NIST Internal Report
NIST IR 8482

National Institute of Standards and Technology Environmental Scan 2023

Societal and Technology Landscape to Inform Science and Technology Research

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NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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Abstract

The 2023 National Institute of Standards and Technology Environmental Scan provides an analysis of key external factors that could impact NIST and the fulfillment of its mission in coming years. The analyses were conducted through three separate lenses: Societal & Political (Sec. 2), Investment & Geopolitical (Sec. 3), and Technology & Science (Sec. 4). Most of the issues discussed in the previous environmental scans conducted in 2018 and 2020 are still relevant, but a number of key issues have emerged in society that will impact NIST since the writing of those reports. Societal, political, financial, and workforce issues will challenge NIST to maintain and advance its leadership in metrology, standards, and technology. However, a broad range of emerging technology issues present opportunities for NIST to have significant impact in advancing the nation's innovation and industrial competitiveness.

Keywords

Environmental Scan; NIST Policy; Strategic Planning.

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Preface

In preparation for the launch of a strategic planning effort in 2018, the NIST Program Coordination Office (PCO) developed the 2018 NIST Environmental Scan to provide context for NIST senior leadership in developing that plan. While the Strategic Plan was completed and efforts to implement that plan have progressed, it is valuable to regularly assess the key issues facing NIST; this manuscript serves that role by re-examining the findings from the 2018 and 2020 environmental scan. As with those scans, the analyses herein are not intended to be a comprehensive list of all opportunities for, and threats to, NIST. Instead, they highlight significant trends and developments that may impact NIST in the next ten years. Any viewpoints and recommendations are made strictly based on observations and are not an official NIST position. In developing this scan, the PCO staff used a variety of external sources, which are cited in the References section.

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Executive Summary

An environmental scan is a general-purpose tool used by organizations to identify, monitor, and track external trends that may serve as opportunities for growth, or could pose risks, to that organization. This is the third Environmental Scan that the Program Coordination Office (PCO) at the National Institute of Standards and Technology (NIST) has conducted. In all of the scans, the societal, political, and geopolitical landscape were included. Trends in these areas have impact on NIST's workforce, its stakeholders (e.g., the United States taxpayer), and how effectively NIST can deliver on its mission.

The technology drivers that are included in the scans have changed from version to version, which reflects the pace at which technology changes. Each Scan highlights the topics that are of national and international importance at the time. They are snapshots, limited in scope, and thus do not cover all research and activities at NIST. The table below compares the technology drivers covered across the three scans (2018, 2020 and the current one for 2023) conducted by NIST.

Notable additions to the current 2023 Scan are trends in pandemic preparedness, bioeconomy, standards leadership, and semiconductors spurred by advances in science, recent U.S. Executive Orders, the development of a National Standards Strategy for Critical and Emerging Technology, and the passing of the Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act. Technology drivers that have remained through the three scans are cybersecurity, sustainable innovations, health, advanced communications, artificial intelligence, and quantum (i.e., quantum information science and technology). Drivers that were excluded from subsequent scans are neither an indication of their importance to NIST nor an indication of the status of the work. For example, NIST has made a strategic investment in autonomous vehicles through internal exploratory funding since the last Scan.

Table 1. Comparison of technology drivers across the three NIST environmental scans

2018	**2020**	**2023**
Security	Security	*Expanded to* Cybersecurity and Privacy
Sustainable Energy Solutions	*Renamed* Sustainable Innovations	*Renamed* Climate Change and Sustainable Innovations
Smart Cities and Communities	*Included under Sustainable Innovations*	*Included under Sustainable Innovations*
Health	Health	*Expanded to* Health and Pandemic Preparedness
Drones and Autonomous Vehicles	Drones and Autonomous Vehicles	*Not covered in 2023 Scan*
Human Augmentation	Human Augmentation	*Not covered in 2023 Scan*

2018	2020	2023
5G and Next-Generation Communication	5G and Next-Generation Communication	*Expanded to* Advanced Communications
Artificial Intelligence	Artificial Intelligence	Artificial Intelligence
Quantum	Quantum	*Renamed* Quantum Information Science & Technology
Internet of Things	Internet of Things	*Included under Health and Pandemic Preparedness*, *Cybersecurity and Privacy*
Blockchain	*Included under Security and Advanced Manufacturing*	*Not covered in 2023 Scan*
	Privacy	*Expanded to* Cybersecurity and Privacy
	Data	*Expanded to* Big Data
	Advanced Manufacturing	Advanced Manufacturing
	Space	Space
	Engineering Biology	*Expanded to* Bioeconomy
		Standards Leadership *added*
		Semiconductors and Hardware Supply Chains *added*

1. Introduction

Since its inception as the National Bureau of Standards (NBS) in 1901, the National Institute of Standards and Technology (NIST) has played a defining role in standardization and innovation in the United States. Situated within the U.S. Department of Commerce (DOC), NIST's mission is "to promote United States innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life." This mission is achieved through NIST's core competencies of measurement science, rigorous traceability, and the development and use of standards, as well as core organizational values of perseverance, integrity, inclusivity, and excellence. As NIST maintains a consistent set of core competencies and organizational values, it is imperative that NIST be organizationally and programmatically nimble so that its programs can respond to changing technologies and societal needs. In 2023, as NIST plans for the near- and mid-term future, decisions must be made about where efforts should be placed to most effectively execute the NIST mission.

