural resource economics (Green et al. 2023; EPA 2024). Economic impact traditionally assesses short- or medium-term impacts, whereas the timescales involved in addressing climate change can be multi-generational (Sundstrom et al. 2023). Today, even corporations are realizing their important social purpose beyond the bottom line. As reported in Harvard Business Review, the 200 largest multinational corporations based in the U.S. recently declared that they will "*no longer focus solely on shareholders or on the short run*" (Winston 2020). This trend indicates longer-term visions of industry, where societal and environmental impacts are valued as elements of success in parallel to profitability. In this new socio-economic environment, large corporations are expected to invest in greener processes and invest in environmental solutions.

Building on the *framework* of systems-level thinking is the *practice* of convergence research that aims to address complex challenges within science, engineering, and society. Convergence research generally aims to tackle a specific problem of importance to society by answering deep scientific questions across a range of diverse disciplines and perspectives. By drawing on a number of different fields and disciplines, new solutions may arise that would not have been possible through investigations within a single field. In the case of leveraging the potential of nanotechnology to address climate change, convergence research may be a particularly promising approach to develop nanoscale solutions while also considering a broader range of socio-economic, cultural, and political factors. Such non-technical factors that involve individuals, communities, and groups are especially critical to developing results that are inclusive and provide equitable solutions. Therefore, use-inspired nanotechnology research needs to be undertaken in a way that incorporates perspectives and needs from diverse stakeholders and within context-specific economic and political systems, processes that are innate to convergence research.

4 Convergence research on specific and compelling topics of appropriate scope

Given the breadth and diversity of the systems and stakeholders involved in many climate change problems, and the need to integrate a range of knowledge bases, we must often think beyond interdisciplinarity to even more meaningful integration of individuals from different backgrounds and experiences. Convergence is a practice that is ideal for describing this process. Convergence means a "*broad rethinking of how scientific research can be conducted*" (Sharp et al. 2011), from the motivation of the research itself to the approaches or methods to the application and implementation. Though convergence was introduced in science & engineering several decades ago, e.g., see (Roco 2002), convergence as a formalized practice for the research process itself is still nascent. Several different definitions of convergence exist and, here, we adopt one published recently by Sundstrom et al. (Sundstrom et al. 2023), which was itself inspired by the framing of convergence in a National Academies report (National Research Council 2014): "*Convergence research works across disciplinary boundaries to deeply integrate multiple perspectives, expertise, knowledge, methods, tools,* *and analytical approaches into synthetic, high-level frameworks in order to solve complex intellectual questions confronting humanity.*"

A key characteristic of convergence research is how humans are involved with the research—this includes the integration of diverse expertise as well as the engagement of stakeholders, the latter being described in detail in the subsequent section. Working on solutions to climate change is difficult for many reasons, not the least of which is the time and size scales associated with the problem and with realizing change. For this reason, key actors could make decisions that seem appropriate in the short term, i.e., an "easy fix," but miss the more important alternative due to imperfect information. Such moral hazards can be avoided or mitigated by engaging stakeholders in the research process from the outset.

Nanotechnology is a leading example of a powerful tool for convergence research, e.g., using scanning probes with nanoscale or better resolution to visualize relevant nanoscale features in a variety of applications. An early program funded in nanotechnology after the establishment of the NNI was the Center for Biological and Environmental Nanotechnology (CBEN) in 2001. This Center and others established around this timeframe evidenced the integration of traditional nanotechnology disciplines (e.g., physics, electrical engineering, materials science) with intellectually diverse contributors from fields such as environmental science, toxicology, business, and social science, spurring the formalization of convergence research.

In 2017, the NSF published Ten Big Ideas, one of which was Growing Convergence Research. The NSF suggests that convergence research is "*a means of solving vexing research problems, especially those focusing on societal needs*" (NSF 2024). We emphasize the word "solving" in this description, which implies scalability of solutions and adoption by users, which are essential considerations in convergence problems. NSF further defined two key characteristics that evidence convergence research. The first characteristic is that the problem being addressed must be specific and compelling, which can be motivated either by deep scientific questions or pressing societal needs. The second characteristic is that the problem requires deep integration across disciplines, which involves integration of intellectually diverse researchers as well as developing methods of communicating across disciplines.

