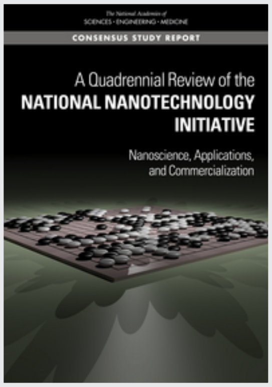

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A Quadrennial Review of the National Nanotechnology Initiative

Nanoscience, Applications, and Commercialization

Committee on National Nanotechnology Initiative: A Quadrennial Review

National Materials and Manufacturing Board

Division on Engineering and Physical Sciences

A Consensus Study Report of

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Cover: Strategies for developing timely and beneficial technologies using nanoscience to help society is as important as ever. This NNI review looks carefully at applications and commercialization of nanoscience and their strategies. In the game "Go," where the strategy one employs is critical, the number of ways that the game can play out is extremely large—some even claim it is larger than the number of atoms in the universe. The cover depicts the first game won by a computer program over a 9th dan−ranked human player. In the future, one can expect that an ever-increasing use of artificial intelligence will augment human efforts in moving all fields forward. *Artist:* Erik Svedberg.

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Preface

The National Nanotechnology Coordination Office (NNCO) asked the National Academies of Sciences, Engineering, and Medicine to form an ad hoc review committee to conduct a quadrennial review of the National Nanotechnology Initiative (NNI) pursuant to the 2003 21st Century Nanotechnology Research and Development Act, Section 5 of Public Law 108-153.1, which authorized the NNI to coordinate the nanotechnology-related research and development (R&D) of 26 federal agencies. The research coordinated by the NNI is highly interdisciplinary, is conducted in an increasingly competitive global arena, and is making transformative impacts in fields as diverse as microelectronics and medicine. The translation of past NNI coordinated work is now making significant contributions to the nation's high-technology economy, its security, and the health and prosperity of its citizens. The statement of task for the quadrennial review was to analyze the relative position of the U.S. nanotechnology program relative to the programs of other nations, determine whether NNI coordination should continue, and if it should, identify how to improve the NNI's R&D strategy and R&D portfolio to further enhance the economic prosperity and national security of the United States.

The report that follows shows that the United States maintains a strong nanoscience and technology R&D program. It argues that this program's coordination is becoming more critical in the current era of intensifying global competition from developed nations such as Japan and those within the European Union, and from developing nations such as India, but especially from China. In the latter case, researchers are witnessing aggressive, and in many cases effective, planning of a national R&D strategy that seeks to harvest the economic, medical, and national security benefits of nanotechnology as quickly as possible. This, combined with very large investments in state-of-the-art facilities and the allocation of substantial resources for the education/training and attraction of top research international talent, is clearly intended to result in Chinese leadership of this critically important area of technology. This report identifies changes to the NNI to promote a resurgence of the nation's nanotechnology program and enable it to respond to the dynamic changes of the new global research environment in which it functions.

The committee thanks the review committee members for dedicating their remarkable technical expertise and experience to the task that was assigned to them. In executing its charge, the committee met five times between March 14, 2019, and November 7, 2019. The committee is also grateful to the many people and organizations that have provided the information needed to compile this report. The committee heard from a broad spectrum of speakers from government, industry, consultant organizations, nonprofit trade organizations, and academia. In particular, the committee thanks the following for their contributions to this study and participation in the committee's meetings: Lisa Friedersdorf, NNCO; Lloyd Whitman, NIST; Mihail C. Roco, NSF; Stephanie Morris, NIH; Anil Patri, FDA; Michael A. Meador, NASA; Hongda Chen, USDA NIFA; Khershed Cooper, NSF; Paul Westerhoff, Arizona State University; Yan Borodovsky, retired; Hilary Godwin, University of Washington; Nathan S. Lewis, California Institute of Technology; Andre Nel, UCLA; Peter Dröll, Germany; Antti J. Makinen, CIV USN CNR; James Alexander Liddle, NIST; World Nieh, USDA; Alan Rudie, USDA; Samuel Brauer, Nanotech Plus, LLC; Celia Merzbacher, SRI; Treye A. Thomas, U.S. CPSC Office of Hazard Identification and Reduction; Peidong Yang, Berkeley; Matthew Hull, Virginia Tech; Chad Mirkin, Northwestern University; Matt Laudon, TechConnect; Orin Herskowitz, Columbia Technology Ventures; Waguih Ishak, Corning; and Emilie J. Siochi, NASA.

The committee also thanks the director of the National Materials and Manufacturing Board, James Lancaster, and the study director, Erik Svedberg, for their help and guidance in performing this quadrennial review. We also express special appreciation to staff members Joe Palmer, Amisha Jinandra, and Neeraj Gorkhaly for assistance with meeting arrangements and all the daily tasks.

Liesl Folks, *Chair*
Haydn Wadley, *Vice Chair*

Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

Muhammad Alam, Purdue University,
Jennifer Dionne, Stanford University,
Michael Ettenberg, NAE,[1] Dolce Technologies,
Michael Liehr, SUNY Polytechnic Institute,
Henke E. Riel, IBM Research, and
Matthew Tirrell, NAS[2]/NAE, University of Chicago.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Martin A. Philbert, NAM,[3] University of Michigan. He was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the National Academies.

Every member of the committee made heroic efforts to complete this task. Erik Svedberg provided guidance and management and we also appreciate such from Jim Lancaster.

[1] Member, National Academy of Engineering.
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Contents

Summary

Global advances in medicine, food, water, energy, microelectronics, communications, defense, and other important sectors of the economy are increasingly driven by discoveries in nanoscience and the development of nanotechnologies and justify a continued focus by the United States on, and investments in, these fields. To cite just one topical example, the recently launched National Quantum Initiative (NQI), which seeks to advance emerging quantum computing, quantum sensing, and quantum communication technologies with the potential to transform large sectors of the economy and national security, is a direct result of previous U.S. investments in nanoscience and nanotechnology, largely motivated by the research efforts of the National Nanotechnology Initiative (NNI). Other nations such as China, Japan, and Europe have also made large investments in nanoscience and nanotechnology, resulting in an accelerating pace of education and workforce training and translational research and development (R&D) efforts related to nanoscience and nanotechnology. In some cases, these are outpacing and outperforming U.S. federal government investments. The gap between the top competitors has been closing, per many metrics, such as annual numbers of publications and patents, investment in R&D, and number of scientists publishing in nanotechnology. It is troubling that, by almost all of these metrics, the United States is now trailing several other nations and regions.[1]

Given these concerns about national competitiveness, and with the priority placed on economic prosperity, the health of U.S. citizens, and national security in considering the future of the NNI, the committee recommendations arising from this quadrennial NNI review should provide a framework for an urgent redesign of the NNI and its coordination with the goal of achieving a U.S. resurgence in nanotechnology. Going forward, the NNI should be restructured to (1) improve its alignment with the stated national priorities for R&D, (2) broaden its work to accelerate technology transfer to relevant markets, (3) strengthen state-of-the-art enabling R&D infrastructure, and (4) expand domestic workforce education and training. Engaging the nanoscience and technology community in the crafting of some national priorities, developing novel approaches for translating fundamental discovery to a technology readiness level appropriate for venture/industry funding, increasing domestic student interest in nanoscience to expand the workforce pipeline, and exploring new ways of coordinating the NNI work going forward are all imperatives if the United States is to fully reap the societal benefits of nanotechnology.

The highest priority of this report is to provide recommendations that will restore the United States to the global forefront of nanotechnology-enabled advances in electronics, health care, clean energy production and storage, food production, and clean water and air, and to contribute to the robust defense of U.S. national security interests.

IMPACTS OF THE NNI TO DATE

The NNI is widely viewed nationally and globally as a highly successful cross-disciplinary and interagency coordination effort—arguably the best modern example of such an effort in the United

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

States.[2] The committee is deeply impressed with the tangible outcomes that have emerged from these coordination efforts. The committee notes in particular that the NNI has supported advances in materials science, novel device designs, and new manufacturing processes that have been essential to the recent formation of the NQI, which is structured with operating principles similar to those of the NNI.[3]

The goals of the NNI (unchanged since its proposal in 2000) are as follows:

1. Advance a world-class nanotechnology R&D program;
2. Foster the transfer of new technologies into products for commercial and public benefit;
3. Develop and sustain educational resources, a skilled workforce, and a dynamic infrastructure and toolset to advance nanotechnology; and
4. Support responsible development of nanotechnology.

The committee strongly support these well-crafted goals. However, this review finds that not all the goals have received adequate attention, investment, or coordinated effort. The NNI performed exceptionally well on Goal 1 in the first 10-12 years of its existence, although success in delivering "world-class" R&D is now being challenged unambiguously by robust efforts in many other countries and regions. The NNI has delivered a smaller set of activities, outcomes, and impacts related to Goal 2, and arguably has not been as strongly competitive globally as it was for Goal 1. Similarly, the NNI has not developed a national strategy to develop the appropriate workforce to address Goal 3, although it has certainly contributed some expanded opportunities for nanotechnology workforce training. As foreign and domestically trained scientists and engineers increasingly find work in other nations and regions, the United States is confronted with a serious shortage of skilled researchers and technical staff, just as it enters an era of intensified global competition in nanotechnology. That said, the NNI has succeeded in establishing the necessary nanoscience and nanotechnology infrastructure (i.e., world-class tooling and laboratory facilities), which must now be maintained and expanded going forward. Last, on Goal 4 the committee considers that the NNI has performed exceptionally well and is recognized internationally for its leadership in responsible nanotechnology development and for leveraging international collaborations, although agency engagement appears to be waning.

The committee was unified in a positive assessment of the value of the NNI to the U.S. economy, but developed a serious concern that the recent, focused, and in some cases novel commercialization approaches of other nations may be yielding better societal outcomes. The committee therefore considered whether the nanotechnology effort could be organized in more effective ways to accelerate the transition of nanotechnology discoveries to the higher technology readiness levels that bring societal benefits.

Given this uneven performance and the apparent threats to economic prosperity and national security by a loss of nanotechnology leadership, the committee believes that the NNI should be refocused, with the overall vision of the initiative to be as follows:

> Creation of innovative mechanisms to realize the transformational societal benefits that flow from faster commercialization of nanotechnologies while reestablishing scientific leadership through aggressive, strategic investment in basic nanoscience R&D, improved infrastructure, and expanded education and training necessary to fuel future expansions in foundational knowledge and technological revolutions.

While the committee does not advocate for any specific commercialization model (which is a responsibility of the National Nanotechnology Coordination Office [NNCO] and Nanoscale Science,

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[2] For an overview of the structure and operating principles of the NNI, see Chapter 1 of the *2013 Triennial Review of the National Nanotechnology Initiative*, at https://www.nap.edu/catalog/18271/triennial-review-of-the-national-nanotechnology-initiative.

[3] See the NQI bill, at https://www.congress.gov/bill/115th-congress/house-bill/6227/text, and related press coverage—for example, from the American Institute of Physics, at https://www.aip.org/fyi/2019/national-quantum-initiative-signed-law.

Engineering, and Technology [NSET], and our elected representatives), it has observed that Europe's Interuniversity Microelectronics Centre (IMEC) and Micro and Nanotechnology Innovation Campus (MINATEC), Japan's Tsukuba Innovation Area, and China's Nanopolis are examples of directed, at-scale, commercialization efforts. Each of these is better positioned than the current U.S. effort to reap the rewards of nanoscience and technology R&D. The committee believes that for U.S.-developed nanotechnology to compete in the current hypercompetitive era,[4] the United States must rethink the entirety of its policy/funding/IP framework, within which nanotechnology knowledge is created, innovation is protected, and products are developed/commercialized by industry. The committee was encouraged by the NNCO's recognition of this challenge, and its formation of a platform to strengthen the link between nanotechnology and a commercialization path in the form of the Nanotechnology Entrepreneurship Network (NEN), launched in late 2019. This emerging network provides a forum for sharing best practices for advancing nanotechnology commercialization and the lessons learned along the technology development pathway. While current activities include a monthly podcast series, webinars, workshops, and town hall discussions, the committee remains concerned that these efforts will be insufficient in the current hypercompetitive environment for nanoscience and technology.

A VISION FOR THE FUTURE OF THE NNI

Carrying out this vision will require setting priorities and goals. The committee identifies three such priorities:

Priority 1. The NNI should partner broadly to improve the efficiency of *translation* of nanoscience/nanotechnology research and development into economic, environmental, and societal benefits.

Priority 2. The NNI should *focus* on strategically selected environmental and societal challenges with nanoscience and nanotechnology.

Priority 3. The NNI should expand the nation's nanotechnology ecosystem via increased *recruitment* and *training* of future scientists and engineers, with an intentional focus on accelerated technology translation, and with robust investments in *next-generation infrastructure* to support basic science and commercialization.

Last, the following five key recommendations, if implemented, will provide the actions needed to meet these priorities and carry out this vision.

Key Recommendation 1: The Nanoscale Science, Engineering, and Technology (NSET) Subcommittee and the National Nanotechnology Initiative (NNI) agencies should align the efforts of the NNI to deliver responsible and sustainable nanotechnology-based solutions that address the federal research and development (R&D) priorities, which currently include security, artificial intelligence, quantum information sciences, manufacturing, bio-based materials, water, climate change, space travel, exploration, inhabitation, energy, medical innovations, and food and agriculture.

Key Recommendation 2: The Nanoscale Science, Engineering, and Technology (NSET) Subcommittee and the National Nanotechnology Coordination Office (NNCO) should strengthen and expand the lab-to-market innovation ecosystem in support of the transfer of nanotechnologies from bench research to products, to ensure U.S. competitiveness.

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[4] See, for example, Statement of E.W. Priestap, Assistant Director, Counterintelligence Division, Federal Bureau of Investigation, Before the Committee on the Judiciary, United States Senate, "Hearing Concerning China's Non-Traditional Espionage Against the United States: The Threat and Potential Policy Responses," presented December 5, 2018, https://www.judiciary.senate.gov/imo/media/doc/12-12-18%20Priestap%20Testimony.pdf.

Key Recommendation 3: New investments by the National Nanotechnology Initiative (NNI) agencies are required to strengthen and renew the U.S. network of fabrication and characterization facilities to retain international leadership. These investments should make readily available new tools, expertise, techniques, and processes to support fundamental research in existing and emerging areas, as well as prototyping and pilot/scale-up capabilities.

Key Recommendation 4: The Nanoscale Science, Engineering, and Technology (NSET) Subcommittee, the National Nanotechnology Coordination Office (NNCO), and the National Nanotechnology Initiative (NNI) agencies should significantly increase efforts to attract and train the best students to studies in relevant nanoscience/nanotechnology science, technology, engineering, and mathematics (STEM) disciplines to ensure a diverse world-class workforce to support our national interests and security, including via public-private partnerships that support student fellowships.

Key Recommendation 5: The National Nanotechnology Initiative (NNI), through the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee and the National Nanotechnology Coordination Office (NNCO), should continue to perform its important coordinating role. The NNCO should be adequately resourced and appropriately staffed to deliver an agile and globally competitive nanotechnology program. The work of the NNCO should also be augmented through expanded collaborations with not-for-profit organizations and by establishing new public-private partnerships.

1

Introduction

This report is a quadrennial review of the National Nanotechnology Initiative (NNI) requested by the White House Office of Science and Technology Policy (OSTP) in 2019. The statement of task from the OSTP is provided in Appendix A.

WHAT IS "NANOTECHNOLOGY" AND WHY IS IT OF PERVASIVE INTEREST?

When small numbers of atoms are allowed, or are induced, to assemble into very small objects with dimensions of 1-100 nm, they have properties that are sometimes unlike any exhibited by their macroscopic counterparts—for example, the mesoporous zeolites described in Box 1.1, or cage-like fullerenes, cylindrical or flattened carbon nanotubes, or carbon formed as sheets of single-layer graphene.[1] While fullerenes have yet to find a major application, the other nanoforms of carbon possess remarkable stiffnesses and strengths, ultra-high thermal and electrical conductivities, and a host of interesting and potentially transformative electrical transport behaviors. Counterparts made of silicon, boron nitride, and other molecules have been discovered or await discovery, and promise similar exciting technological prospects.

But nanotechnology embraces much, much more than this. For example, the controlled assembly of 100-10,000 cadmium and tellurium atoms into quantum dots of controlled size and shape results in nanoparticles whose quantized energy levels enable highly selective absorption and luminescent emission of monochromatic visible radiation. Their ability to produce red, green, and blue light has led to their widespread use in backlit TV displays. They are also used in emerging quantum-dot light emitting displays (QD-LED) with the potential to displace this current major application of quantum dot technology. Quantum dots also exhibit a host of other opto-electronic properties that are controllable by changing the composition of the atoms used to assemble them as well as their shape and geometry. Today they are used to manipulate the color of glass,[2] for biomedical assays,[3] and embedded in nanowires within quantum photonic systems.[4] Their likely future impacts are even more compelling. Silicon quantum dots[5] and nanoscale Josephson junctions[6] are two of the most promising approaches for synthesizing the qubits of emerging quantum computers.

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[1] P.M. Ajayan, 2019, The nano-revolution spawned by carbon, *Nature* 575:49-50, at https://www.nature.com/articles/d41586-019-02838-4.

[2] D. Bera, L. Qian, and P.H. Holloway, 2010, Quantum dots and their multimodal applications: A review, *Materials* 3:2260-2345.

[3] E. Petryayeva, W.R. Algar, and I.L. Medinitz, 2013, Quantum dots in bioanalysis: A review of applications across various platforms for fluorescence spectroscopy and imaging, *Applied Spectroscopy* 67(3):215-222.

[4] M. Heiss et al., 2013, Self-assembled quantum dots in a nanowire system for quantum photonics, *Nature Materials* 12:439-444.

[5] R.M. Wilson, 2018, Silicon-based quantum dots have a path to scalable quantum computing, *Physics Today* 71(4):17-20.

[6] See https://en.wikipedia.org/wiki/Phase_qubit, accessed 11/04/2019.

BOX 1.1
Mesoporous Zeolites

The journal *Nature* recently selected a paper on mesoporous zeolites (materials containing aligned cylindrical pores with pore diameters of 2-50 nm) as one of its top 10 Extraordinary Papers in its 150 years of publication.[1] These remarkable materials can be formed using cylindrical, molecular templates with controllable diameters. After appropriate alignment and packing processes, a silicate can be deposited on them and the template simply removed. The resulting materials complement widely used alumino-silicate zeolite catalysts with 1 nm diameter pores that account for a significant fraction of catalysts in use today. This synthesis approach was extended to so-called nanocasting, leading to the development of many other mesoporous materials including organic systems, a variety of metals, metal oxides, and carbon. These materials act as molecular sieves and are opening up new applications for chemical sensing, for the control of light, for high-capacitance charge storage devices (supercapacitors), and for batteries. They are also under study for in vivo controlled release and drug delivery systems, and with the emerging ability to coat the interior of the nanopores with catalytically active elements, they show great promise for a new generation of catalysts.[2]

[1] R. Ryoo, 2019, Birth of a class of nanomaterial, *Nature* 575:40-41, at https://www.nature.com/articles/d41586-019-02835-7.
[2] K. Na, C. Jo, K. Jeongnam, et al., 2011, Directing zeolite structures into hierarchically nanoporous architectures, *Science* 333:328-332, at https://science.sciencemag.org/content/333/6040/328.

Nanotechnology is pacing the performance of the most sophisticated and economically important computing and data storage technologies. The number of transistors in state-of-the-art integrated circuits has roughly doubled every 2 years for the past 5 decades,[7,8] packing now billions of transistors per chip[9] at densities above 100 million transistors/mm^2.[10,11] This extraordinary scaling of device density is achieved by pushing the fabrication of ever smaller feature sizes, now into the single-digit nm regime. For example, the "fin width," or critical dimension, in a fin field effect transistor (FinFET), is now less than 10 nm.[12] Such dense device packing has driven down the cost per device at a truly remarkable rate, but has required massive investments by industry to develop integrated circuit design software, silicon wafer processing and metrology tools, and new designs to manage the enormous thermal flux that must be removed from devices in operation. Partnerships between the Defense Advanced Research Projects Agency (DARPA)—one of the participating NNI agencies—and the U.S. semiconductor industry via programs such as STARnet,[13] a program of Semiconductor Research Corporation (SRC), have had an

[7] M.M. Waldrop, 2016, The chips are down for Moore's law, *Nature News* 530(7589):144.
[8] T.N. Theis and H.-S.P. Wong, 2017, The end of Moore's law: a new beginning for information technology, *Computing in Science and Engineering* 19(2):41.
[9] M. Bathe, L.A. Chrisey, D.J. Herr, Q. Lin, D. Rasic, A.T. Woolley, R.M. Zadegan, and V.V. Zhirnov, 2019, Roadmap on biological pathways for electronic nanofabrication and materials, *Nano Futures* 3(1): 012001.
[10] A. Malinowski, J. Chen, S.K. Mishra, S. Samavedam, and D. Sohn, 2019, in "What Is Killing Moore's Law? Challenges in Advanced FinFET Technology Integration," 2019 MIXDES—26th International Conference, "Mixed Design of Integrated Circuits and Systems," June 27-29, 2019, pp. 46-51.
[11] See https://newsroom.intel.com/newsroom/wp-content/uploads/sites/11/2017/03/Kaizad-Mistry-2017-Manufacturing.pdf.
[12] A. Malinowski, J. Chen, S.K. Mishra, S. Samavedam, and D. Sohn, 2019, in "What Is Killing Moore's Law? Challenges in Advanced FinFET Technology Integration," 2019 MIXDES—26th International Conference, "Mixed Design of Integrated Circuits and Systems," June 27-29, 2019, pp. 46-51.
[13] See https://www.src.org/program/starnet/about/, accessed 11/04/2019.

important role in maintaining U.S. competitiveness. As researchers approach the physics-defined limits of conventional circuit scaling and confront limits to the ability to pattern and process silicon, fundamental studies have been initiated to explore alternative device designs and materials that will allow the continued pace of computer chip performance increases into the foreseeable future. This work includes the integration of nanoelectronics with nanophotonics. In 2015, the American Institute for Manufacturing Integrated Photonics (AIM Photonics)[14] was established in support of this objective. AIM Photonics is a public-private partnership program funded at $600 million to deliver coordinated R&D among more than 100 companies, nonprofits, and universities.

These few brief examples show that nanotechnology has been, and will continue to be, a highly interdisciplinary field of research (indeed, arguably the most interdisciplinary), with many discoveries and inventions awaiting. The early work has now advanced to a stage where nanotechnology is underpinning a rapidly growing range of economically important applications, including nanoelectronics, displays, catalysts, ultra-strong materials, energy storage, drug delivery systems, and so on, and is making important contributions to the technologies that underpin U.S. national security.

THE NNI FRAMEWORK

Formally established in January 2000 with expenditures authorized in 2003, the NNI is a U.S. government research and development (R&D) initiative that currently spans the nanotechnology-related activities of 20 government participating departments and agencies. *It is important to note that there has been no specific federal funding appropriated and allocated by Congress toward the work of the NNI. Instead, the NNI leadership leverages the existing budgets of the participating departments and agencies to execute the NNI goals.* Practically, the role of the NNI is to *coordinate* the individual and cooperative nanotechnology-related activities of participating departments and agencies, which have a range of research priorities, regulatory roles, and responsibilities. That is, the nanoscience and nanotechnology R&D programs taking place in academic, government, and industry laboratories across the United States originate from, and are funded by, the participating departments and agencies, not the NNI. In its capacity as an interagency coordination effort, the NNI informs and influences the federal budget and strategic planning processes through engagement with its involved departments and agencies and with the National Science and Technology Council (NSTC). As the coordinating entity, the NNI is charged with bringing together the expertise needed to advance the fields of nanoscience and nanotechnology, and with creating a framework for shared goals, priorities, and strategies that help each participating federal agency leverage the resources of all participating agencies. This operational framework is starkly different from the explicitly directed nanoscience and nanotechnology investments of other nations reviewed by the panel.[15]

NNI Coordination

The NNI is overseen by the White House Office of Science and Technology Policy (OSTP) via the NSTC's Subcommittee on Nanoscale Science and Technology (NSET), which comprises a representative from each major NNI participating department or agency. The National Nanotechnology Coordination Office (NNCO) provides administrative support to the NSET Subcommittee and acts as the primary point of contact for information on the NNI. The NNCO (1) provides technical and administrative support to the NSET Subcommittee, including the preparation of multiagency planning, budget, and assessment documents; (2) connects the NNI agencies and departments to academia, industry, professional societies, and foreign organizations; (3) provides public outreach on behalf of the NNI; (4) promotes access to, and

[14] See https://www.manufacturingusa.com/institutes/aim-photonics, accessed 11/04/2019.
[15] The global competitive landscape is summarized in Chapter 3.

early application of, the technologies, innovations, and expertise derived from NNI activities;[16] and (5) develops, updates, and maintains the public-facing NNI website.[17] The essential coordination work of the NNI, by NSET and the NNCO, is funded via "contributions" from the largest NNI participating agencies and departments at levels that are roughly proportional to their nanoscience and nanotechnology R&D expenditures, which are self-reported on an annual basis. Whereas it was originally proposed that these contributions should amount to 0.3 percent of the total NNI budget, it has been noted in previous NNI reviews that this level of support for the coordination effort has not been achieved, and appears to have been held flat at just less than $3 million, which for 2020 is about two-thirds of the proposed level of support.[18] It has been reported to the committee that this model for supporting the NNI is essentially self-limiting, in that participating departments and agencies have a disincentive for reporting expanded R&D expenditures as nanotechnology, since doing so would trigger a higher contribution for support of the NNI mission and the work of NSET and the NNCO specifically. This is a very different coordination model from the directed funding allocations and robust support and coordination structures that other nations and regions use for investments in nanoscience and nanotechnology. The U.S. approach appears to be less agile and much less robust in the current dynamic international environment with increasing competitive threats.

NNI Vision, Goals, and Program Component Areas

The NNI currently operates under a Strategic Plan published in October 2016. Within this plan, so-called Program Component Areas (PCAs) provide an organizational framework for categorizing the major NNI activities under which related projects and activities are grouped (see Box 1.2). Progress in the PCAs measure advancement toward the NNI's vision and goals. The investment in each PCA is reported in the annual NNI supplement to the President's Budget.[19]

The NNI Budget

Annually, the NNCO prepares an NNI Budget Supplement to the President's Budget, which also serves as an Annual Report for the NNI. The supplement to the President's 2020 Budget requests over $1.4 billion for the NNI for continued investment in basic research, early-stage applied research, and technology transfer efforts.[20] Including the 2020 request, the cumulative NNI investment has reached nearly $29 billion since the inception of the NNI. The budget distribution by agency since the start of the NNI is shown in Figures 1.1 and 1.2, while the largest agency/department contributors are described in Box 1.3.

Since 2009, OSTP has worked with NNI agencies via the NNCO to assemble a set of Nanotechnology Signature Initiatives (NSIs) under PCA 1 that are intended to focus attention, resources, and more intensive program-level coordination on domains uniquely ready for accelerated development or that represent a priority national interest (see Box 1.2 and Box 1.4).

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[16] See https://www.nano.gov/about-nni/nnco, accessed 11/04/2019.
[17] Located at www.nano.gov, accessed 11/04/2019.
[18] See, for example, the narrative on page 31 of "The National Nanotechnology Initiative: Overview, Reauthorization, and Appropriations Issues," J.F. Sargent Jr., 2014, Congressional Research Service, at https://fas.org/sgp/crs/misc/RL34401.pdf.
[19] See http://nano.gov/about-nni/what/funding, accessed 11/04/2019.
[20] See https://www.nano.gov/2020BudgetSupplement, accessed 11/04/2019.

BOX 1.2
Program Component Areas

The current NNI's Program Component Areas (PCAs) are:

1. Current Nanotechnology Signature Initiatives (NSIs) and Grand Challenges
   a. Sustainable Nanomanufacturing: Creating the Industries of the Future
   b. Nanoelectronics for 2020 and Beyond
   c. Nanotechnology Knowledge Infrastructure: Enabling National Leadership in Sustainable Design
   d. Nanotechnology for Sensors and Sensors for Nanotechnology: Improving and Protecting Health, Safety, and the Environment
   e. Water Sustainability Through Nanotechnology: Nanoscale Solutions for a Global-Scale Challenge
   f. Nanotechnology-Inspired Grand Challenge for Future Computing
2. Foundational Research
3. Nanotechnology-Enabled Applications, Devices, and Systems
4. Research Infrastructure and Instrumentation
5. Environmental Health and Safety

BOX 1.3
Nanotechnology Investments

The federal departments and agencies making the largest nanotechnology investments through the NNI are

- *National Institutes of Health (NIH)*, which is focused on nanotechnology-based biomedical research at the intersection of life and physical sciences.
- *National Science Foundation (NSF)*, to address fundamental nanoscale research and education across all disciplines of science and engineering.
- *Department of Energy (DOE)*, to pursue both fundamental and applied research in support of new and improved energy-related technologies.
- *Department of Defense (DOD)*, to conduct science and engineering research advancing defense and dual-use capabilities.
- *National Institute of Standards and Technology (NIST)*, which focuses on fundamental R&D in support of measurement and fabrication tools, analytical methodologies, metrology, and standards for nanotechnology.

Other departments and agency components investing in mission-related nanotechnology research are the Consumer Product Safety Commission, the Department of Homeland Security, the Department of Justice (including the National Institute of Justice), the Department of the Interior (including the U.S. Geological Survey), the Department of Transportation (including the Federal Highway Administration), the Environmental Protection Agency, the Food and Drug Administration, the National Aeronautics and Space Administration, the National Institute for Occupational Safety and Health, and the U.S. Department of Agriculture (including the Agricultural Research Service, the U.S. Forest Service, and the National Institute of Food and Agriculture).

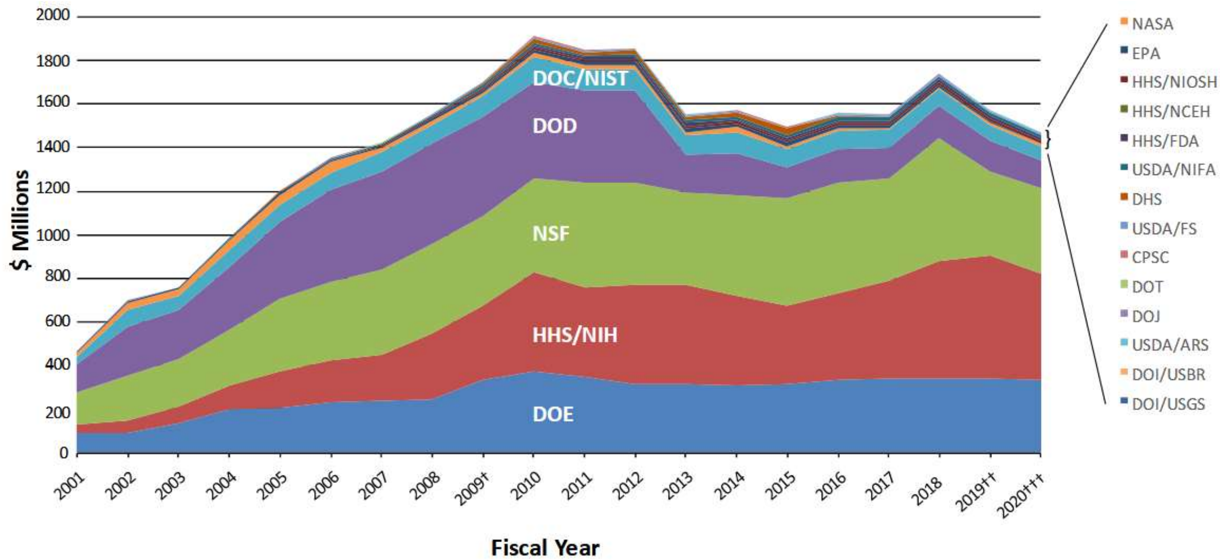

FIGURE 1.1 The distribution of NNI funds since the inception of the NNI in 2000, broken out by participating department and agency. SOURCE: "The National Nanotechnology Initiative Supplement to the President's 2020 Budget," page 3.

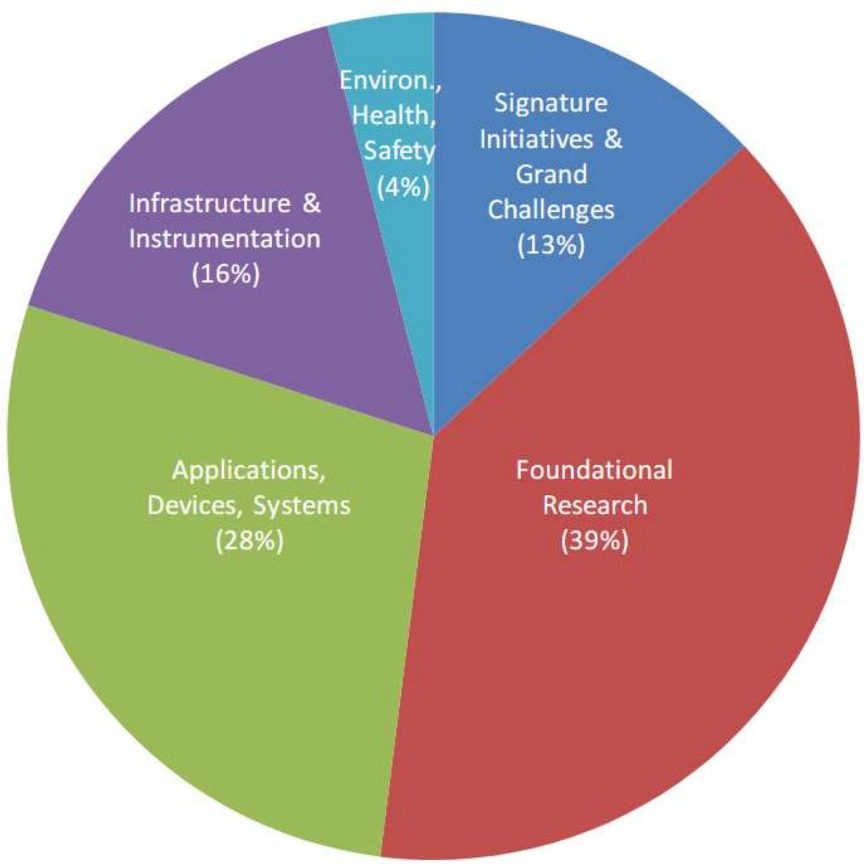

FIGURE 1.2 The distribution of the President's 2020 NNI budget by program component area. SOURCE: "The National Nanotechnology Initiative Supplement to the President's 2020 Budget," page 7.

