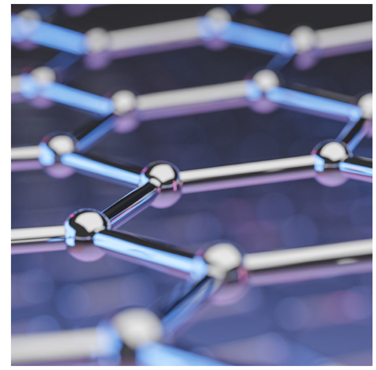
RICE UNIVERSITY'S BAKER INSTITUTE FOR PUBLIC POLICY

REPORT 02.01.21

# Recommendations for Realizing the Full Potential of Nanotechnology and Carbon Nanotubes in the Energy Transition



**Rachel A. Meidl, LP.D., CHMM**, Fellow in Energy and Environment, Center for Energy Studies

Nanotechnology is an emerging, rapidly growing, and promising field with advanced applications in industrial, commercial, and medical sectors. It has the ability to deliver solutions to help the world meet global climate targets and sustainability goals. Carbon nanotubes (CNTs), a family of carbon-based hollow cylindrical structures, have distinctive electrical, thermal, and mechanical properties that hold promise in advancing American leadership in innovative materials, energy, and environment. By creating a domestic source for materials production through methane pyrolysis, CNTs and other nanomaterials can reduce dependencies on foreign markets for critical materials; replace energy-intensive materials that are hard to decarbonize such as cement, steel, and aluminum; and minimize the impact on vulnerable communities where these minerals are currently sourced and processed. Thus, CNTs are critical components for future decarbonization strategies. There are a number of U.S. leadership opportunities that CNT advancements present in global economic, energy, environment, and geopolitical arenas and in building a stronger, more resilient nation.

As society progresses toward a clean energy revolution to meet global climate targets and sustainability goals, it will be imperative that the field of CNTs and other advanced nanomaterials have a clear and consistent path to commercialization that is shepherded by industry best practices; guided by informed policies that take into account the connectivity between society, the environment, and the economy; and underpinned by a comprehensive, interdisciplinary research strategy. To progress CNT development, more research is essential to address an unmet need to standardize, define, and communicate information to drive policies on their safe manufacturing, handling, use, transportation, and disposal. This would advance a world-class research portfolio, expedite commercialization of nanotechnology-enabled applications, support a dynamic and skilled workforce, and ensure responsible development from lab to market.

**There is a critical need to clarify, harmonize, and disseminate knowledge regarding CNTs with respect to chemical identity, toxicity, and environmental and human health impacts to enable informed regulatory decisions and to transfer the technology from lab to marketplace.**

## CNTs, KNOWLEDGE GAPS, AND SUSTAINABILITY

Nanotechnology is an emerging, cross-disciplinary science platform designed to create and synthesize new materials at the nanoscale to generate innovative or altered material properties. The introduction of all new products and technologies will have risks and unexpected consequences, both beneficial and harmful. Despite tremendous advancements in the field of nanotechnology and progress made in developing and

**Developing ways of capturing the carbon emissions from fossil fuels and upgrading them to higher-value CNT materials may be the most straightforward path toward reducing emission sources and meeting rising energy demand without completely overhauling these sectors.**

implementing research-based environmental, health, and safety (EHS) protocols for addressing nano-safety issues, challenges remain in risk assessments and adequately investigating health and toxicity effects given: 1) the many different nanomaterial types, 2) the various potential routes of exposure, 3) nanomaterial characterization issues, 4) limitations in research methodologies, such as time-course and dose-response issues, and 5) inadequate in vitro methodologies that can be validated for representing in vivo effects in standardized guideline toxicity testing.[1] Although nanotoxicity has been researched for many years, and the United States is internationally recognized for its leadership in responsible nanotechnology development, risk assessments have primarily centered on the occupational health and safety of workers manufacturing and handling the materials. As more applications of nanotechnology are realized, the entire life cycle of such products should be assessed for safety issues or other potential impacts, including during production, manufacturing, shipping, use, and end-of-life. Life cycle assessments (LCAs) will play a significant role in ensuring the sustainability and safety of the products for researchers, manufacturers, consumers, and the environment and in helping the United States remain innovative, competitive, and cognizant of threats to economic prosperity and security.