In terms of being "specific and compelling," we emphasize here that the size or scope of specificity is important in developing nanotechnology research projects to address climate change. "Climate change" is insufficiently specific, i.e., too broad, as is "nanotechnology." In the earlier section on systems-level thinking, we discussed the Earth as one of the largest systems of relevance. While recognizing the Earth as a system is appropriate and useful, especially for prioritizing attention and effort, it is also not specific enough to define a convergence research project.

In the space of use-inspired basic research in nanotechnology to address climate change, several examples of reasonably scoped projects could be

- **Developing novel, completely recyclable and sustainable energy conversion and storage systems**, a topic that has economic, societal, and physical science components
- **Maximizing CO_2 capture in oceans**, a topic involving multiple disciplines in the physical and life sciences
- **Developing net-negative carbon emission infrastructure materials**, a topic founded in civil engineering and materials science with significant economic and societal impacts
- **Nanoengineered aerosols for geoengineering applications**, a topic needing convergence because of the complexity of governance, deep, and varied uncertainties on environmental impacts to altering the climate, engagement, and social acceptance
- **Rapid-response water treatment for dynamically changing water conditions through both detection and treatment**, a challenging topic because of the unique local stakeholders and conditions in different areas of the world

Once appropriately scoped, convergence research projects, such as the examples shown above, could be considered as part of the "focused phase" of the convergence process as described by Sundstrom et al. and reprinted as Fig. 3, which is part of a larger "convergence cycle" in which space for unfettered idea exploration is also encouraged. This "focused phase" of the convergence process is where the second characteristic of the NSF definition emerges, which involves the "deep integration across disciplines." One can think about nanotechnology and all of its various applications as a constant flow around the entirety of the convergence cycle. A key attribute of this convergence cycle is the iteration between a focused phase (with focus coming from an appropriately scope of convergence project) and transcendent phases (occurring from unpredicted new knowledge). This circular convergence process is reminiscent of the convergence-divergence cycle reported by Roco and Bainbridge (Roco and Bainbridge 2013), which was used to describe the developing field of nanotechnology between 2000 and 2020.

Now fully introduced, it can be recognized that undertaking convergence research is intellectually demanding, likely consuming more time than traditional basic research, and results in outcomes and products that are non-traditional, e.g., publications in highly interdisciplinary spaces, cultivated stakeholder networks, or even