In 2014, in response to recommendations from the President's Council of Advisors on Science and Technology (PCAST), OSTP worked with NNI member agencies to identify and select Nanotechnology-Inspired Grand Challenges, each intended to represent "an ambitious but achievable goal that harnesses nanoscience, nanotechnology, and innovation to solve important national or global problems and has the potential to capture the public's imagination."[21] The Future Computing Grand Challenge that emerged from that process laid the essential groundwork for the recent launch of the National Quantum Initiative (NQI).[22]

BOX 1.4
Nanotechnology Signature Initiatives

Each NSI combines the focused efforts of a number of contributing Federal agencies with related missions that are committed to coordinating research and implementing strategies to achieve the goals defined for the NSIs, and to updating and prioritizing those goals as the research progresses. Individual agency-funded or mission-specific programs have benefited from improved awareness of complementary activities at other agencies and have been developed in the context of broader Federal activities.

SOURCE: https://www.nano.gov/signatureinitiatives, accessed 11/04/2019.

THE EVOLVING GLOBAL ENVIRONMENT

The combination of state-of-the-art facilities that allow increasingly complex nanostructures to be synthesized and characterized, appropriate investments in safety and standards, together with the remarkable scientific and engineering talent that has been drawn to the NNI program, has enabled the U.S. program to achieve remarkable scientific and technology advances. However, there are clear signs that the competitive backdrop against which so much has been achieved has been changing rapidly. The 2016 Triennial Review of the NNI identified a concern that the development of U.S. talent necessary to grow and sustain a vibrant U.S. nanotechnology program was showing signs of stagnating.[23] It found that the number of science, technology, engineering, and mathematics (STEM) undergraduates was not increasing as rapidly as in some other regions of the world. Since this is the pool from which domestic students are drawn for graduate studies and to advance much of the R&D in nanotechnology, the future U.S. talent needed to support nano-related research and commercialization will likely be compromised, along with the prospects for growing the nation's increasingly knowledge-based economy. The recent National Science Board (NSB) *Science & Engineering Indicators 2020* report[24] confirms these trends, as shown in Figure 1.3, and highlights the rapid growth in conferred STEM degrees in other countries, and especially in China. By 2016, the number of science and engineering (S&E) first undergraduate degrees awarded by the United States had slowly risen to about 800,000, whereas in China, the number of similar awarded degrees had risen sharply to around 1.8 million. While the United States still leads in producing

[21] See https://www.nano.gov/grandchallenges, accessed 11/04/2019.
[22] C. Monroe, M.G. Raymer, and J. Taylor, 2019, The U.S. National Quantum Initiative: from act to action, *Science* 364(64390):440-442.
[23] National Academies of Sciences, Engineering, and Medicine, 2016, *Triennial Review of the National Nanotechnology Initiative*, Washington, D.C.: The National Academies Press, https://doi.org/10.17226/23603.
[24] National Science Board, *Science & Engineering Indicators 2020*, https://ncses.nsf.gov/pubs/nsb20201/u-s-and-global-education.

S&E graduates on a per capita basis, the trendline for growth in China's growth in S&E graduates suggests that this will not be true for long. Given the growing importance of a STEM-trained workforce for the economic prosperity of nations, these are concerning trends.

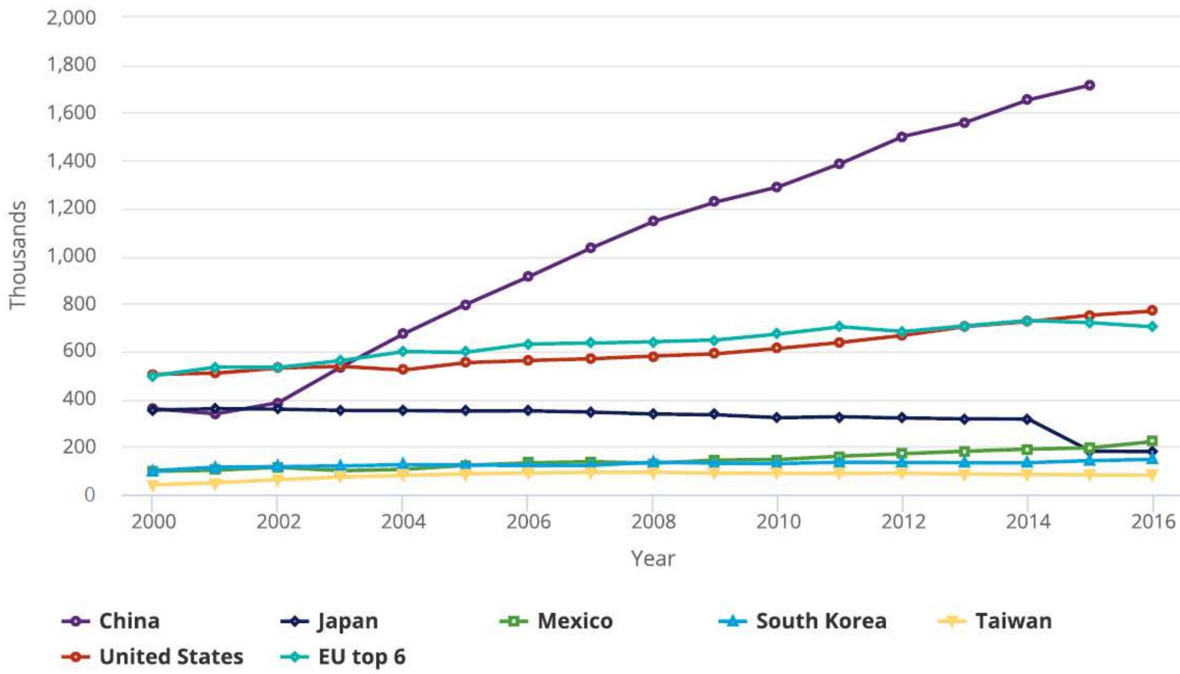

FIGURE 1.3 Bachelor's degree awards in S&E fields by region, country, or economy. EU = European Union; EU top 6 = France, Germany, Italy, Poland, Spain, and the United Kingdom. Data are not available for all regions, countries, or economies for all years. To facilitate international comparison, data for the United States are those reported to the OECD, which vary slightly from the National Center for Science and Engineering Statistics (NCSES) classification of fields presented in other sections of the report. Data are not available for all countries or economies for all years. The EU top 6 total includes aggregated data for the six EU countries producing the highest number of S&E first university degrees in 2016:. The data source for Japan changed in 2014, which may potentially result in a time series break. SOURCE: National Science Board, *Science & Engineering Indicators 2020*, https://ncses.nsf.gov/indicators, Figure 3.

The same NSB report has also assessed the number of doctoral degrees awarded in science and engineering between 2000 and 2016, and those data are replicated here in Figure 1.4. The United States awarded about 40,000 doctoral degrees in 2016. It can also be seen that the number of doctoral degrees awarded leveled off after a decade or more of sustained growth. The report shows that the top six research nations of the EU continue to produce almost 50 percent more Ph.D. degree recipients per year than the United States.[25] It also shows that Chinese Ph.D. production has sustained a period of rapid growth, and now rivals the Ph.D. production of the United States. The NSB report notes that a significant fraction of the Ph.D. degrees awarded in the United States were granted to foreign students studying in the United States on temporary visas. For example, in 2017 temporary visa holders were awarded about one-third of the doctoral S&E degrees in the United States. Most of these students (between 64 and 71 percent) were

[25] Considering that the number of Ph.D. degrees awarded by the EU top 6 is certainly only a fraction of the Ph.D. degrees of all EU countries, the lead of the EU in this metric becomes even more pronounced.

subsequently granted another visa and remained in the United States for at least another 5 years. However, the committee was concerned that if the number of students granted visa extensions declined, or if these talented people chose to work elsewhere, the domestic workforce pipeline is likely to be inadequate for the United States to successfully compete in future nanoscience discovery and nanotechnology commercialization.

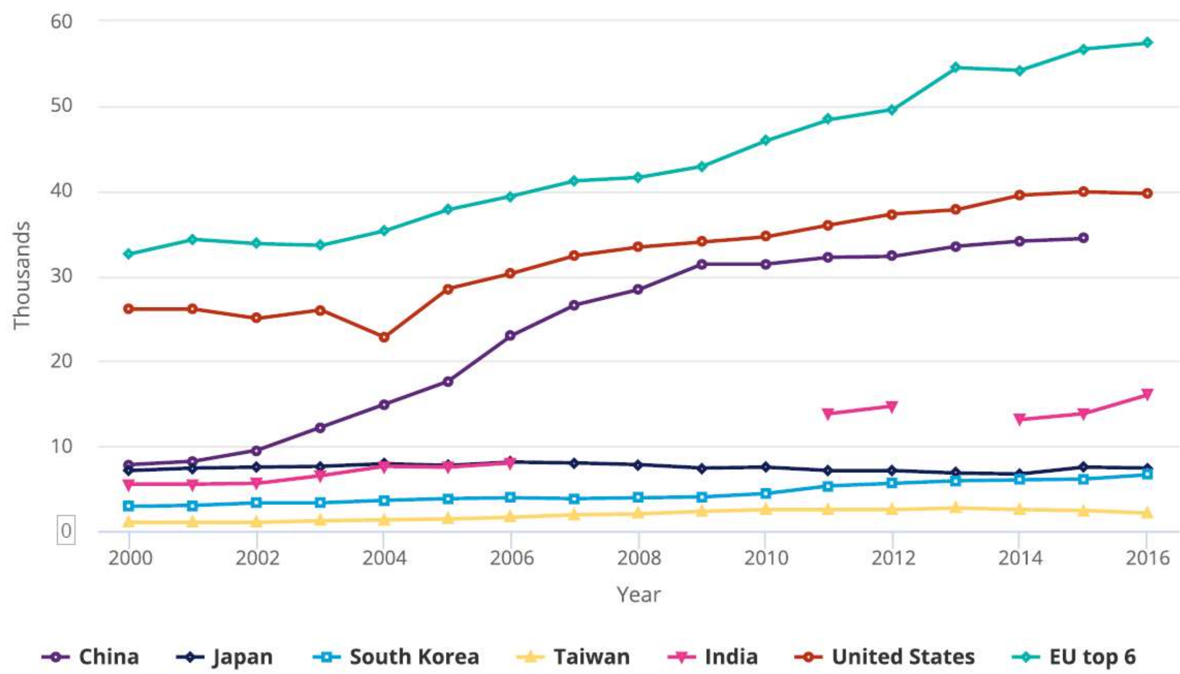

FIGURE 1.4 Doctoral degrees awarded in S&E fields by selected region, country, or economy. EU = European Union; EU top 6 = France, Germany, Italy, Spain, Sweden, and the United Kingdom. Data are not available for all regions, countries, or economies for all years. To facilitate international comparison, data for the United States are those reported to the OECD, which vary slightly from the NCSES classification of fields presented in other sections of the report. EU top 6 includes estimated data for some countries and some years when country data are not available. SOURCE: OECD, *Education and Training Indicators*, 2019; Eurostat, Education and Training Database; Ministry of Education, Culture, Sports, Science, and Technology (Japan), *Survey of Education* (various years); National Bureau of Statistics (China), *China Statistical Yearbook* (various years); Ministry of Education (Taiwan), *Educational Statistics* (various years). National Science Board, *Science & Engineering Indicators 2020*, https://ncses.nsf.gov/indicators, Figure 4.

To gain insight into the changing global nano-related research environment since the NNI's launch, the committee reviewed the number of research papers on nanotechnology published annually. Zhou et al. have analyzed these published papers by region of origin.[26] Their analysis indicates that the number of nanotechnology-related papers published per year has grown from 20,000 in 2000 to about 160,000 in 2016—a global annual growth rate of about 15 percent. However, the growth in papers from the United States has lagged behind that of several other regions. Consequently, while the United States contributed

[26] H. Zhu, S. Jiang, H. Chen, and M.C. Roco, 2017, International perspective on nanotechnology papers, patents, and NSF awards (2000-2016), *Journal of Nanoparticle Research* 19:370, at https://doi.org/10.1007/s11051-017-4056-7.

about 30 percent of the research papers in 2000, by 2016 this had decreased to ~18 percent—well below the contribution from the EU (25 percent) and notably behind China (33 percent). While the United States remains the largest contributor of high-impact publications (it contributes about two-thirds of the publications in *Nature*, *Science*, and *PNAS*, for example), contributions to these journals from the EU and China are growing rapidly. Deeper assessments indicate that the United States continues to innovate, coordinate, and focus research funding to achieve significant success. However, extrapolation of current trends indicates that the nation's leadership in the most innovative areas is beginning to be challenged.

The review committee understood from the outset that past NNI investments in nanotechnology have already made robust contributions to the U.S. high-technology economy. The most recent NSB report has determined the regional distribution of economic contributions arising from high-technology (HT) manufacturing, to which nanotechnology makes a substantial contribution, and is reproduced here in Figure 1.5 for the period 2003-2016. Note that in 2003, about $300 billion of HT manufacturing output occurred in the United States, followed by the EU and Japan. The report shows that by 2016, the U.S. contribution to the approximately $1.6 trillion of HT manufacturing had grown to around $500 billion, but that from China had grown faster, exceeding that of the EU (which had not changed since 2008) and Japan, and was rapidly approaching the U.S. level. These observations motivated the review committee to investigate the global nanotechnology enterprise, and the effectiveness of the NNI technology transfer activities, and to propose several changes to the coordination of the U.S. commercialization effort.

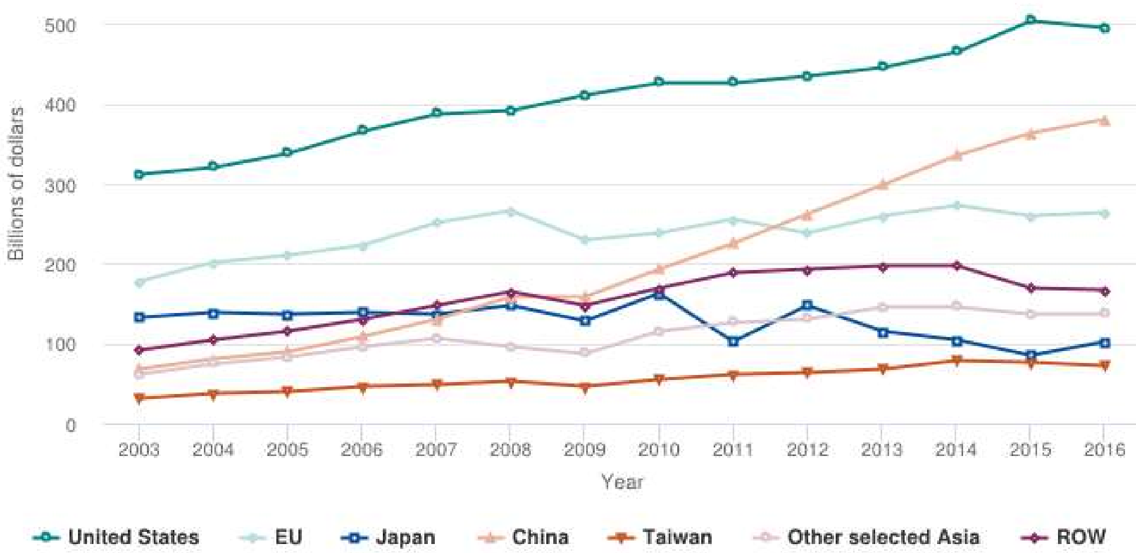

FIGURE 1.5 Output of high-technology manufacturing industries for selected regions, countries, or economies. Output is measured on a value-added basis. Value added is the amount contributed by a country, firm, or other entity to the value of a good or service and excludes purchases of domestic and imported materials and inputs. HT manufacturing industries include aircraft and spacecraft; communications and semiconductors; computers; pharmaceuticals; and testing, measuring, and control instruments. Data are not available for EU members Cyprus, Estonia, Latvia, Lithuania, Luxembourg, Malta, and Slovenia. China includes Hong Kong. Other selected Asian countries include India, Indonesia, Malaysia, Philippines, Singapore, South Korea, Taiwan, and Vietnam. SOURCE: IHS Global Insight, World Industry Service database (2017); see Appendix Table 6-8. National Science Board, 2018, *Science and Engineering Indicators*, https://www.nsf.gov/statistics/2018/nsb20181/, Figure 6-11.

2

The U.S. Nanotechnology R&D Ecosystem

THE NNI PROGRAM COMPONENT AREAS

The United States has structured its National Nanotechnology Initiative (NNI) investment in nanoscience and technology into five Program Component Areas (PCAs), the first of which (currently) includes six Nanotechnology Signature Initiatives (NSIs), as shown in Box 1.2 in Chapter 1. Established first in 2010, and strategically adjusted periodically since, the NSIs[1] were intended to be

> Focused areas of national importance that may be more rapidly advanced through enhanced interagency coordination and collaboration. These NSIs provide a spotlight on critical areas and define the shared vision of the participating agencies for accelerating the advancement of nanoscale science and technology from research through commercialization. By combining the expertise, capabilities, and resources of appropriate Federal agencies, the NSIs aim to accelerate research, development, and insertion, and overcome challenges to the application of nanotechnology-enabled products.[2]

The cross-agency teams behind the NSIs have accordingly sought to integrate knowledge, infrastructure, and resources across appropriate federal agencies to achieve effective translation of nanotechnologies to the marketplace. Below is a brief review of the NNI activities by NSI, including for completeness one former NSI on "Nanotechnology for Solar Energy Collection and Conversion," which has ended.

PCA 1: Nanotechnology Signature Initiatives and Grand Challenges

The following subsections provide a description of each of the six signature initiatives and the future computing Grand Challenge.

NSI on Nanotechnology for Solar Energy Collection and Conversion (2010-2015)

This NSI was in place from 2010 to 2015 and was supported by the Department of Energy (DOE), National Institute of Standards and Technology (NIST), National Science Foundation (NSF), Department of Defense (DOD), intelligence community (IC), National Aeronautics and Space Administration (NASA), and U.S. Department of Agriculture (USDA). It sought to use nanotechnology to accomplish three goals:

1. Improve photovoltaic (PV) solar electricity generation.
2. Improve solar thermal energy generation.

[1] See https://www.nano.gov/signatureinitiatives, accessed 11/04/2019.
[2] See https://www.nano.gov/node/1536, accessed 11/04/2019.

3. Improve solar-to-fuel conversions.

In the United States, commercial solar PV panels were expected to have a solar-to-electric energy conversion efficiency of 20-23 percent in 2019.[3] The maximum solar efficiency of a single p-n junction cell (owing to recombination within the panel) is given by the Shockley Queisser Efficiency Limit and is ~33.7 percent for typical solar illumination conditions.[4] Increasing solar photovoltaic efficiency toward this limit is clearly an important objective, provided it does not adversely impact cost. This will have significant benefits to both the public use of renewable energy sources and for national security (for all nations). Apart from widespread impacts on public energy costs, the combination of more efficient solar electricity generation and more affordable energy storage systems is expected to pervasively impact the future operations and missions of the DOD and other national security agencies, especially for operations where other power sources are absent (e.g., forward-deployed forces and space platforms) as well as those of agencies such as NASA as it prepares for extended missions to the moon and Mars.

Although this NSI was terminated in 2015, much work continues in-the area of solar-to-fuel conversion and energy storage at centers such as the Joint Center for Artificial Photosynthesis (JCAP; $15 million/year), Caltech, and Lawrence Berkeley National Laboratory (LBNL), and including center collaborators from the Stanford Linear Accelerator Center (SLAC); University of California, Irvine (UCI); University of California, San Diego (UCSD); National Renewable Energy Laboratory (NREL); and at least six DOE Energy Frontier Research Centers (EFRCs). The Advanced Research Projects Agency-Energy (ARPA-E) SunShot initiative aimed at reducing the cost of photovoltaic electricity production was/is likely a part of DOE NNI. The NSI enabled a focused effort by a number of centers and supported integrated, multidisciplinary, experimental, and theoretical efforts.

That said, with the exception of SunShot, a set of clearly articulated quantitative goals and milestones did not emerge from the NSI, and a great deal of further basic science needs to be advanced in solar-to-fuel conversion before widespread deployment at multiple scales is likely. Solar-thermal is being deployed in multiple locations in California and Arizona, with plants typically generating a few hundred MW of electricity.[5] However, cost remains a significant issue. The issue of energy storage remains the most serious roadblock to widespread deployment of solar technologies. According to Ramamoorthy Ramesh, DOE, solar PV plus battery storage is needed at 5 cents/kW hour for grid parity.[6] This translates to a need for batteries that can be built at a cost of $50/kW hour—that is, one-seventh that provided by today's state-of-the-art commercial providers.

In January 2020, DOE launched its Energy Storage Grand Challenge building on the $158 million Advanced Energy Storage Initiative announced in the President's 2020 budget request. The aim is to create a comprehensive program to accelerate the development, commercialization, and utilization of next-generation energy storage. Although focused on energy storage, the Grand Challenge will also encompass scale-up challenges including manufacturing, workforce development, valuation, and technology transfer. The Grand Challenge sets five goals to be reached by 2030.[7]

In the solar-to-fuel technology domain, the three leading countries are considered to be the United States, China, and Japan. Germany, Sweden, and Switzerland are also highly regarded. The United States is the origin of the majority of highest cited publications. However, in 2010 China surpassed the United States in total output of both publications and patents, and China now has four times as many patents in this area than the next nearest country. In terms of innovation, the United States perhaps still leads, but in terms of collaboration with industry, China and Japan appear to have taken the lead. As one example, the

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[3] See https://news.energysage.com/what-are-the-most-efficient-solar-panels-on-the-market/, accessed 11/04/2019.

[4] See https://en.wikipedia.org/wiki/Shockley%E2%80%93Queisser_limit, accessed 11/04/2019.

[5] See https://eia.gov/energyexplained/solar-thermal-power-plants.php, accessed 11/04/2019.

[6] See https://www1.eere.energy.gov/solar/pdfs/47927.pdf, accessed 11/04/2019.

[7] See https://www.energy.gov/articles/us-department-energy-launches-energy-storage-grand-challenge, accessed 01/27/2020.

United States does not have systems-level prototypes for CO_2 reduction, whereas Europe and Asia have sizable programs in this area in addition to their fundamental research and development (R&D) programs. The development of systems-level prototypes for CO_2 reduction seems to be an opportunity of considerable promise for the United States but will require industry and academia to work together with appropriate support and incentive from U.S. government agencies.

NSI on Sustainable Nanomanufacturing: Creating the Industries of the Future

Industries that are based on nanotechnology require the development of scalable synthesis and manufacturing tools capable of reliably and reproducibly creating nanomaterials and devices in a cost-effective, safe, and environmentally (sustainably) responsible manner, and for integrating them into nanotechnology-enabled products. While the semiconductor industry has largely succeeded in this through its use of industry-government consortia, many other areas of nanotechnology have struggled, and so this interagency initiative led by NIST and the National Science Foundation (NSF) and supported by DOD, DOE, Environmental Protection Agency (EPA), IC, NASA, National Institutes of Health (NIH), National Institute for Occupational Safety and Health (NIOSH), Occupational Safety and Health Administration (OSHA), U.S. Department of Agriculture (USDA), and U.S. Forest Service (USFS)[8] seeks to form partnerships with industry and academia with a shared interest in the development of new manufacturing approaches.[9] For example, the city of Lanzhou, China, hosts a demonstration project for direct solar fuel synthesis at the thousand-ton scale,[10] while the EU and Switzerland funded a mobile pilot plant producing jet fuel at a scale large enough to be relevant to large-scale industrial implementation.[11]

Two thrust areas are supported by the 11 participating agencies:

1. Design of scalable and sustainable nanomaterials, components, devices, and processes, with a specific focus on carbon nanotube-based and cellulosic nanomaterials.
2. Nanomanufacturing measurement technologies, with a focus on high-throughput, in-line metrologies to ensure good manufacturing process control, product quality, and yield.

This signature initiative is advancing the scientific understanding and developing the physical infrastructure necessary for the ongoing lab-to-market transition for both classes of nanomaterials. It has involved the development of high-throughput measurement methods that are complemented by modeling and simulation tailored to realistic manufacturing conditions. It has increased the national capability to produce commercially relevant engineered nanomaterials at pilot plant-scale levels, and enabled demonstrations for several high-end applications, while simultaneously addressing environmental health and safety (EHS) responsibilities. The advanced nanomanufacturing knowledge and infrastructure being developed is extendable to other new classes of nanomaterials and will impact the manufacturing of materials for lightweighting, advanced composites, flexible electronics, and advanced textiles. The national security enterprise is often an early adopter of new materials, and the scalable manufacture of nano-enabled products being developed within this initiative promises a new generation of lightweight materials produced via sustainable processes.

Advancing the science and technology of nanomanufacturing is an essential step in translating research discoveries into commercial nano-enabled products. This NSI can impact the Manufacturing USA/National Network for Manufacturing Innovation (NNMI) institutes that are focused all or in part on advanced materials and their production. The proof-of-principle demonstrations achieved to date establish milestones for the viability of scaled-up nanomanufacturing that impact several distinct industry sectors

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[8] See https://www.nano.gov/node/611, accessed 11/04/2019.
[9] See https://www.nano.gov/NSINanomanufacturing, accessed 11/04/2019.
[10] See https://www.eurekalert.org/pub_releases/2020-01/caos-tsd011620.php, accessed 02/03/2020.
[11] See https://www.eurekalert.org/pub_releases/2017-08/kift-p2l080817.php, accessed 02/03/2020.

such as roll-to-roll nanomanufacturing, and applications of graphene and related two-dimensional (2D) materials. Sustainable nanomanufacturing processes and products have a potential economic impact by providing greater profit margin, lower health risks, and entirely new commercial markets.[12,13,14,15]

It is important to place the work of this initiative in the global context. While the NSI has made significant advances in sustainable nanomanufacturing, commensurate with its level of funding, greater efforts are necessary if the nation is to successfully compete with foreign efforts. These efforts include a substantial R&D effort on nanocellulose in Canada, and a European Network of Pilot Production Facilities (EPP), which includes 161 pilot facilities with emphasis on various nanomaterials.[16] The U.S. effort is also competing with the EU Horizon 2020 Program on Nanotechnologies, Advanced Materials, Advanced Manufacturing and Processing, and Biotechnology.[17] This large program seeks to help small and medium-size enterprises (SMEs) via open innovation test-beds; materials characterization and computational modeling; factories of the future; sustainable process industries, see for example the roadmap of the Sustainable Process Industry through Resource and Energy Efficiency(SPIRE) proposal;[18] clean energy through innovative materials; and energy-efficient buildings. The program includes a 2019 solicitation on sustainable nanofabrication intended to "establish industrial-scale manufacturing of functional systems based on manufactured nanoparticles with designed properties for use in semiconductors, energy harvesting and storage, waste heat recovery, medicine, etc."[19] Considerable nanomanufacturing efforts are also under way in South Korea, Japan, and China, as described further in Chapter 3.

NSI on Nanoelectronics for 2020 and Beyond

According to the Semiconductor Industry Association, the semiconductor industry is the fourth largest industrial sector in the United States, with almost half of the global market share; it directly employs 250,000 people and impacts another million U.S. jobs. The rapid pace of miniaturization and cost reduction has profoundly transformed computing, and communications. The miniaturization of complementary metal-oxide-semiconductor (CMOS) devices used for these applications entered the nanoregime about a decade ago, and this stimulated NSF, DOD, NIST, DOE, and IC to form a signature initiative in nanoelectronics. Its goals are to "accelerate the discovery and use of novel nanoscale fabrication processes and innovative concepts to produce revolutionary materials, devices, systems, and architectures to advance the field of nanoelectronics."[20] Its five thrusts have remained the same as those of the July 2010 white paper: (1) alternative state variables for computing; (2) merging of nanophotonics and nanoelectronics; (3) carbon-based nanoelectronics; (4) quantum information systems; and (5) national nanoelectronics and manufacturing infrastructure.

The Defense Advanced Research Projects Agency (DARPA) has also started a 5 year, $1.5 billion electronics resurgence initiative (ERI) to address the long foreseen problems that are encountered as it

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[12] A. Busnaina et al., 2013, Nanomanufacturing and sustainability: opportunities and challenges, *Journal of Nanopartical Research* 15:1984, doi:10.1007/s11051-013-1984-8.

[13] C. Geraci et al., 2015, Perspectives on the design of safer nanomaterials and manufacturing processes, *Nanoparticle Research* 17(9):366, doi:10.1007/s11051-015-3152-9.

[14] X. He et al., 2019, The current application of nanotechnology in food and agriculture, *Journal of Food and Drug Analysis* 27:1-21, https://doi.org/10.1016/j.jfda.2018.12.002.

[15] H. Koga et al., 2017, Renewable wood pulp paper reactor with hierarchical micro/nanopores for continuous-flow nanocatalysis, *ChemSusChem* 10:2560-2565, doi:10.1002/cssc.201700576.

[16] See https://www.eppnetwork.com/, accessed 11/04/2019.

[17] See https://ec.europa.eu/programmes/horizon2020/en/h2020-section/nanotechnologies-advanced-materials-advanced-manufacturing-and-processing-and, accessed 11/04/2019.

[18] See https://www.spire2030.eu/sites/default/files/pressoffice/spire-roadmap.pdf, accessed 02/29/2020.

[19] See https://www.efsa.europa.eu/en/funding/calls/sustainable-nano-fabrication-csa, accessed 01/29/2020.

[20] See https://www.nano.gov/node/1932, accessed 11/04/2019.

becomes more challenging to adhere to Moore's law[21] for predicted improvements in computational performance.[22] The NSF has had a steady focus on nanoelectronics and has sustained funding at around $100 million/year since 2015 with attention on high energy efficiency electronics within the Convergence Research element of the "10 Big Ideas" for future NSF investments.[23] There have been strong collaborations with NIST and SRC for new founding rounds (e.g., Energy-Efficient Devices, Systems, and Architectures). NSF has been very effective at coordinating with other agencies and leveraging results. It has also played a role in advancing neuromorphic computing and engineering, which is further along than quantum computation in industry. The Air Force Office of Scientific Research (AFOSR) has focused on nanoelectronics through Basic Programs and Multidisciplinary University Research Initiatives (MURIs; e.g., fiscal year [FY] 2016: Ultralow Power, Ultrafast, Integrated Nano-Optoelectronics and FY 2017: Scalable Certification of Quantum Computing Devices and Networks), with dedicated emphasis on the five NSI thrust areas. The National Nanotechnology Coordinated Infrastructure (NNCI) network is coordinating regional centers, universities, and education outreach. The largest public-private commitment (>$610 million) for a manufacturing institute in 2015 focused on integrated photonics and involved DOD.

This signature initiative has been recently complemented by a new effort in quantum-enabled systems. In December 2018, the President signed into law the new National Quantum Initiative (NQI), which supports a multiagency (NSF, NIST, and DOE) program to develop science and implement training in quantum information science (QIS).[24] To be successful with the NQI, quantum information communities will need to coordinate strongly with nanotechnology communities. Sensors related to national security could most likely benefit from nanoelectronics advances, although they are not a primary emphasis of the NSI. A relevant Institute of Electrical and Electronics Engineers (IEEE) report[25] from 2015 suggested that the United States does well in devices, materials, and architectures but that its unfunded areas include exotic nonequilibrium concepts and thermal management.

NSI on Nanotechnology Knowledge Infrastructure (NKI): Enabling National Leadership in Sustainable Design

The Nanotechnology Knowledge Infrastructure (NKI) signature initiative was launched in 2012 to "provide a community-based, solutions-oriented knowledge infrastructure to accelerate nanotechnology discovery and innovation."[26] The aim was to coordinate 11 member agency efforts (Consumer Product Safety Commission [CPSC], DOD, DOE, EPA, Food and Drug Administration [FDA], NASA, NIH, NIOSH, NIST, NSF, OSHA) to develop a community of practice that would leverage an agile modeling network for multidisciplinary research and applications development and develop a cyber-toolbox to turn models into effective materials design rules and a data and information sharing infrastructure across disciplines, applications, and agencies. This initiative was funded at the level of $20 million per year on average, until 2019. Upon completion, it was deemed a success, as the involved agencies have adopted the NKI-developed approach as a working protocol.

The coordination of large amounts of data across a wide variety of materials, disciplines, and application sectors was a considerable challenge clearly laid out in a 2012 white paper titled "Enabling

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[21] G. Moore, 1975, "Progress in Digital Integrated Electronics," *Technical Digest 1975*, International Electron Devices Meeting, IEEE, 1975, pp. 11-13.

[22] See https://www.darpa.mil/work-with-us/electronics-resurgence-initiative, accessed 11/04/2019.

[23] See https://www.nsf.gov/od/oia/convergence/index.jsp and https://www.nsf.gov/od/oia/convergence/exemplars.jsp, accessed 02/29/2020.

[24] See https://www.aip.org/fyi/2019/national-quantum-initiative-signed-law, accessed 11/04/2019.

[25] K. Golatsis, P. Gargini, T. Hiramoto, et al., 2015, Nanotechnology research gaps and recommendations, *IEEE Technology and Society Magazine* pp. 21-30, at http://www.nxtbook.com/nxtbooks/ieee/technologysociety_summer2015/index.php?startid=39#/22.