Globally there is a growing recognition and commitment within industry, through corporate social responsibility (CSR) and environmental, social, and governance (ESG) reporting, and the economy at large, via the United Nations Sustainable Development Goals (UN SDGs), to address responsible consumption and production; affordable and clean energy; sustainable and resilient infrastructure and industrialization; climate action; and waste in the ecosystem. Addressing these issues will require embracing a transparent, systems-level approach to social, environmental, and economic factors throughout a nanomaterial's life cycle and being responsible stewards of valuable resources.

CNTs comprise a diverse class of materials with many different sizes, shapes, chemical groups, and resulting physicochemical properties and biological and environmental effects. The lack of standardized nomenclature, experimental procedures, analytical methods, reporting and handling protocols, material standards, etc. has resulted in a large body of inconsistent, unreliable research and an inability to reproduce, compare, or build upon pre-existing work to understand life-cycle impacts. There is a critical need to clarify, harmonize, and disseminate knowledge regarding CNTs with respect to chemical identity, toxicity, and environmental and human health impacts to enable informed regulatory decisions and to transfer the technology from lab to marketplace. Unless there is standardization in metrology, taxonomy, testing, risk assessment, reporting, and communication across the CNT sphere, it will be difficult to even measure or report on sustainability in a meaningful way. Further, without a system for classifying and testing nanomaterials against a set of globally harmonized standards, commercial CNTs on the market and entering commerce can be misidentified or misrepresented. The construction of a comprehensive, novel framework that is specific to CNTs and other advanced nanomaterials and enables informed regulation will have a significant positive impact on research and industry by creating a uniform playbook to establish a baseline for the nanocommunity. A clear set of guidelines, best practices, and standard operating procedures, formulated with input from academia, industry, and regulatory bodies, will greatly improve the public understanding and acceptance of CNTs. This will increase their commercial viability and sustainability by helping define a unified framework under which the field will operate.

## NANOTECHNOLOGY: PRIORITIZE ENERGY AND ENVIRONMENT

Global energy and environmental challenges have spurred increased focus on regenerative and sustainable sources of energy. The transition to low-$CO_2$ or zero-$CO_2$ energy technologies is hampered by the fact that there are few suitable alternatives at scale for fossil fuels in the industrial sector, which in 2019 accounted for 35% of total U.S. end-use energy consumption and 32% of total U.S. energy consumption[2] (representing 22% of global $CO_2$ emissions).[3]

Developing ways of capturing the carbon emissions from fossil fuels and upgrading them to higher-value CNT materials, thus reducing the need for industries that combust hydrocarbons and release $CO_2$ to lower their emissions, may be the most straightforward path toward meeting rising energy demand without completely overhauling these sectors.[4] For example, unconventional processes that entirely eliminate the production of $CO_2$, such as the direct conversion of methane in natural gas to hydrogen and value-added carbon materials such as CNTs (otherwise known as methane pyrolysis), have gained traction among research communities and some of the major oil and gas companies.[5] There are other numerous opportunities where nanomaterials or nanotechnology could enhance current or future innovations, such as soil amendments to withdraw $CO_2$ from the atmosphere or protecting and restoring marine ecosystems as carbon sinks. These strategies use multidisciplinary approaches like bioeconomics, which integrates biology and economics to create a green and sustainable economy while minimizing the effects of climate change, providing greater flood protection, and improving water quality. The innovations and scientific advancements required to facilitate the transition (many of which can and do leverage nanomaterials and nanotechnology), including lithium-ion batteries in electric vehicles and energy storage systems, wind turbines, and solar panels, all come with social, economic, and environmental impacts that arise throughout their life cycles, oftentimes in emerging market supply chains. Most of these impacts are unquantified, including illegal waste disposal and underdeveloped waste management technologies; import-reliant minerals that are mined, processed, smelted, traded, and transported; social imbalances due to weak or absent EHS and labor laws; and the effect of operating in opaque and corrupt regimes. While CNTs ostensibly offer a host of benefits, these technologies may present their own complex ESG life-cycle issues. Therefore, life-cycle issues for nanomaterials also need to be addressed to ensure sustainability. Current net-zero strategies do not account for sustainability outside of U.S. borders—they simply shift the risk to another part of the value chain, leaving those impacts unrealized. The United States should build policies that capture and quantify these impacts to understand the trade-offs and how a technology that is being sold as a solution behaves throughout its life so that our actions do not reinforce weak governance and exacerbate local tensions and grievances beyond U.S. borders.