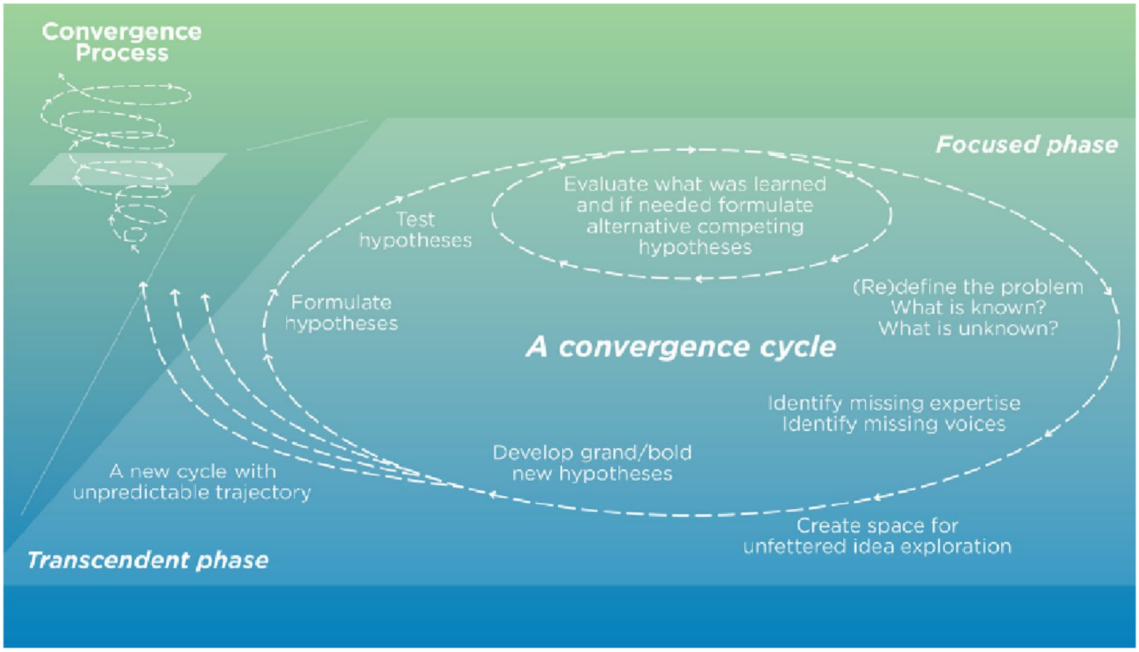

Fig. 3 Schematic representation of a convergence process, including both a focused phase in which specific use-inspired research can be pursued and a transcendent phase, which can allow for unpredicted trajectories, reprinted from Sundstrom et al. (2023), which was distributed under a Creative Commons Attribution Non-Commercial License 4.0 (CC BY-NC), https://creativecommons.org/licenses/by-nc/4.0/

policy documents. Non-traditional outcomes and products and longer timeframes can be exacerbated in the largest of research spaces like climate change. Non-traditional outcomes and products can also conflict with many traditional reward systems which often favor products that can be readily judged by single academic disciplines, e.g., during tenure and promotion of faculty or in the final exam of a doctoral dissertation, or weighed in a review by a funding agency, e.g., numbers of publications that cite the award. As we consider how to apply or realign nanotechnology to more use-inspired basic research opportunities that take a convergence research approach, we note that the reward systems will need to adapt. With agencies like the NSF recognizing and promoting convergence research, there is both a need and motivation to address both the evaluation activities and the reward systems. In fact, it is worthwhile to note that, while the NSF promoted convergence research as a Big Idea in 2017, the NSF has been involved with the development of these concepts from the beginning as described in the work of Donald Stokes in the late 1990's (Stokes 1997). On the other hand, academic organizations are often more decentralized and, while convergence research is recognized and rewarded in select units, centers, or organizations, more work is required to make convergence research widely recognized and accepted.

5 Stakeholder engagement

While certain types of research can be conducted without consideration of its use (e.g., the Bohr quadrant of the Stokes diagram, Fig. 2), research in climate change solutions is use-inspired (Pasteur's quadrant). Therefore, research in climate change solutions is strongly connected to specific individuals, communities, and groups, some of whom will define whether the final research results or innovations are adopted and, thus, will define the ultimate success of the research effort.

Stakeholders can be defined as individuals or groups who can affect, or are affected by, an event, activity, process, or decision (Colvin et al. 2016; Kliskey et al. 2021). Key stakeholders and community members can be identified through a number of approaches, such as mapping individuals/groups who are affecting or affected by a given decision or action, considering different geographical contexts, interests, knowledge and/or influence levels, and involved in networks or consortia (Reed et al. 2009; Colvin et al. 2016; Franklin 2020).

Stakeholder engagement in research is well developed in certain areas of study, e.g., agricultural extension and medicine. However, in many areas of science and engineering research (including many areas of nanotechnology), stakeholders have been less directly engaged in research activities (e.g., Grieger et al. 2012; Cummings et al. 2021; Stebbing 2009). As nanotechnology research and solutions to addressing climate change are further developed, it is imperative that stakeholders are brought into nanotechnology research and innovation processes because solutions offered by a given technology to resolve the problems brought on by other technologies can potentially introduce a strange set of concerns. For example, some stakeholders may feel that technology "fixes" add entirely new sets of risks in the climate change problem set, concerns that climate change is as much a behavioral problem as a technological one. In fact, technology may impede behavioral changes or new technologies developed in one part of the world may not help the global situation. Given the push and pull of these concerns and the sacrifices that will need to be made by publics of all sorts, engagement is critical. In fact, stakeholder engagement is emphasized in the ERVA report by acknowledging the power of engineering (and science) to "*create community awareness and enable convergent and inclusive solutions*" (ERVA 2022).