[26] See https://www.nano.gov/NKIPortal, accessed 11/04/2019.

National Leadership in Sustainable Design."[27] It leveraged a remarkable array of resources including the caNanoLab,[28] InterNano,[29] nano-hub,[30] the Nanomaterials registry,[31] the Nanomaterial-Biological Interactions Knowledgebase,[32] the Nanoparticle Information Library,[33] and Toxcast.[34] Tangible outputs from its objectives included the following:

1. A set of Data Readiness Level (DRL) definitions to provide a shorthand method for conveying coarse assessments of data maturity from experiments or model predictions;
2. A collaboration between the National Cancer Institute (NCI) Cancer Nanotechnology Laboratory portal (caNanoLab) and the Nanomaterial Registry;
3. A five-tiered process to evaluate the potential hazard of, and exposure risk associated with, a nanotechnology-enabled product or process (nanoGRID);[35] and
4. A collaboration between the Nanomaterial Registry and Nanohub.

Note that the activities of one U.S. federal agency in particular has captured the interest of other international players in nanotechnology—NIOSH has raised the bar for the global community in terms of work practices, evaluation protocols, and evaluation processes related to nanomaterials. In addition, the EU-U.S. Nanoinformatics 2030 Roadmap,[36] developed in 2017, used the results from the Nanotechnology Knowledge Infrastructure Signature Initiative.

However, while the 2012 white paper laid out expected outcomes, many were not subsequently tracked and measured, making a performance evaluation difficult. The available reports were brief and were not formulated within a framework amenable to performance evaluation. For instance, the white paper identifies the need to coordinate with the U.S. government's Materials Genome Initiative (MGI),[37] since it has overlapping goals and addresses a broader range of materials. However, this committee was unable to determine if efforts were coordinated and what tangible outcomes have resulted.

Shortening the time taken to bring new materials to market is key to competitive advantage and promoting national economic prosperity. Advances in materials are at the heart of technologies that are key to cybersecurity and defense; hence, key partners in this initiative were the DOD and NASA. In the age of data analytics and artificial intelligence (AI), the required data governance demanded by digital thread concepts[38] for manufacturing is particularly important. The NKI initiative is particularly relevant in

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[27] See https://www.nano.gov/node/825, accessed 11/04/2019.

[28] NIH Cancer Nanotechnology Laboratory. See https://cananolab.nci.nih.gov/caNanoLab/#/, accessed 11/04/2019.

[29] An information resource for the nanomanufacturing community, hosted by the National Nanomanufacturing Network. See https://www.internano.org/, accessed 11/04/2019.

[30] The U.S. federal site for computational nanotechnology research, education, and collaboration. See https://nanohub.org/, accessed 11/04/2019.

[31] Part of nanoHub, the Nanomaterials Registry is a central registry and growing repository of publicly available nanomaterial data. See https://nanohub.org/groups/nanomaterialregistry, accessed 11/04/2019.

[32] A repository for annotated data on nanomaterial characterization. See https://greennano.org/research/projects/knowledgebase, accessed 11/04/2019.

[33] NIOSH's web-based Nanoparticle Information Library (NIL). See http://www.nanoparticlelibrary.net/, accessed 11/04/2019.

[34] EPA Toxicity Forecasting tools. See https://www.epa.gov/chemical-research/toxicity-forecasting, accessed 11/04/2019.

[35] Z.A. Collier et al., 2015, Tiered guidance for risk-informed environmental health and safety testing of nanotechnologies, *Journal of Nanoparticle Research* 17(3):1-21.

[36] See https://www.nanosafetycluster.eu/outputs/eu-us-roadmap-nanoinformatics-2030/, accessed 11/04/2019.

[37] See https://www.mgi.gov/, accessed 11/04/2019.

[38] For an introduction to the concepts of the digital thread, see the 2016 *Industry Week Magazine* article, at https://www.industryweek.com/technology-and-iiot/systems-integration/article/22007865/demystifying-the-digital-thread-and-digital-twin-concepts, accessed 11/04/2019.

this context, not only for the building of databases and knowledge dissemination, but also for the training of highly qualified personnel capable of navigating the world of data analytics and informatics.

A number of countries and regions have systematically invested in nanoscience knowledge infrastructure (especially Japan and the EU) and have been diligent in measuring progress through clear key performance indicators. Fortunately, the U.S. competitive position has been monitored by the EU and others, providing the data that are not reported through the NNI. After investing in a number of AI centers across Canada (mostly academic expertise tied to universities, banks, Google, and Facebook), the Canadian government is now looking into materials development acceleration mechanisms. By contrast, the current state and investments in knowledge infrastructure for nanotechnology in China, especially in terms of coordination across its R&D institutions, is presently unknown.

NSI on Nanotechnology for Sensors, and Sensors for Nanotechnology: Improving and Protecting Health, Safety, and the Environment

Sensors play a key role in areas such as food safety, biological threats, chemical threats, personnel safety, and explosive detection. Nanotechnology is a component that can improve the performance of sensors for these diverse applications. The goal of this NSI is to support research on engineered nanomaterial properties and to develop supporting technologies that enable next-generation sensing of biological, chemical, and nanoscale materials.[39] This is a diverse initiative. One focus is to develop inexpensive, portable devices for biological and chemical sensing. Another focus is to develop methods and devices to detect and identify engineered materials across their life cycles in order to assess their potential impact on human health and the environment. The NNI sensor signature initiative research annual research funding has been in the range of $150 million to $250 million. However, the nanotechnology-specific component of the sensor economic impact is difficult to identify.

There appears to be broad interest among funding agencies in the general area of sensors and coordination to enhance the availability of the most effective technologies for national security applications. Communication among these agencies and coordination of research funding programs is valuable, as similar technologies can have applicability in different areas. For example, related technologies can be applied to spacecraft environmental monitoring, agricultural sensing, and medical diagnostics. The evaluation of impact of nanoparticles in the environment is important. The initiative is broad in scope. While it is clear that nanotechnology has been and remains an important component of sensor technologies, specific examples of major advances attributable to engineered nanostructures are somewhat lacking, as the committee has found.

Water Sustainability Through Nanotechnology

The goal of the Water Sustainability NSI, launched in 2016, is to use the unique properties of engineered nanomaterials to develop technological solutions that can alleviate current stresses on the water supply and provide methods to sustainably utilize water resources in the future.[40] The three thrusts of the NSI on water sustainability are (1) increase water availability using nanotechnology, (2) improve the efficiency of water delivery and use with nanotechnology, and (3) enable next-generation water monitoring systems with nanotechnology.

NNI efforts, beginning in 2016 at the launch of the NSI on water sustainability, have clearly promoted interagency collaboration, as evidenced by a collaborative white paper[41] identifying key

[39] See https://www.nano.gov/SensorsNSIPortal, accessed 11/04/2019.

[40] See summary and white paper from this NSI launch, at https://www.nano.gov/nsiwater, accessed 11/04/2019.

[41] See https://www.nano.gov/sites/default/files/pub_resource/water-nanotechnology-signature-initiative-whitepaper-final.pdf, accessed 11/04/2019.

challenges and goals with quantifiable outcomes against which progress can be measured. In 2016/2017, the National Nanotechnology Coordination Office (NNCO) produced three webinars, available on the website of the NNCO, highlighting challenges related to water sustainability that require solutions. The webinars involved participants from multiple federal agencies, providing further evidence of interagency collaboration stimulated by the NSI on water sustainability.

Within each of the federal agencies collaborating under the umbrella of the NSI on water sustainability, there are strong research programs bridging basic and translational research aligned with the NSI goal, including an Engineering Research Center (ERC; Nanosystems Engineering Research Center for Nanotechnology-Enabled Water Treatment [NEWT]) supported by NSF, a Small Business Technology Transfer (STTR) program supported by NASA, and USDA research programs on sensors for agriculture. The quality of the research performed under programs such as NEWT is excellent, and is advancing nanotechnology to address the water NSI thrust areas.

Subsequent to an initial burst of interagency activity coinciding with the launch of the NSI on water sustainability (in 2016), the committee found little evidence of follow-up collaborative efforts between the agencies in 2017 to 2019. The NNCO director indicated that several interagency efforts have recently been launched under the NSI, including organization of a symposium at a national meeting to showcase progress and interagency collaboration on a funding initiative. It is important that the NNCO continue to promote interagency collaboration and dissemination of the efforts.

Water is a critical national security issue. Within the United States, extreme weather events are increasingly common, and potentially disruptive to water supplies. Nanotechnologies have the potential to generate potable water at point of use. Outside the United States, the lack of availability of water is a potential contributor to international conflicts, many with substantial national security implications for the United States. Additionally, the development of technologies capable of providing clean water is critical for U.S. defense forces abroad and for strategic goals related to exploration of space.

Agricultural output of the western states of the United States relies heavily on the availability of water, and technologies that lead to more efficient transportation and availability of water will play a key role in sustaining economic prosperity. Nanotechnologies being developed within the scope of the NSI on water have the potential to provide significant energy savings by minimizing the need to transport water over long distances. The quality of basic research at the intersection of nanoscience and water sustainability, as evidenced by efforts such as the Engineering Research Center at ASU/Rice supported by NSF (NEWT), is excellent and world leading. A new DARPA program on Atmospheric Water Extraction also holds promise for a low-power approach for increasing the availability of potable water globally.[42] Relative to other countries (particularly in Europe), the NSI on water in the United States has apparently placed less effort on translational initiatives aimed at commercializing new technologies.

The NSI on water has been effective in promoting efforts in basic funding within federal agencies to address agency specific challenges related to, for example, space exploration, defense, and agriculture, but its impact on efforts to commercialize water-related nanotechnologies appears to have been limited. Since this NSI was launched 4 years ago, it would be timely to perform an interagency assessment of progress made toward the objectives of its three key thrusts, including identification of critical gaps in progress that need directed investment of resources.

Nanotechnology-Inspired Grand Challenge for Future Computing

This Grand Challenge[43] brings together scientists and engineers from many disciplines to look beyond the near-universal von Neumann computing architecture as implemented with transistor-based processors, and to chart a new path that will continue the rapid pace of innovation beyond the next decade to enable low-power cognitive computing. Specifically, the challenge is to "create a new type of computer that can

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[42] See https://www.darpa.mil/news-events/2019-12-12, accessed 02/03/2020.
[43] See https://www.nano.gov/about-nni/what/vision-goals, accessed 11/04/2019.

proactively interpret and learn from data, solve unfamiliar problems using what it has learned, and operate with the energy efficiency of the human brain." It is a coordinated and collaborative effort across multiple levels of government, industry, academia, and nonprofit organizations. R&D focus areas for federal R&D investments in support of this goal include (1) materials; (2) devices and interconnects; (3) computing architectures; (4) brain-inspired approaches; (5) fabrication/manufacturing; (6) software, modeling, and simulation; and (7) applications. Currently, there does not seem to be much publicly available material about this NSI, other than the overarching government *National Strategic Computing Initiative Update: Pioneering the Future of Computing* from the White House in 2019.[44]

PCA 2: Foundational Research

As defined by the NNI, foundational research includes the following:[45]

- Discovery and development of fundamental knowledge pertaining to new phenomena in the physical, biological, and engineering sciences that occur at the nanoscale;
- Elucidation of scientific and engineering principles related to structures, processes, and mechanisms;
- Research aimed at discovery and synthesis of novel nanoscale and nanostructured materials and at a comprehensive understanding of the properties of nanomaterials ranging across length scales, and including interface interactions; and
- Research directed at identifying and quantifying the broad implications of nanotechnology for society, including social, economic, ethical, and legal implications.

The committee observed that the relative strength of citations for U.S.-origin scientific publications is a strong indicator that it is among the leading nations for advancing foundational nanotechnology research in nanoscale materials and structures, even though its relative position is being eroded rapidly by competitors.[46,47] That said, it is not at all clear how much of this published foundational work depends causally on the coordination by the NNI, given that the NNI does not enumerate or otherwise account for the actual scientists and engineers who are actively involved in the NNI's aggregated activities. Further, although the committee was highly interested in assessing the impact[48] of PCA 2 on national security matters after nearly two decades of investment, it found that there are not substantive, validated means to assess the relative position of the United States in national security terms.[49] There are numerous, specific material systems and categories that differ in priority and emphasis by region (e.g., the strong investments in graphene in the EU) as well as relative strength and depth.

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[44] See https://www.whitehouse.gov/wp-content/uploads/2019/11/National-Strategic-Computing-Initiative-Update-2019.pdf, accessed 11/04/2019.

[45] See https://www.nano.gov/about-nni/what/vision-goals, accessed 11/04/2019.

[46] See H. Dong et al., 2016, The nanotechnology race between China and the United States, *Nano Today* 11:7-12, https://doi.org/10.1016/j.nantod.2016.02.001.

[47] Nanotechnologies output, impact, and collaboration: A comparative analysis of France and other countries, https://www.elsevier.com/__data/assets/pdf_file/0011/159959/Report_SciVal_Nanotechnology_France_2015.pdf, accessed 11/04/2019.

[48] See, for example, the section below, "Transfer of Discovery into Products for Commercial and Public Benefit," which addresses how other government programs document their direct impact on scientific output.

[49] See, for example, Implementation Recommendation 2a, in Chapter 4.

PCA 3: Nanotechnology-Enabled Applications, Devices, and Systems

PCA 3 addresses R&D that applies the principles of nanoscale science and engineering to create novel devices and systems, or to improve existing ones. It includes the incorporation of nanoscale or nanostructured materials and the processes required to achieve improved performance or new functionality, including metrology, scale-up, manufacturing technology, and nanoscale reference materials and standards. To meet this definition, the enabling science and technology must be at the nanoscale, but the applications, systems, and devices themselves are not restricted to that size.

Importantly, PCA 3 brings together efforts that incorporate and utilize nanoscale science into actual devices and systems at larger scales. Because this subject area is where nanoscience and nanoengineering are applied to actual devices or macro-scale systems, it is no surprise that PCA 3 is the second most highly funded. Its value has been mostly recognized and prioritized by NIH, which contributes almost 77 percent of PCA 3's funding toward medical devices, nanotherapeutics, drug delivery systems, and novel radiotherapeutics.

That said, from the definition and scope of PCA 3, there seems to be a natural overlap with some of the NSIs (e.g., Nanoelectronics for 2020 and Beyond, Nanotechnology for Sensors and Sensors for Nanotechnology, Nanotechnology-Inspired Grand Challenge for Future Computing), but the areas of overlap are not stated explicitly and the contributions of the NSIs to PCA 3 may not be accounted for clearly. Further, it appears that the strategic relevance of areas such as AI, Internet of Things (IoT), and quantum devices is not reflected in the budget allocation for PCA 3 nor in the overall body of information related to PCA 3.

Once more, the committee finds that it is hard to develop a quantitative evaluation of the outcome of R&D efforts within PCA 3 because the essential data for this are not tracked (e.g., by number of grants, number of people involved, papers, patents, students trained, etc. as a result of the awards funded by each agency in subjects pertaining to PCA 3).

While the impact of nanoscience and nanotechnology on national security is stated in the strategic plan of NNI and in the contributions to NNI from DOD, there does not seem to be an explicit description or available data for how the investments on PCA 3 have impacted national security. Nonetheless, DOD (the third largest contributor to funding for PCA 3) states that "Nanotechnology is an enabling technology for the new classes of sensors (such as novel focal plane arrays), communications, and information processing systems needed for qualitative improvements in persistent surveillance. The DOD also invests in nanotechnology for advanced energetic materials, photocatalytic coatings, active microelectronic devices, and a wide array of other promising technologies."[50]

It is regrettable that no data are readily available to evaluate contributions to economic prosperity from PCA 3. However, turning once again to patents as a measure of economic intensity, it seems clear that the U.S. Patent and Trademark Office (USPTO) and the European Patent Office (EPO)—the patents that target the richest economic markets—still issue many more patents to U.S. inventors.[51,52]

PCA 4: Research Infrastructure and Instrumentation

The fourth PCA supports the establishment and operation of user facilities and networks, the acquisition of major instrumentation, its use for workforce development, and other activities that develop, support, or enhance the nation's physical, cyber, or workforce infrastructure for nanoscience, engineering, and technology. It includes research to develop the tools needed to advance nanotechnology research and commercialization, including informatics tools and next-generation instrumentation for characterization,

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[50] See DOD information at https://www.nano.gov/DOD, accessed 11/04/2019.

[51] H. Zhu, S. Jiang, H. Chen, and M.C. Roco, International perspective on nanotechnology papers, patents, and NSF awards (2000–2016), *Journal of Nanoparticle Research* 19(11): 370, 2017.

[52] See https://statnano.com/report/s102, Accessed 11/04/2019.

measurement, synthesis, and design of materials, structures, devices, and systems. While student support to perform research is captured in other PCAs, dedicated educational efforts ranging from curriculum development to advanced training are included as resources supporting the workforce infrastructure of the NNI.

As the most recent NNI Strategic Plan states,[53]

> The nanotechnology enterprise requires support for a widely accessible state-of-the-art physical infrastructure. As nanotechnology rapidly advances, shared-use facilities must maintain existing tools and continuously refresh their equipment to meet the evolving needs of users from industry, academia, and government for synthesis, processing, fabrication, characterization, modeling, and analysis of nanomaterials and nanosystems. In many cases, single researchers or institutions find it difficult to justify funding the acquisition of and support for all necessary tools. Therefore, user facilities critically enable R&D and accelerate commercialization by co-locating a broad suite of nanotechnology tools, maintaining and replacing these tools to keep them at the leading edge, and providing expert staff to ensure the most productive use of the tools. The facilities also support the development of advanced nanoscale fabrication methods and measurement tools. Finally, shared facilities are a vital resource for training nanotechnology researchers and for creating a community of shared ideas by mixing researchers from different disciplines and sectors.

Through its partnering agencies, the NNI supports a number of world-class physical user facilities and user facility networks, including:

- NSF National Nanotechnology Coordinated Infrastructure (NNCI)[54]
- DOE Nanoscale Science Research Centers (NSRCs)[55]
- NIST Center for Nanoscale Science and Technology (CNST)[56]
- National Cancer Institute (NCI) Nanotechnology Characterization Laboratory (NCL)[57]

This physical nanotechnology infrastructure is complemented by the NSF Network for Computational Nanotechnology (NCN);[58] a cyber-physical infrastructure for nanoscience and technology research.

Since the launch of the NSF-funded National Nanotechnology Infrastructure Network (NNIN; 2004-2015)—the predecessor program to the NNCI—the U.S. nanotechnology infrastructure programs have been recognized as international leaders and viewed as a “role model” by which infrastructures in other countries have been developed. They have worked collaboratively across agencies and sites to ensure that the United States was at the forefront of tool development for materials production, processing and forming, and related metrology. Concerted efforts were made to collocate tool-sets that would facilitate groundbreaking R&D at the nanoscale. Today, however, comparable infrastructure resources exist in many parts of the world with very significant financial resources committed to maintain and expand them. Examples from North America, Europe, and Asia include the following:

- Canada’s National Design Network[59] (managed by CMC-Microsystems[60])
- Nanotechnology Platform Japan (NTPJ)[61]

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[53] National Nanotechnology Initiative Strategic Plan, October 2016, at https://www.nano.gov/sites/default/files/pub_resource/2016-nni-strategic-plan.pdf, accessed 11/04/2019.

[54] See https://www.nnci.net, accessed 11/04/2019.

[55] See https://nsrcportal.sandia.gov, accessed 11/04/2019.

[56] See https://www.nist.gov/cnst, accessed 11/04/2019.

[57] See https://ncl.cancer.gov, accessed 11/04/2019.

[58] See https://nanohub.org/groups/ncn, accessed 11/04/2019.

[59] See https://www.cmc.ca, accessed 11/04/2019.

[60] See https://www.cmc.ca/, accessed 11/04/2019.

[61] See https://www.nanonet.go.jp/ntj/english/, accessed 11/04/2019.

- Australian Nanotechnology Network[62]
- EuroNanoLab[63]
- Nordic Nanolab Network[64] in Scandinavia
- NanoLabNL[65] in the Netherlands
- Forschungslabore Mikroelektronik Deutschland (ForLab)[66] in Germany
- National Center for Nanoscience and Technology,[67] in Beijing, China
- National Engineering Research Center for Nanotechnology,[68] in Shanghai, China
- Suzhou Institute of Nano-Tech and Nano-Bionics (SINANO),[69] in Suzhou, China

These international infrastructure programs and nanotechnology hubs represent significant. investments in their respective regions. As an example, SINANO was founded in 2006 by the Chinese Academy of Sciences with local authorities to support nanotechnology research related to information, energy, life sciences, and the environment. In 2014, construction started for the Vacuum Interconnected Nano-X Research Facility[70] as part of SINANO, which claims to be the largest multifunctional research platform in the world, with hundreds of pieces of equipment for material growth, device fabrication, and testing, all interconnected by vacuum pipelines to avoid contamination of surfaces. The initial investment was RMB 320 million (about $45 million) with a total planned investment of RMB 1.5 billion ($210 million USD). The committee knows of no equivalently equipped site in the United States. In Japan, the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) established the NTPJ[71] in 2012 to ensure a reliable research infrastructure to support scientific innovation through sharing cutting-edge equipment and research know-how across 25 institutes and universities comprising 37 facilities.[72] The NTPJ includes an Advanced Characterization Platform, a Nanofabrication Platform, and a Molecule and Materials Synthesis Platform.

Besides infrastructure networks and hubs, several countries have established significant innovation and technology transfer hubs in the area of nanotechnology, specifically to accelerate product development. Examples include

- China: Nanopolis Suzhou (http://www.nanopolis.cn/en/Index.aspx)
- Japan: nano (https://www.nano.jp)
- Belgium: IMEC (https://www.imec-int.com/en/home)
- France: MINATEC (https://www.minatec.org/en/)
- Canada: C2MI (https://www.c2mi.ca/en/)

National nanotechnology associations—such as Nanotechnology Business Creation Initiative (NBCI) in Japan, Nanotechnology Research Alliance (NTRA) in Korea, NanoCanada, Malaysia Nanotechnology Association, and the Nano Regions Alliance across 17 European countries—also plays an important role in connecting their stakeholders small and mid-size enterprises (SMEs), multinational enterprises

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[62] See http://ausnano.net, accessed 11/04/2019.
[63] See http://euronanolab.net, accessed 11/04/2019.
[64] See http://nordicnanolab.se, accessed 11/04/2019.
[65] See https://nanolabnl.nl, accessed 11/04/2019.
[66] See https://www.elektronikforschung.de/service/aktuelles/forschungslabore-mikroelektronik-deutschland-gestartet, accessed 11/04/2019.
[67] See http://english.nanoctr.cas.cn, accessed 11/04/2019.
[68] See http://en.sjtu.edu.cn/research/centers-labs/national-engineering-research-center-for-nanotechnology, accessed 11/04/2019.
[69] See http://english.sinano.cas.cn, accessed 11/04/2019.
[70] See http://english.sinano.cas.cn/au/NANOX/, accessed 11/04/2019.
[71] See https://www.nanonet.go.jp/ntj/english/, accessed 11/04/2019.
[72] See https://www.nanonet.go.jp/ntj/english/insti/, accessed 11/04/2019.

(MNEs), academia, and government so that expertise and facilities can be deployed to advance nanoscience and the commercialization of nanotechnologies. They do so through coordination of infrastructure; business matching; road-mapping activities; organization of international, national, and regional symposia and conferences; as well as international outreach for global competitiveness.

The U.S. nanotechnology infrastructure remains a considerable strength. While the particular access models to U.S. physical user facilities are somewhat different from facility to facility, the underlying goal of all the user facilities is to provide simple access for academia, industry, and government researchers to state-of-the-art nanofabrication and nanocharacterization tools and the associated highly trained staff expertise. The impact and reach of these user facilities can be assessed from their annual reports. As an example, the newest annual report of the NNCI, published in March 2019,[73] states that the more than 2,000 tools within the network of 16 sites and 13 partners have "been accessed by more than 13,000 users including nearly 3,400 external users, representing >200 academic institutions, >900 small and large companies, ~50 government and nonprofit institutions, as well as 46 foreign entities." These numbers continue to increase, highlighting the continued growing need for access to enabling research infrastructure well after the official start of the NNI. This establishment and operation of core facilities, such as the NNCI, is considered a key strength of the NNI, with impact reaching communities even beyond the classical nanoscale engineering and science. The five DOE NSRCs provide complimentary facilities capabilities that are internationally accessible,[74] NIST operates a NanoFab user facility,[75] and the NCI operates an NCL.[76] These broadly accessible core facilities are particularly useful for small companies and users from universities outside the network institutions. Access to these core facilities is truly enabling, as many of the tools are simply too expensive to acquire. To ease access and promote a diverse user base, the user facilities have developed a wealth of programs, including seed grant programs to fund scientists to try out new ideas and "remote work" capabilities, whereby the work is actually performed by facilities' staff. The training aspect of the user facilities is often overlooked. The NNCI network alone trains more than 5,000 new users on an annual base. It is understood that many of these users are Ph.D. students who join nanotechnology companies or continue to do nanotechnology research at U.S. academic institutions after finishing their Ph.D.'s. They are a critical component of the talent pipeline that is so essential to this field. Last but not least, state-of-the-art core facilities help attract top overseas talent to the United States, ranging from undergraduate and graduate students to exceptionally gifted faculty and senior researchers. This activity is viewed by the committee as being crucial for the U.S. nanotechnology program to remain competitive on an international scale.

Besides the physical infrastructure in form of nanotechnology core facilities, the Network for Computational Nanotechnology (NCN) maintains a cyber-physical infrastructure, which includes the operation and advancement of nanoHUB.[77] Today, the nanoHUB provides over 5,500 resources for research and education, including courses, tutorials, seminars, discussions, and facilities to foster nano-research collaboration. This includes a library of over 500 simulation tools, free from the limitations of running software locally. Annually, over 1.4 million visitors participate in nanoHUB and over 12,000 people annually use simulation tools on nanoHUB.[78]

The critical weakness, first identified in the 2016 Triennial Review of the NNI,[79] is that equipment recapitalization of the facilities has become a key challenge. R&D workers observe that it is often more challenging to fund replacement of aging "workhorse" tools in nanotechnology core facilities, such as a mask aligner, a metal deposition system or an etching tool, than to purchase state-of-the-art research

[73] NNCI Coordinating Office Annual Report for Year 3, https://www.nnci.net/nnci-annual-report, accessed 11/04/2019.

[74] See https://nsrcportal.sandia.gov/Home/About, accessed 11/04/2019.

[75] See https://www.nist.gov/cnst, accessed 11/04/2019.

[76] See https://ncl.cancer.gov, accessed 11/04/2019.

[77] See https://nanohub.org/, accessed 11/04/2019.

[78] See https://nanohub.org/usage, accessed 1/30/2020.

[79] National Research Council, 2016, *Triennial Review of the National Nanotechnology Initiative*, Washington, D.C., The National Academies Press.

equipment, such as the latest aberration-corrected electron microscope or next-generation electron beam lithography system. The NSF Major Research Instrumentation (MRI) program, the NIH Shared Instrumentation Grants (SIG), and the DOD Defense Research Instrumentation Program (DURIP) are all excellent programs designed to enable the acquisition of new capabilities; however, because of the funding review processes and evaluation criteria, they are generally not suitable sources of support for replacement of aging workhorse tools. Many U.S. universities also invest heavily in nanotechnology core facilities, as highlighted by the recently opened $400 million MIT Nano building.[80] However, other countries are investing heavily in their nanotechnology infrastructure, and "the U.S. has already seen some of its top nanotechnology researchers leave for international opportunities because of the availability of superior research infrastructure."[81]

Furthermore, it is noted that the current infrastructure programs (e.g., NSF NNCI, NSF NCN, NIST NanoFab, and the DOE NSRCs) could be more impactful if better coordinated through the NNCO. Indeed, the community would benefit from a stronger coordination of facilities/tools, activities, and collaborative efforts, especially considering the complementary expertise and capabilities of the infrastructure networks. At the moment, the NNCI's educational and simulation resources being hosted on nanoHUB, provides a limited platform for networks to collaborate.

Many of the international infrastructure networks have been modeled after the U.S. nanotechnology infrastructure networks—in particular, the NNIN. However, the funding of these networks has evolved to sustain the operation of physical and cyber-physical infrastructure as well as tool recapitalization. A robust infrastructure investment model is key for the United States to avoid losing its international competitiveness.

Barriers to access also still remain, ranging from lack of awareness, to limits to accessibility, to unaffordable cost of use. Therefore, the NNI user facilities and networks must continue to develop programs, in partnership with funding agencies, to overcome such barriers. As an example, while research grants might pay for the access to user facilities, the researcher typically must travel to the user facility, and travel cost, especially in case of extended stays, is often a limiting factor.

Last, other countries leading in the field of nanotechnology in terms of its translation into the marketplace have created national nanotechnology organizations that provide effective and often synergistic links across their ecosystem; they monitor and share data on the competitive landscape, analyze emerging trends, and advocate for strategic, and in some cases rapid, investments in key technology areas. An opportunity for the NNI to be a catalyst for the creation of such an organization in the United States now exists.

The impact upon economic prosperity resulting from use of the physical and cyber-physical nanotechnology infrastructure is considered to be tremendous by the committee, even though it is difficult to assess numerically, at least in part because the NNI has not been highly effective in collating relevant data. As mentioned above, the NNCI network alone is used by more than 900 companies on an annual basis, with more than 700 of these being small companies; many start-up companies develop their first prototypes in the core facilities.

PCA 5: Environmental Health and Safety

The United States has implemented and maintained a sustained R&D commitment to responsible nanomaterials innovation, and this continues at a time of decreased investment in this area. In 2016, about 10 percent of NNI agency funding was devoted to the environmental health and safety (EHS) of nanomaterials and devices, while in 2020, the estimate is 4 percent, or $80 million, according to the NNI

[80] See http://mitnano.mit.edu, accessed 11/04/2019.
[81] C. Mirkin, presentation to the committee.

Supplement to the 2020 President's Budget.[82] The focus continues to advance the goals of PCA 5, Environmental Health and Safety, under NNI Goal 4 (to support responsible development of nanotechnology).

When materials are synthesized or otherwise fabricated with dimensions in the nanoscale regime, the ratio of their surface area to weight dramatically increases. As a consequence, they sometimes exhibit much higher reaction rates with other materials and can exhibit different behaviors in the environment as compared to their bulk counterparts. Their very high surface area to mass ratio can result in very long sedimentation times once particles enter the atmosphere, and their very small dimensions allow penetration through skin and other membranes within the body, enabling them to be efficiently transported throughout living systems. The bio-chemo-physical properties of some nanomaterials are influenced by their surface structure, leading them to exhibit properties that are different from bulk forms of the same materials. It has therefore been important to understand the impact of these novel states of matter upon living systems and the environment before large-scale commercialization begins.

The U.S. research on the effects of exposure to nanomaterials in the workplace, in products, and upon the environment is unparalleled. This has been achieved through extensive interagency collaborations that have both advanced knowledge and improved methods and practices in occupational safety. These collaborations include voluntary workplace testing by NIOSH, by research on consumer product nanoparticle releases by CPSC and NIOSH, and by CPSC collaboration with NIST on a dust exposure survey with NIST. The EPA, CPSC, and NIOSH are also cooperating on characterizing nanoscale exposures related to three-dimensional (3D) printing. The USDA National Institute of Food and Agriculture (NIFA) advances biological and environmental safety research for food and agriculture, while NIH collaborates with FDA on National Toxicology Program bioassays and funds a consortium focused on toxicology research. In addition, the U.S. Forest Service (USFS) participates in a public-private partnership known as P3Nano to advance commercialization.[83] In collaborations with the U.S. Endowment for Forestry and Communities, it is funding safety methods and data development involving collaborations with NIST, NIOSH, and industrial producers of cellulose nanomaterials. This partnership is working to establish the safety of cellulose nanomaterials, since these are expected to become high production volume bio-based nanomaterials, with a wide range of applications such as in automotive composites, building products, electronics, food, and barrier packaging.[84] This innovative public-private funding model allows the USFS to advance work necessary for commercialization more quickly and at a fraction of the cost to the government.

Advancing knowledge of the biological activity and environmental behavior of nanomaterials is essential for sustainable commercial development of advanced materials and technologies, and leads to safer manufacturing and product designs. Past U.S. investment has focused on the toxicity of relatively few pristine materials at high exposure levels, meaning that research designs have limited the utility of studies to be used for risk assessment.[85,86,87] However, the current focus remains on measurement infrastructure, health and environment (including ecosystem behavior and impacts), linking exposure to health outcomes, human exposure assessment to workers and products risk assessment and management

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[82] See https://www.nano.gov/sites/default/files/pub_resource/NNI-FY20-Budget-Supplement-Final.pdf, accessed 11/04/2019.

[83] See https://www.usendowment.org/what-we-do/innovation/p3nano-advancing-commercialization-of-cellulosic-nanomaterials/, accessed 02/29/2020.

[84] A. Rudie, USDA, presentation to the committee, July 30, 2019, Washington, D.C.

[85] J.D. Ede, K.J. Ong, M. Goergen, A. Rudie, C.A. Pomeroy-Carter, and J.A. Shatkin, 2019, Risk analysis of cellulose nanomaterials by inhalation: current state of science, *Nanomaterials* 9(3):337, doi:10.3390/nano9030337.

[86] D.B. Warheit and E.M. Donner, 2015, How meaningful are risk determinations in the absence of a complete dataset? Making the case for publishing standardized test guideline and "no effect" studies for evaluating the safety of nanoparticulates versus spurious "high effect" results from single investigative studies, *Science and Technology of Advanced Materials* 16(3):034603.

[87] H.F. Krug, 2014, Nanosafety research—are we on the right track? *Angewandte Chemie International Edition* 53(46):12304-12319.