## RESPONSIBLE DEVELOPMENT OF NANOTECHNOLOGY—AN EHS PERSPECTIVE IS FOUNDATIONAL

The National Nanotechnology Initiative (NNI) is a U.S. federal government program that serves as the central point of communication, cooperation, and collaboration for all federal agencies engaged in the science, engineering, and technology of nanoscale research and development.[6] The NNI is overseen by the White House Office of Science and Technology Policy (OSTP) via the cabinet-level National Science and Technology Council (NSTC) and the Nanoscale Science, Engineering, and Technology (NSET) subcommittee. The NNI informs and influences the federal budget and planning processes through its member agencies and via the NSTC.

One of the main pillars of the NNI strategic plan is "to support the responsible development of nanotechnology."[7] However, in order to achieve responsible development, an understanding of the behavior of nanomaterials with respect to EHS considerations, along with the potential ethical, legal, economic, and societal implications across the life cycle, is needed. This information is critically important for establishing regulatory certainty and public trust and confidence in nanotechnology safety so that companies can successfully bring products to market. The reality is that EHS nanotechnology research and policies are not keeping pace with technology and product development, which encumbers public acceptance, delays commercial uptake, and ultimately prevents innovations from advancing U.S. leadership in science and technology. Considering the relevance of nanotechnology to a wide variety of market segments (health care, military, wastewater, energy, etc.), well-coordinated, transparent, and consistent EHS research is vital to American innovation and economic competitiveness.

Despite the criticality of EHS information, only a fraction of the NNI budget is dedicated to this category. In 2016, 7% of NNI agency funding was devoted to the EHS of nanomaterials and devices, while in 2021, the estimate is 3%, or $80 million of the requested $1.7 billion, according to the NNI Supplement to the President's 2021 Budget.[8] Accounting for the 2021 request, the cumulative NNI investment has reached over $31 billion since the inception of the NNI. The NNI currently operates under the 2016 Strategic Plan with Program Component Areas (PCAs), which provides an organizational framework for categorizing the major NNI activities and measures advancement toward the NNI's vision and goals. The NNI's fourth top-level strategic goal is, "to support responsible development of nanotechnology" by understanding potential EHS implications. This goal is guided and implemented via the fifth PCA: environmental health and safety. Although challenges in scale-up, market pull, and the complexity of new technology innovation are all factors to protracted commercialization, the lack of a bona fide health and safety demonstration jeopardizes public confidence and decelerates market uptake.

On November 14, 2019, the International Chemical Secretariat (ChemSec), an independent non-profit organization that advocates in favor of stricter regulatory controls on potentially hazardous chemicals, announced the addition of all CNTs to the 'Substitute It Now' (SIN) list due to their presumed carcinogenic properties.[9] The addition of all forms and classes of CNTs to the list has been challenged by many scientists due to the virtually infinite possible material variants and modifications that elicit a variety of diverse physical, chemical, mechanical, and biological properties,[10] each with very distinct biological outcomes in vitro and in vivo,[11] various routes of exposure, and limitations and inconsistencies in research methodologies. The SIN list is a globally utilized and referenced database of chemicals that ChemSec believes should be banned or restricted due to their purported alignment with the European Union's (EU) Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulations for "substances of very high concern (SVHC)."[12] Once a chemical is identified as an SVHC by REACH, it is added to EU's candidate list for subsequent inclusion in the authorization list for eventual phaseout. The SVHC classification and placement on the EU's candidate list triggers legal obligations for the importers, manufacturers, producers, and suppliers of an article that contains such a substance. However, chemicals on ChemSec's SIN list have not undergone an objective evaluation by the EU and are thus not yet deemed a SVHC nor regulated under the REACH purview.

The mere placement on the list carries such reputational risk and consequences that it has the effect of a ban. A chemical incorporated into the SIN list affects a company's Dow Jones Sustainability Index, discourages research and development (R&D) and investment, impacts trade, causes market deselection, and diminishes the potential value of CNTs. The ChemSec SIN list is used by companies and governments around the world, investors and financial analysts, environmental organizations, and many other national and international institutions and research centers as a part of their chemical management strategies to incorporate sustainable, non-toxic chemicals into their products, practices, processes, and supply chains. Those entities referring to this list may avoid investing in or using any variety of CNTs due to their purported toxic classification and the stigma this listing conveys, which significantly inhibits the opportunity to fully commercialize CNTs on a global scale and to realize the great potential they can play in the clean energy revolution.