In order to realize these opportunities, robust and inclusive stakeholder and community engagement strategies are needed with iterative linkages between stakeholders and technologies, which is illustrated in Fig. 4. First, key stakeholders should be identified for relevant contexts in which nano-based innovations are considered. In general, stakeholders should include both "upstream" individuals or groups who may affect a given decision, activity, and/or outcome and who may often have decision-making power (e.g., industry, regulators), as well as "downstream" individuals or groups who may be affected by upstream decisions and may not have decision-making power (e.g., environmental advocacy groups, community members). The specific stakeholders to engage will depend heavily on the nanotechnology product or innovation being considered and the broader contexts, including socio-economic, cultural, and regulatory circumstances. Nonetheless, common stakeholder groups involved in engagement activities often include industry, scientists and researchers, government officials (local, regional, national levels), advocacy groups (e.g., environmental, consumer community), trade unions, non-governmental organizations, and Indigenous communities (Kliskey et al. 2021).

After stakeholders are identified, their needs and wants related to addressing climate change should be elicited. In some cases, stakeholders may need or want strategies for mitigation (e.g., reducing their GHG emissions through energy storage and transmission using nano-enabled materials), whereas in other cases stakeholders may need or want solutions for adaptation and resilience-building in communities (e.g., improving infrastructure resilience to withstand extreme weather or floods). To elicit and understand these needs and wants, a variety of methods may be used, such as surveys, focus groups, and interviews, depending on the context and time or resource constraints. In parallel, an evaluation of the potential benefits, risks, and uncertainties of various nanotechnology-based solutions and innovations to address climate change should be conducted, including those already developed and those

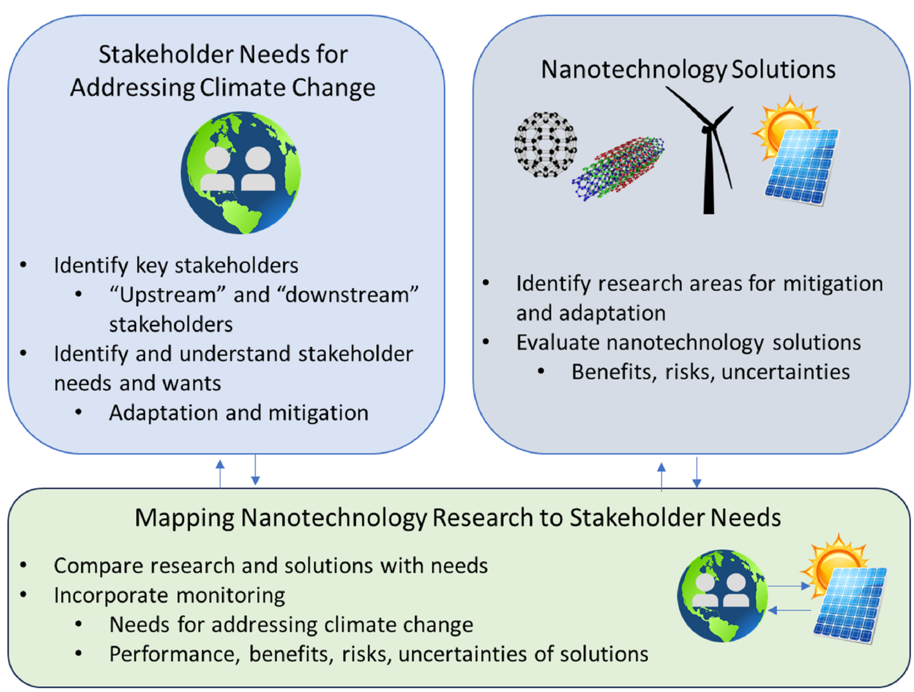

Fig. 4 Iterative engagement can help map nanotechnology research and solutions with stakeholder needs

still in R&D stages. This evaluation should be conducted for innovations and technologies focused on mitigation as well as adaptation, and can be conducted using, e.g., literature reviews, gap analyses, research studies (e.g., risk assessment, life cycle assessments, cost–benefit analysis), and expert elicitation processes (especially in cases of data gaps), e.g., see Mohammed 2020 and Horgan et al. 2023. In parallel, nanotechnology researchers and innovators may also benefit from incorporating practices of safe and sustainable by design within research and innovation stages to help minimize or avoid potential risks and improve sustainability of their nanotechnology-based products and innovations (Jiménez et al. 2022).