(focus on research gaps and priorities, in vitro and alternative testing strategies), informatics and modeling, and other areas including collaborations, workshops, outreach and signature initiatives. International collaborations are supported by the NNCO through seven committees in Communities of Research between the United States and Europe.

Because of issues such as lack of standard sample preparation techniques and diversity of test conditions, there remains limited insight about how the physical and chemical properties of engineered nanomaterials influence their biological behavior. Unanswered questions critical for commercial adoption remain, especially regarding behavior of more complex nano-enabled materials, such as 2D materials as well as emerging and advanced materials and technologies. There is a need for more thorough evaluation in risk assessments drawing on the foundations established by NNI agencies.[88]

International Competitiveness

The EU has also been a leader in responsible nanomaterials innovation and has increased funding and strengthened its public-private cooperation through the Horizon 2020 Framework Program, and the follow-on Horizon EU program. The situation in Europe is enviable: the EU NanoSafety cluster[89] continues to advance knowledge, cooperation, and policy-relevant data sets, a result of funding large, multistakeholder projects, such as NanoSafe,[90] NanoReg,[91] and NanoReg2.[92,93] These projects engage companies, governmental researchers, and academics to conduct research and integrate findings into practice. An example is the Horizon 2020 Graphene Flagship, a €10 billion, 10-year project, with one component advancing knowledge of the 2D material for biomedical and EHS purposes. The shifting focus of the Horizon Europe funding program is toward innovation in advanced materials, including their role in climate, energy mobility, health, food, agriculture, the bioeconomy, environment, and natural resources. “Safer by design” and safety are key components of the EU Horizon 2020 initiative.

One of government’s responsibilities is the requirement to keep an updated repository of nanomaterials and gather information on their safety and use. This requires government agencies and departments to collaborate to share information and toolsets, and coordinate participation in international standards and regulation development. For example, in 2017, the European Union launched the EU Observatory of Nanomaterials (EUON)[94] to create a one-stop shop where citizens and stakeholders (e.g., NGOs, industry, and regulators) can find relevant safety information on nanomaterials on the EU market. The NNCO also provides analogous relevant safety-related information on its website.[95]

Japan has also made substantial investment in EHS of nanomaterials. The model is different, as companies generally participate in initiatives in which the research is performed by a government agency. The Japanese Ministry of Economy Trade and Industry started the Nanocellulose Forum with over 300 corporate members,[96] and is conducting research to develop methods for use by industry for occupational health and safety testing. Japan is the global leader in commercial development of cellulose-based nanomaterials.

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[88] J.D. Ede, K.J. Ong, M. Goergen, A. Rudie, C.A. Pomeroy-Carter, and J.A. Shatkin, 2019, Risk analysis of cellulose nanomaterials by inhalation: current state of science, *Nanomaterials* 9(3):337, doi:10.3390/nano9030337.

[89] See https://www.nanosafetycluster.eu/, accessed 11/04/2019.

[90] See http://www.cea.fr/cea-tech/pns/nanosafe/en/Pages/European%20Commission/European-Commission.aspx, accessed 11/04/2019.

[91] See http://www.nanoreg.eu/, accessed 11/04/2019.

[92] See http://www.nanoreg2.eu/about, accessed 11/04/2019.

[93] See https://www.nanosafetycluster.eu/wp-content/uploads/NSC%20Outputs/Compendium/2017_NSC_Compendium.pdf?_t=1537124047, accessed 11/04/2019.

[94] See https://euon.echa.europa.eu/, accessed 11/04/2019.

[95] See https://www.nano.gov/LabSafety, accessed 11/04/2019.

[96] See https://unit.aist.go.jp/rpd-mc/ncf/index_en.html, accessed 11/04/2019.

Accomplishments of PCA 5

The impacts of the NNI on EHS have included the development of a knowledge base sufficient to allow regulatory and safety processes to develop and be streamlined, which is critical to successful technology development by the private sector. Efficient regulatory and market processes rely on safety demonstration to adopt new technologies and authorize their use. The foundational understanding has been accomplished through the investments and coordination of the NNI, and the continued focus on EHS and responsible innovation. Unlike previous types of innovation, EHS issues for nanomaterials have been investigated in real time, as basic research on their synthesis and properties was also being conducted. This has been inherently challenging, as there was significant work required on metrology and characterization. In review, a significant body of knowledge has been built over the 16 years of the NNI. Further, the collaborative partnerships resulting from NNI coordination on EHS has built a professional community and shared infrastructure that will support responsible innovation as nanotechnology continues on its path to commercialization.

These observations indicate that for the United States to compete successfully in future nanotechnology commercialization, it should be a leader in R&D of the tools needed to ensure responsible development and safe use of nanotechnology. This includes improved occupational test methods, alternative testing assays, predictive modeling and risk assessment across the product life cycle, and economically important materials, such as alternatives to limited critical materials, including carbon-based nanomaterials such as graphene and carbon nanotubes whose commercial applications appear to be growing closer. Beyond research, the United States has the opportunity to assert leadership in responsible innovation through investments in bio-based high-performance materials, such as cellulose nanomaterials, and safer-by-design innovation methodologies. The resulting materials and technologies will contribute to economic prosperity by allowing more efficient and sustainable manufacturing with lower energy and material costs.

Over 16 years, EHS funding resulted in the development of some broader data sets for select key materials, as well as test methods, including the advancement of alternative testing strategies for assessing the toxicity and grouping nanomaterials.[97] The body of EHS research relieved some unfounded early concerns about the safety of nanomaterials relative to their conventional counterparts, and elucidated novel mechanisms related to the physical or particulate aspects of nanomaterials.[98] NNI agency funding from NIST and NSF included reviews of trends advancing nano-EHS risk assessment.[99] Safety demonstration is integral to commercialization and adoption. Further, interagency collaboration via NNI/NNCO and international cooperation with the Organization for Economic Cooperation and Development (OECD), the US-EU Communities of Research (US-EU CORs), and the International Standards Organization (ISO) has fostered increased efficiency in EHS investigation and use of the work to advance programmatic objectives (EPA/FDA/USDA) of regulatory agencies. In terms of international competitiveness, the EHS research strategy coordinated by the NNI continues to improve regulatory acceptance of new technologies, as noted in the more than 200 premanufacturing notices for new nanoscale materials by the EPA, as well as NIOSH Field Team investigations into more than 100 private manufacturing facilities.

The NNI remains a critical enabler of foundational environmental health and safety research related to nanotechnology. In particular, coordination of research efforts across agencies leverages expertise and resources to advance knowledge and state of practice. NIOSH leads federal research in occupational safety and health, with a dedicated research center and industry collaboration via field studies teams. The field teams "assess workplace processes, materials, and control technologies associated with nanotechnology. Research laboratories, producers and manufacturers working with engineered

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[97] H. Godwin, University of Washington, presentation to the committee.
[98] H. Godwin, University of Washington, presentation to the committee.
[99] NNI NSET, 2019, The National Nanotechnology Initiative Supplement to the President's 2020 Budget.

nanomaterials have the opportunity to participate in a cost-free, on-site assessment."[100] To date, NIOSH has "completed assessments at over 100 facilities that are involved in the research, manufacture, or use of various types of nano and advanced materials and manufacturing processes."[101,102]

From 2009-2016, NIST led the establishment of fundamental measurement infrastructure in support of nanotechnology-related EHS research.[103] The program produced 9 reference materials and 24 engineered nanomaterial measurement protocols available online[104] in addition to over 200 publications. Further, program leadership engaged in relevant standards development organizations and facilitated collaboration across agencies and governments. Federal agencies have also extensively partnered across industry, academia, and professional associations as a result of NNI focus and support to foster responsible nanotechnology innovation.

The nation's EHS research on responsible innovation directly supports the NNI mission by addressing one of the major obstacles to transfer of new technologies into safe products. This occurs by the collection of data, the development of safety guidelines and the transfer of safety test methods to the private sector. Less obvious, but of equal importance is general support of science, technology, engineering, and mathematics (STEM) education and workforce training programs on EHS and related topics by NNI agencies. However, past work has tended to focus on analysis of a relatively few, well-studied, and relatively conventional nanoscale substances—for example, silver, carbon nanotubes (CNT), and titanium dioxide (TiO_2)—toward methods development. Further, there were few instances of interlaboratory comparisons of repeat experiments[105] limiting comparability or interpretation of studies for risk assessment. As mentioned, many studies conducted at unrealistically high concentrations led to findings that are not easy to interpret for risk assessment.[106]

The International Coordination of Standardization Efforts of Environmental Health and Safety

Standards are essential for the successful commercialization of nanotechnology-enabled products. Internationally, the ISO, the OECD, and others develop standards that regulators, researchers, and industry use to develop specifications, provide guidance, or indicate best practices, and many impact environmental health and safety aspects of nanomaterials and nanotechnologies. The United States participates in most of these efforts. Standards are needed to facilitate clear communication about materials using common language. Clear terminology is especially important when researchers from different fields are communicating about quality, properties, amounts, and observations from different materials. Standards for measurement and characterization are necessary to ensure that what is produced meets specifications, and what is tested in assays is consistently reported. There are a variety of standards, including documentary standards for practices and reference standards for materials. ISO has developed more than 47 standards and 23 reports for nanomaterials and nanotechnologies in Technical Committee 229 (TC229), with many in revision and many others in development. All of these documents are consensus standards, and are described as Technical Specifications, Technical Reports, Technical Guides, and others.

Many standards have been developed that relate to and support responsible development, for example, that include occupational handling guidelines, testing strategies, and sample dispersion protocols for testing. Standards improve the reliability of data and promote consistency in standards of

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[100] See https://www.cdc.gov/niosh/topics/nanotech/nanotechnology-research-center.html, accessed 11/04/2019.

[101] See https://www.cdc.gov/niosh/topics/nanotech/field.html, accessed 11/04/2019.

[102] *Highlights of Recent Research on the Environmental, Health and Safety Implications of Engineered Nanomaterials*, https://www.nano.gov/sites/default/files/pub_resource/Highlights_Federal_NanoEHS_FINAL.pdf, accessed 11/04/2019.

[103] See https://doi.org/10.6028/NIST.SP.1233, accessed 11/04/2019.

[104] See https://www.nist.gov/mml/nano-measurement-protocols, accessed 11/04/2019.

[105] See https://ehp.niehs.nih.gov/doi/10.1289/ehp.1306561, accessed 11/04/2019.

[106] See https://www.sciencedirect.com/science/article/pii/S2452074817300629, accessed 11/04/2019.

practice. While international standards are voluntary, they are promoted as a way to generate consistent information, making it easier for regulatory agencies to accept studies, and for commercial organizations to create information and implement actions that facilitate quality and reliability. In some cases, regulatory agencies accept these standards for meeting testing requirements. The ISO TC229 2011 Business Plan suggests that international standardization efforts will "support technological development, societal acceptance and market expansion" in the nanoscale sciences and technologies in a variety of ways, including by identifying gaps and needs, developing test protocols, and supporting regulation and communication.[107] There was an effort to develop a Responsible Nanotechnology document by the European Committee for Standardization (CEN), but it was never finalized.

Intersectoral Collaboration on EHS

The NNI, through the NNCO, facilitates coordination and outreach regarding standards, including hosting webinars, participating in the American National Standards Institute (ANSI), and other efforts to advance standards development. The NNI has helped foster public and private cooperation in the United States. There are several examples of intersectoral cooperation between industry and others on responsible innovation. Many of these began or occurred more than 10 years ago—for example, the Responsible Nano Code, a multisector derived set of principles for nanomaterials research. In 2005, the American Chemistry Council and the Environmental Defense (now the Environmental Defense Fund, or EDF) issued a set of jointly agreed to principles on the development of nanotechnologies. In 2007, DuPont collaborated with the EDF to develop a nano risk framework to establish a process for responsible development of nanomaterials. This facilitated cooperation with the EPA, DOE, DOD, as well as OECD and ISO. Long-term collaboration between NASA, NIOSH, DOD, NIST, and others with small and large companies included EHS testing and manufacturing design to address occupational and regulatory requirements during scale up.[108] The Nanotechnologies Industry Association (NIA) is an industry group in Europe that participates in a variety of EU-funded research efforts, standards development among others. Companies such as DuPont, Cabot, Chemours, BASF, and Evonik participate in international efforts such as the American Chemistry Council Nanotechnology Panel, which participates in the OECD WPMN via the BIAC (Business at OECD) Nanotechnology Committee, a business and industry council, as well as national and international standards panels. Some of these companies are also participants in a German governmental initiative called NanoCare,[109] with 14 other companies, universities, and research facilities. The BASF code of conduct is based on the German federal government principles. In 2014, BASF developed a code of conduct to ensure responsible handling of nanomaterials. This was and continues to be part of their commitment to nanosafety research, workplace safety, and participation in international efforts.

In the United States, the U.S. NanoBusiness Commercialization Association[110] was founded in 2001 to advance research, innovation, and commercialization, and includes specific focus on regulatory aspects of commercial development in its monthly and annual meeting. Chemicals industry groups such as the American Chemistry Council,[111] the Personal Care Products Council,[112] and the American Cleaning Institute[113] have also been active in providing perspectives on nanotechnology standardization and regulation.

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[107] F. Wickson and E. Forsberg, 2014, Standardising responsibility? The significance of interstitial spaces, *Science and Engineering Ethics* 21, doi:10.1007/s11948-014-9602-4.

[108] E.J. Siochi, NASA, presentation to committee, November 2019.

[109] See https://nano-care.com/company/, accessed 02/29/2020.

[110] See https://www.nanobca.org/, accessed 02/29/2020.

[111] See https://www.americanchemistry.com/, accessed 02/29/2020.

[112] See https://www.personalcarecouncil.org/, accessed 02/29/2020.

[113] See https://www.cleaninginstitute.org/, accessed 02/29/2020.

OVERALL ASSESSMENT OF VALUE OF THE PCAS

After conducting this assessment, the committee recognized that the PCAs have served a useful organizing purpose that has promoted interagency coordination in areas of national relevance. Further, the current coordination approach has resulted in uneven investments across the four goals, leaving technology transfer and workforce development are relatively poorly funded in comparison to fundamental research, infrastructure, health, and public safety. However, it has been difficult to quantify the real level of effort applied to each area owing to the lack of data and to determine the true impact of each of these investments. Without an improved capability to quantify resource allocations and measure progress, there is a concern that effective leadership of the existing PCAs will be difficult to execute. Even more problematic, the committee's preliminary analysis indicates the presence of significant inertia to change that will make it very difficult for the United States to adapt quickly and adeptly to technical breakthroughs and adapt national priorities in a timely manner. In the past, when the global nanotechnology arena was paced by the work of the United States, this approach to NNI coordination was more appropriate. However, in the current era of intense competition and increasing risk of technological surprise, the committee is concerned that the organizing principles and budgetary arrangements to execute an agile program are inadequate. The identification of a new approach has become an imperative.

Transfer of Discovery into Products for Commercial and Public Benefit

The NNI, as coordinated via the NSET and the NNCO starting in 2000, enabled the United States to establish early leadership in the development of knowledge and facilities in many facets of nanoscience and nanotechnology. As other countries then followed the U.S. lead by formulating and implementing their own nano-initiatives, the investments in R&D of these other countries have naturally occurred further along the nanoscience-to-technology continuum. This delayed timing of investment outside the United States has allowed other countries to benefit from foundational nanoscience research developed through early efforts in the United States, and to more effectively focus their investment in areas ripe for commercialization and public benefit. While the United States has begun to benefit from knowledge flows in the opposite direction, there is a growing concern, as detailed below, that other countries have establish facilities and innovative mechanisms for agile commercialization that go beyond those that currently exist in the United States. A particular focus abroad has been directed toward the development of multifaceted innovation ecosystems that aim to increase success in navigating the "valley of death" by integration of resources that go beyond those found in NNI legacy infrastructure and facilities in the United States. This valley of death typically occurs 10-15 years after an initial breakthrough when the immediate luster of the discovery has worn thin or been swamped by newer developments, and before commercial "application pull" has been firmly established. Researchers are at this point for many of the discoveries and inventions achieved in the early years of the NNI. Examples of technologies enabled by the NNI in the early 2000 that remain in the valley of death include nanophotonics (including 2D materials), DNA nanotechnology, nanosensors for medical diagnostics, and nanoelectronics (molecular electronics).[114]

A March 2018 report from the Center for R&D Strategy[115] (which is part of the Japan Science and Technology Agency),[116] shares that Japan's prioritized nanoscience and nanotechnology goals are (1) the development of strong industry-university collaboration and (2) the establishment of an ecosystem for trial commercialization. This priority is reflected in the Tsukuba Innovation Arena,[117] with its focus on providing facilities and expertise in key areas of nanoscience and nanotechnology, including

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[114] M, Roco, presentation to the NNI committee, March 14, 2019.
[115] See https://www.jst.go.jp/crds/pdf/en/crds_brochure201907.pdf, accessed 11/04/2019.
[116] See https://www.jst.go.jp/EN/, accessed 11/04/2019.
[117] See https://unit.aist.go.jp/adperc/cie/tia/index.html, accessed 11/04/2019.

nanoelectronics, power electronics, N-MEMS, nano-GREEN, carbon nanotubes, and nanomaterials safety. In 2015, the innovation arena comprised 145 companies and engaged 600 external researchers. Complementing this central hub, Japan created the Nanotechnology Platform Japan in 2012, a delocalized national platform that by 2016 had facilities in 26 member institutes and universities, 3,000 users annually, and an annual budget of 1.7 billion yen ($15.5 million USD).[118]

The Nanotechnology Business Creation Initiative (NBCI) in Japan[119] is an industry-driven organization supported by membership dues (e.g., from participating multinationals, small and medium-size enterprises, trading companies, venture capital and consulting firms, and universities). NBCI works across the Japanese nanotechnology ecosystem to support related business activities, linking public or private research with industry needs, developing public policies around the use of nanotechnology, promoting open-innovation platforms, and developing technology roadmaps and standards and the exchange of knowledge and best practices both nationally and internationally.

Similarly, NanoMalaysia Berhad[120] provides a number of programs for industry, academia, and research institutions through their iNanovation, IP, NanoVerify, and Advanced Materials industrialization programs. Interestingly, NanoMalaysia Berhad holds an intellectual property portfolio and serves as a single point of contact in brokering deals such as licenses, research contracts, and investments.

China's 15-year "medium-long term plan"[121] defined a series of goals to be sequentially achieved, which can be summarized as establishing global dominance in academic efforts (publications), then patents (ongoing), and last indigenous innovation (the next challenge). China appears to be largely succeeding in meeting these goals, including in the broad field of nanoscience and nanotechnology. Toward the goal of achieving indigenous innovation based on nanoscience, large investments from Chinese city, provincial, and central governments have created mega-technology parks, such as the Suzhou Industrial Park, which contains the Nanopolis nanotechnology-incubator. These industrial parks integrate venture investors, intellectual property management, and shared instrumentation facilities. They also have close ties to academic institutions, and academicians are provided with generous financial incentives and terms of ownership of intellectual property to start companies within the industrial parks. Additionally, the industrial parks are aggressively recruiting companies from abroad, using favorable terms of investment relative to that typically available in the United States. In China, while the investments are large, and the designs of the ecosystems are impressive, it is in many cases too early to assess the success of the initiatives. Some reports suggest that these investments have structural vulnerabilities, including distortion of market forces created by government venture funding and role of state-owned enterprises in technology development.

After a decade of significant funding in nanoscience and nanotechnology, many European countries have moved from a mode of investing in individual nanoscience projects to the design and creation of sustainable ecosystems comprised of academic institutions, small and large commercial enterprises, and government agencies to create long-term socioeconomic benefits through translation of knowledge into proofs of concept, prototypes, and products. While there are many ways to construct a nanotechnology ecosystem, a particularly interesting endeavor is the creation of NanoNextNL in 2010, a public-private partnership that matched €125 million from the Dutch government over 6 years with an expected 4:1 return on investment (ROI).[122] Some of the innovative aspects of the program were the integration of risk analysis and technology assessment in research programs, business case development tools, intellectual property training, and entrepreneurship for trainees. The committee does not see similarly structured, at-scale, programs in effect in the United States at this time.

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[118] 1.7 billion Japanese yen is approximately $15.5 million USD as of January 2020.
[119] See http://www.nbci.jp/en/, accessed 11/04/2019.
[120] See http://www.nanomalaysia.com.my/, accessed 02/29/2020.
[121] See https://www.itu.int/en/ITU-D/Cybersecurity/Documents/National_Strategies_Repository/China_2006.pdf, accessed 11/04/2019.
[122] See https://www.nanonextnl.nl/wp-content/uploads/NNXT_EndTermReport_WEB_spreads.pdf, accessed 03/24/2020..

Horizon 2020, a European research and innovation Framework Program, is the financial instrument implementing the Innovation Union,[123] a Europe 2020 flagship initiative aimed at securing Europe's global competitiveness. The aim of the Innovation Union is (1) to make Europe into a world-class science performer; (2) to remove obstacles to innovation like expensive patenting, market fragmentation, slow standard-setting, and skills shortages; and (3) to revolutionize the way public and private sectors work together through Innovation Partnerships. As part of Horizon 2020, Europe has created Open Innovation Platforms with the goal of de-risking the commercialization of emerging technologies by sharing common challenges between technology developers to establish low-volume manufacturing and prototyping capabilities. Importantly, the Open Innovation Platforms are more than just facilities. They focus on creating/coordinating all dimensions of the ecosystem needed for commercialization, including training of workers, intellectual property expertise, and mechanisms to bring companies and investors together.

> Open innovation is a paradigm that assumes that companies can benefit from external ideas/technologies (Outside-In) and valorise internal ideas/technologies with external partners (Inside-Out) to reduce the financial risks associated to innovation, and quickly get a competitive advantage. Open Innovation implies accelerating internal R&D, and innovation along value chains through collaboration between the technological supply—and demand—side within networked, multi collaborative ecosystems.[124,]

Horizon Europe[125] will be the successor of Horizon 2020 and will pursue disruptive innovation and test-beds across six broad sectors:

1. Digital, industry. and space;
2. Civil security for society;
3. Health;
4. Food, bioeconomy, natural resources, agriculture, and environment;
5. Culture, creativity, and inclusive societies; and
6. Climate, energy, and mobility.

Another example of open innovation facilities in Europe includes the Interuniversity Microelectronics Centre (IMEC) in Belgium. In addition to providing physical facilities and technical expertise to aid prototyping and product manufacturing, IMEC provides innovation support and venturing services to advance product development and commercialization. This suite of services is assembled to suit the specific stage of product development, including facilities and expertise such as living labs, prototyping and testing, IP licensing, technology test labs, production and growth, start-up, scale-up, expansion, spin-off, mentoring, as well as partnering innovators with users, partners, advisors, and venture capital funders.[126] To highlight different approaches by other countries, Minatec/LETI[127] in France places "transferring technology to industry" as a top priority, offering assistance for nanotechnology commercialization through teaming innovation-focused businesses with Minatec/LETI scientists and engineers, providing turnkey facilities for incubation and product piloting, and assisting with project management as far as the company wants (e.g., until the demonstrator, prototyping, or pilot run phases).

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[123] See https://ec.europa.eu/info/research-and-innovation/strategy/goals-research-and-innovation-policy/innovation-union_en, accessed 11/04/2019.

[124] See http://ec.europa.eu/digital-single-market/en/news/open-innovation-open-science-open-world-vision-europe accessed on 8/8/2019, accessed 11/04/2019.

[125] See https://ec.europa.eu/info/horizon-europe-next-research-and-innovation-framework-programme_en, accessed 02/29/2019.

[126] See https://www.imec-int.com/en/what-we-offer, accessed 11/04/2019.

[127] Minatec (formerly the Micro and Nanotechnology Innovation Centre) was launched as a partnership between LETI (the Electronics and Information Technologies Laboratory of CEA, the French Atomic Energy Commission) and the Grenoble Institute of Technology.

The Fraunhofer Nanotechnology Alliance[128] in Germany provides technical and business services across seven Fraunhofer Institutes that "covers the whole value chain from application oriented research up to the support for the industrial implementation of nanotechnological solutions."[129] The areas of focus include nanomaterials, nanobiotechnology, nanooptics and nanoelectronics, processes, and analytics and consulting.

In the United States, an ongoing decrease in funding of basic science research by industry[130] is shifting greater importance to federal funding of research, and expands the role of universities in innovation. This shift, combined with significant changes in attitude toward innovation and entrepreneurship on campuses over the period coincidently corresponding to that of the NNI has led to the proportion of patents relying on federal funding outstripping the overall increase in patents. The number of patents relying on federal funding almost doubled between 2008 and 2017 (22,647 to 45,220).[131] This upward shift in importance of universities in innovation is seen, and even more strongly embraced elsewhere, as evidenced by the robust engagement of universities in all of the foreign nanotechnology centers described here.

In the United States, corporations of all sizes account for most of the increase in reliance on government-supported research, with 34.6 percent of patents assigned to venture-backed companies between 1976 and 2016 citing federally supported research. The agencies dominating the NNI portfolio also contribute most to the total of inventions: in 2017, the percentage contributions were DOD 6.2 percent, HHS 5.4 percent, DOE 3.9 percent, NSF 2.9 percent, and NASA 1.0 percent of the total number of patents. Interestingly, Fleming et al.[132] conclude that corporate patents that rely on federal research appear to be consistently more important than those that do not, as judged by the number of prior-art citations on subsequent patents.

In view of the increasing importance of universities and federal funded research in the United States, this report comments briefly on best practices in university technology transfer offices (TTOs) and efforts to encourage entrepreneurship at universities. The most effective TTOs are well funded and staffed, with the higher performing offices having 20-45 staff members. They can exist effectively within the university structure; however, an increasingly utilized option is to create a separate 501(c)(3). This facilitates paying market rate salaries for staff with significant industry experience and the creation of independent advisory boards.

Many universities have begun to create programs to support entrepreneurship among faculty and students. However, there is as yet little comprehensive evidence that university tenure and promotion reviews include entrepreneurship activities in the evaluations, in addition to the conventional assessment of research, teaching, and service categories. Efforts to foster entrepreneurship on campus can be categorized as (1) educational programs such as business and engineering or business and chemistry combined degrees with entrepreneurship as a connecting theme, (2) educational and funding mechanisms for individual entrepreneurial faculty, (3) start-up accelerator programs, (4) university-associated venture funds, and (5) local funds independent of the university. Undergraduate entrepreneurship appears to be a relatively untapped source of innovation in part because undergraduates generally lack robust knowledge of the ecosystem and processes for innovation and commercialization. The offering of more courses and programs for undergraduates to gain knowledge and practice in innovation and entrepreneurship could ultimately advance inventorship and commercialization in the United States. Access to information as resources and modest investment in support and education systems could unlock this potential source of creativity.

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[128] See https://www.nano.fraunhofer.de/en.html, accessed 02/29/2020.

[129] See https://www.nano.fraunhofer.de/en/about-us.html, accessed 01/30/2020.

[130] A. Arora, S. Belenzon, and A. Patacconi, Papers to patents, *Nature* 552(7683), 2017.

[131] L. Fleming, H. Greene, G. Li, M. Marx, and D.Yau, 2019, Government-funded research increasingly fuels innovation, *Science* 364:1139-1141, https://science.sciencemag.org/content/364/6446/1139.

[132] L. Fleming, H. Greene, G. Li, M. Marx, and D. Yau, 2019, Government-funded research increasingly fuels innovation, *Science* 364:1139-1141, https://science.sciencemag.org/content/364/6446/1139.

The Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Awards in the United States for small businesses are funding mechanisms to help bridge the gap between innovations in basic science and commercialization, including in the area of nanotechnology.[133] The SBIR/STTR program provides funding across several agencies, including the DOD, DOE, Department of Health and Human Services (HHS), NASA, and the NSF. In addition, industry consortia, including Semiconductor Research Corporation, the American Chemistry Council, and the American Forest and Paper Association have played a key role in nanotechnology tech transfer and commercialization, providing technology development roadmaps and funding for public-private partnerships. The National Network for Manufacturing Innovation (NNMI), also known as Manufacturing USA,[134] is a network of 14 institutes in the United States that focuses on developing manufacturing technologies through public-private partnerships among U.S. industry, universities, and federal government agencies. Note however that although Manufacturing USA addresses advanced manufacturing broadly, it incorporates nanotechnology development only tangentially in its portfolio of institutes.

The NSF's I-Corps[135] introduced in 2011, is another program that has assisted the commercialization of laboratory innovations in nanotechnology. Focused primarily on training in the customer discovery and venture exploration process, the I-Corp program was created by the NSF in 2011 to help move academic research to market. The program engages participants in moving products out of the lab and into the market by talking to potential customers, partners, and competitors and encountering the challenges and uncertainty of creating successful innovations. The NIH now also offers I-Corps opportunities.

A weakness noted by the panel is exemplified by a 2012 NNI-hosted workshop that engaged regional, state, and local (RSL) representatives in a dialogue regarding commercial opportunities related to nanoscience and technology. Although the NNCO has since participated in annual TechConnect conferences, there has been no subsequent workshop by the NNCO to update RSL representatives on the status of commercialization efforts or potential partnerships and resources created by NNI for commercialization. In contrast, in other parts of the world, RSL initiatives are playing a key role in commercialization efforts, particularly in China. Although many RSLs had nano-specific commercialization efforts in 2012, the efforts in the United States have largely been integrated into broader initiatives (e.g., high-tech development offices). The maturation of nanoscience into commercial-ready nanotechnology since 2012, however, makes reengagement of RSLs by the NNCO particularly timely.

The NNI is closely involved in a National Nanomanufacturing Network (NNN) intended to support progress in nanomanufacturing in the United States via workshops, road mapping, interinstitutional collaborations, technology transition, test-beds, and information exchange services.[136] At the core of the NNN are the six NSEC facilities supported by the NNI agencies. Other U.S. commercialization focused centers include the New York-centric Albany Nanotech Center at the University of Albany—SUNY,[137] and AIM Photonics[138] based in Rochester, New York. The committee does not find clear counterparts to Europe's IMEC and MINATEC, or the analogous commercialization-oriented centers in Japan and China, at which the very best technologies are aggregated in one location to support prototyping and product development of nanoscale materials and devices. In other words, while the NNI has been capably coordinating the science and early-stage technology development, Europe, Japan, and China have conceived of more innovative models for exploiting the economic, health care, and national security benefits of nanotechnologies.

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[133] See https://www.sbir.gov/about/about-sttr, accessed 08/08/2019.

[134] See details at the Manufacturing USA website, https://www.manufacturingusa.com/, accessed 12/20/19.

[135] See https://www.nsf.gov/news/special_reports/i-corps/, accessed 02/29/2020.

[136] See http://www.internano.org/nnn, accessed 02/03/2020

[137] See https://sunypoly.edu/, and https://en.wikipedia.org/wiki/SUNY_Poly_College_of_Nanoscale_Science_and_Engineering, both accessed 02/03/2020.

[138] See http://www.aimphotonics.com/mission-and-vision, accessed 02/03/2020

The committee also notes that although the NNI, through the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee and the NNCO, has engaged in important efforts to facilitate commercialization of nanoscience in the United States, evaluation of the impact of those efforts, and those of stakeholders in the NNI, are nearly impossible to evaluate without data that quantify the outcomes. Prioritization of investments, and informed decision making related to initiatives that do not yield a significant return, is not possible. Similarly, evaluation of the competitive status of the United States in the context of commercialization of nanotechnology is not possible without relevant data. The committee was unable to obtain data from the NNCO regarding the outcome of initiatives related to commercialization.

An opportunity now exists to identify new concepts to significantly strengthen technology transfer. The U.S. federal government has recently launched the U.S. Return on Investment (ROI) Initiative, which aims to increase the lab-to-market return on the government's investment in R&D.[139] This includes (1) optimizing the management, discoverability, and ease-of-license of the 100,000+ federally funded patents; (2) increasing the utilization of federally funded research facilities by entrepreneurs and innovators; (3) ensuring that relevant federal institutions and employees are appropriately incentivized to prioritize R&D commercialization; (4) identifying steps to develop human capital with experience in technology transfer, including by expanding opportunities for entrepreneurship education; and (5) maximizing the economic impact of the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs.[140] Although not specifically aimed at nanotechnology, the ROI Initiative can be leveraged to develop more successful nanotechnology innovation, entrepreneurship and commercialization ecosystem. However, the committee believes that an array of novel technology transfer concepts should be identified and those that promise the best impact upon U.S.-based technology transfer be implemented.

Sustaining Educational Resources and Growth of a Skilled Workforce

Over the course of its deliberations, the committee became concerned about the workforce supply, or workforce "pipeline" for nanotechnology. Developing the skills to conduct state-of-the-art research and support the workforce needs of nanomanufacturing is a slow, arduous, and challenging process. Today, the many employment opportunities for technically talented people raises a concern that the nations' work in nanotechnology will become increasingly constrained without a renewed emphasis of the development of the necessary human capital. In the past, the shortfall has been filled by talented individuals from overseas who have chosen to pursue their training and then chose to remain in the United States, but as opportunities for fulfilling work in nanotechnology open up around the world, and the U.S. stance on immigration has become more negative, this source of talent is at risk.

The NNI website offers a wide range of K-12 educational resources, both for teachers and for students.[141] It has become the "go-to" resource for many countries seeking to build a compendium of educational resources. The NNCO is to be commended in recognizing the importance of role models and featuring intergenerational video clips of nanoscience and nanotechnology practitioners. The website provides links to sites, developed with funding from various agencies. For example, the Materials World Modules website[142] focuses on inquiry-based modules for grades 6-12, while the nanohub.org site provides undergraduate and graduate students with modeling tools access as well as access to educational resources. The safety-related resources are very useful and should be kept up to date as more information

[139] *Return on Investment Initiative for Unleashing American Innovation*, 2019, NIST Special Publication 1234, at https://doi.org/10.6028/NIST.SP.1234.