This emphasizes a need to promote international connectivity and for the United States to reengage on the global stage, with the EU in particular, to help in standardization and harmonization of transparent classification and research methodologies. This will guide safe and informed commercial developments of manufactured nanomaterials and benefit consumers and the U.S. industry. An understanding of the behavior and EHS considerations of CNTs will establish public confidence and afford regulatory certainty so companies can readily bring transformative nanotechnology products to market. An internationally coordinated, standardized, science-based approach for nanomaterial methodologies, coupled with policies that guide technology transfer, are essential for U.S. economic competitiveness and innovation and the successful commercialization of nanotechnology-enabled products that will play an important role in advancing climate and sustainability policies.

## U.S. INNOVATION AND COMPETIVENESS

U.S. research on the effects of exposure to nanomaterials in the workplace, in products, and on the environment is unparalleled, achieved through extensive interagency collaborations that have both advanced knowledge and improved methods and practices in occupational safety.[13] However, when assessing metrics such as annual numbers of patents related to nanotechnology, investments in R&D dedicated to nanotechnology, and the number of publications in nanotechnology, the gap between the top competitors has been surpassed where the U.S. is now lagging behind several other nations and regions.[14] Between 1997 and 2016, China claimed 45% of patent applications globally in areas related to nanoscience and technology[15] and outperformed the U.S. in the total number of nanotechnology patents sometime between 2009 and 2011.[16] Additionally, their nanotechnology investments have resulted in an extraordinary growth in annual publications from about 3,000 in 2000 to around 70,000 in 2017.[17] China not only dominates in the number of publications during the last decade, a common measure of research productivity, but as of 2017, has published almost twice as many scientific papers per year as the United States.[18] China is now the largest contributor to the top 1% of most-cited papers related to nanoscience and nanotechnology,[19] significantly outperforming the United States.

The National Academies of Sciences, Engineering, and Medicine (NASEM) have reported that basic nanoscience advances occurring in the United States are being translated into societal and economic benefits outside the nation, detracting from U.S. competitiveness and placing U.S. economic prosperity and national security at risk. As an example, the manufacturing of solar nanomaterials has almost entirely shifted abroad.[20] Additionally, China dominates 80% of the refining and processing of the world's battery materials, 77% of the world's cell capacity, and 60% of the world's component manufacturing,[21] competencies that are critical to renewable and low-carbon technologies that will purportedly bring us closer to sustainability and climate stability. China's nanoscience research (and the research of other nations leading in the nanotechnology front) is strategically focused on a few select issue areas, giving them a transformative, global competitive advantage. One of the four priority areas is energy and environment with a focus on renewable energy and energy efficiency, particularly catalysis, photovoltaics, and rechargeable batteries. Having the long-term vision, strategy,

**Basic nanoscience advances occurring in the United States are being translated into societal and economic benefits outside the nation, detracting from U.S. competitiveness and placing U.S. economic prosperity and national security at risk.**

and foresight to proficiently identify and converge resources on specific, future-focused areas that can be leveraged globally are defining characteristics of the Chinese nanotechnology coordination effort. The United States could benefit from improved strategic focus and sustained nanotechnology investments toward accelerating market adoption, predominantly in the domains of current national R&D priorities—this is essential for reestablishing scientific global leadership.

## REVISED AGENDA, REFOCUSED STRATEGY: CONNECTING FEDERAL PRIORITIES WITH EHS NANOTECHNOLOGY NEEDS

The United States should determine flagship themes—the most critical, innovative research areas where the country can lead the world—and provide focused support and prolonged stable funding of basic science research and technology development around those themes.

The United States is recognized internationally for its leadership around responsible nanotechnology development in EHS matters. Thus, nano-related EHS programs and initiatives are a logical and focused competency the United States could identify as a critical research area, where there is a clear global need and where dedicated, sustained resources and funding are warranted. This multidisciplinary arrangement would also require investment in competencies to address other essential areas, like the need for understanding the social, economic, and environmental impacts across the life cycle of a product or technology. This strategy will allow national capacity-building training and education to form a diverse, new generation of scientists and engineers who are cognitively adaptable in interdisciplinary fields and who understand the importance and connectivity of the social, behavioral, environmental, and economic sciences as being a critical part of sustainability.