Next, a "mapping" of promising nanotechnology solutions or research opportunities (including those both at low and high TRLs) with stakeholder needs could be conducted to pair the climate change need with the best solution(s) or research area(s), considering known benefits, risks, and uncertainties. The goal of this process is to match the best use-inspired nanotechnology opportunities with specific stakeholder wants or needs to address climate change. It should be noted that there is often a trade-off in deciding when best to engage stakeholders and mapping new nanotechnology opportunities with their wants or needs. On one hand, innovations at higher TRLs typically have more information and knowledge about their performance as well as potential costs and impacts, which can be easier for stakeholders to understand and assess. On the other hand, it is important to engage stakeholders in early stages of research and innovation (including in early TRL stages) to align the proposed research with stakeholder needs and wants before there is 'technology set-in' and it becomes more difficult to change directions. At the same time, there is generally more uncertainty and less knowledge about innovations with lower TRLs and its potential impacts, and conversations about risks tend to be value-based rather than based on available data. Therefore, a balance is needed when considering when and how best to engage stakeholders and map their needs and wants to nanotechnology research and innovations, taking into account degrees of uncertainty, TRLs, and degree of technology set-in.

Throughout the aforementioned steps, continuous monitoring of both the nanotechnology solutions in terms of technological advancements, benefits, risks, uncertainties, as well as of stakeholders and their perspectives is needed for decision-making and oversight. Monitoring, which is considered to be essential for managing emerging risks and new or novel technologies (IRGC 2015; Grieger et al. 2019a), also allows for more information-gathering on how well nanotechnology-based solutions may (or may not) perform in a given location or context to help address climate change, both for mitigation and adaptation.

The nanotechnology research community has, in fact, already developed several effective models for engaging a range of stakeholders to understand key research needs in the field of nanotechnology safety. For example, the NNCO has hosted many in-person and online stakeholder meetings over the past 15 years to identify key research challenges, taking into account perspectives, mostly from experts in academia, industry, government, and other sectors. In addition, the NNCO also established international nano-safety Communities of Research (CORs) to identify key research needs and formulate collaborative strategies to address these needs based on partnerships in the U.S. and European Union (US-EU CORs 2023). While these efforts are commendable and have served as exemplary models for public dialogue regarding emerging technologies in society (e.g., Kuzma and Grieger 2020; Grieger and Kuzma 2023), such approaches could be expanded to include a wider range of stakeholders, including consumer and environmental groups and diverse members of the public.

6 Design and adaptation of nanotechnology infrastructure

As the field of nanotechnology is now matured to general-purpose and mass use, we can question how established nanofabrication and characterization user facilities such as those exemplified by NSRCs and NNCI Sites need to be designed or adapted to a different and evolving user base which is increasingly interdisciplinary and that works on increasingly complex systems. These nanotechnology facilities, built up and maintained through decades of investments, are a critical national resource with significant potential to continue advancing science and technology in areas of societal needs.

Reflecting over a longer history, in the years after World War II, the U.S. established the national laboratory system to leverage the nation's scientific capacity and talent to address emerging problems of societal relevance. These national laboratories still serve their missions today and support a broad range of interdisciplinary work in the physical, life, and social sciences. More recently, in the first two decades of the 21st Century, the NNI helped to establish NSRCs and grow NSF nanotechnology infrastructure programs (e.g., NNIN, NNCI) in a similar vein but with a different purpose. Having matured in a similar way to national laboratories, these facilities and past investments can be leveraged to continue to advance the original NNI mission, which is to understand and control matter at the nanoscale, but for specific areas of societal need, i.e., use-inspiration.

While NSRCs and NSF nanotechnology infrastructure programs are used in this Perspective as exemplary, as the applications for nanotechnology grow, we acknowledge a much broader set of related facilities beyond typical nanotechnology and microelectronics cleanrooms, materials synthesis laboratories, and materials characterization facilities, e.g., environmental engineering laboratories, field research test sites, greenhouses, pilot plants, and shared computational resources, among others. It is also important to recognize that infrastructure not only includes highly specialized equipment and facilities, but also the expert personnel needed to operate and maintain the capabilities and train the next generation of scientists and technologists.