[140] Refer to performance.gov website for federal activities to facilitate faster ROI. Refer also to the "lab-to-market" effort led by NIST, which is also an interagency activity, at https://www.nist.gov/tpo/lab-market, accessed 11/04/2019.

[141] See NNI's educational resources at https://www.nano.gov/education-training, accessed 11/04/2019.

[142] See https://www.materialsworldmodules.org/, accessed 02/29/2020.

becomes available. Many professional societies, such as SPIE, AVS, ACS, APS, MRS, and OSA, have relevant symposia and subgroups at their annual or semiannual meetings. The American Chemical Society Journals feature nanotechnology explicitly with publications such as *Nano Letters* and *ACS Nano*.

The European Union provides an excellent website[143] with information about nanotechnology in the form of games, videos, posters, images, and art, as well as virtual and hands-on activities to deepen the understanding of properties of materials at the nanoscale. The tools are geared for the age groups 11-13 years and 14-18 years. The site also features resources for educators—for example, training kits, school programs, and blogs. The site provides links to specific resources developed in EU countries and beyond (including the United States). Publications focusing on nanoscience and nanotechnology include Springer's *Nano-Micro Letters* and as well as the Royal Society of Chemistry (RSC) *Nanoscale Advances*, *Nanoscale Horizons*, *Environmental Science: Nano*, and *Lab on a Chip* journals. The RSC's *Nanoscale* journal is a collaborative venture with the National Center for Nanoscience and Technology[144] in China.

Switzerland offers a comprehensive range of nanotechnology knowledge and education platforms that involve all stakeholders, the public, academia, industries, and government.[145] The "Swiss nano cube" is aimed at teachers and students from vocational schools, secondary schools, as well as higher professional schools. Contactpointnano.ch provides scientific and regulatory knowledge required by companies and establishes links to expertise or assistance. InfoNano[146] is the central federal information platform for nanotechnology. As a repository of knowledge from different government agencies, academia, and economic development experts, it seeks to advance informed dialogue among stakeholders. In addition, TA-Swiss (Centre for Technology Assessment) uses expert studies to inform public policy, advise elected officials, and promote discussion with citizens.[147]

Many academic institutions across the world offer undergraduate and graduate degrees with specialization in nanoscience and nanotechnology engineering. When anchored in institutions with dedicated growth, fabrication, and characterization core facilities, the students acquire a depth of knowledge and instrumentation experience that is a key asset for future jobs in industry. As start-ups are often the path to bringing a technology to market, many institutions have added training in entrepreneurship to the mix. The nano.gov website provides a repertory of associate degrees and certification as well as graduate degrees in nanoengineering. Nano-link[148] is an NSF-funded Advanced Technological Center for Nanotechnology Education serving students, educators, and industry to ensure a supply of highly skilled workforce for the nanotechnology industry.

Other countries have been particularly successful at highlighting the impact of their training. For example, NanoNextNL,[149] the Netherlands nanotechnology flagship program, was successful in training industrial researchers, graduate students, and postdoctorates who took courses in entrepreneurship, intellectual property and technology valorization, risk analysis and technology assessment, and analytic storytelling. In Canada, the University of Waterloo offers both undergraduate and graduate degrees in nanoscience and nanotech engineering in an environment where entrepreneurship and cooperative learning are greatly valued. The Canadian ecosystem also benefits from Canada's National Design Network (managed by CMC Microsystems[150]), which offered 10,000 academics at 66 Canadian universities and colleges access to CAD, Lab, and Fab infrastructure to conduct excellent research, design and create novel technologies, and take part in extraordinary training opportunities leading to industry-

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[143] See EU's educational resources at https://nanoyou.eu, accessed 11/04/2019.
[144] See http://english.nanoctr.cas.cn/, accessed 01/30/2020.
[145] See http://www.swissnanocube.ch/, accessed 11/04/2019.
[146] See https://www.bag.admin.ch/bag/de/home/gesund-leben/umwelt-und-gesundheit/chemikalien/nanotechnologie.html, accessed 11/04/2019.
[147] See https://www.ta-swiss.ch/en/, accessed 11/04/2019.
[148] See https://www.nano-link.org, accessed 11/04/2019.
[149] See https://www.nanonextnl.nl, accessed 11/04/2019.
[150] See https://www.cmc.ca, accessed 11/04/2019.

ready graduates. The Nano and Advanced Materials Institute (NAMI)[151] in Hong Kong trains its staff to focus on market- and demand-driven R&D to develop platforms required for innovative products and upgrade the technology of existing enterprises. Korea offers intensive programs for undergraduate and graduate students as well as businesspeople; education in nanotechnology starts at the K-12 level with training for teachers and continues with programs in technical high schools, colleges, engineering schools, and universities where cooperative learning and interdisciplinary approaches are encouraged. In Japan, institutions like the University of Tokyo, the National Institute of Advanced Industrial Science and Technology (AIST) and the National Institute for Materials Science (NIMS) and other academic institutions provide nanotechnology training to students in world-leading, state-of-the-art facilities.

The National Science Board (NSB) has recently completed a detailed assessment of the trends in science and engineering degrees, and its analysis shows that the advantage of a highly educated workforce that the nation has enjoyed is eroding as many other nations have ramped up their educational programs. In 1998, China began to make major investments in the education of its population and now graduates about three times the number of bachelor's degree students compared to the United States.[152]

Economic prosperity resulting from nanotechnology is possible only if continued investments are made and attention is paid to education and training, keeping and renewing state-of-the-art training facilities, and deploying innovative ways to collaborate across a dynamic ecosystem. While other countries are tracking the outputs of their translational efforts and their impacts, such coordination across the entire nanotechnology ecosystem is not as robust in the United States.

CONCLUDING REMARKS ON THE U.S. NANOTECHNOLOGY R&D ECOSYSTEM

To summarize, since the inception of the NNI, the NNCO has played an important role in promoting the international competitiveness of the United States in nanoscience and nanotechnology on a very small budget (less than ~$3 million per year for all coordination and communications activities). The NSIs identified by the Nanoscale Science and Technology (NSET) Subcommittee have been effective in coalescing the efforts of federal agencies to share knowledge and approaches and achieve efficiencies that have placed the United States in leadership positions in key areas of nanotechnology. Examples of successes include the NSIs on water sustainability and environmental nanosensors to detect heavy metal contamination.[153,154] Additionally, NNI efforts have established the United States as a global leader in the integration of EHS considerations into commercialization efforts, which have played a key role in generating acceptance of nanotechnologies by the public. Other notable successes of the NNI include the early establishment of a network of world-class facilities for academic nanoscience research. The NNCO and NSET committee have fostered several successful interagency collaborations through these efforts.

A comparison of U.S. and international efforts,[155] however, reveals increasing evidence of a key competitive weakness in the current U.S. efforts in nanoscience and nanotechnology. As noted above, while there is much to celebrate in the early successes of the NNI, key opportunities emerging from nanoscience, and the strategic needs of the United States, have evolved substantially since the start of the NNI. Specifically, 20 years ago, the central opportunity for the United States was to create new knowledge and new materials and to deepen our understanding of nanoscopic phenomena. While support of basic nanoscience research must continue, the opportunity now for the United States is to realize the societal benefits of nanoscience in the context of commercialization of responsible nanoproducts. In light

[151] See http://www.nami.org.hk/en/, accessed 11/04/2019.

[152] See https://www.weforum.org/agenda/2017/04/higher-education-in-china-has-boomed-in-the-last-decade, accessed 1/28/2020.

[153] For some examples, see M.R. Willner and P.J. Vikesland, 2018, Nanomaterial enabled sensors for environmental contaminants, *Journal of Nanobiotechnology* 16:95, doi:10.1186/s12951-018-0419-1.

[154] M.R. Willner and P.J. Vikesland, 2018, Nanomaterial enabled sensors for environmental contaminants, *Journal of Nanobiotechnology* 16:95, doi:10.1186/s12951-018-0419-1.

[155] See Chapter 3.

of this opportunity, there exists an urgent need to better integrate nanoscience, infrastructure development, and workforce development into ecosystems that support the goal of responsible commercialization of nanotechnology.

Relative to other countries, the United States has been slow to pivot toward coordinated and directed support for commercialization. Other countries have changed their models for support of nanoscience and nanotechnology to achieve the central goals of responsible development and commercialization. The consequences of this lag in competitiveness in the United States are tangible. [156] Basic nanoscience advances occurring in the United States are being translated into societal and economic benefits outside the United States. To cite just one example, manufacturing of many nanomaterials, such as solar nanomaterials, has almost entirely moved abroad. Further, the committee fears that evaluation of the return on investment in U.S. basic nanoscience research in terms of societal and economic benefit is challenging in many cases because of lack of systematic data gathering, particularly when compared with the data gathering efforts of other countries. The absence of such data also hampers efforts to communicate to the public the benefits of the federal investment in nanoscience research.

[156] *Mapping Study on Regulation and Governance of Nanotechnologies*, http://innovationsgesellschaft.ch/wp-content/uploads/2013/07/FramingNano_MappingStudy.pdf, accessed 01/29/2020.

3

A Global Perspective

This chapter offers a review of the U.S. program in nanoscience and nanotechnology as it is positioned in the context of the rapidly evolving global efforts. At the start of the National Nanotechnology Initiative (NNI), 20 years ago, government investment into nanotechnology research and development (R&D) was on par between the United States, Western Europe, and Japan, while the United States had a strong lead in the number of nanotechnology patents over the rest of the world.[1] However, during the intervening years, researchers have witnessed sustained investments by other developed nations and the European Union (EU), as well as an acceleration of work by developing nations, especially China. Today, the United States is but one of several nations where nanoscience discoveries and technology applications are making important contributions to the economy and to the health of their citizens. This chapter compares the current efforts of the United States to those of other nations and attempts to assess the NNI investment in the context of global commitments. In light of this assessment, the committee concludes that it is unrealistic to expect or to advocate that the United States should lead in every area of nanoscience and technology, and instead argues that it should identify the most critical research areas where the United States should lead the world. This chapter begins with an assessment of the recent changes in the global nanotechnology ecosystem. It goes on to evaluate the status of global facilities for nanotechnology development, approaches to nanotechnology transfer and commercialization, the training of a skilled workforce able to adapt to the rapidly (sometimes disruptively) changing needs of industry, and global efforts to ensure responsible development of nanotechnology, and concludes with a review of the U.S. nanotechnology signature initiatives through which much of the domestic NNI R&D is coordinated.

THE GLOBAL NANOTECHNOLOGY R&D ECOSYSTEM

To assess the status of nanotechnology R&D programs and their scientific and economic impact across the world, the committee assessed several indicators of the resource inputs into regional programs and the return on these investments, including the level of investment in nanotechnology R&D, the number of related publications and patents, and the focal areas of the investments. For comparison with the United States, the following four regions have been studied in most depth: (1) China; (2) Japan, South Korea, and Taiwan; (3) Europe (the EU-28 group consisting of the combined efforts of Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom); and (4) Canada.

[1] M.C. Rocco, 2003, Broader societal issues of nanotechnology, *Journal of Nanoparticle Research* 5: 181-189.

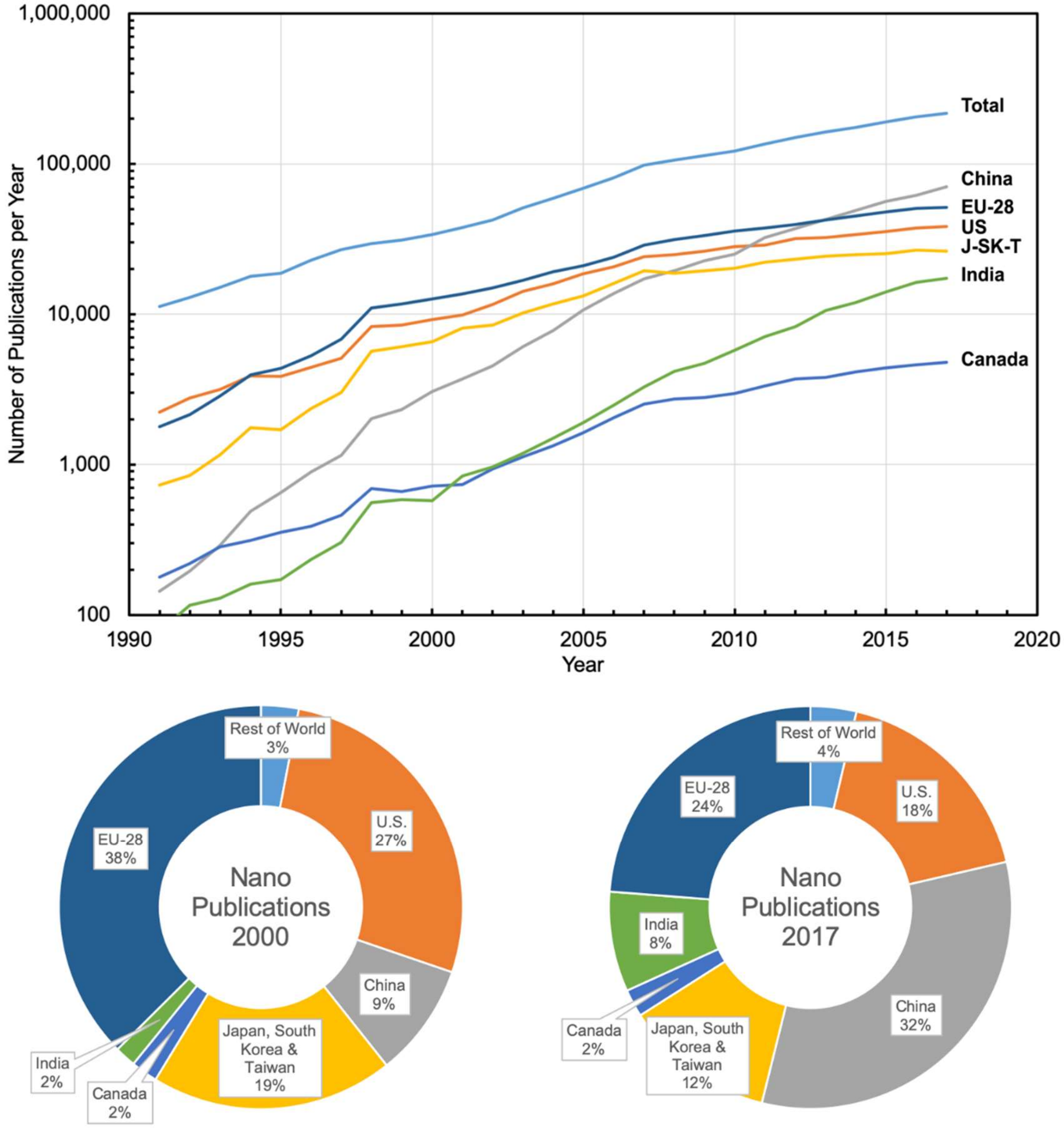

FIGURE 3.1 *Top:* Number of nanotechnology-related scientific publications per year, shown by region of origin. The data has been extracted from the nanotechnology database recently published in Z. Wang, A.L. Porter, S. Kwon, J. Youtie, P. Shapira, S.F. Carley, and X. Liu, 2019, Updating a search strategy to track emerging nanotechnologies, *Journal of Nanoparticle Research* 21(9):199. The committee thanks the authors for permitting a customized search of their database. *Bottom left:* Data only for year 2000. Bottom right: Data only for year 2017.

One, easily measured, indicator of the scale and impact of regional nanotechnology programs is the number of nanotechnology papers published in archival journals, by the region.[2] Figure 3.1 shows the

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[2] See also National Research Council, 2013, *Triennial Review of the National Nanotechnology Initiative*, Washington, D.C.: The National Academies Press, https://doi.org/10.17226/18271. For recommendations on other types of data that can be collected to measure the impact of nanotechnology, see, for example, Recommendation S-2.

number of nanotechnology publications per year for the different regions.[3] Note that these data are plotted on a logarithmic scale that visually compresses differences between regions. The data show that since the beginning of the NNI (2000), the total of annual publications has risen from about 30,000 per year to about 200,000 per year in 2017, consistent with the growing importance of nanotechnology. The data also show that in 2000, the United States accounted for about one-third (approximately 10,000 per year) of the international papers published per year. While the number of papers from the United States has risen to about 40,000 per year by 2017, the fraction of U.S. publications has fallen to about one-fifth of the global total. The data in Figure 3.1 show that the EU-28 countries have consistently published more papers per year than the United States, while Japan, South Korea, and Taiwan have consistently published slightly less. The annual publication production of these three regions appears to be leveling out with time, suggesting either maturation of the field or stagnation in investment levels for basic nanoscience studies. The most significant trend shown by the data is the rapid growth in publications of the developing nations of China and India, and, to a lesser extent, Canada. China's investments in nanotechnology have resulted in an extraordinary growth in annual publications from about 3,000 in 2000 to around 70,000 in 2017. The data of Figure 3.1 indicate that this growth in annual publications shows no evidence of abating and easily exceeds the growth rate of publications from the United States. It is these startling data that lead us to conclude that basic nanoscience has not yet fully matured, and alternative explanations must be sought for the decline in the U.S. share of the published nanoscience literature.

Nanotechnology in China

The remarkable rise in annual publications from China has coincided with its major commitment to the development of nanoscience and nanotechnology; a decision grounded in a belief, shared by the United States and indeed all the nations with large programs, that nanotechnology underpins future national economic expansion, prosperity, health, and security. China established the National Steering Committee for Nanoscience and Technology in 2000, just as the United States established the NNI. The Chinese effort and achievements have been dramatic, and that country is now leading per several metrics. The number of journal publications, for example, is often cited as a measure of research productivity, and Figure 3.1 shows that China not only took the lead in the number of publications during the last decade, but as of 2017, has published almost twice as many papers per year as the United States. Moreover, China is now the largest contributor to the top 1 percent of most-cited papers related to nanoscience and nanotechnology,[4] significantly outperforming the United States in this metric also. While there may be uncertainties in how papers are counted and assigned to categories, it is clear that China is leading in both the numbers of relevant publications, and with the impact of these publications in the nanotechnology R&D community.

The number of patents in a given field is an indication of research that can have commercial impact. Chinese nanoscience and technology programs emphasize the importance of patenting of technology. According to data available from the publicly accessible aggregator site StatNano,[5] while the United States leads all countries in total number of nanotechnology patents filed in the U.S. and European Patent Offices, this is not the case on a global scale. Recent assessments of nanotechnology patenting recorded in the World Intellectual Property Organization (WIPO) database provide important insights in future

[3] These data have been extracted from the nanotechnology database recently published in Z. Wang, A.L. Porter, S. Kwon, J. Youtie, P. Shapira, S.F. Carley, and X. Liu, 2019, Updating a search strategy to track emerging nanotechnologies, *Journal of Nanoparticle Research* 21(9):199. The committee thanks the authors for permitting a customized search of their database.

[4] The power of the tiniest shoot, Editorial, *Nature Nanotechnology* 12:833(2017), doi:10.1038/nnano.2017.197.

[5] See https://statnano.com/, accessed 11/04/2019. StatNano is a website hosted in Iran that aggregates data and reports on nanotechnology from all over the world.

nanotechnology commercialization, as shown in Figure 3.2.[6] It is evident that by 2015, nanotechnology patents resulting from research in the United States accounted for about 15 percent of the global total, while those from China now account for around 52 percent of this total. It is also clear that the rate of growth of Chinese nanotechnology patents is increasing rapidly, while the U.S. fraction of the global total has remained changed little since 2008. China now claims 45 percent of the global patent applications in areas related to nanoscience and technology between 1997 and 2016.[7] According to Zhu et al.[8] and Applebaum et al.,[9] China surpassed the United States in total number of nanotechnology patents sometime between 2009 and 2011. While the number of patents may not correlate perfectly with economic and national security impact, and the relative value of patents filed in different countries is hard to assess, the trend in patent numbers paints a similar picture to that seen from the number of publications, confirming China's growing leadership in nanotechnology.

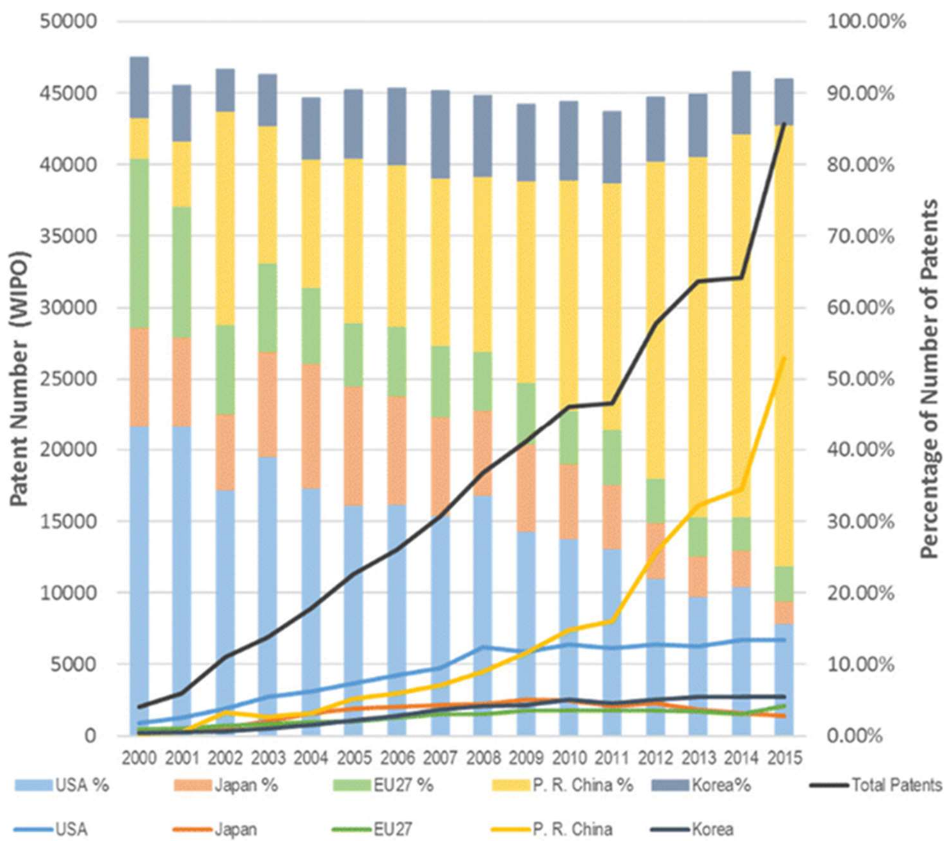

FIGURE 3.2 Global nanotechnology patents recorded in the WIPO data base, by lead author location. SOURCE: Reprinted by permission from Springer Nature: H. Zhu, S. Jiang, H. Chen, and M.C. Roco, 2017, International perspective on nanotechnology papers, patents, and NSF awards (2000-2016), *Journal of Nanoparticle Research* 19:370, https://doi.org/10.1007/s11051-017-4056-7; copyright 2017.

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[6] H. Zhu, S. Jiang, H. Chen, and M.C. Roco, 2017, International perspective on nanotechnology papers, patents, and NSF awards (2000-2016), *Journal of Nanoparticle Research* 19:370, https://doi.org/10.1007/s11051-017-4056-7.

[7] Small science in Big China: An overview of the state of Chinese nanoscience and technology, *Springer Nature*, https://media.springernature.com/full/springer-cms/rest/v1/content/15302926/data/v3, accessed 11/04/2019.

[8] Zhu et al., 2017.

[9] R.P. Appelbaum et al., 2016, Will China's quest for indigenous innovation succeed? Some lessons from nanotechnology, *Technology in Society* 46:149-163.

This shift in nanotechnology patenting from the United States to the developing world, and particularly the ascendancy of China, is correlated with the shift in global locations of high-technology (HT) manufacturing. The most recent (2018) National Science Board (NSB) report showed that the $1.6 trillion value of high-technology manufacturing is now distributed between China (31 percent) and the United States (24 percent) in 2016 (see Chapter 1, Figure 1.5).

The R&D output metrics are clearly related to the level of investment directed to nanotechnology. The Chinese National Guideline on Medium- and Long-Range Programs for Science and Technology Development for 2006-2020,[10] issued by the Chinese central government, identified nanoscience as the largest of its four areas of basic research. Strong government funding has attracted many Chinese scientists to move into nanoscience research and induced foreign-trained Chinese researchers to return to China. As of 2015, the Chinese Nanoscience Research program has invested about ¥1.0 billion to support nanotechnology projects (¥1 billion ~ $142 million USD). This investment amount (if accurate) is much smaller than the U.S. investment, which certainly reflects the different costs of performing R&D in the two countries, and may also reflect a more narrow set of priority topics in China.

The Chinese nanotechnology effort focuses on four areas:

1. *Materials and manufacturing* is the most general and is where many of the benefits of nanotechnology have been found historically, a trend that is likely to continue.
2. *Information technology* has been and will continue to be driven by nanotechnology.
3. *Energy and environment* focuses on renewal energy and energy efficiency, with emphasis on catalysis, photovoltaics and rechargeable batteries.
4. *Medicine and health* represents a major thrust (see Box 3.1). Overall, the specific areas of catalysis, renewable energy, and medicine are highlighted as areas in which China expects to lead.

The ability to quickly identify, and then very effectively focus resources on areas that will create a global competitive advantage are defining features of the Chinese nanotechnology coordination effort.

BOX 3.1
The Transformational Impact of Nanomedicine

Nanomedicine designs and synthesizes nanoscale materials and material systems that improve human health. There are many ways that this can be accomplished, including therapeutics, in- vitro diagnostics, vaccines, in vivo imaging, and regenerative medicine. Opportunities in new therapeutics and imaging agents are based on nanoparticles or devices that permit the control of biodistribution and toxicity of a drug or biological agent and enhance their efficacy. The impact of nanoscience and technology upon medicine has been dramatic. For example, Figure 3.1.1 shows some of the many ways that nanotechnology can impact the field of orthopedics.[1]

Therapeutics represents the biggest component of a nanomedicine market that has risen from about $80 billion in 2013 to a projected $140 billion by 2024.[3] Dozens of FDA-approved nanodrugs (consisting of nanoparticle liposomes, micelles, proteins, and polymers) are in use, with hundreds more in early-stage development or clinical trial. As fundamental understanding of the composition-structure/shape-activity relationships emerge, their applications to other disease requirements is expected to rapidly grow. Worldwide, the nanomedicine market is growing fastest growth in the Asia Pacific region, while the largest market is North America (accounting for 42 percent of the global market as of 2018).[4]

[10] See https://www.itu.int/en/ITU-D/Cybersecurity/Documents/National_Strategies_Repository/China_2006.pdf, accessed12/20/2019.

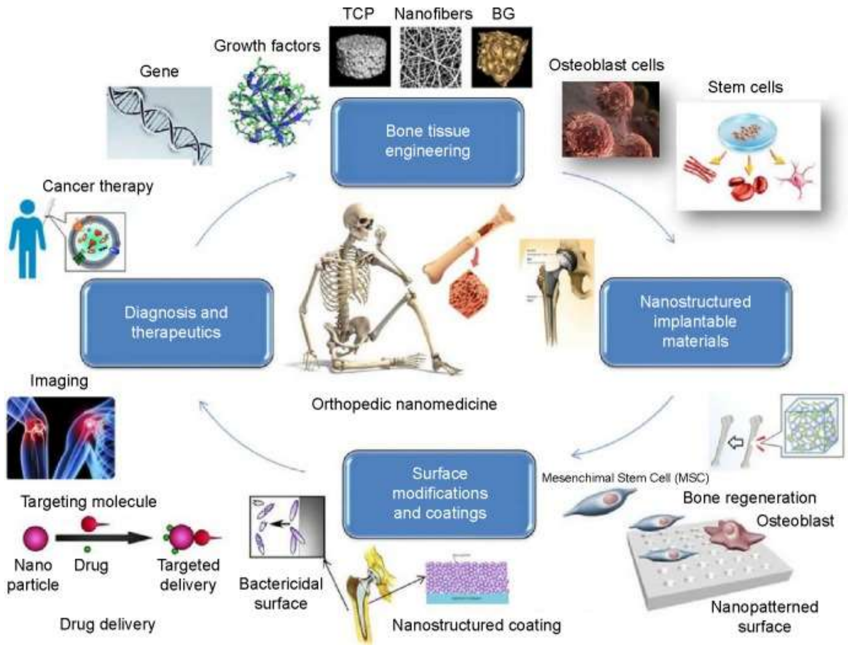

FIGURE 3.1.1 Schematic illustration of potential ways in which nanomedicine can impact orthopedics.[2]

[1] M. Mazaheri, N. Eslahi, F. Ordikhani, E. Tamjid, and A. Simchi, 2015, Nanomedicine applications in orthopedic medicine: state of the art, *International Journal of Nanomedicine* 10:6039-6054, doi: 10.2147/IJN.S73737.
[2] See https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4592034/figure/f1-ijn-10-6039/.
[3] See https://globalmarketresearchinsight.wordpress.com/tag/nanomedicine-market/ and https://www.grandviewresearch.com/industry-analysis/nanomedicine-market.
[4] André Nel, presentation to the committee.

Nanotechnology in Europe

According to a 2019 Eurostat news release,[11] the EU-28 countries of the European Union spent almost €320 billion on R&D in 2017; 2.07 percent of its GDP (€1 billion ~ $1.1 billion), which is a little lower than the U.S. investment rate, which was at 2.79 percent of GDP in 2017.[12] It has invested a substantial fraction of this through both its Seventh Framework Programme (known as FP7)[13] and the Horizon 2020 Framework Programme (known as H2020).[14] Nanotechnology is seen as a horizontal and enabling technology and, as such, is funded under each of the three pillars of the H2020 program, but particularly under the pillar "Excellent Science and Industrial Leadership." According to the NanoData

[11] See https://ec.europa.eu/eurostat/documents/2995521/9483597/9-10012019-AP-EN.pdf/856ce1d3-b8a8-4fa6-bf00-a8ded6dd1cc1, accessed 11/04/2019.
[12] See data at https://data.oecd.org/rd/gross-domestic-spending-on-r-d.htm, accessed 02/29/2020.
[13] FP7, 2007-2013, at https://ec.europa.eu/research/fp7/index_en.cfm, accessed 11/04/2019.
[14] H2020, 2014-2020, at https://ec.europa.eu/programmes/horizon2020/en, accessed 11/04/2019.

Landscape Compilation 2017 published by the European Commission (EC) in 2018,[15] nanotechnology projects accounted for 8.8 percent of all H2020 projects as of July 2017, representing 8.4 percent (€1.95 billion) of the EC contribution to the H2020 funding to that date. This is reduced slightly from FP7, for which 10.4 percent (€4.66 billion) of the funding had the term "nano" in a project title or abstract. That said, it is noted that H2020 is only one source for nanotechnology R&D funding in Europe. The total EU-28 investment into nanotechnology R&D may be much larger.

While the number of annual nanotechnology publications originating from the EU-28 and the European Free Trade Agreement (EFTA) states is still increasing year by year,[16] the share of the EU-28 contribution to the worldwide nanotechnology publications has decreased from 40 percent in 2000 to 26 percent in 2017. This trend is similar to the United States and largely owing to the exponential increase of publications from China. Among the EU-28 and EFTA countries, Germany, the UK, France, Spain, and Italy—in that order—had the greatest number of publications. The NanoData Landscape Compilation Update Report 2017[17] breaks the nanotechnology field down by eight impacted application areas: (1) Information and Communications Technology (ICT); (2) Manufacturing; (3) Health; (4) Energy; (5) Photonics; (6) Environment; (7) Transport; and (8) Construction. Reviewing the percentages of publications in these eight subfields compared with the total number of nanotechnology publications in each field, from the data reproduced in Table 3.1, provides an indication of the regional strength for each application domain. These data suggest that Asia is leading in ICT, Manufacturing, and Energy, while for the EU-28 and EFTA and North America, Health, Transport, and Construction have the highest representation. (It should be noted, however, that these are cumulative publications data covering 2000-2016 and may not represent more recent trends.)

Another way to look at particular regional focus areas is via particular initiatives. Among the EU-28, there are currently three funded "European Flagship" projects (each funded at €1 billion[18] over 10 years), the Human Brain Project, the Graphene Flagship (both funded originally under FP7), and the recent Quantum Technology Flagship. Two of these are intensively nanotechnology centric.

To assess patents granted and patent applications, the EC's NanoData Landscape Report[19] reviewed data from the U.S. Patent and Trademark Office (USPTO), European Patent Office (EPO), and World Intellectual Property Organization (WIPO) for the period 1993-2013; the review yielded more than 50,000 nanotechnology patent families (granted patents and patent applications). Among the nanotechnology areas provided in Table 3.1 above, ICT had the highest number, followed by Health, Manufacturing, Construction, Energy, Photonics, Environment, and Transport. The EU-28 and EFTA contribution in each of these areas ranges from 14 to 23 percent, with the highest relative contributions to the areas of Photonics, Construction, and Energy, again hinting at regional priorities. The committee finds the emphasis on ICT to be of particular significance in considering the U.S. ability to ensure its national security in the digital age.

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[15] European Commission, 2018, NanoData Landscape Compilation Update Report 2017, doi: 10.2777/031727, at https://op.europa.eu/en/publication-detail/-/publication/69470216-f1f6-11e8-9982-01aa75ed71a1/language-en/format-PDF/source-81483247.

[16] H. Zhu, S. Jiang, H. Chen, and M.C. Roco, 2017, International perspective on nanotechnology papers, patents, and NSF awards (2000-2016), *Journal of Nanoparticle Research* 19:370, https://doi.org/10.1007/s11051-017-4056-7.

[17] European Commission, 2018, *NanoData Landscape Compilation Update Report 2017*, doi: 10.2777/031727, https://op.europa.eu/en/publication-detail/-/publication/69470216-f1f6-11e8-9982-01aa75ed71a1/language-en/format-PDF/source-81483247.

[18] €1 billion ~ $1.1 billion.