Federal investments enable future discoveries that build upon and expand the existing body of knowledge and ensure that the U.S. remains at the forefront of nanotechnology. The NNI should review the OSTP's strategic goals and objectives along with the Biden administration's R&D budget priorities and align their research agenda with such priorities. Even if the NNI takes the steps to align their mission and goals with current and future federal R&D priorities, as NASEM recommends, there remains a fundamental and unmet need to appropriately characterize CNTs and to harmonize and clarify research methodologies to understand the life-cycle EHS implications. This would allow the United States to accelerate the transition of nanotechnology discoveries to higher technology readiness levels and deliver societal and ecosystem benefits.

The NSET subcommittee and the Nanotechnology Environmental and Health Implications (NEHI) working group should expand their mission to include sustainability goals and LCAs. Additionally, the 2011 NNI EHS research strategy should be adapted to address evolving research needs that assess and manage potential risks of current and anticipated CNTs and other nanomaterials throughout their life cycles and should thus collaborate internationally to improve and standardize LCAs. Funding for EHS-related research in the NNI budget has steadily decreased every year from 7% of the total budget in 2016 to 3% of the 2021 budget request.[22] Increased and sustained funding for EHS-related research as well as a budget dedicated toward the social and ethical implications of nanotechnology, including full life-cycle impacts, are necessary for American energy and environmental leadership and sustainability on a global scale.

**Increased and sustained funding for EHS-related research as well as a budget dedicated toward the social and ethical implications of nanotechnology, including full life cycle impacts, are necessary for American energy and environmental leadership and sustainability on a global scale.**

## POLICY LAB, POLICY ROADMAP, AND COMMUNICATION AS A PRIORITY NEED

As emerging technologies chart new opportunities and businesses attempt to navigate the regulatory abyss, governments, with the rapid rate of innovation, struggle to keep pace in developing policy pathways. The preeminent issue is how to protect society and ensure fair markets while addressing the potential unintended consequences of disruption and still allowing innovation and businesses to prosper.

### Policy Roadmap and Accelerating Lab-to-Market Innovations

Public concerns have been mounting over the safety of CNTs and other nanomaterials, and even if such products are fully compliant with the Toxic Substance Control Act in the United States and the EU's REACH, successfully bringing those materials to market will be an extensive uphill battle in changing the public's perception.[23] Continued uncertainty and limitations around EHS and LCA impacts for nanomaterials will only prolong and complicate the lab-to-market process and deprive society of the benefits sustainable innovations can offer in helping us confront the most globally complex issues. Efforts toward a coordinated system for classifying and testing CNTs against a set of globally harmonized standards and EHS research, coupled with insights into LCA impacts across the entire value chain to objectively inform regulatory decision-making and risk management, can foster the transfer of new CNT technologies into products for commercial and public benefit, consistent with the NNI's strategic plan. The Biden administration should issue a memorandum to federal agencies prioritizing the acceleration of the safe and informed commercialization of federal research and make these lab-to-market efforts a core part of the management agenda. Drawing on the foundations established by NNI agencies, the new administration can provide a roadmap to assist the nanotechnology-based business community in understanding the government's regulatory and policy environment, as the nanotechnology landscape is a rich and deeply complex sequence of scientific and technical contexts embedded within multifaceted, ambiguous jurisdictional and market layers. The U.S. federal government, via the NNI, can serve as a clearinghouse and central repository of open-source scientific information, risks, benefits, and uncertainties related to nanotechnology. The government can also devise new strategies for coordinating and communicating the tools, data, and information that will help shepherd the scientific community through expedient technology transfer and alleviate regulatory barriers to international trade and commerce.

### Communication

Public perception and public opinion are powerful and can be enough to destabilize an entire product, technology, or industry. Although the interdisciplinary field of nanotechnology commenced over 25 years ago, it is still very much considered an "emerging technology," characterized by public misunderstanding, unrealized transformational potential, vastly growing innovation in all sectors, unquantified risks that are not yet fully appreciated, and regulatory and scientific uncertainty. The more data and transparency there are around sustainability factors, the more likely the uptake will be in the public and political arenas, and the more likely CNTs will gain traction in regulatory systems. The lack of common terminology can lead to erroneous conclusions about the source of potential EHS impacts, as well as misinformation about how to perform appropriate surveillance and exposure monitoring, as is currently playing out in the global CNT community. A lack of common terminology can also undermine risk communication. As EHS research increases for CNTs and other nanomaterials, the question of how to interpret the results in terms of potential health or environmental risks must be communicated effectively. In sensitive domains such as human health and the environment, transparent communication about the uncertainties in the scientific evidence is a safer approach than assuming and communicating a lack of risk.