An important observation from this project is that nanotechnology infrastructure facilities and programs may need to reconsider how the value proposition of existing nanotechnology infrastructure is framed to users and stakeholders from disciplines or sectors who do not traditionally use these facilities. For example, one cannot expect that highly application-oriented researchers working on, e.g., climate change, will be able to navigate and identify the right resources, opportunities, or technical expertise inside specialized nanotechnology facilities. To accelerate work in areas such as nanotechnology for addressing climate change, the experiences and needs of these non-traditional users must be considered to create a clear message of how these facilities and experts are useful and accessible to them and, furthermore, used to create entry pathways that cater to their perspectives. Thus, a shift may be needed from a paradigm of describing specific instruments and tools that cater to a broad variety of applications (e.g., a general scanning transmission electron microscope or atomic layer deposition tool) to tailoring information to those working in specific application spaces. Such a shift will increase the reach, awareness, inclusivity, and participation by individuals and enable growth in supporting use-inspired basic research. In areas of climate change, for example, prospective users or stakeholders may want to know which user facilities offer opportunities for studying, e.g., solid–gas interfaces or microbial systems. We note that a current Site in the NNCI adopted this model of specificity, even extending it into their name, NanoEarth (2024), which caters to earth and environmental nanotechnology scientists. Creating a value proposition specific to certain use cases does not necessarily need to occur through changes to facility missions or names, but could occur through application-specific promotional materials, websites, or workshops.

There may also be opportunities in evaluating and realigning the breadth of technical expertise throughout a nanotechnology user facility, e.g., in its technical staff and leadership. As convergence research brings a broader set of users and knowledge bases that present both more opportunities and demands, facilities can consider recruiting technical experts with expertise in specific application spaces, e.g., biological sciences or ecology, or individuals who have experience in conducting convergence research. In some cases, existing staff may desire new professional development opportunities that would be able to address some of this diversification.

When working with an increasingly diverse user base, there will be increasing requirements to pivot across diverse applications, which may require increased adaptability in available equipment or daily process flows, or even the complete redesign of spaces within infrastructure facilities. Here, we reemphasize the reward systems, and specifically for technical staff in nanotechnology facilities; these reward systems may need to be reevaluated such that staff are encouraged to assume and be rewarded for any additional burden or complexity associated with supporting convergence research.

Research centers that support highly interdisciplinary work can help to bridge these disciplinary divides. For example, the U.S. Department of Energy's Energy Frontier Research Center (EFRC) Program, which brings together multidisciplinary teams to tackle tough grand scientific challenges. And, while many interdisciplinary center-level programs could be named at the National Science Foundation, the NSF Science and Technology Centers are known for promoting complex and potentially transformative research through integrative partnerships and convergence research, in some cases leading to new areas of science.

Finally, a major challenge in advancing nanotechnology to address climate change is the need to scale technologies from the bench scale to the environmental scale, which is not only much larger in size scale, but often contains much more diversity in conditions. In fact, some see scaling as the primary challenge underpinning deployment of nanotechnology applications to address climate change. Current capabilities at nanotechnology user facilities typically support small-scale bench/prototyping research with predictable conditions, although deploying nanotechnology-based solutions in the environment will require both significant scale-up (e.g., prototype manufacturing) and testing and performance at scale (e.g., for validation). Recently, the Department of Defense created the Microelectronics (ME) Commons through the CHIPS and Science Act (Congress 2022), which consists of Hubs that provide access to U.S.-based semiconductor prototyping, an example of major investments in scaling infrastructure. In the ME Commons, many industrial partners are involved, which reinforces the need for academic-industrial partnerships in scaling technologies. Furthermore, in applications related to climate change, collaboration between nanotechnology user facilities and other facilities such as environmental engineering laboratories, field research test sites, greenhouses, and pilot plants may provide resources needed by nanotechnology researchers to overcome scaling challenges.

In summary, many aspects of nanotechnology user facilities and the associated infrastructure, e.g., equipment, personnel, and physical spaces, should be reconsidered in light of an evolving user base, which is increasingly interdisciplinary and is composed of researchers working on increasingly complex systems, especially those in areas related to addressing climate change.