This updated and expanded document builds on the 2018 National Institute of Standards and Technology Environmental Scan [1] and the National Institute of Standards and Technology Environmental Scan 2020 [2], updating topics and presenting new ones in areas where the global landscape has changed. Environmental scans provide a mechanism for gathering prospective information during strategic planning exercises. They provide insights into external factors that may influence how an institution plans and operates. To provide a holistic view of the current environment, this exercise was conducted through three separate lenses: societal and political, investment and geopolitical, and technological.

The following sections address the views through each of these lenses and provide an informative breakdown of ongoing trends in the current global environment. These trends may not directly influence NIST's strategic direction but will likely impact mission-oriented decisions of the future, including decisions on workforce, processes, and partners.

2. Societal and Political Landscape

The societal and political landscape scan focuses on two major trends: societal changes and how political ideologies have impacted public trust (or distrust) in information and science. The subtopics addressed include: demographics, economics, diversity and inclusion in the workplace, digital and media literacy, and information privacy. Social justice and the COVID-19 pandemic are highlighted throughout this section.

According to the U.S. Census Bureau, starting in the year 2030, one in every five U.S. residents will be older than age 65 (including the entire "baby boomer" generation). Older adults are expected to outnumber children for the first time in U.S. history by 2034. Dubbing this phenomenon "a graying nation," the Census Bureau also notes that similar trends are observed in other nations including Japan, Canada, and many European countries that are already grappling with these challenges [3]. This projection presents a major challenge for federal programs such as Social Security and Medicare, but also suggests that working adults may have increased caregiving responsibilities as life expectancies have been increasing in recent years with the exception of 2020[1] [4]. In turn, this may also be reflected by a higher desire and need by employees to work remotely and to work past the full retirement age (Table 2).

Table 2. Four countries with the highest retirement age globally

Country	Full Retirement Age (years)
Greece	67
Denmark	Between 66 and 68
USA	67[1]
Ireland	66

1. For persons born in and after 1960

Source: World Population Review [5]

In 2016, five generations constituted the workforce for the first time in U.S. history (see Table 3 for definitions of the generations) (Figure 1). [6]

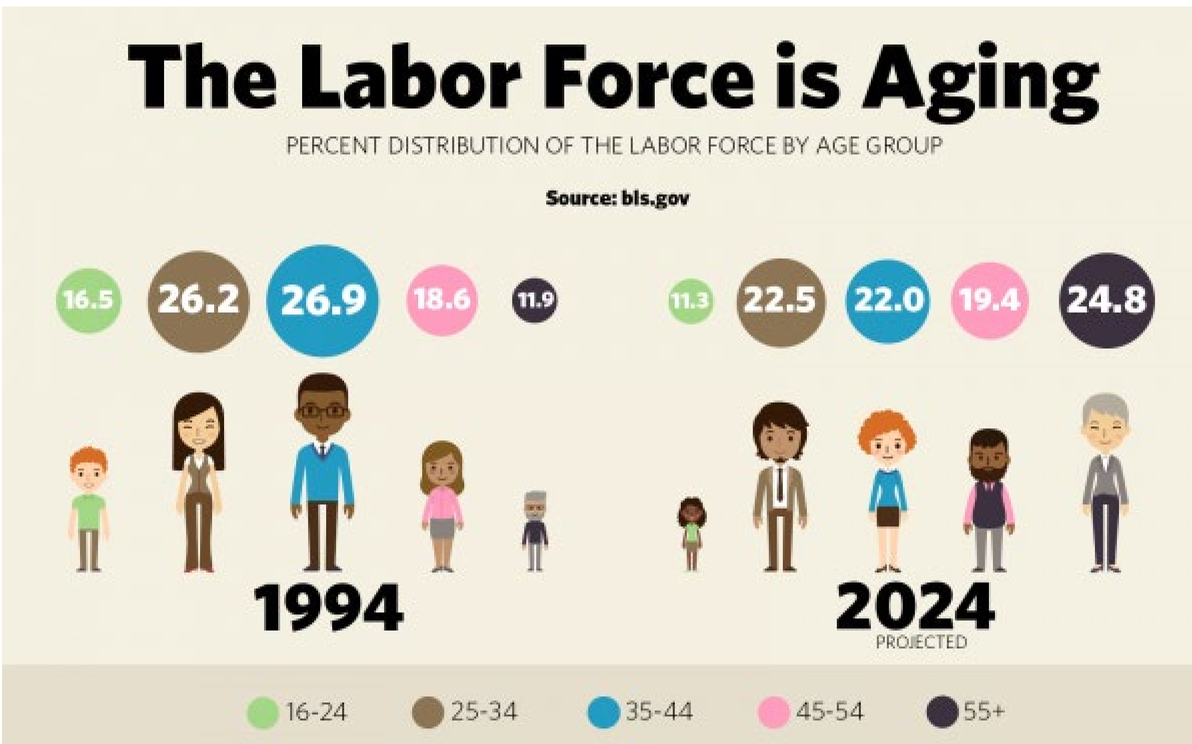

Figure 1. Percent distribution by age of workers in U.S. labor force in 1994 and projected in 2024 [6].