**Investments in policy, safety, and standards that support nanotechnology EHS research and the transition to a lower-emissions future while meeting growing energy needs is vital to reestablishing climate leadership, attaining the global targets of the UN SDGs, and contributing to U.S. national security interests.**

### Establishment of NNI Center of Excellence 'Policy Lab'

Science is one of many sources of knowledge that informs policy, and sustainability challenges will require the best available science. In the current political climate, policymakers, now more than ever, require access to high quality, objective science to inform their policies and key decisions, and the very policy issues for which scientific involvement is most needed are matters that are scientifically complex, uncertain, and contested.

As the NNI takes the necessary steps to restructure, refocus, and realign its vision, mission, and goals (as recommended by NASEM's quadrennial review of the NNI), the Biden administration should consider establishing a dedicated "policy lab" within the NNI that unites multidisciplinary experts from the social, political, and natural sciences with policymakers, public policy scholars, economists, business leaders, and other stakeholders to ground actions and policies in the best available science. The policy lab would increase access to the best science by partnering internationally with bodies such as the UN, the European Commission, the Organisation for Economic Co-operation and Development, the World Bank, and other global entities. These collaborations would allow the lab to shape policymaking with science, leverage investments and infrastructure, and ultimately support the sharing and expansion of knowledge in EHS-related nanomaterials to advance a world-class nanotechnology R&D program. By design, the policy lab would ensure alignment between the NNI and national R&D strategies and incorporate policy in both research and practice. It would bridge the gap between the realm of nanomaterial science, technology, and theory and the world of action through policy and economics. This proposed configuration will tangibly connect the NNI R&D strategy to a policy framework and an integrated roadmap for which nano-innovations can be brought to market. In order for CNTs to be truly sustainable, socially accepted, and politically palatable, a baseline understanding of policies and standards across the global value chain is needed to shepherd consistent and practical policy solutions for full integration into global networks. Recent decisions in the EU to place CNTs on a proposed list for consideration of banning can have enormous global implications for the entire advanced carbon industry, ultimately hindering R&D, federal funding, and commercialization. This makes strategizing short- and long-term policy interventions and understanding the gaps and disparities even more time-sensitive, and the foundation of the policy lab all the more important.

The policy lab ecosystem would promote consistency of policies and practices across diverse sectors, applications, and jurisdictions; reflect a proficient science and innovation policy community; and function as an inclusive hub for nanotechnology connectivity, convening, capacity building, and catalyzing of research in support of an effective and integrated science policy community. This vision can only be attained through national R&D priorities set by the new Biden administration and the OSTP; dedicated and sustained funding; enhanced interagency collaboration; strong international coordination of research activities and a consensus on standards efforts; and expanded partnerships with industry.

In redesigning the NNI with the recommendations put forth by NASEM, the suggestions herein further build upon and enhance the NASEM advice and provide a clear pathway for the Biden administration to begin establishing and executing its priorities on climate, sustainability, and environmental justice. Consistent with the NASEM recommendation for the NNI to "improve its alignment with the stated national priorities for R&D,"[24] and with the presumed national priorities of a establishing a clean energy revolution, a climate plan, and a path forward for environmental justice and sustainability, a refined NNI focus on energy and the environment is a logical foundation. The NASEM recommendation to "broaden its work to accelerate technology transfer to relevant markets,"[25] can only be truly undertaken by refocusing NNI priorities, placing greater emphasis on intellectual resources, and ensuring increased, dedicated funding for nano-related EHS research initiatives that begin closing the existing knowledge and data gaps. This critical data and the standardization of classification and research methodologies can then be leveraged to create data-driven policies that are informed through LCA requirements to ensure that vulnerable communities and ecosystems in the United States and abroad are not disproportionately impacted by climate technologies and solutions. NASEM additionally advises the NNI to "strengthen state-of-the-art enabling R&D infrastructure,"[26] which can be partially attained through its collaborations and partnering agencies. Many countries modeled their nanotechnology infrastructure after the United States, as it was considered the gold standard around the world. Lastly, NASEM recommends the NNI "expand domestic workforce education and training."[27] As previously noted, the United States is well respected for its responsible nanotechnology development in EHS matters. However, due to the extensive EHS knowledge and data deficiencies and challenges in CNT and nanomaterials classification and analysis, only a partial picture of the impacts across the life cycle exist, with limited to almost no insights into the environmental and social risks across the value chain. Including a life-cycle dimension to business outlooks and future policies will promote technologies and processes that result in more sustainable solutions rather than unintended consequences. If the Biden administration prioritizes clean energy, climate innovation, and environmental and social justice, a diversified and trained workforce that understands life-cycle thinking and is fluent in multiple disciplines will be imperative to attaining systems-level sustainability.