The Law of the Instrument, attributed to Maslow and Kaplan, states that, "*If the only tool you have is a hammer, it is tempting to treat everything as if it were a nail.*" It is important to emphasize that, because nanotechnology is now fit for general-purpose and mass use, it is positioned to address a variety of challenges facing society, including but not limited to climate change. The many different types of "nails" should be appropriately scoped, use-inspired problems, and then the "hammer" can be optimized to help address it. Moreover, we may need to develop new tools that the hammer is not able to address.

7 Conclusions and outlook

As society faces significant and growing challenges due to climate change, it must leverage the full force of its knowledge base, science, technology, and innovation and its associated past investments to advance research and solutions. Over the past two decades, the U.S. has substantially increased its capacity to pursue nanotechnology research and development through, e.g., both advancing the fundamental understanding of nanoscale phenomena and increasing the capacity of the U.S. infrastructure through creating large-scale facilities that are widely available to the research community. Similar research investments have been made in other countries and international contexts. These resources and knowledge are now ideally situated to contribute to advancing societal challenges such as climate change, at both national and international levels.

This Perspective presents five characteristics to most effectively and efficiently advance research toward solutions at the intersection of nanotechnology and climate change. Our aim in distilling these characteristics is to build consensus around this compelling and complex research topic and direct, inform, and accelerate actions in the research community to advance solutions. The first characteristic is that research needs to be use-inspired, meaning it seeks a fundamental understanding while also being guided by specific applications (i.e., Pasteur's quadrant), distinguishing it from pure basic research that only seeks fundamental understanding. Second, the challenges associated with climate change are so complex and interrelated that systems-level thinking is essential to structuring the research questions, goals, and approaches so that, ultimately, effective solutions can be accepted by and adopted within broad socio-economic, cultural, and political contexts while also considering potential impacts to the environment, health, and society. Systems-level thinking is also needed to advance nanotechnology research and innovation toward commercialization and adoption, taking into account broader international contexts in which cooperation and collaboration will be key. A third characteristic of the research, associated with the research process itself, involves the practice of convergence research. Convergence research is a way of integrating diverse intellectual contributions and perspectives toward addressing a specific, compelling, and appropriately scoped problem associated with climate change. Convergence also supports the engagement of stakeholders, the fourth characteristic, who are necessary for prioritizing research effort and assisting in the design of research projects such that solutions can ultimately be adopted. Finally, the fifth characteristic addresses research infrastructure, e.g., equipment, personnel, and facilities, much of which has been built up over a period of years or decades and may need to be redesigned or adapted to an evolving user base that is working on increasingly complex systems.

While nanotechnology and climate change are two topics that are both timely and critical, the characteristics described in this Perspective are not unique to these two topics and can be generalized to other areas of past investment and current societal grand challenges. As one example, past investments and infrastructure for AI/ML could be applied to develop Sustainable Cities and Communities, a United Nations Sustainable Development Goal (United Nations 2015), and all five research characteristics presented in this Perspective can apply. A more recent example introduced earlier and enabled by the CHIPS and Science Act (Congress 2022) involves the creation of the Department of Defense ME Commons, which is a network of Hubs that provide access to U.S.-based semiconductor prototyping. Although microelectronics is a general-purpose technology, the Hubs and the projects undertaken within must all fall within specific application areas (i.e., use-inspiration) of 5G/6G Technology, Artificial Intelligence/Hardware, Commercial Leap-Ahead Technologies, Electromagnetic Warfare, Secure, Edge/IoT Computing, and Quantum Technology. The Hubs also represent strong collaboration between researchers and the Department of Defense, which is the key stakeholder in the program.

Finally, while developing research strategies, it may be worthwhile to reflect on a range of lessons learned from developing other technologies to solve societal challenges. Such previous experiences include, e.g., first generation biotechnologies and more recently artificial intelligence (AI), which have been subject to extensive debates and backlash in some cases (e.g., Kuzma and Grieger 2020; Maynard and Dudley 2023). Drawing on these previous lessons and others, developing new climate change solutions using nanotechnology may also benefit from developing transparent data-sharing between stakeholders while protecting privacy and confidentiality, and developing monitoring and controlling of new nanotechnology-based solutions implemented at field scale.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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