[19] European Commission, 2018, *NanoData Landscape Compilation Update Report 2017*, doi: 10.2777/031727, https://op.europa.eu/en/publication-detail/-/publication/69470216-f1f6-11e8-9982-01aa75ed71a1/language-en/format-PDF/source-81483247.

TABLE 3.1 Cumulative Publications Using "nano*" Search Term from 2000-2016, Divided by Application Field and Region

	Total	**Asia**		**EU-28 and EFTA**		**North America**	
		Number	%	Number	%	Number	%
ICT	809,820	419,031	51.7	255,411	31.5	166,130	20.5
Manufacturing	286,447	158,468	55.3	84,476	29.5	51,245	17.9
Health	266,741	112,740	42.3	87,452	32.8	71,418	26.8
Energy	197,539	116,294	58.9	51,263	26.0	41,353	20.9
Photonics	112,378	56,012	49.8	36,215	32.2	29,711	26.4
Environment	66,100	28,683	43.4	21,595	32.7	14,915	22.6
Transport	22,803	8,767	38.4	9,090	39.9	6,353	27.9
Construction	21,648	7,124	32.9	8,651	40.0	4,042	18.7
	1,783,476	**907,119**	**50.9**	**554,153**	**31.1**	**385,167**	**21.6**

SOURCE: Data from European Commission, 2018, NanoData Landscape Compilation Update Report 2017, doi: 10.2777/031727, at https://op.europa.eu/en/publication-detail/-/publication/69470216-f1f6-11e8-9982-01aa75ed71a1/language-en/format-PDF/source-81483247, accessed 11/04/2019.

Nanotechnology in Japan

Japan has made significant investments in nanotechnology R&D since the year 2000. Its scholarly and commercial contributions have captured the world's attention, and many of the ubiquitous Japanese high-tech products are nanotechnology enabled. Japan started a large-scale national nanotechnology investment in 2001, shortly after the start of the NNI. Japanese policy in nanotechnology R&D has been included from the second to the fifth Science and Technology Basic Plans issued by the Japan Science and Technology Agency. According to Japan's Center for R&D Strategy (CRDS),[20] Japan was the second leading country in nanotechnology funding with ¥164 billion (~$1.5 billion USD) allocated to nanotechnology in 2014. According to the same CRDS report, in 2014, China was first with the largest number of publications, followed by the EU and United States, with Japan and South Korea almost tied in fourth place. This trend is consistent with the recent report by Zhu et al.[21] While Japanese output in nanotechnology publications has been relatively steady over the years, South Korea has increased significantly since the year 2000. By 2016, it had surpassed Japan with a total global share of publications of 5.8 percent versus 4.8 percent for Japan.

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[20] Nanotechnology and Materials R&D in Japan (2018): An Overview and Analysis/CRDS-FY2017-XR-02, https://www.jst.go.jp/crds/en/publications/CRDS-FY2017-XR-02.html, accessed 11/04/2019.

[21] H. Zhu, S. Jiang, H. Chen, and M.C. Roco, 2017, International perspective on nanotechnology papers, patents, and NSF awards (2000-2016), *Journal of Nanoparticle Research* 19:370, https://doi.org/10.1007/s11051-017-4056-7.

In terms of nanotechnology patents in the USPTO, Japan has seen a decrease in its share of patents from 10.51 percent in 2010 to 6.54 percent in 2016, occupying fourth place after South Korea (7.43 percent). The United States maintains a substantial lead, but it has also seen its share decrease significantly from 61.88 percent in 2010 to 42.54 percent in 2016. When considering WIPO patent awards, Japan has seen its share decrease even further, mostly owing to the exponential growth of China's contributions. In 2015, Japan's position in WIPO awards was fifth place, with a 3.25 percent share. The leading four patent producers were China (61.78 percent), United States (15.70 percent), South Korea (6.34 percent), and the EU (4.91 percent). In the past two decades, China revised its patent law to better align and comply with international standards. China's increasing ability to innovate has led to a transition from acquiring knowledge and technology from abroad to developing and protecting its own. The will to develop an innovation capacity at home has led to leadership in patent quantity but not uniform quality. Given the size of its domestic market, China has not always sought U.S. patent protection. This is an evolving patent landscape.

With the recognition that experimental nanotechnology R&D efforts are ever more complex and sophisticated, it is more common than ever for nanotechnology research to be conducted in specialized shared facilities whose costs can be spread and knowledge shared. Accordingly, Japan launched in 2010 the Tsukuba Innovation Area for Nanotechnology[22] (TIA-nano) as the Innovative Network for Nanotechnology Applications, with research areas in nanoelectronics, power electronics, N-MEMS, nano-GREEN, carbon nanotubes, and nano-material safety, and light and quantum measurements. TIA operates in ways that are similar to other prominent international research, development, and innovation hubs, such as the Interuniversity Microelectronics Centre (IMEC)[23] in Belgium, the MINATEC Innovation Campus[24] in France, or Albany Nanotech Campus[25] in New York State in the United States. Additionally, since 2012, Japan launched the Nanotechnology Platform Japan,[26] comprising a network of 38 facilities, contributed by 26 member institutes and universities that are joined to establish one single structure for a "Shared-Use Cutting-Edge Facility for Nanotechnology."

The CRDS report[27] enumerates 37 major R&D fields in Nanotechnology and Materials grouped in seven categories: Environment/Energy, Life Sciences/Health Care, ICT/Electronics, Social Infrastructure, Design and Control of Functions/Materials, Science and Technology Fundamentals, and Common Supporting Policies. The CRDS also enumerated 10 key current commercial opportunities for nanotechnology: Separation Technologies, Biomaterials and Devices for Controlling Interactions Between Living and Artificial Materials, Development of Super-Composite Materials Through Nanodynamic Control, Innovation in IoT/AI Chips, Nano-IT-Bio-Mechanical Integrated Manufacturing, Integrated Design and Control Technology for Quantum Systems, Operando Measurements, Data-Driven Materials Design (Materials Informatics), Strategic Measures on ELSI/EHS for Nanotechnology, and Forming R&D Centers and Platforms to Absorb the World's Knowledge.[28] It is this set of objectives that is driving the strategic investments within Japan.

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[22] See https://www.tia-nano.jp/page/dir000002.html, accessed 12/20/2019. See additional information at https://www.rieti.go.jp/en/publications/summary/15100012.html, accessed 11/04/2019.

[23] See https://www.imec-int.com/en/home, accessed 11/04/2019.

[24] See https://www.minatec.org/en/, accessed 12/20/2019.

[25] See https://sunypoly.edu/research/albany-nanotech-complex.html, accessed 12/20/2019.

[26] See https://www.nanonet.go.jp/ntj/english/, accessed 12/20/2019.

[27] Nanotechnology and Materials R&D in Japan (2018): An Overview and Analysis/CRDS-FY2017-XR-02, https://www.jst.go.jp/crds/en/publications/CRDS-FY2017-XR-02.html, accessed 11/04/2019.

[28] Nanotechnology and Materials R&D in Japan (2018): An Overview and Analysis/CRDS-FY2017-XR-02, https://www.jst.go.jp/crds/en/publications/CRDS-FY2017-XR-02.html, accessed 11/04/2019.

Nanotechnology in Canada

While Canada has substantial efforts in nanotechnology, its influence in the global community is less than that of the countries assessed above (China, the EU, Japan, South Korea) as a natural consequence of scale, but it is still of high relevance because of its special relationship with the United States. Canada supports the advancement of nanotechnology through federal and provincial Science and Technology funding programs with a particular emphasis on regional clusters and national ecosystems. Since 2001, the federal government has invested in two nanotechnology R&D infrastructure centers (the National Institute for Nanotechnology[29] in Edmonton and the Waterloo Institute for Nanotechnology[30]), funded 125 Canada Research Chairs in Nanotechnology,[31] and invested in state-of-the-art nanofabrication and characterization facilities across the country through its Canada Foundation for Innovation.[32] In 2019, the federal government funded a NanoMedicines Innovation Network[33] through its Networks of Centers of Excellence (NCE) program.[34] Annual federal investment in nanotechnology is of the order of CAD$230 million, equivalent to ~$174 million USD, as compared with ~$1.4 billion annual investment in the United States. The 2012 nanotechnology ecosystem map produced by Global Advantage Consulting group Statistics Canada identified the creation of 70,000 jobs and annual revenues of CAD$25 billion, equivalent to ~$19 billion USD for nano-enabled Canadian companies.[35] Canada has a particular strength in the area of advanced materials, supported through research in universities, prototyping facilities, and pilot plants in government research centers and companies. Canada's established global leadership in cellulose nanocrystals[36] is an example of directed investments to establish a Canadian manufacturing basis for a promising materials system. As a result of both federal and provincial investments, two pilot/production plants[37] were established by FPInnovations, Canada's national forest research institute, almost a decade ago to support Canada's global competitiveness in this field. To similarly leverage Canada's strength in semiconductor materials for electronics and photonic applications, federal and provincial governments have invested in two foundries providing prototyping and low-volume manufacturing facilities for companies in Canada and from abroad. Building on an early investment in low-dimensional electron systems and nanostructures in semiconductors, Canada now has a world-renowned effort in quantum information science and technology with investments in quantum materials, quantum computing, and quantum circuits and devices. This deep-rooted expertise has led to a number of commercial enterprises, including D-Wave Systems (first quantum computer based on superconducting circuits) and 1Qbit (quantum software and algorithms). While it may not represent the whole of nanotechnology in Canada, the research program areas at the National Institute for Nanotechnology in 2016 were focused on hybrid nanoelectronics, energy generation and storage, metabolomics sensors

[29] See http://www.mcw.com/Projects/Details?f=p&title=National-Institute-of-Nanotechnology-NINT, accessed 11/04/2019.

[30] See https://uwaterloo.ca/institute-nanotechnology/, accessed 11/04/2019.

[31] See https://www.chairs-chaires.gc.ca/about_us-a_notre_sujet/index-eng.aspx, accessed 11/04/2019.

[32] See https://www.cmc.ca/discover-facilities-and-capabilites/, accessed 11/04/2019.

[33] See https://www.nanomedicines.ca/, accessed 11/04/2019.

[34] See https://www.cfn-nce.ca/about-us/our-network-community/networks-of-centres-of-excellence/, accessed 11/04/2019.

[35] See https://globaladvantageconsulting.com/portfolio/canadas-nanotechnology-innovation-ecosystem-2017/, accessed 11/04/2019.

[36] See information on Canada's Nanocrystalline cellulose (NCC) technology, at https://www.nrcan.gc.ca/our-natural-resources/forests-forestry/forest-industry-trade/forest-products-applications/cellulose-nanocrystals/13349, accessed 11/04/2019.

[37] The Canadian nanocellulose plants are in Montreal (https://newsroom.domtar.com/cellulose-nanocrystals/) and Windsor, Quebec (https://www.celluforce.com/en/technology/), both accessed 11/04/2019.

systems, and nano-enabled materials.[38] Similarly, the research activities at the Waterloo Institute for Nanotechnology focus on smart and functional materials, connected devices, next-generation energy systems, and therapeutics and theranostics.[39]

Nanotechnology in South Korea

South Korea has sustained a nanotechnology R&D policy since 2001. In 2017, its investment was KRW 643 billion (~$0.5 billion USD). South Korea has quickly grown its influence and share of influence in nanotechnology. In terms of direct government investment and tax incentives for research in industry, Korea led the Asia Pacific countries with 0.35 percent of its GDP in 2015 according to the OECD Science, Technology, and Industry Scoreboard 2017. In terms of publications per year, South Korea occupies a fourth place, just above Japan. In both USPTO and WIPO patents per year, South Korea sits in third place. In response to China's investment in R&D, the South Korean government announced a massive investment in nanotechnology in 2018. In parallel to the development of a national nanotechnology roadmap (2020-2030), the government is earmarking more than a trillion won[40] to increase industrial competitiveness and basic R&D in key sectors such as automotive, energy, health, and ICT. Founded in 2001, the Nano Technology Research Association (NTRA) was tasked with promoting the commercialization of nanotechnology and supporting the creation of nanotech companies. It created the NanoKorea conference and exhibition as a means to connect businesses engaged in the commercialization of nano-convergence technologies and to cultivate foreign markets and international collaboration (see Box 3.2). The NTRA also gathers statistics on nano-convergence industries, informs policy planning, and addresses bottlenecks in its ecosystem through a Technology to Business platform ($T^{+}2B$).

BOX 3.2
NanoKorea

LG has developed a roll-to-roll CVD graphene synthesis and processing technology for mass production in various electronics applications.[1] Similarly, researchers at the Samsung Advanced Institute of Technology (SAIT) developed a unique graphene-based battery material that enables a 45 percent increase in capacity, and five times faster charging speeds than standard lithium-ion batteries.[2] Additionally, Samsung is making very large investments in extreme ultraviolet lithography to enable its current 7 nm feature scale technology to reach 5 nm.[3] It is also reported to be making a $116 billion investment to achieve chip manufacturing supremacy,[4] and to leapfrog Taiwan Semiconductor Manufacturing Corporation's domination of today's $250 billion chip manufacturing market.

[1] See https://www.idtechex.com/graphene-2d-materials-usa/show/en/speakers/13747/innovative-cvd-graphene-technology, accessed 11/04/2019.

[2] See https://news.samsung.com/global/samsung-develops-battery-material-with-5x-faster-charging-speed, accessed 11/04/2019.

[38] See evaluation report on Canada's National Institute for Nanotechnology (NINT) in Edmonton for the period 2008-2009 to 2013-2014, at https://nrc.canada.ca/en/evaluation-national-institute-nanotechnology, accessed 11/04/2019.

[39] See Waterloo Institute of Technology annual report 2018-2019, at https://uwaterloo.ca/institute-nanotechnology/about, accessed 11/04/2019.

[40] One trillion won is equal to $850 million USD as of January 2020.

[3] See https://samsungatfirst.com/euv/ and https://news.samsung.com/global/samsung-successfully-completes-5nm-euv-development-to-allow-greater-area-scaling-and-ultra-low-power-benefits, both accessed 11/04/2019.
[4] See https://www.bloomberg.com/news/articles/2019-12-23/behind-samsung-s-116-billion-bid-for-chip-supremacy?srnd=premium, accessed 11/04/2019.

CONCLUDING REMARKS ON THE GLOBAL NANOTECHNOLOGY R&D ECOSYSTEM

The assessments above indicate that while the United States remains a competitor in nanotechnology, the committee concludes that it is no longer the unambiguous leader of R&D in this field. Programs, initiated by other developed and emerging economies, at around the same time the NNI was formed, have implemented a variety of mechanisms that seem to have been highly effective in raising the scale and productivity of their programs. The most effective of these mechanisms include:

- Focused support of the most innovative basic science research and technology development with a prolonged period of stable funding that has encouraged a migration of each nations' most able technical talent to nanotechnology.
- Agile, and highly effective, coordination among the various national or regionally supported funding agencies with the goal of maximizing the impacts of fundamental research to advance applications and solutions to societal problems in recognized areas of strategic importance.
- Successful, integrated R&D efforts addressing societal challenges that are highly interdisciplinary, involving nanotechnology-enabled materials, structures, devices, and systems. (The novel, and in many cases highly effective, coordination of research in disparate fields has contributed significantly to the rapid rise of new centers of leadership outside the United States.)
- The establishment of mechanisms to promote government-industry partnerships, to create and nurture national nanotechnology ecosystems, and to speed the commercialization of the promising R&D results.
- The creation and maintenance of shared state-of-the-art nanotechnology infrastructure that supports fundamental and applied science, commercialization of nanotechnology products, and development of nanotechnology-enabled systems and applications.
- National educational and training policies to promote the rapid growth of a highly trained and nanotechnology-skilled workforce that meets the ever-changing but constantly expanding needs of high-technology industry.

4

Findings, Recommendations, and Implementations

The statement of task for this review asked that the committee assess the current state of nanoscience and nanotechnology resulting from the National Nanotechnology Initiative (NNI) as authorized in 2003, including the current impact of nanotechnology on U.S. economic prosperity and national security. Based on this assessment, the committee was asked to consider the foundational question of if and how the NNI should continue. The committee has therefore devoted considerable discussion to this. The key questions are both (1) absolute—did the United States derive sufficient benefit from the investments of the NNI?—and (2) relative—have the investments and strategies for supporting nanotechnology advancement in other countries been *more* beneficial than in the United States? The committee is unified in a positive assessment of the value of the NNI to the U.S. economy, but concerned that the recent, technically focused approaches of other nations may be yielding better societal outcomes. The committee therefore considered whether the U.S. nanotechnology effort could be organized in *more effective ways* to accelerate the transition of nanotechnology discoveries to the higher technology readiness levels that bring societal benefits.

The committee notes that large-team science and engineering is unambiguously a critical component of the engine driving all advanced economies, and that individual and small-scale efforts are unlikely to deliver globally competitive outcomes. Accordingly, were coordination of the NNI to be dismantled, the committee anticipates that the U.S. ability to bring the breadth and depth of the nation's research enterprise together to focus on cross-disciplinary nanotechnology challenges would be greatly attenuated, putting the national competitiveness at even greater risk. Thus, the committee has arrived at the view that the NNI should be continued, but with significant modification to the coordination of its priorities and its methods and modes of operation to ensure that the United States is able to maintain a leadership position against a global backdrop of increasingly robust competition, as described elsewhere in this report. Rebranding is also recommended, to signal the shift in efforts and reaffirmation of the initiative. The specific recommendations for these proposed changes are described in detail in the rest of this chapter.

STRATEGIC ALIGNMENT WITH NATIONAL PRIORITIES

The NNI was established in 2000 and authorized in December 2003 with the goal of *coordinating* nanotechnology-related activities of federal departments and agencies. This coordination task has been accomplished with considerable effectiveness, despite its relatively small annual budget of ~$3 million for the actual work of coordination provided by Nanoscale Science and Technology (NSET, in setting direction) and the National Nanotechnology Coordination Office (NNCO, in supporting the implementation). The Nanotechnology Signature Initiatives (NSIs)[1] were formulated to give strategic structure to this effort, and clearly address worthy topics of national concern.

However, in the years since the NNI was launched, the national priorities for science and technology have shifted, in response to external factors (e.g., national security following the terrorist attacks of September 11, 2001), in recognition of growing challenges (e.g., the effects of climate change) and new

[1] See https://www.nano.gov/signatureinitiatives, accessed 11/04/2019.

opportunities (e.g., the promise of quantum computing). The committee has formed the view that the NNI overall and the NSIs in particular have not stayed sufficiently closely aligned with the stated national priorities provided by successive administrations. This guidance impacts nanoscience and nanotechnology in numerous ways. For example, the FY 2020 Administration R&D Budget Priorities calls for improvements to the security of the nation through investments in artificial intelligence (AI), autonomous systems, hypersonics, and nuclear deterrent capabilities, and requires advancing our microelectronics, strategic computing, and cyber capabilities. It calls for leadership in quantum information science (QIS) and in advanced communications networks (e.g., 5G wireless networks). The guidance provided in the *FY 2020 Administration R&D Budget Priorities* stresses the importance of next-generation manufacturing, especially smart and digital manufacturing, advanced materials processing, bio-based manufacturing and new design tools, materials, devices interconnects, and architectures for semiconductors. The document also directs investments to ensure American leadership in space, to harness American energy resources, to prioritize basic medical research and personalized medicine, and to advance precision agriculture technologies. Absent explicit alignment with the federal administration's priorities, the NNI risks decreased support among the representative agencies and decreased relevance within the national science and technology agenda.[2] While a mapping of the NNI R&D portfolio and research investments onto these national research priorities would enable an annual realignment of the NNI program with the evolving strategic priorities of the nation, the committee struggled to discover any evidence that this is regularly (i.e., annually) undertaken by the NNI. It was unclear to the panel that any process exists to review the success (or otherwise) of the NNI's research (re-)alignment strategy. These observations point again to the challenges of actively managing the research portfolio of a large program executed by numerous independent agencies via the current "weak" coordination approach.

> **Finding 1.1:** The activities of the National Nanotechnology Initiative (NNI) and its current signature initiatives, while addressing relevant societal challenges, are not explicitly aligned with the current research and development (R&D) priorities established by the federal government.

Clarifying Key Contributions and Relationships: NNI and NQI

In strong alignment with the current administration's research and development (R&D) priority on "Quantum Information Sciences, and Strategic Computing,"[3] the White House has recently established the National Quantum Initiative (NQI). The NQI is envisaged as a whole-of-government approach, and is structured similarly to the NNI, with a coordinating office to align the efforts of the relevant agencies.

This committee feels that it is vitally important to note that the emergence of the NQI is a testament to the success of the NNI. A great many of the recent advances in physics and chemistry that have propelled the field of quantum computing forward, to the point of being considered as a viable applied technology that will serve the national interest, have emerged from work undertaken within the NNI. That is, the NQI may reasonably be viewed as an offshoot of the NNI that partners advances in nanoscience and nanoscale device fabrication with new computational theories and algorithms.

Moving forward, it is clear that there will be some overlap between the work carried out under the NNI and the NQI, even though the NNI is substantially broader in scope. Fundamental advances in the physical sciences at the nanoscale will continue to propel quantum computing infrastructure designs.

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[2] See, for example, Office of Management and Budget & Office of Science and Technology Policy, 2018, *FY 2020 Administration R&D Budget Priorities*, Memorandum for the Heads of Executive Departments and Agencies, M-18-22, July 31, 2018, https://www.whitehouse.gov/wp-content/uploads/2018/07/M-18-22.pdf.

[3] See NQI bill at https://www.congress.gov/bill/115th-congress/house-bill/6227/text and related press coverage, for example, from the American Institute of Physics at https://www.aip.org/fyi/2019/national-quantum-initiative-signed-law.

Accordingly, the committee is of the view that the nation will benefit by having the working relationship between the NNI and the NQI clearly defined and articulated.

The NQI and the NNI overlap in several areas such as the synthesis of new materials chemical processes, modeling and simulation, characterization tools, and nanofabrication to enable qubits and quantum devices. In some ways, QIS is driving and will be driving innovation in several areas including nanotechnology. At the same time, nanotechnology is and will continue to provide novel tools, techniques, materials, and processes that enable QIS. Similarly, some funding initiatives naturally overlap between NNI and NQI projects. For example, the Nanoscale Science Research Center (NSRC) centers, funded by the Department of Energy (DOE), support NQI and NNI projects. Both initiatives and their corresponding coordinating offices need to find ways to leverage efforts in the areas where there is overlap. This could possibly be achieved by creating incentives on projects or programs that make use of resources from both initiatives or by a working group with a specific and well detailed agenda or by a person with a dual appointment at both coordinating offices.

A concern of the committee is that with the introduction of the NQI, with its overlap in R&D scope with the NNI, there will possibly be a reduction in the funding available to support the work of the NNI, since agencies will perhaps seek to minimize the R&D "tax" assessments applied to agency programs and used to support the coordination efforts of the two entities.

Finding 1.2: The National Quantum Initiative (NQI) is, in large part, an important outgrowth of the National Nanotechnology Initiative (NNI), but the degree of coordination and collaboration between these national high-priority efforts is not yet clear.

Emerging Opportunities: Innovations in the Bioeconomy

As discussed, countries outside the United States have shifted their focus toward responsible innovation. This direction represents an opportunity for the NNI to better align with U.S. R&D priorities, including efforts to advance the development and commercialization of bio-based and renewable materials as well as more sustainable methods of manufacturing. The U.S. bioeconomy may be defined as:

> Economic activity that is driven by research and innovation in the life sciences and biotechnology, and that is enabled by technological advances in engineering and in computing and information sciences.[4]

Focusing nanoscience and nanotechnology to advance the U.S. bioeconomy has significant potential to enhance U.S. global leadership and competitiveness in this rapidly growing area. There is a significant overlap between the goals of the Bioeconomy Initiative (also established in the year 2000, with the aim "to maximize interagency coordination to yield greater impact from federal investments and accelerate innovation"[5]) and the NNI, particularly in the area of bioproducts, and the derivation of materials from synthetic biology. Key takeaways from an October 2019 Office of Science and Technology Policy (OSTP) Summit on the Bioeconomy include the following: building the bioeconomy workforce of the future; promoting and safeguarding critical bioeconomy infrastructure and data; and, critically, leveraging the entire U.S. innovation ecosystem, as well as identifying regulatory opportunities and challenges. "Advances realized over the past two decades have resulted from the unique U.S. innovation ecosystem and the convergence between biology and other disciplines and sectors, such as nanotechnology and

[4] NAP, 2020, *Safeguarding the Bioeconomy*, https://www.nap.edu/download/25525.

[5] See https://biomassboard.gov/pdfs/Bioeconomy_Initiative_Implementation_Framework_FINAL.pdf, accessed 11/04/2019.

computer science."[6] Examples of this convergence include organ-on-a-chip and three-dimensional (3D) printing of tissues.

The coordinating efforts of the NNCO represent existing infrastructure well suited to advance initiatives proposed in the U.S. Bioeconomy Initiative, and truly accomplish a highly efficient leveraging, similar to the proposed integration with the Quantum Initiative.

The convergence of the bioeconomy and nanotechnology can create novel and advanced biomaterials more efficiently, sustainably, and with less negative societal impact by tailoring production to performance requirements. Further, biomaterials are made of nanoscale components, which can benefit from the use of advanced manufacturing tools to efficiently produce products from them.

In 2016, the United States used about 365 million dry tons of biomass, about one-third of estimated capacity.[7] A "review committee formed the view that this rich and renewable domestic resource could be greater utilized to improve the economic, environmental, and societal wellbeing, and the security of the United States by exploring and adopting the tools of nanoscience and nanotechnology with biomaterials to improve efficiency and performance." Two key examples of the ability to leverage nanotechnology and the bioeconomy are cellulose nanomaterials, derived from biomass, and synthetic biology.

The highly invested and rapidly growing sectors of the bioeconomy, including the Bioeconomy Initiative, the use of biotechnology to manufacture conventional consumer and industrial products, and innovation in the development of plant-derived biologically based products, creates an opportunity for adoption and integration nanomanufacturing and other tools of nanoscience and nanotechnology to increase the efficiency and economic impact of advanced manufacturing in the United States.[8] The collaborative models of public private partnerships, developed with support from the NNI by several agencies as part of signature initiatives and related manufacturing centers may provide helpful models for navigating the challenges of protecting intellectual property in the biotechnology industry.

Finding 1.3: The goals of the Bioeconomy Initiative overlap with those of the National Nanotechnology Initiative (NNI) toward advanced manufacturing, creating an opportunity to leverage nanomanufacturing infrastructure and the coordinating relationships of the NNI in service of advancing the Bioeconomy Initiative.

A Priority Practice: Transferring Technology from Laboratory to Marketplace

The committee's assessment of nanoscale science and engineering efforts among other nations found that considerable new investments have been made in innovative programs that seek to accelerate the lab-to-market timeline for nanotechnologies in the period since the last NNI review. Prominent examples of such large-scale projects include the Tsukuba Innovation Arena (TIA-nano) in Japan,[9] an open innovation hub that fosters collaboration on innovations among five large agencies, and the multiple Open Innovation Test Beds and Industry Commons model developed by the EU.[10] Further, other nations have taken structured approaches to opening up international markets to their new and emerging nanotechnology products, by investing in targeted trade delegations and other commercial supports. As

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[6] OSTP, 2019, Summary of the 2019 White House Summit on America's Bioeconomy, at https://www.whitehouse.gov/wp-content/uploads/2019/10/Summary-of-White-House-Summit-on-Americas-Bioeconomy-October-2019.pdf.

[7] M.H. Langholtz, B.J. Stokes, and L.M. Eaton (Leads), 2016, *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks*, Oak Ridge, Tenn., U.S. Department of Energy, Oak Ridge National Laboratory, at energy.gov/eere/bioenergy/2016-billion-ton-report.

[8] See https://www.federalregister.gov/documents/2019/09/10/2019-19470/request-for-information-on-the-bioeconomy.

[9] See https://unit.aist.go.jp/adperc/cie/tia/index.html, accessed 11/04/2019.

[10] See https://ec.europa.eu/research/participants/data/ref/h2020/wp/2018-2020/main/h2020-wp1820-leit-nmp_en.pdf, accessed 11/04/2019.

just one example, NanoCanada was launched in 2015 to provide support and coordination activities for accelerating the market launch of nanotechnology products created by small and medium-size enterprises, to the benefit of the economy and peoples of Canada.[11]

Europe has made a strategic investment in graphene, including a (€1 billion ~ $1.1 billion) integrated R&D project, the Graphene Flagship, a partnership of universities, research centers, and companies focused on strategic applications and commercialization. The Graphene Engineering and Innovation Centre in Manchester in the United Kingdom is a research and innovation center for both academia and industry, with shared infrastructure and resources geared toward commercialization. These resources are aimed at rapid commercialization. China has also invested heavily in graphene. The Chinese government has prioritized graphene in the Development Plan for New Materials during the 13th Five-Year Plan Period (2016-2020), which has led to more than 30,000 patents in 2018. Small and large companies producing graphene are emerging in China, reported to account for up to 20 percent of global R&D spending.[12,13]

Improved strategic focus of U.S. investment in nanotechnologies toward accelerating market adoption, particularly in areas of current national R&D priority, is critical for global leadership.

Finding 1.4: U.S. competitiveness in nanotechnology is slipping in some areas, putting U.S. economic prosperity and national security at risk.

Finding 1.5: The United States is not investing significant resources in nanotechnology in ways that are as focused and strategic as in other nations.

While the funded R&D efforts of the NNI have generated new knowledge and innovative technologies in many economic sectors, the return on NNI investment in terms of commercial adoption has not reached its potential. According to Columbia Technology Ventures, roughly 5 percent of inventions by Columbia are now licensed, despite the highly successful lab-to-market resources developed and used there.[14] Many factors contribute to the slow pace of commercialization, including challenges of scale-up, market pull, and the complexity of new technology innovation. After 15 years of investment, nanotechnology is now a more mature field, where increased emphasis on later stages of commercialization is needed.

NNI has organized several events toward commercialization. These efforts bring key stakeholders together, however the "valley of death" remains a critical hurdle in commercialization.[15]

The NNI has played a rather small role in important lab-to-market translational activities. Successful models have built integrated university research, technology transfer, talent pools, start-up resources, and large company partnerships to foster multisector efforts toward commercialization. The coordination efforts of the NNI touch each of these aspects of successful commercialization, but they were not focused in this direction previously.[16] Many voices weighed in during the open session of the NNI Stakeholder Workshop in August 2019. For example, one attendee noted, "there is a lot of research going on and I think that is something that is not only important to the security of the United States, but also to create jobs and have a new technology for consumers." Another mentioned, "I don't mean that we stop the research, but I think we now, after close to 20 years, we want to take a step forward and commercialize a lot of the stuff that has already been done."

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[11] See https://nanocanada.com/2019/09/12/2020-nanocanada-mission-to-tokyo-and-seoul/, accessed 11/04/2019.

[12] See https://www.prnewswire.com/news-releases/global-and-china-graphene-industry-report-2019-2025-300897416.html, accessed 11/04/2019.

[13] China is the world's new science and technology powerhouse, *The Bruegel Report*, 2017, at https://bruegel.org/2017/08/china-is-the-worlds-new-science-and-technology-powerhouse/.

[14] O. Herskowitz, Columbia Technology Ventures, presentation to the committee, September 2019.

[15] The Future of the NNI: A Stakeholder Workshop, Washington D.C., August 2019. See Agenda, Video, and Synopsis, at https://www.nano.gov/2019stakeholderworkshop, accessed 11/04/2019.

[16] C. Mirkin, presentation to the committee, September 2019.

Finding 1.6: U.S. nanotechnology stakeholders report considerable challenges along the lab-to-market path for nanotechnology-based products.

Recommendation and Implementations

These six findings lead to the following key recommendation and implementations.

Key Recommendation 1: The Nanoscale Science, Engineering, and Technology (NSET) Subcommittee and the National Nanotechnology Initiative (NNI) agencies should align the efforts of the NNI to deliver responsible and sustainable nanotechnology-based solutions that address the federal research and development (R&D) priorities, which currently include security, artificial intelligence, quantum information sciences, manufacturing, bio-based materials, water, climate change, space travel, exploration, inhabitation, energy, medical innovations, and food and agriculture.

Implementation Recommendation 1a: Convene multiagency coordination efforts to align the National Nanotechnology Initiative (NNI) priorities with federal research and development (R&D) priorities.

Implementation Recommendation 1b: Facilitate ongoing close partnership and collaboration between the National Nanotechnology Initiative (NNI) and National Quantum Initiative (NQI) to minimize duplication of effort, maximize the utilization of existing infrastructure, and allow for cross-pollination of ideas across both initiatives.

Implementation Recommendation 1c: Through the National Nanotechnology Coordination Office (NNCO) and interagency efforts, align the National Nanotechnology Initiative (NNI) and the Bioeconomy Initiative to leverage research and development (R&D) and coordination efforts on nanotechnology to strengthen the bioeconomy, including biotechnology, bio-based products, and sustainable bioproduction, including molecular assembly.

Recommendation 1d: To address the need for closer coordination and agile refocus on strategic opportunities, the NNCO should be adequately resourced to fully interact with NNI agencies and hold those agencies accountable to the new plan.

COMMERCIALIZATION OF NANOTECHNOLOGY

The NNI, as implemented via NSET and the NNCO starting in 2003, enabled the United States to establish early leadership in the development of knowledge and facilities in many of the facets of nanoscience and nanotechnology. The 2016 NNI review examined the global revenues from the nano-enabled technologies market at that time, and provided forward-looking projections, based on external market analyses.[17] At that time, it was estimated that the EU and Asia regions had *both* surpassed the United States in the fraction of market share in 2012 and that they both accelerated strongly past the United States in the years following. The market in 2018 was projected to be on the order of $3.4 trillion, with the prediction that the U.S. share would decrease from ~ 25 percent in 2016 to ~ 23 percent as the efforts to support commercialization activities in the EU and Asia are further ramped up.