The NNI policy lab concept would be a historic commitment and investment in clean energy and climate research and innovation, synchronized with the national R&D priorities of the incoming administration. The policy lab would allow the new administration to boldly chart a sustainable course for the most pioneering nanotechnologies, paving the way to alignment with the UN SDGs and global climate targets. The policy lab could play a prominent role in level-setting, harmonizing, and elevating the disparate knowledge and information around CNTs and nanomaterials by using a multidisciplinary R&D platform that anticipates, measures, and predicts social, economic, and environmental life-cycle impacts along the global supply chain; identifies practical solutions; and evaluates options and policy pathways for adaptation and accelerated technology transfer.

## CONCLUSION

The development of advanced CNT solutions and their resultant EHS and sustainability profiles must be a national and global priority in order to stimulate and support research and growth and for the United States to regain nanotechnology leadership. CNTs are disruptive, critical components to future decarbonization strategies and can drive U.S. leadership in the clean energy revolution by reducing dependencies on foreign markets with solutions that strengthen and safeguard U.S. health, yield economic and national security advantages, and enhance environmental justice, quality, and energy independence. Appropriate investments in policy, safety, and standards that support nanotechnology EHS research and the transition to a lower-emissions future while meeting growing energy needs is vital to reestablishing climate leadership, attaining the global targets of the UN SDGs, and contributing to U.S. national security interests. There is a clear, unmet need for sound and consistent CNT policy. It is important to bring together actors across the value chain and as a vehicle for communicating objective, data-driven science so that communities and ecosystems across the globe can safely benefit from transformative U.S. clean-energy innovations.

These recommendations will help restore the United States to the global forefront of nanotechnology-enabled advances in energy and environment through facilitated multisector partnerships, building interdisciplinary capacities for the CNT science and technology workforce, and accelerated technology transfer that has insights into life-cycle systems thinking. 'Building back better' in America requires access to domestic sources of clean, affordable, and reliable energy. Unleashing these abundant domestic energy resources will require investment in next-generation, nano-enabled energy technologies that will improve the resiliency and sustainability of the nation and fashion a future in which responsible development and deployment of nanotechnology provides maximum benefit to the environment and to human social and economic well-being.

## ENDNOTES

1. David B. Warheit, "Hazard and risk assessment strategies for nanoparticle exposures: How far have we come in the past 10 years?" *F1000Research 7*, no. 376 (2018) https://doi.org/10.12688/f1000research.12691.1.

2. U.S. EIA (Energy Information Administration), "Uses of Energy Explained," July 28, 2020, https://www.eia.gov/energyexplained/use-of-energy/industry.php. End-use energy consumption includes primary energy consumption by the sector and retail electricity sales to (or purchases by) the sector (see https://www.eia.gov/tools/glossary/index.php?id=Primary%20energy). Total energy consumption includes primary energy consumption, retail electricity sales/purchases, and electrical system energy losses associated with the retail electricity sales/purchases (see https://www.eia.gov/tools/glossary/index.php?id=Electrical%20system%20energy%20losses).

3. U.S. EPA (Environmental Protection Agency), "Sources of Greenhouse Gas Emissions," https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

4. Emily Yedinak and Rachel A. Meidl, *Measuring the True Cost of Sustainability: A Case Study in a Green Energy Approach*, Issue brief no. 04.28.20. Rice University's Baker Institute for Public Policy, Houston, Texas.

5. Ibid.

6. NNI (National Nanotech Initiative), "About the NNI," https://www.nano.gov/about-nni.

7. Lloyd J. Whitman et al., *National Nanotechnology Initiative Strategic Plan*, 2016, https://www.nano.gov/sites/default/files/2016_nni_strategic_plan_public_comment_draft.pdf.

8. See National Science and Technology Council, "The National Nanotechnology Initiative Supplement to the President's 2021 Budget," October 2020, https://www.nano.gov/sites/default/files/NNI-FY21-Budget-Supplement.pdf.