[17] See Figure 1.2, Triennial Review of the National Nanotechnology Initiative, 2016, at https://www.nap.edu/catalog/23603/triennial-review-of-the-national-nanotechnology-initiative.

Global Developments

The committee notes that as Europe and Asia followed the lead of the United States in formulating and implementing their own nano-initiatives, their investments in R&D, perhaps naturally, occurred further along the nanoscience-to-technology continuum. That is, it is plausible that the timing of investments in countries outside the United States has allowed other countries to benefit from foundational knowledge developed earlier in the United States, and to focus their investment in areas ripe for commercialization. In some cases, this has permitted other countries to establish facilities and innovative mechanisms for commercialization that exceed those that exist in the United States. A particular focus abroad is directed toward the development of multifaceted innovation ecosystems that aim to increase success in navigating the "valley of death" by integration of resources that go beyond those found in NNI legacy infrastructure and facilities in the United States. Examples include Japan's Tsukuba Innovation Arena (TIA), the EU's Open Innovation Platforms, and China's Nanopolis, all described in Chapter 3.

> **Finding 2.1:** Several other countries and regions have evolved their central nanotechnology research and development (R&D) efforts to incorporate a strong emphasis on commercial translation, yielding lab-to-market pathways that are accelerated relative to those in the United States.

The Role of Regional, State, and Local Entities in Commercialization of Nanotechnology

In 2012, the NNI hosted a workshop that engaged regional, state, and local representatives in a dialogue regarding commercial opportunities related to nanoscience and technology. Although the NNCO has participated in annual TechConnect conferences since 2012, there has been no subsequent workshop by the NNCO to specifically update regional, state, and local (RSL) representatives on the status of commercialization efforts or on potential partnerships and resources created by NNI for commercialization. In contrast, in other parts of the world, RSL initiatives are playing a key role in commercialization efforts, particularly in China. Although many RSLs had nano-specific commercialization efforts in 2012, the efforts in the United States have become diffuse, and largely been integrated into broader initiatives (e.g., high-tech development offices). The maturation of nanoscience into commercial-ready nanotechnology since 2012, however, makes reengagement of RSLs by the NNCO particularly timely.

> **Finding 2.2:** There has not been a National Nanotechnology Initiative (NNI) workshop that targets economic development with regional, state, and local (RSL) government engagement since 2012.

Nanotechnology Innovation Ecosystems

After a decade of significant funding in nanoscience and nanotechnology, many countries moved from a nanoscience project-funding mode to the creation of a sustainable ecosystem comprised of academic institutions, small and large commercial enterprises, and government agencies, with the goal of creating long-term socioeconomic benefits through translation of knowledge into proof of concepts, prototypes, and products. The European Union (EU) uses its research funding program to provide access to state-of-the-art fabrication and characterization facilities and for the development of low-volume fabrication capabilities, through the Open Innovation Platforms. Another particularly interesting endeavor was the creation of NanoNextNL in 2010, a public-private partnership that matched €125 million (~$138 million USD) from the Dutch government over 6 years, which delivered a 4:1 return on investment

(ROI).[18] Some of the innovative aspects of the program were the integration of risk analysis and technology assessment in research programs, business case development tools, intellectual property training, and entrepreneurship for trainees. Another interesting example is the Nanotechnology Business Creation Initiative (NBCI) in Japan, an industry-driven organization supported by its membership (e.g., multinationals, small and medium-size enterprises, trading companies, venture capital and consulting firms, and universities). NBCI works across the Japanese nanotechnology ecosystem to support business matching activities—linking public or private research with industry needs, the development of public policies around the use of nanotechnology, the promotion of open-innovation platforms, the development of technology roadmaps and standards and the exchange of knowledge and best practices both nationally and internationally. Similarly, NanoMalaysia Berhad's model explicitly addresses the needs of industry, academia, and research institutions in support of nanotechnology commercialization.

The United States has long relied largely on market-inspired commercialization activity in most business sectors, strongly preferring that to government-supported commercialization activity. For the NNCO to pivot to a more intentional, coordinated, and centralized approach to accelerating nanotechnology commercialization will require significant changes in how the NNI-involved agencies operate and how they work together. Funding will need to be carved out of budgets for robust multiyear commitments to a shared vision with a whole-of-government approach. A willingness to engage in public-private partnerships will need to be cultivated in a multiagency framework, and flexible legal and IP structures will need to be developed to allow these partnerships to be attractive and fruitful. Separate legal entities, outside the NNI-involved agencies, may be needed to allow for nimble execution of business objectives on the path to commercialization. The committee fully recognizes that such efforts will be challenging for the involved agencies and the NNCO to address, even while recognizing the value of the deep agency knowledge that the NNCO brings to the problem of commercialization.

The committee was concerned that the current organizational structure of the NNI, directed by NSET with support from the NNCO, strongly serving interagency cooperation but less so public-private interactions with industry, may inhibit it from supporting industry in the goals of technology transfer, thus limiting the societal benefits of our federal investments. A separate 501(c)(3) not-for-profit organization or industry consortium may be needed to specification support commercialization.

Finding 2.3: The Nanoscale Science and Technology (NSET) and the National Nanotechnology Coordination Office (NNCO) focus most strongly on an ecosystem comprised of government agencies and departments. Supporting knowledge translation and technology transfer has not been a sufficiently major focus of the National Nanotechnology Initiative (NNI) to date.

Commercialization Databases

The committee struggled to develop a comprehensive understanding of national and global commercialization opportunities. A concern that was discussed by the committee at length is that data to guide potential U.S. and global industry partners on nanotechnology commercialization opportunities is not aggregated and shared by the NNI. It is startling to note that the Iran-based website StatNano provides a wide array of useful global data for industry use which in many cases is more comprehensive than that on the NNI's websites. This struck the committee as being particularly concerning given that *specific recommendations were made in the review of 2013 (Recommendations S.2, S.3, S.4, S.8, in particular) to address this shortfall.*[19]

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[18] See NanoNextNL End Term Report 2010-2016, at https://www.nanonextnl.nl/wp-content/uploads/NNXT_EndTermReport_WEB_spreads.pdf, accessed 11/04/2019.

[19] *Triennial Review of the National Nanotechnology Initiative*, 2013, at https://www.nap.edu/catalog/18271/triennial-review-of-the-national-nanotechnology-initiative.

Finding 2.4: The persistent failure of the National Nanotechnology Initiative (NNI) to engage a data science framework to aggregate and share data on U.S. nanotechnology competitiveness has created a deficit of information that could be used by industry partners to assess commercial promise of different nanotechnologies.

Return on NNI Investment

Identifying the need and opportunity to significantly strengthen technology transfer, the U.S. federal government recently has launched the U.S. Return on Investment (ROI) Initiative, which aims to increase the lab-to-market return on the government's investment in R&D.[20] This includes the following priorities: (1) optimizing the management, discoverability, and ease-of-license of the 100,000+ federally funded patents; (2) increasing the utilization of federally funded research facilities by entrepreneurs and innovators; (3) ensuring that relevant federal institutions and employees are appropriately incentivized to prioritize R&D commercialization; (4) identifying steps to develop human capital with experience in technology transfer, including by expanding opportunities for entrepreneurship education; and (5) maximizing the economic impact of the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. Although not specifically aimed solely at nanotechnology, the ROI Initiative is well positioned as leverage for future NNI enhancements in the development of more successful nanotechnology innovation, entrepreneurship, and commercialization.

Finding 2.5: The recent establishment of the Lab-to-Market Return-on-Investment (ROI) Initiative offers a strategic opportunity for National Nanotechnology Initiative (NNI) collaborations to accelerate nanotechnology commercialization.

Role of the NNCO in Quantifying Outcomes of NNI Funding

Although the NNCO has engaged in efforts to facilitate commercialization of nanoscience in the United States through Global Tech Connect, for example, evaluation of the impact/value of those efforts, and other efforts invested by stakeholders in the NNI, are nearly impossible to quantify without data about the outcomes. Prioritization of investments, and informed decision making related to initiatives that do not yield a significant return, is not possible. Similarly, evaluation of the competitive status of the United States in the context of commercialization of nanotechnology is not possible without relevant data.[21,22] This committee was unable to obtain data via the NNCO regarding the outcome of initiatives related to commercialization, which is problematic for nanotechnology generally, and specifically in light of the federal administration's current efforts to assess ROI across the full R&D portfolio via Performance.gov.[23]

Finding 2.6: Data on the competitive status of the United States with regard to nanotechnology implementation and commercialization is unavailable through the National Nanotechnology Initiative (NNI) public-facing digital portals.

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[20] *Return on Investment Initiative for Unleashing American Innovation*, 2019, NIST Special Publication 1234, https://doi.org/10.6028/NIST.SP.1234.

[21] It is worth reviewing the StatNano.com website, from Iran, as a model.

[22] If the NNCO were to (1) hire a data scientist or information scientist who can provide accurate assessments of competitiveness across all sectors and (2) maintain up-to-date information online in order, it would likely maintain its status as the go-to authority in the United States.

[23] See https://www.performance.gov/, accessed 11/04/2019. And see also https://www.nist.gov/tpo/lab-market, accessed 11/04/2019.

Pilot Plants and Test-Bed Facilities

A number of countries have invested in the creation of pilot plants, or small-scale manufacturing plants, as a means of de-risking the commercialization of emerging technologies. For example, the EU supports low-volume manufacturing and prototyping capabilities through its Open Innovation Platforms Horizon 2020 and IMEC in Belgium, while Canada has semiconductor foundries such as the Canadian Photonics Fabrication Center[24] in Ottawa and the C2MI[25] in Bromont, Quebec, as well as the National Design Network[26] linking 10,000 academic users and 1,000 companies in micro-nanotechnologies. Many of these facilities are very open to having U.S.-based companies utilize their pilot-scale fabrication activities facilities (for fees), and U.S.-based companies have reported considerable satisfaction with using these facilities.

Finding 2.7: Pilot and test-bed facilities are a key part of lab-to-market and return on investment activities. The United States has not maintained a competitive position with this type of facility.

Entrepreneurship Awareness in Workforce Training

Training in best practices in nanotechnology development can be improved in many universities to raise the level of quality in precommercial ideas and prototypes. Although some universities have programs that provide effective tech transfer and training opportunities to students, there is no Accreditation Board for Engineering and Technology (ABET)—like assessment and standards[27] to help achieve uniformly high-quality training in entrepreneurship and technology transfer for engineering and science majors across the United States. On the technical side, an entrepreneurial student should be aware of intellectual property management, technology integration and scale-up, packaging and manufacturing costs, product safety, and life cycle assessments. In addition, typical entrepreneurship courses should include: foundations in entrepreneurial management, market intelligence and customer demand, business model design, marketing and sales, building and managing a team, and finding and managing financing. Not every student will pursue a career involving tech transfer or R&D, but foundational training leading to an awareness of the key challenges and approaches underlying technology development is likely beneficial for all or most.

Finding 2.8: The training of competent nanotechnology professionals in entrepreneurship, technology transfer, and commercialization are essential to lab-to-market return on investment.

Recommendation and Implementations

These eight findings led the committee to propose a key recommendation and identify several approaches for its implementation.

Key Recommendation 2: The Nanoscale Science, Engineering, and Technology (NSET) Subcommittee and the National Nanotechnology Coordination Office (NNCO) should strengthen and expand the lab-to-market innovation ecosystem in support of the transfer of nanotechnologies from bench research to products, to ensure U.S. competitiveness.

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[24] See https://nrc.canada.ca/en/research-development/nrc-facilities/canadian-photonics-fabrication-centre, accessed 11/04/2019.

[25] See https://www.c2mi.ca/en/, accessed 11/04/2019.

[26] See https://navigator.innovation.ca/en/facility/queens-university/canadas-national-design-network-cndn, accessed 11/04/2019.

[27] See https://en.wikipedia.org/wiki/ABET.

Implementation Recommendation 2a: The National Nanotechnology Coordination Office (NNCO) should, within a year from the issuance of the quadrennial review, develop appropriate data collection methods and a data repository to allow routine assessment of (1) the global status of nanotechnology, (2) new and emerging trends, and (3) the status and return on investment (ROI) of the National Nanotechnology Initiative (NNI) to be readily assessed. Ideally the data collection process should not become a significant burden on the researchers.

Implementation Recommendation 2b: Within 2 years, the National Nanotechnology Coordination Office (NNCO) should develop a service model strategy to support commercialization activities so as to ensure that (1) nanoproducts are made in the United States whenever possible, (2) relevant skills and expertise are developed locally, (3) barriers to commercialization are identified quickly, and (4) the national return on investment (ROI) is maximized.

Implementation Recommendation 2c: Through the National Nanotechnology Coordination Office (NNCO), immediately expand efforts to build a national community of National Nanotechnology Initiative (NNI) participants, and then leverage this community to improve access to national facilities, increase opportunities for collaboration, create public-private partnerships, and generate pathways for commercialization of products to global markets.

Implementation Recommendation 2d: By April 2022, create a not-for-profit organization whose mandate is to connect National Nanotechnology Initiative (NNI) participants, industry, and academia through membership and provision of services such as ecosystem studies, national and international conferences, regional workshops, and turnkey missions for stakeholders to international trade shows abroad.

Implementation Recommendation 2e: Interface with Manufacturing USA to assess the value of establishing a Nano-Manufacturing Institute that would offer tools to and share expertise with small and medium-size enterprises (SMEs) to accelerate product development. Such a Nano-Manufacturing Institute would ideally provide a path for SMEs to partner with the existing National Nanotechnology Initiative (NNI) user facilities.

Implementation Recommendation 2f: Expand international collaborations on responsible development and manufacturing, with the European Union in particular, and other countries as appropriate, to ensure transparent global standards emerge to the benefit of consumers and U.S. industry.

Implementation Recommendation 2g: The NSET and the NNCO should consider how to implement an agile and highly effective coordination among the various national or regionally supported funding agencies with the goal of maximizing the impacts of fundamental research to advance applications and solutions to societal problems in recognized areas of strategic importance.

NANOTECHNOLOGY INFRASTRUCTURE

State-of-the-Art Facilities and Their Challenges

Maintaining and constantly updating a state-of-the-art infrastructure is critical to support a world leadership position in science and technology. This has been recognized in the FY 2020 Administration R&D Budget Priorities,[28] where *Managing and Modernizing R&D Infrastructure* is considered an R&D priority practice. Access to state-of-the-art experimental apparatus and fabrication capabilities is an important enabler of advanced nanomaterials, device and systems research. In addition, centers that foster collaboration and interdisciplinary interactions help to promote innovative R&D. This has been a continued and critical emphasis of the NNI, as is highlighted in PCA 4 of the NNI Strategic Plan. This emphasis on developing and maintaining physical and cyber-physical infrastructure has led to its current networks of world-class user facilities: five DOE Nanoscale Science Research Centers (NSRCs),[29] the NSF National Nanotechnology Coordinated Infrastructure (NNCI),[30] the NSF Network for Computational Nanotechnology (NCN),[31] the NIH Nanotechnology Characterization Laboratory (NCL),[32] and the NIST Center for Nanoscale Science and Technology (CNST).[33]

These nanotechnology networks were often seen as a model by other countries. Today, several nations follow the U.S. model and are making substantial investments in nanotechnology infrastructure supporting a wide spectrum of nanotechnology efforts from basic science, to first demonstration, to first products for commercialization. Examples include Nanotechnology Platform in Japan,[34] ForLab in Germany,[35] Nano-X Research Facility in China,[36] IMEC in Belgium,[37] MINATEC[38] in France, Horizon 2020 Innovation Platforms in Europe,[39] and the National NanoFab Center in Korea.[40]

While the United States has been a leader in establishing the infrastructure to support nanotechnology research for the past two decades, the rest of the world has followed this example and several countries have invested heavily in research facilities and regional centers of expertise. In terms of current research interests such as quantum devices, China is outspending the United States significantly. For example, China has invested $11 billion to build a single facility in Hefei, while the United States has allocated $1.2 billion over 5 years as part of the National Quantum Initiative. Continued leadership of the United States in nanotechnology is not a forgone conclusion. In particular, research equipment becomes obsolete in a matter of years and new capabilities emerge that need to be made available. Therefore, continual renewal and updating of equipment and research capabilities is necessary.

Planning for facilities refresh cycles in the NNI core infrastructure sites should accommodate this reality in order to sustain U.S. competitiveness. This concern was already stated in the 2016 Triennial

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[28] Office of Management and Budget and Office of Science and Technology Policy, 2018, *FY2020 Administration R&D Budget Priorities*, Memorandum for the Heads of Executive Departments and Agencies, M-18-22, https://www.whitehouse.gov/wp-content/uploads/2018/07/M-18-22.pdf.

[29] See https://nsrcportal.sandia.gov/Home/About, accessed 11/04/2019.

[30] See https://www.nnci.net/, accessed 11/04/2019.

[31] See https://nanohub.org/groups/ncn, accessed 11/04/2019.

[32] See https://ncl.cancer.gov/, accessed 11/04/2019.

[33] See https://www.nist.gov/cnst, accessed 11/04/2019.

[34] See https://www.nanonet.go.jp/ntj/english/, accessed 11/04/2019.

[35] Germany Forschungslabore Mikroelektronik Deutschland (ForLab), at https://www.elektronikforschung.de/service/aktuelles/forschungslabore-mikroelektronik-deutschland-gestartet), accessed 11/04/2019.

[36] See http://english.sinano.cas.cn/au/NANOX/, accessed 11/04/2019.

[37] See https://www.imec-int.com/en/home, accessed 11/04/2019.

[38] See https://www.minatec.org/en/, accessed 11/04/2019.

[39] See https://ec.europa.eu/programmes/horizon2020/en, accessed 11/04/2019.

[40] See https://www.nnfc.re.kr/eng/, accessed 11/04/2019.

Review of the NNI.[41] While the 2020 NNI Proposed Budget[42] notes that NSF is planning a 5-year renewal of NNCI and lists all the major infrastructure funded through the government agencies, when measured as a fraction of the gross domestic budget, funds for facilities (infrastructure) have been trending downward since the mid-1970s (see Figure 4.1) although in terms of actual dollars, they have remained flat since 2015 (see Table 4.1). The NSF recently introduced its Mid-Scale Research Infrastructure program[43] (with first awards announced recently) in addition to its Major Research Instrumentation (MRI) program and Major Research Equipment and Facilities Construction (MREFC) projects; however, it is not clear how many of these will influence nanotechnology infrastructure.

> **Finding 3.1:** Several countries have followed the U.S. lead and are investing heavily into underlying infrastructure to support nanotechnology efforts, placing continued U.S. leadership in doubt.

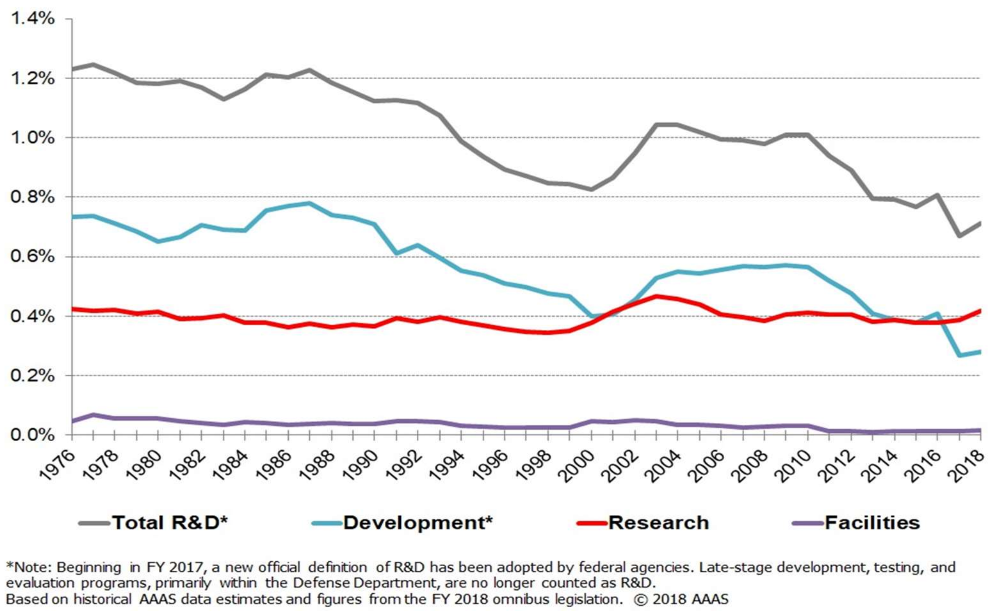

FIGURE 4.1 Federal R&D expenditures as percent of the GDP over time, broken down into research, development and facilities expenditures. SOURCE: M. Hourihan and D. Parkes, January 2019 "Federal R&D Budget Trends: A Short Summary," AAAS. © 2018 AAAS..

[41] NRC, 2016, *Triennial Review of the National Nanotechnology Initiative*, Washington, D.C., National Academies Press.

[42] The National Nanotechnology Initiative Supplement to the President's 2020 Budget.

[43] See details at the NSF website, at https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505602, accessed 12/20/2019.

TABLE 4.1 Research Infrastructure and Instrumentation Budget by Agency from 2015 to 2020

Agency	2015	2016	2017	2018	2019 *	2020 **
DOC/NIST	36.2	35.7	35.8	34.1	33.4	28.5
DOD	2.0	2.0	1.8	2.1	3.5	1.7
DOE	123.0	132.9	136.2	137.1	142.1	133.9
DOI/USGS	0.0	0.0	0.0	0.0	0.0	0.0
DOJ/NIJ	0.0	0.2	0.2	0.1	0.3	0.3
DOT/FHWA	0.0	0.0	0.0	0.0	0.0	0.0
NIH	15.0	26.4	23.6	23.4	24.2	21.2
NASA	0.0	0.2	0.0	0.0	0.0	0.0
NSF	40.5	56.5	52.6	45.6	43.7	42.0
NIFA	2.0	2.0	1.0	1.0	1.0	1.0
FS	1.2	0.6	0.0	0.0	0.0	0.0
Total	219.9	256.4	251.3	243.3	248.2	228.6

*Estimated. **Proposed.
SOURCE: Data sourced from "PCA#4 Research Infrastructure and Instrumentation Budget by Agency (Million USD)," The National Nanotechnology Initiative Supplement to the President's Budget (2017-2020).

Aging of the Nanoscience and Technology Infrastructure

The experimental tools needed to make, characterize, and optimize nanomaterials and devices is complex. Processing tools such as atomic layer deposition that enable the atomic layer-by-atomic-layer synthesis and growth of thin films on topology structure surfaces and direct write electron beam systems for sub-10 nm lithography are often too expensive for single investigator use and are increasingly being located in shared nano-foundry research facilities. Electron microscopes with sub-atom resolution, new atomic force and tunneling microscopes, and the surface analytical tools are essential to the characterization of the materials made in these nano-foundries. Increasingly, major national laboratories with synchrotrons that include high-intensity beam lines are vital for nanoscience discovery and development. However, the maintenance and eventual replacement by new tools with superior capabilities is a continual challenge. This leading-edge scientific instrumentation typically becomes obsolete or outdated on scales of 5-7 years. Failure to invest in modernizing R&D infrastructure will threaten U.S. workforce development, competitiveness, and long-term security. At the same time, the recapitalization challenge opens an opportunity for the United States to take a new scientific and technological lead by a timely and strategic renewal of its aging infrastructure.

Finding 3.2: The United States, as an early investor in nanotechnology infrastructure, is consequently now facing the challenges of an aging toolset.

The Best Infrastructure Attracts the Best Talent

The NNI physical and cyber-physical infrastructure have been a key enabler for nanotechnology R&D over the past two decades. As is highlighted in Chapter 2, the NNCI facilities and tools were accessed by more than 13,000 users in 2018, including nearly 3,400 external users, representing more than 200 academic institutions in the United States and more than 900 small and large companies.[44] More than 5,000 users, many of them Ph.D. students, are trained by the NNCI network per year.[45]

Finding 3.3: Easy access to core facilities has been a critical enabler to start-up companies and researchers. These facilities allow nanotechnologists to try out new ideas and develop prototypes and are of vital importance for training students.

Moreover, the availability of first-class research capabilities is considered a key component in recruiting the best talent. There is a perceived risk that talent is moving off-shore because of better infrastructure[46] or better incentives or both. The industrial research landscape has changed from the days when places like Bell Labs provided a significant pull for talent in physical sciences and for what later became nanotechnology. Today, the complexity and cost of such leading-edge sites may be found in shared public-private centers or consortia. Some examples in the United States could be SRC or the newly formed QED-C, which provide an industry pull for academic research; however, they do not include the infrastructure. Notably, European examples like IMEC and LETI also provide state of the art facilities where ideas can be tested in a single location. The NNI agencies should consider potential models in which the networks of nanotechnology centers could be made available and participate in the consortia where government participation already occurs. Reciprocity models across facilities should also be considered.

Finding 3.4: A state-of-the-art infrastructure helps the United States to attract the best talent, including students, researchers, and entrepreneurs.

Infrastructure to Scale Up Nanotechnology-Enabled Future Products

With two decades of NNI supported and coordinated research, there is considerable new scientific understanding and technological capabilities that are being commercialized and utilized in new applications. The NNI physical infrastructure has been a critical resource to many start-ups and small and medium-size companies to access the staff expertise within the facilities and develop new technologies.[47,48] Thus, the NNI infrastructure and its advanced capabilities plays an essential role in translational research and the technology transfer ecosystem. Likewise, China and European countries have recognized this important role in the technology transfer ecosystem and have established dedicated organizations and institutes to work with companies on the development of new products. It would be valuable for U.S. institutions to evaluate which aspects of these off-shore efforts could be adapted and integrated within the U.S. nano-related research infrastructure. As an example, in the specific area of nanoelectronics, the NNI infrastructure has been critical to support innovation and first demonstrations of numerous new nanotechnologies. The relevance of nanoelectronics has motivated the signature initiative nanoelectronics for 2020 and beyond.[49] However, when it comes to tech transfer and commercialization, the costs and infrastructure needed to scale up new ideas to the next stage can be prohibitively expensive.

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[44] See https://www.nnci.net/, accessed 11/04/2019.
[45] Task Force on American Innovation, 2019, "Benchmarks 2019: Second Place America? Increasing Challenges to U.S. Scientific Leadership," http://www.innovationtaskforce.org/wp-content/uploads/2019/05/Benchmarks-2019-SPA-Final4.pdf.
[46] C. Mirkin, Northwestern University, presentation to the committee.
[47] National Nanotechnology Initiative Strategic Plan, 2016.
[48] See https://nsrcportal.sandia.gov/Home/Industrial, accessed 11/04/2019.
[49] See https://www.nano.gov/node/832, accessed 11/04/2019.

Finding 3.5: The U.S. nanotechnology infrastructure has played an important role in the technology transfer ecosystem, particularly at the initial stages. However, it is lacking accessible scale-up capabilities that are available in other countries, especially in the area of nanoelectronics.

Off-shore micro/nanotechnology centers, such as MINATEC and IMEC, attract not only major global corporations to utilize their facilities but also small and medium-size enterprises from the United States. In Japan, the Tsukuba Innovation Arena and China's Nanopolis are also successfully creating environments where researchers from industry, academia, and government are collocated with state-of-the-art facilities, IP specialists, and venture capital with the objective of accelerating the commercialization of nanotechnology and reaping a greater share of the economic rewards of global R&D investments. These entities promote their IP arrangements as being flexible enough to attract international companies.[50,51,52] This is a model that helps emerging technologies, especially resource-intensive applications or those requiring state-of-the-art semiconductor fabrication services. These large research and technology organizations that provide critical infrastructure for nanoelectronics participate on the nanotechnology initiatives in their respective countries. U.S. efforts to collocate companies with state-of-the-art nanofacilities and government/academic researchers and venture capital are lagging those of Europe, Japan, and China.

Finding 3.6: Non-U.S. micro/nanotechnology centers, such as MINATEC and IMEC, have technology transfer capabilities that attract U.S. companies. As an example, IMEC has developed innovation services to guide innovators along the commercialization path.

In addition to the physical infrastructure, it is also important to have up-to-date information to identify the best facilities and other available resources for those innovators that want to bring their ideas to the next level in the commercialization path. Currently, the nano.gov portal points to some available resources on its tech transfer page.[53] Nonetheless, a number of these links are incorrect or dated. Other resources like the FLC or TechLink, while powerful and well organized, are centered around available inventions by federal laboratories. There are no "inventor-centric" resources. There are notable omissions like Cyclotron Road.[54] The resources available to inventors and entrepreneurs listed in nano.gov contrast with those on the European Horizon 2020 test-beds and on IMEC's innovation services and solutions.[55] As a coordinating office, NNCO may have visibility to innovation hubs or incubation centers that support commercialization of nanotechnology and that are sponsored by the same government agencies that fund NNI. The sponsor agencies could forward a list of web links to these centers or hubs to be posted and updated on nano.gov ("networks and communities" or "commercialization" tabs) along with current opportunities, activities and events.

Finding 3.7: As nanotechnology matures and its commercialization becomes increasingly relevant to sustain U.S. competitiveness, it will be necessary to redesign and streamline the resources available to inventors to facilitate commercialization of nanotechnology, especially for those that are heavily dependent on infrastructure.

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[50] See https://www.imec-int.com/en/icon/faq/faq-about-intellectual-property-rights-ipr, accessed 11/04/2019.
[51] See http://www.leti-cea.com/cea-tech/leti/english/Pages/Industrial-Innovation/Innovate%20with%20Leti/research-contracts.aspx, accessed 11/04/2019.
[52] See https://unit.aist.go.jp/tia-co/orp/scr/index_en.html, accessed 11/04/2019.
[53] See https://www.nano.gov/techtransfer, accessed 11/04/2019.
[54] See https://www.cyclotronroad.org, accessed 11/04/2019.
[55] See https://www.imec-int.com/en/innovation, accessed 11/04/2019.

Recommendation and Implementations

The committee is convinced that leadership in nanotechnology will not be possible without state-of-the-art, well-maintained infrastructure and resources for making and characterizing nanomaterials, nanodevices, and related products.

Key Recommendation 3: New investments by the National Nanotechnology Initiative (NNI) agencies are required to strengthen and renew the U.S. network of fabrication and characterization facilities to retain international leadership. These investments should make readily available new tools, expertise, techniques, and processes to support fundamental research in existing and emerging areas, as well as prototyping and pilot/scale-up capabilities.

Implementation Recommendation 3a: The National Nanotechnology Initiative (NNI) agencies should solicit and promote innovative approaches to transform models of access to, and modernization of, the nanotechnology infrastructure to ensure U.S. leadership in lab-to-market outcomes. A whole-of-government approach is required to develop more thoughtful, strategic, and effective approaches to accelerate technology transfer. Effective collection of performance metrics is also needed. A mechanism for moving this activity forward is to appoint a responsible person from, for example, the Department of Commerce.

Implementation Recommendation 3b: National Nanotechnology Initiative (NNI) agencies/organizations should develop programs that fund replacement of aging infrastructure (tools) in addition to programs for new, state-of-the-art infrastructure.

WORKFORCE DEVELOPMENT: GLOBAL VIEW ON COMPETITIVENESS

As Chapter 3 described, researchers have witnessed a startling disruption of the global innovation ecosystem with the rapid rise of R&D intensity in China and other developing nations.[56] China's subsidy of capital-intensive industries and developing nation's low labor costs has resulted in nearly all of the high-tech products invented in the United States being manufactured in Asia. They have also focused intensively upon the development of a workforce with the necessary skills to continue this disruption into the foreseeable future. China's increased investment in education is similar to that of its investment in high-tech sectors. Although science, technology, engineering, and mathematics (STEM) investment and enrollment in K-12 increased in the United States during the past decade, these are now falling and this is resulting in lower numbers of STEM majors at universities.[57] In contrast, the number of bachelor's degrees awarded in STEM in China increased 460 percent from 2000 to 2014, while the corresponding change for the United States was 40 percent.

Growing and Attracting the Global Talent Pool

The United States has witnessed striking and substantial decreases in international students for the first time in many years.[58] International graduate applications and enrollment has declined over the past 2

[56] See http://www.innovationtaskforce.org/wp-content/uploads/2019/05/Benchmarks-2019-SPA-Final4.pdf, accessed 11/04/2019.
[57] See https://www.nano.gov/education-training/teacher-resources, accessed 11/04/2019.
[58] National Science Board, *Science and Engineering Indicators*, NSB-2019-7.

years in the United States,[59] especially in master's and certificate programs. Across fields of study, engineering was down by 16 percent and physical and earth sciences by 9 percent, although the health sciences and math and computer science saw minor increases (5 percent) in application numbers. Data from the U.S. Immigration and Customs Enforcement (ICE) indicates the number of international students at all levels declined by 2.7 percent.[60] Also, ICE data show a 2 percent year-to-year decline from March 2018 to March 2019 from the leading sending country, China; a 1.2 percent decline from India, the number 2 sender; and a 7.6 percent decline from the number 3 sending country, South Korea.[61] The number of institutions reporting increased delay or denial in visa issuance grew from 33.8 percent in fall 2016 to 68.4 percent in fall 2017.[62]

Finding 4.1: The United States is losing global competitiveness in recruiting international graduate students and in training science, technology, engineering, and mathematics (STEM) students at all levels.

Recruitment and Training

The presence of talent development programs elsewhere as well as substantially increased investment in R&D is leading to a reverse brain drain, with scientists and engineers trained in the United States returning to their home countries (particularly China and South Korea). This applies to both recent graduates and long-time residents of the United States. The best U.S. universities have trained top-level faculty for Chinese universities, and these nationals are now returning to China in a reverse brain drain.[63] Moreover, even U.S. scientists are being recruited to institutions in Singapore, Korea, and Switzerland, given the abundant research resources.