9. "Carbon Nanotubes," ChemSec SIN List, https://sinlist.chemsec.org/chemical-groups/carbon-nanotubes/.

10. Daniel A. Heller et al., "Banning carbon nanotubes would be scientifically unjustified and damaging to innovation," *Nature Nanotechnology* 15, no. 3 (March 1, 2020): 164-166.

11. Bengt Fadeel and Kostas Kostarelos, "Grouping all carbon nanotubes into a single substance category is scientifically unjustified," *Nature Nanotechnology* 15, no. 164 (March 2, 2020) https://doi.org/10.1038/s41565-020-0654-0.

12. "The SIN List is based on the EU REACH criteria," ChemSec SIN List, https://sinlist.chemsec.org/what-is-the-sin-list/the-sin-list-is-based-on-the-eu-reach-criteria/.

13. NASEM (National Academies of Sciences, Engineering, and Medicine), *A Quadrennial Review of the National Nanotechnology Initiative: Nanoscience, Applications, and Commercialization*, Consensus Study Report, National Academies Press, 2020, https://doi.org/10.17226/25729.

14. Task Force on American Innovation, *Second Place America? Increasing Challenges to U.S. Scientific Leadership*, May 2019, http://www.innovationtaskforce.org/wp-content/uploads/2019/05/Benchmarks-2019-SPA-Final4.pdf.

15. Ed Gerstner et al., "Small Science in Big China: An Overview of the State of Chinese Nanoscience and Technology," *Springer Nature*, accessed April 16, 2020, https://media.springernature.com/full/springer-cms/rest/v1/content/15302926/%20data/v3.

16. Hongyi Zhu et al., "International perspective on nanotechnology papers, patents, and NSF awards (2000–2016)," *Journal of Nanoparticle Research* 19, no. 370 (2017) https://doi.org/10.1007/s11051-017-4056-7.

17. NASEM, *A Quadrennial Review of the National Nanotechnology Initiative*, 2020.

18. Ibid.

19. "The power of the tiniest shoot," *Nature Nanotechnology* 12, no. 833 (2017) https://doi.org/10.1038/nnano.2017.197.

20. Jeffrey Ball et al., *The new solar system: China's evolving solar industry and its implications for competitive solar power in the United States and the world*, Stanford University, March 2017, https://law.stanford.edu/wp-content/uploads/2017/03/2017-03-20-Stanford-China-Report.pdf.

21. "China Dominates the Lithium-ion Battery Supply Chain, but Europe is on the Rise," *BloombergNEF*, September 16, 2020, https://about.bnef.com/blog/china-dominates-the-lithium-ion-battery-supply-chain-but-europe-is-on-the-rise/.

22. NNI, NNI Budget Supplements and Strategic Plans, https://www.nano.gov/NNIBudgetSupplementsandStrategicPlans

23. Steffen Foss Hansen and Anna Lennquist, "Carbon Nanotubes Added to the SIN List as a Nanomaterial of Very High Concern," *Nature Nanotechnology* 15, no. 1 (January 2020): 3–4, https://doi.org/10.1038/s41565-019-0613-9.

24. NASEM, *A Quadrennial Review of the National Nanotechnology Initiative*, 2020.

25. Ibid.

26. Ibid.

27. Ibid.

## AUTHOR

**Rachel A. Meidl, LP.D., CHMM**, is the fellow in energy and environment at the Baker Institute. She was previously appointed deputy associate administrator for the Pipeline and Hazardous Materials Safety Administration, an agency of the U.S. Department of Transportation. Her research focuses on the intersection between domestic and international policy and law as it relates to the transboundary movement of hazardous wastes; upstream and end-of-life management of byproducts and wastes; and alternative and renewable energy, among other issues.

center for ENERGY STUDIES
Rice University's Baker Institute for Public Policy

**This report is part of an abridged Baker Institute series titled "Realizing the Full Potential of Nanotechnology and Carbon Nanotubes in the Energy Transition."**

See more Baker Institute Reports at:
**www.bakerinstitute.org/baker-reports**



Cite as:
**Meidl, Rachel A. 2021.**
***Recommendations for Realizing the Full Potential of Nanotechnology and Carbon Nanotubes in the Energy Transition.***
**Baker Institute Report no. 02.01.21.**
**Rice University's Baker Institute for Public Policy, Houston, Texas.**

**https://doi.org/10.25613/H3KW-9525**