Finding 4.2: The United States lacks an overarching strategy for graduate student recruitment and development to support nanotechnology advancement.

Undergraduate Research and Training

As described in Chapter 2, there are opportunities to increase innovation and entrepreneurial activities at the undergraduate level that could increase the scope of STEM training. NSF Research Experiences for Undergraduates (REU) Centers have provided important training for undergraduates and produced a cohort that can address current key issues with tools of nanoscience and nanotechnology. Unfortunately, since the NSF REU programs were affiliated with the Nanoscale Science and Engineering Centers (NSECs), when these were sunset, the REU programs were also. However, REUs through the National Nanotechnology Coordinated Infrastructure (NNCI) persist.

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[59] International student data by countries of origin (2017-2018, latest available via Open Doors report), at https://www.iie.org/Research-and-Insights/Open-Doors/Data/International-Students/Places-of-Origin, accessed 11/04/2019.

[60] H. Okahana and E. Zhou, 2019, International Graduate Applications and Enrollment: Fall 2018, Washington, D.C., Council of Graduate Schools, at https://www.cgsnet.org/ckfinder/userfiles/files/Intl_Survey_Report_Fall2018.pdf.

[61] See https://studyinthestates/dhs.gov/sevis-by-the-numbers, accessed 11/04/2019.

[62] See http://www.innovationtaskforce.org/wp-content/uploads/2019/05/Benchmarks-2019-SPA-Final4.pdf, accessed 11/04/2019.

[63] Statement of E.W. Priestap, Assistant Director, Counterintelligence Division, Federal Bureau of Investigation, Before the Committee on the Judiciary, United States Senate, "Hearing Concerning China's Non-Traditional Espionage Against the United States: The Threat and Potential Policy Responses," presented December 5, 2018, https://www.judiciary.senate.gov/imo/media/doc/12-12-18%20Priestap%20Testimony.pdf.

Finding 4.3: U.S. science, technology, engineering, and mathematics (STEM) undergraduates are a relatively untapped source of nanotechnology innovation, and access to entrepreneurship training and resources could unleash this source of creativity.

Diversity

Along with international recruitment, STEM workforce growth, appeal, and diversity also present opportunities for the United States to cultivate and deploy nanotechnology-related expertise—and to maintain critical expertise across disciplines and sectors.[64] Hispanics and blacks are underrepresented in the STEM workforce, and women are underrepresented in specific occupational clusters, such as engineering and computer science in the United States.

Finding 4.4: Low diversity (by gender and ethnicity) across many National Nanotechnology Initiative (NNI)-relevant disciplines results in yet fewer science, technology, engineering, and mathematics (STEM)-educated workers than would otherwise be present in the United States.

Expanding the Domestic STEM Pipeline

As the international component of the domestic STEM workforce declines, the need for STEM talent is expanding as high-technology manufacturing makes an increasingly vital contribution to the economy and national security of the nation. The review committee is therefore concerned that over time the supply of talent will be insufficient to meet the needs of U.S. high-technology manufacturing industry in general. There is a concern that the research that underpins this will migrate overseas. The issues will need to be addressed in multiple ways but must begin with a concerted effort to show the value of a STEM education to the U.S. population and provide resources to translate the broadened public appeal of nanotechnology into a skilled workforce.

Finding 4.5: The National Nanotechnology Coordination Office (NNCO) has excelled in developing and distributing training and introductory materials for K-12 in nanoscience and nanotechnology.

Recommendation and Implementations

The committee's hypothesis is that an innovation ecosystem is critical to attract top talent worldwide. An effective innovation ecosystem requires: (1) an appropriately trained workforce; (2) collaboration between industry, government, and academia; and (3) support for start-up enterprises. The first requirement motivates Key Recommendation 4.

Key Recommendation 4: The Nanoscale Science, Engineering, and Technology (NSET) Subcommittee, the National Nanotechnology Coordination Office (NNCO), and the National Nanotechnology Initiative (NNI) agencies should significantly increase efforts to attract and train the best students to studies in relevant nanoscience/nanotechnology science, technology, engineering, and mathematics (STEM) disciplines to ensure a diverse world-class workforce to support our national interests and security, including via public-private partnerships that support student fellowships.

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[64] See https://www.pewsocialtrends.org/2018/01/09/diversity-in-the-stem-workforce-varies-widely-across-jobs/, accessed 11/04/2019.

Implementation Recommendation 4a: The National Nanotechnology Initiative (NNI) agencies, such as the National Science Foundation (NSF), should seed the creation of undergraduate certificate programs in entrepreneurship in partnership with universities.

Implementation Recommendation 4b: The NNI agencies should increase and sustain the number of Research Experiences for Undergraduates (REU) programs focused on nanoscience and nanotechnology.

Implementation Recommendation 4c: The NNI should create targeted internship programs between nanotechnology companies and universities for undergraduate and graduate students, facilitated by National Nanotechnology Coordination Office (NNCO) or TechConnect.

Implementation Recommendation 4d: The National Nanotechnology Initiative (NNI) agencies should foster models that create teams of nanotechnology graduate students, business school students, and private sector stakeholders to advance interdisciplinary training in support of accelerated U.S. lab-to-market outcomes.

Implementation Recommendation 4e: The NNI should expand the diversity of science, technology, engineering, and mathematics (STEM) students by gender, age, and ethnicity to greatly increase the U.S. pool of nanotechnology workers.

Implementation Recommendation 4f: The NNCO should modernize the nano.gov website to be useful as an outreach and communication tool to attract new talent to nanoscience by emphasizing the big societal themes (energy, medicine, technology, security) that are addressed by nanotechnologies.

STRUCTURE AND MANAGEMENT

The previous four key recommendations address areas for the NNI to modify in its future embodiment. An overarching issue is what organization and management structure should exist to support the future NNI activity. The committee finds significant value to coordination of diverse nanotechnology activities via the NSET interagency subcommittee and particularly the NNCO.

NNI Coordination by NNCO

There are areas where the NNCO has been particularly effective. The NNCO has provided a critical role in convening studies and workshops on emerging topics involving nanotechnology. This is an effective use of limited resources and helps to foster interdisciplinary research programs essential to realizing the full value of nanotechnology developments. The NNCO convenes coordinating meetings and provides valuable information to funding agencies in their coordination of new and ongoing programs.

Finding 5.1: The National Nanotechnology Coordination Office (NNCO) effectively convened workshops, including participating agencies in the National Nanotechnology Initiative (NNI), and has provided educational materials and broad community outreach. The NNCO has particularly excelled in international coordination in topics such as workplace safety, environmental health, and standards advocacy.

NNI Accountability

It would be invaluable for the public and the R&D community to have a clearer understanding of the impact of the NNI. There is uncertainty in the research community about what the NNI is, and individual researchers are not necessarily aware whether they are "part of the NNI" since their funding is often not specifically labeled as such. While specific projects or programs may be rolled up into the NNI activity for particular agencies, the researchers involved in this research may not be aware of this. Furthermore, few funding calls and announcements are explicitly listed as nanotechnology efforts, even though nanoscience and technology are important components of topical funding announcements. For example, the devices that will become the components of quantum computing will critically depend on nanoscale devices and fabrication technologies. Thus, more explicit awareness would be valuable for the research community and individual researchers.

Finding 5.2: The National Nanotechnology Coordination Office (NNCO) has been efficiently run and made good use of a limited budget and small staff, but the level and unpredictable nature of that funding has undermined its ability to accurately assess and communicate the broader benefits owed to the nation for its investment in nanotechnology development.

Funding Model

The NNCO is the sole funded coordinating organization for this diversely funded activity. Funding for the NNI is distributed across the U.S. funding agencies. The NNCO, while congressionally mandated, does not have an independent funding source and draws its operational budget from the funding agencies in approximate proportion to their reported nanotechnology activity.

Finding 5.3: The current National Nanotechnology Coordination Office (NNCO) structure and participating agency flow-through funding to NNCO is not sufficient to accomplish the critical goals originally noted in the legislation creating the National Nanotechnology Initiative (NNI). Furthermore, although the interagency Nanoscale Science and Technology (NSET) and NNCO organizational structures function reasonably well as a baseline coordination mechanism, the lines of responsibility remain wholly inadequate to respond to the recommendations in this and prior reviews.

Constraints of the NNCO Coordination Role

The NNI does not have a mandate to direct the funding of any agency. Accordingly, the funding for the work of NSET and NNCO may vary with time in an unpredictable way. This creates challenges and limits to the scope of NSET and NNCO activity.

Finding 5.4: The Office of Science and Technology Policy (OSTP) and the Nanoscale Science and Technology (NSET) Subcommittee are responsible for the oversight and management of National Nanotechnology Coordination Office (NNCO), but the NNCO as constituted does not seem adequately resourced or staffed to address all four National Nanotechnology Initiative (NNI) goals effectively.

Alternative Coordination Models

The committee has been impressed by the focused and well-funded efforts that other nations have put in place to deliver on the societal benefits that nanotechnology promises. The committee notes in particular that partnerships between government and industry in pursuit of commercialization seem stronger in all the countries/regions that were reviewed in detail. While the model for conducting a large R&D activity such as the NNI may have been appropriate in the early stages of nanoscience and technology, now 20 years after creation of the early vision, this review argues for significant shift in NNI emphasis, and it is therefore likely that a more appropriate model would now be appropriate. The review of global nanotechnology programs (Chapter 3) indicates many models have been used for the planning, coordination and execution of national programs. Some appear to be highly effective at addressing workforce development and training and commercialization of nanotechnology. However, the U.S. environment is very different from any of those in the nations and national groups reviewed in Chapter 3. The availability of SBIR/STTR funds, legislation that encourages protection of IP created by federally funded work, and a vibrant venture capital community are all advantages that can be exploited in a new model.

Finding 5.5: There are robust international models for public-private partnerships toward achieving the expected returns to society on investments in nanotechnology.

A Paucity of Data

A coordinating role that requires expansion is the assimilation of unclassified and nonconfidential data on U.S. and international nanotechnology research and output. This would facilitate high-level assessments by government, corporations, and inventors of ongoing nanotechnology coordination, competitive positions, and strategic funding decisions. There is also a need for effective coordination of workforce training and particularly focused efforts on technology transfer.

Finding 5.6: The lack of performance data available through the National Nanotechnology Initiative (NNI) impacts the perception of the output and performance of the NNI, and may slow technology transfer activities. Other countries and regions provide more performance data related to nanotechnology investments and metrics related to commercialization activities.

Recommendation and Implementations

The committee is convinced of the continued value of the NNI, and has considered how the administration and oversight of the NNI should be modified to adequately respond to the recommendations that are made in this report.

Key Recommendation 5: The National Nanotechnology Initiative (NNI), through the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee and the National Nanotechnology Coordination Office (NNCO), should continue to perform its important coordinating role. The NNCO should be adequately resourced and appropriately staffed to deliver an agile and globally competitive nanotechnology program. The work of the NNCO should also be augmented through expanded collaborations with not-for-profit organizations and by establishing new public-private partnerships.

Implementation Recommendation 5a: The National Nanotechnology Initiative (NNI) should signal to all stakeholders that it is refocusing its efforts through a renaming or rebranding that captures the revised priorities recommended in this report.

Implementation Recommendation 5b: The Office of Science and Technology Policy (OSTP) should evaluate the current budget level and funding mechanism with consideration to the

expanded role of the National Nanotechnology Coordination Office (NNCO) and provide specific guidance through the Office of Management and Budget (OMB) to modify the level of flow through funding from participating agencies to ensure that the NNCO has the resources necessary to execute its responsibilities on behalf of the Nanoscale Science and Technology (NSET) Subcommittee.

Implementation Recommendation 5c: Nanoscale Science and Technology (NSET) and the National Nanotechnology Coordination Office (NNCO) should actively leverage the Nanotechnology Signature Initiative (NSI) mechanism to focus and coordinate agency work and funding on activities such as technology transfer or training.

Implementation Recommendation 5d: Nanoscale Science and Technology (NSET) should coordinate with grants.gov (or other federal research and development reporting avenues) to develop mechanisms to collect and present accurate, current performance data on the outcome of the National Nanotechnology Initiative (NNI) research and make clear to all, including to the researchers involved, what research is part of the NNI.

Appendixes

A

Statement of Task

The NRC will appoint an ad hoc committee to conduct the quadrennial review of the National Nanotechnology Initiative (NNI). The overall objective of this review is to make recommendations to the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the White House National Science and Technology Council and to the National Nanotechnology Coordination Office that will improve the value of the NNI's R&D strategy and portfolio to the economic prosperity and national security of the United States. Toward this objective, this quadrennial NNI review will include the following tasks:

A. Analyze the relative position of the United States compared to other nations with respect to nanotechnology R&D, including trends and developments in nanotechnology science and engineering and the identification of any critical research areas where the United States should be the world leader to best achieve the goals of the Program;
B. Assess the current state of nanoscience and nanotechnology resulting from the NNI as authorized in 2003, including the current impact of nanotechnology on U.S. economic prosperity and national security. Based on this assessment, consider if and how the NNI should continue. If continuation is suggested, make recommendations regarding new or revised Program goals, new research areas and technical priorities, partnerships, coordination and management mechanisms, or programs to be established to achieve these goals.

B
Committee Biographical Information

LIESL FOLKS, *Chair*, is the senior vice president and provost at the University of Arizona, and professor of electrical and computer engineering. Dr. Folks is the chief academic officer of the university and oversees all affairs related to the academic mission of the university, including the faculty, students, academic programs, and related budgeting. Previously, she served as the dean of University of Buffalo's School of Engineering and Applied Sciences. Dr. Folks is an internationally recognized expert in nanotechnology, in particular magnetic nanomaterials, spin-electronic nanodevices, and nanoscale metrology. She holds 12 U.S. patents and is the author of more than 50 peer-reviewed technical publications. Dr. Folks served as president of the IEEE's Magnetics Society in 2013 and also in 2014. She was a member of the congressionally mandated panel for the Triennial Review of the National Nanotechnology Initiative, conducted by the National Academy of Sciences in 2013. Dr. Folks has an exemplary record of support for STEM education initiatives, from her promotion of innovative programs at the pre-K-12 level, to her role in launching a graduate magnetics summer school program through the IEEE. Prior to joining the University of Buffalo, Dr. Folks worked for 16 years in Silicon Valley in the data storage sector, with IBM Almaden Research Center, Hitachi Global Storage Technologies, and Western Digital. A native of Australia, Dr. Folks earned a B.Sc. (1989) and a Ph.D. (1994), both in physics, from The University of Western Australia in Perth. She also holds an M.B.A. from Cornell University (2004).

HAYDN WADLEY, *Vice Chair*, is University Professor and the Edgar A. Starke Professor of Materials Science and Engineering at the University of Virginia, Charlottesville. Dr. Wadley is a member and current chair of the National Academies Defense Materials, Manufacturing, and Infrastructure Standing Committee (2011-present); was a member of the National Materials and Manufacturing Board (2010-2018); was a member and chair of the Defense Science Research Council (1996-2016); and served on the Defense Science Board's Summer Study (2000). He has very broad interests in materials science, micromechanics, and thermal management. Dr. Wadley's current research explores high-temperature materials, ceramic coating systems, the synthesis of opal crystals and their inverses, and ultralight lattice materials. He has previously addressed many fundamental questions associated with the atomic assembly of nanoscopic materials from the vapor phase, the topological structuring of cellular materials and the processing of high-performance composites. These fundamental studies have been used to develop models and numerical simulations to establish the linkages between a material's composition, synthesis/processing and its performance. Some have been coupled with in situ ultrasonic and electromagnetic sensors and nonlinear, feedback control algorithms to implement intelligent process control concepts for materials processing. Dr. Wadley has invented and commercialized several vapor deposition technologies that enable the growth of novel thin films and coatings, and developed numerous concepts for designing and making multifunctional cellular materials. He has published more than 475 papers, co-authored a book on cellular materials, been awarded more than 30 U.S. patents, spun out two companies from his research group, received a number of awards including the Werner Koester Award, the Robert W. Cahn Prize, and is a fellow of the American Society for Materials.

NICHOLAS ABBOTT is the Tisch University Professor at Cornell University. Dr. Abbott received a bachelor's of engineering (chemical engineering) from University of Adelaide, Australia, in 1985 and a Ph.D. in chemical engineering from the Massachusetts Institute of Technology in 1991. He was a postdoctoral fellow in the Chemistry Department of Harvard University from 1991-1993. Dr. Abbott's initial academic appointment was at University of California, Davis. He then moved to the Department of Chemical and Biological Engineering at the University of Wisconsin, Madison, in 1998 as professor and served as chair of the department from 2009 to 2012. From 2012 to 2018, Dr. Abbott served as director of the Wisconsin Materials Research Science and Engineering Center, and held the title of Sobota Professor and Hilldale Professor of Chemical and Biological Engineering. In 2018, he joined the Department of Chemical and Biomolecular Engineering at Cornell University as the Tisch University Professor. Dr. Abbott is a member of the U.S. National Academy of Engineering and serves as co-editor-in-chief of *Current Opinion in Colloid and Interface Science*.

OLIVER BRAND is the executive director of the Institute for Electronics and Nanotechnology and a professor at the School of Electrical and Computer Engineering at Georgia Institute of Technology (Georgia Tech). Dr. Brand received his undergraduate degree in physics from Technical University Karlsruhe, Germany, in 1990, and his Ph.D. degree (Doctor of Natural Sciences) from ETH Zurich, Switzerland, in 1994. He was a postdoctoral fellow at Georgia Tech from 1995-1997 and a lecturer at ETH Zurich in Zurich, Switzerland and deputy director of the Physical Electronics Laboratory (PEL) from 1997 to 2002. In January 2003, Dr. Brand joined the Electrical and Computer Engineering faculty at Georgia Tech. Dr. Brand has co-authored more than 200 publications in scientific journals and conference proceedings. His research interests are in the areas of CMOS-based microsystems, microsensors, MEMS fabrication technologies, and microsystem packaging.

HAROLD CRAIGHEAD is the Charles W. Lake, Jr., Professor in Engineering at Cornell University. Dr. Craighead received his bachelor's of science degree in physics, with high honors, from the University of Maryland, College Park, in 1974 and his Ph.D. in physics from Cornell University in 1980. His thesis work involved an experimental study of metal nanoparticles. From 1979 until 1984, Dr. Craighead was a member of the technical staff in the Device Physics Research Department at Bell Laboratories. From 1984 until 1989, he was research manager of the Quantum Structures Research Group at Bellcore. Dr. Craighead joined the faculty of Cornell University as a professor in the School of Applied and Engineering Physics in 1989. From 1989 until 1995, he was director of the National Nanofabrication Facility at Cornell University. Dr. Craighead was director of the School of Applied and Engineering Physics from 1998 to 2000 and director of the Nanobiotechnology Center from 2000 to 2001. He served as interim dean of the College of Engineering from 2001 to 2002, as co-director of the Nanobiotechnology Center from 2002-2006, and as director of the Nanobiotechnology Center from 2006 to 2009. Dr. Craighead is an elected member of the National Academy of Engineering. He has been a pioneer in nanofabrication methods and the application of engineered nanosystems for research and device applications. Throughout his career, he has contributed to numerous scientific journals with over 280 published papers. Dr. Craighead's recent research activity includes the use of nanofabricated devices for biological applications. His research continues to involve the study and development of new methods for nanostructure formation, integrated fluidic/optical devices, nanoelectromechanical systems, and single molecule analysis.

MARIE D'IORIO is a senior strategy advisor with the Office of the Vice President Research at the University of Ottawa and is president of NanoCanada. Prior to joining the University of Ottawa, Dr. D'Iorio led the National Institute for Nanotechnology (2011-2016) and the Institute for Microstructural Sciences (2003-2011) at the National Research Council of Canada (NRC). Dr. D'Iorio obtained a master's and a doctorate's degree in solid state physics from the University of Toronto. After a postdoctoral fellowship at IBM Zurich Research Laboratories, she joined the NRC, where she established Canada's first very low temperature, high magnetic field laboratory to study quantum semiconductor devices and later led one of Canada's first research programs on organic light emitting devices. In 2015, Dr. D'Iorio launched NanoCanada, to connect the nanotechnology community across the country and to facilitate partnerships and collaborations between academia, industry, and government, linking facilities and expertise to support the translation of scientific breakthroughs to the marketplace. She has served as president of the Academy of Science of the Royal Society of Canada and president of the Canadian Association of Physicists.

TRAVIS EARLES leads far-reaching innovation for Lockheed Martin by cultivating a holistic ecosystem to drive an agile process of ideation to implementation. Lockheed Martin is a global leader in security and aerospace principally engaged in the research, design, development, manufacture, integration, and sustainment of advanced technology systems, products and services. From 2016 to 2019, Earles established the Digital Transformation structure and operations strategy for the Rotary and Mission Systems business area, ensuring talent and emerging technologies alignment to support production, sourcing, and sustainment for base growth. Prior to 2016, Earles led advanced materials and nanotechnology innovation across the corporation. Before joining Lockheed in 2011, Mr. Earles served as assistant director for nanotechnology in the White House Office of Science and Technology Policy, where he was recruited in 2007. He co-chaired the National Science and Technology Council Subcommittee for Nanoscale Science, Engineering, and Technology (NSET), overseeing interagency coordination of the $1.8 billion National Nanotechnology Initiative and reaching out to the science and technology community across academia, government, and industry to foster responsible development of nanotechnology. At the National Cancer Institute earlier, Mr. Earles played a central role launching the Alliance for Nanotechnology in Cancer in 2005, which as of 2019 has generated over 70 platforms in clinical trials for diagnostic and therapeutic applications. Mr. Earles holds a bachelor's degree in biomedical engineering from Catholic University of America as well as an M.B.A. and an M.S. in technology management from the University of Maryland. He resides with his wife and four children in Maryland, where he avidly coaches soccer.

GRAHAM FLEMING is a professor of chemistry at the University of California, Berkeley. Dr. Fleming has served as vice chancellor for research at UC Berkeley and deputy laboratory director for Lawrence Berkeley National Laboratory. In those positions, he has been involved in the formation and operation of multiple major initiatives. These include the $500 million British Petroleum (BP)-funded Energy Biosciences Institute, the California Institute for Quantitative Bioscience, and the Simons Institute for the Theory of Computing. Born in Barrow, England, in 1949, Dr. Fleming earned his bachelor's of science degree from the University of Bristol in 1971 and his Ph.D. in chemistry from the University of London in 1974. Following a postdoctoral fellowship at the University of Melbourne, Australia, he joined the faculty of the University of Chicago in 1979. There, Dr. Fleming rose through the academic ranks to become the Arthur Holly Compton Distinguished Service Professor, a post he held for 10 years, starting in 1987. At the University of Chicago, he also served for 3 years as the chair of the Chemistry Department. In that role, he led the creation of University of Chicago's first new research institute in more than 50 years, the Institute for Biophysical Dynamics. In 1997, Dr. Fleming came to University of California, Berkeley, as a professor of chemistry, and he started and directed a new division of physical biosciences for Berkeley Laboratory. Throughout his administrative career, Dr. Fleming has remained a highly active and successful scientific researcher. He has authored or co-authored more than 530 publications, and is widely considered to be one of the world's foremost authorities on ultrafast processes. His ultimate goal is to develop artificial photosynthesis that would provide humanity with clean, efficient and sustainable energy. Dr. Fleming is a member of the National Academy of Sciences and the American Philosophical Society, a fellow of the Royal Society and the American Academy of Arts and Sciences, and a foreign fellow of the Indian National Science Academy.

TERI ODOM is Charles E. and Emma H. Morrison Professor of Chemistry and chair of the Chemistry Department at Northwestern University. Dr. Odom is an expert in designing structured nanoscale materials that exhibit extraordinary size and shape-dependent optical properties. She has pioneered a suite of multiscale nanofabrication tools that have resulted in plasmon-based nanoscale lasers that exhibit tunable color, flat optics that can manipulate light at the nanoscale, and hierarchical nanowrinkled substrates that show controlled wetting properties. Dr. Odom has also invented a class of biological gold nanoconstructs that are facilitating insight into nanoparticle-cell interactions and that show superior imaging and therapeutic properties. She is a fellow of the American Chemical Society (ACS), the Materials Research Society (MRS), the American Physical Society (APS), the Optical Society of America (OSA), and the Royal Society of Chemistry (RSC). Selected honors and awards include the ACS National Award in Surface Science; a Research Corporation TREE Award; a U.S. Department of Defense Vannevar Bush Faculty Fellowship; a Radcliffe Institute for Advanced Study Fellowship at Harvard University; a National Institutes of Health (NIH) Director's Pioneer Award; the MRS Outstanding Young Investigator Award; the National Fresenius Award from Phi Lambda Upsilon and the ACS; and a David and Lucile Packard Fellowship in Science and Engineering. Dr. Odom was founding chair of the Noble Metal Nanoparticles Gordon Research Conference and founding vice chair of Lasers in Micro, Nano, and Bio Systems. She is on the Editorial Advisory Boards of *ACS Nano*, *Annual Reviews of Physical Chemistry*, *ChemNanoMat*, *Bioconjugate Chemistry*, and *Nano Letters*. Dr. Odom was founding associate editor for *Chemical Science* (2009-2013), was founding executive editor of *ACS Photonics* (2013-2019), and is editor-in-chief of *Nano Letters* (2020).

RICARDO RUIZ is a staff scientist at the nanofabrication facility at Lawrence Berkeley National Laboratory. Previously, Dr. Ruiz was a research technologist at Western Digital Corporation. His research interests span alternative nanofabrication techniques for storage and memory devices, block copolymer lithography, and colloidal self-assembly. From 2013 to 2016, Dr. Ruiz managed a Nanopatterning and Self Assembly group at Hitachi Global Storage Technologies (HGST) dedicated to block copolymer and colloidal lithography. Prior to that, he was a research staff member at HGST, where he helped to introduce block copolymer lithography for magnetic bit-patterned media technology. Before joining HGST, he was a postdoctoral scientist at IBM T.J. Watson. Dr. Ruiz received his Ph.D. in physics from Vanderbilt University in 2003. He has co-authored over 50 publications and holds 35 U.S. patents. Dr. Ruiz is a fellow of the American Physical Society and was the recipient of the 2016 ACS Applied Materials and Interfaces Young Investigator Award.

JO ANNE SHATKIN is the president and founder of Vireo Advisors. Dr. Shatkin founded Vireo Advisors in 2013 to provide guidance and leadership—raising the bar on sustainability in innovation. She collaborates with organizations on environmental aspects of new product development and on commercialization of technologies for environmental applications. Dr. Shatkin brings nearly 20 years of expertise in environmental leadership, stakeholder engagement, health and environmental risk analysis, sustainability science, nanotechnology, and life cycle impacts of materials in the environment. Dr. Shatkin brings extensive experience in working with entrepreneurs to guide responsible product development and commercialization. As CEO of CLF Ventures, she worked with early-stage and large organizations on new technology introduction strategies, including business planning, environmental impact assessment, and networking for financing. Dr. Shatkin is an environmental health scientist and recognized expert in environmental science and policy, human health risk assessment, emerging contaminants policy, and environmental aspects of nanotechnology. She combines her business acumen and technical expertise into strategies for sustainable innovation. Since 2005, Dr. Shatkin has provided leadership on the responsible development of nanotechnology and on approaches for decision making under uncertainty. She serves on several international committees addressing cutting-edge science policy issues and standardization for emerging nanoscale materials. She also teaches courses, has published papers and book chapters on topics of environmental health and safety, and is working to advance life cycle approaches to risk analysis for nanotechnology, including for product design and development. Dr. Shatkin is author of *Nanotechnology Health and Environmental Risks, Second Edition* (CRC Press, 2012). She received an Individually Designed Ph.D. in environmental health science and policy and her

M.A. in risk management and technology assessment from Clark University, Worcester, Massachusetts, and earned a bachelor's of science degree from Worcester Polytechnic University in molecular biology and biotechnology.

MARK TUOMINEN is a professor of physics at University of Massachusetts, Amherst, where he performs research in experimental condensed matter physics and nanotechnology, including research in the manufacturing and physics of materials and devices with nanoscale features. Nanomanufacturing science addresses the challenge of fabricating nanoscale structures by convenient methods suitable for integration into systems. One important example is directed self-assembly using diblock copolymer template patterning in combination with complementary techniques. Recent fundamental physics research includes electronic transport through bacterial pili and biofilms, microbial fuel cells, ultra-high-density magnetic arrays, domain-wall motion in ferromagnetic nanorings, proton transport in materials for fuel cells, superconducting single-electron devices and charge shuttling phenomena. Strategic cooperative activities include nanomanufacturing, informatics for science, and integrated nanosystems. Dr. Tuominen's work helps to advance the science and applications of nanoscale charge transport, magnetism, bioelectronics, superconductivity, self-assembly, and nanomanufacturing. He was instrumental in establishing the NSF Center for Hierarchical Manufacturing and the National Nanomanufacturing Network. Dr. Tuominen's educational innovations are in the areas of research learning and professional development. He received a bachelor's degree in chemical engineering and a Ph.D. in physics from the University of Minnesota and was a postdoctoral research associate at Harvard University.

C

Acronyms

2D	two-dimensional
3D	three-dimensional
AAAS	American Association for the Advancement of Science
ABET	Accreditation Board for Engineering and Technology
ACS	American Chemical Society
AFOSR	Air Force Office of Scientific Research
AI	artificial intelligence
AIM Photonics	American Institute for Manufacturing Integrated Photonics
AIST	National Institute of Advanced Industrial Science and Technology
ANSI	American National Standards Institute
ARO	Army Research Office
ARPA-E	Advanced Research Projects Agency-Energy
ARS	Agricultural Research Service
CEN	European Committee for Standardization
CMOS	complementary metal-oxide-semiconductor
CNST	Center for Nanoscale Science and Technology
COR	Communities of Research
CPSC	Consumer Product Safety Commission
CRDS	Center for R&D Strategy
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOJ	Department of Justice
DOT	Department of Transportation
DRL	Data Readiness Level
DURIP	Defense Research Instrumentation Program
EC	European Commission
EDF	Environmental Defense Fund
EFTA	European Free Trade Agreement
EFRC	Energy Frontier Research Center
EHS	environmental health and safety
EPA	Environmental Protection Agency
EPO	European Patent Office
EPP	European Network of Pilot Production Facilities

ERC	Engineering Research Center
ERI	electronics resurgence initiative
EUON	EU Observatory of Nanomaterials
FDA	Food and Drug Administration
FinFET	fin field effect transistor
FY	fiscal year
GDP	gross domestic product
HGST	Hitachi Global Storage Technologies
HHS	Department of Health and Human Services
HT	high technology
IC	intelligence community
ICT	Information and Communications Technology
IEEE	Institute of Electrical and Electronics Engineers
IMEC	Interuniversity Microelectronics Centre
IoT	Internet of Things
ISO	International Standards Organization
JCAP	Joint Center for Artificial Photosynthesis
LBNL	Lawrence Berkeley National Laboratory
MEXT	Ministry of Education, Culture, Sports, Science and Technology
MGI	Materials Genome Initiative
MINATEC	Micro and Nanotechnology Innovation Campus
MNE	multinational enterprise
MREFC	Major Research Equipment and Facilities Construction
MRI	Major Research Instrumentation
MRS	Materials Research Society
MURI	Multidisciplinary University Research Initiative
NAMI	Nano and Advanced Materials Institute
NASA	National Aeronautics and Space Administration
NBCI	Nanotechnology Business Creation Initiative
NCSES	National Center for Science and Engineering Statistics
NCI	National Cancer Institute
NCL	Nanotechnology Characterization Laboratory
NCN	Network for Computational Nanotechnology
NEN	Nanotechnology Entrepreneurship Network
NEWT	Nanosystems Engineering Research Center for Nanotechnology-Enabled Water Treatment
NIA	Nanotechnologies Industry Association
NIFA	National Institute of Food and Agriculture
NIH	National Institutes of Health
NIMS	National Institute for Materials Science
NINT	National Institute for Nanotechnology
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology

NKI	Nanotechnology Knowledge Infrastructure
NNCI	National Nanotechnology Coordinated Infrastructure
NNCO	National Nanotechnology Coordination Office
NNI	National Nanotechnology Initiative
NNIN	National Nanotechnology Infrastructure
NNMI	National Network for Manufacturing Innovation
NNN	National Nanomanufacturing Network
NQI	National Quantum Initiative
NREL	National Renewable Energy Laboratory
NSB	National Science Board
NSET	Nanoscale Science, Engineering, and Technology
NSF	National Science Foundation
NSI	Nanotechnology Signature Initiative
NSRC	Nanoscale Science Research Center
NSTC	National Science and Technology Council
NTPJ	Nanotechnology Platform Japan
NTRA	Nano Technology Research Association
OECD	Organization for Economic Cooperation and Development
OSHA	Occupational Safety and Health Administration
OSTP	Office of Science and Technology Policy
PCA	Program Component Area
PCAST	President's Council of Advisors on Science and Technology
PV	photovoltaic
QD-LED	quantum-dot light emitting displays
QIS	quantum information science
R&D	research and development
REU	Research Experiences for Undergraduates
RFP	Request for Proposals
ROI	return on investment
RSC	Royal Society of Chemistry
RSL	regional, state, and local
S&E	science and engineering
SBIR	Small Business Innovation Research
SIG	Shared Instrumentation Grants
SINANO	Suzhou Institute of Nano-Tech and Nano-Bionics
SLAC	Stanford Linear Accelerator Center
SME	small and medium-size enterprise
SPIE	International Society for Optics and Photonics
SPIRE	sustainable process industry
SRC	Semiconductor Research Corporation
STEM	science, technology, engineering, and mathematics
STTR	Small Business Technology Transfer
TTO	technology transfer office
USDA	U.S. Department of Agriculture

USFS	U.S. Forest Service
USGS	U.S. Geological Survey
USPTO	U.S. Patent and Trademark Office
WIPO	World Intellectual Property Organization