Gen Z, defined as those born in 1997 or later, entered work life fairly recently [6]. They are generally more comfortable with advanced technologies, which were available since their births. They tend to process information quickly and expect instant results. Gen Z tends to distrust the value of higher education, compared to their generational counterparts [7]. In contrast, millennials, defined as those born between 1981 and 1996, have a higher educational level than

[1] CDC reported that the life expectancy drop between 2020 and 2021 was largely driven by the pandemic. Drug overdose deaths also accounted for nearly half of all unintentional deaths due to injury.

previous generations (e.g., having a bachelor's degree or higher): 39 % for Millennials; 29 % for Gen Xers; 25 % for Baby Boomers; and 15 % for the Silent/Greatest generation. In line with overall population trends, diversity in the United States is also rapidly increasing with younger generations. Gen Z is projected to be the most diverse of all generations, with nearly 50 % of people being from traditionally underrepresented racial or ethnic groups [8].

Table 3. Generations defined

Generation	Relevant Years (Age in 2023)
Gen Z/Post-Millennial	Born 1997 or later (26 and younger)
Millennial	Born 1981-1996 (27-42)
Gen X	Born 1965-1980 (43-58)
Baby Boom	Born 1946-1964 (59-77)
Silent/ Greatest	Born 1945 or earlier (78 and older)

Source: Pew Research Center [9]

Immigration trends influence nearly every policy area of concern, from jobs and the economy, to education, health care, and federal, state, and local government budgets. An extensive National Academies of Science, Engineering, and Medicine (NASEM, or "National Academies") study called out the importance of immigration for the nation's economic growth and stated that "the infusion by high-skilled immigration of human capital has boosted the nation's capacity for innovation, entrepreneurship, and technological change." [10]. The American Civil Liberties Union (ACLU) reported that immigrants start new businesses, create jobs, spend their income on American goods, and pay more than $90 billion in taxes [11].

According to the U.S. Census Bureau projections, by 2030, net international migration will overtake the U.S.-born birthrate as the primary driver of population growth in the United States [3]. This increase is also likely to affect the workforce and overall demographics of the population. However, the predictions do not factor in any new or significant immigration policy changes.

The differences in life experiences and contextual factors unique to each generation can lead to workplace conflict. Tension could arise between generations related to: work locations and hours (e.g., telecommuting, flexible work schedules, holidays), gathering and sharing salary and promotion information, and communication preferences (e.g., face-to-face meetings, phone calls, voice messages, emails, texting, or instant messaging). As the workforce becomes more diverse racially, culturally, and ethnically, tensions may also arise related to workplace norms and expectations.

Wealth Gap

The gap between those with the most and least material wealth in the United States has been increasing in recent years. The rising gap gives the United States the highest level of income inequality of any Group of Seve (G7) country [12]. The income and wealth gaps have different impacts depending upon demographics. The Center for American Progress showed that while poverty rates in 2019 for White, Black, Asian American and Pacific Islander (AAPI), and Hispanic people were at their lowest, there were still racial disparities [13]. Blacks and Hispanics had an average 10 % higher poverty rate than AAPI and Whites. Black women continued to have the highest poverty rates of any group while Hispanic women were the second highest. Wealth gaps have implications for access to higher education, which will inevitably impact the makeup of the applicant pool for jobs requiring advanced degrees, including those in science, technology, engineering, and math (STEM).

Students are also choosing not to attend college, due to rising costs (and increased student loan debt) and wanting (or needing) to earn money immediately after qualifying for entry into the workforce [14]. For the population with advanced degrees, principal investigators have reported that the number of post-doctoral fellow ("post-doc") candidates applying for open positions is 10 times less than it was in 2018 to 2019 [15]. If research institutions and universities cannot offer competitive pay to post-docs, they may accept offers outside of academia, especially in emerging technology fields such as cybersecurity and quantum.

Having a diverse workforce has repeatedly been shown to improve productivity and innovation, and having more women in the workplace can improve employee engagement and retention [16]. About $8 billion is spent each year on diversity and inclusion (D&I) training in the United States, but more can be done to find effective practices to increase the diversity of workplaces and ensure that people are treated equitably and feel included [17].

Women in the workforce have made great strides over the last few decades, especially as the number of women in leadership positions has increased. However, sustained progress towards closing the "gender gap" will not occur unless persistent sexual harassment is addressed. A National Academies 2018 study found that 20 % to 50 % of women in science, engineering, and medical academic settings experienced some form of harassment, including gender harassment (the most common being verbal or nonverbal sexist hostility and crude behavior), unwanted sexual attention (unwanted verbal or physical advances), or sexual coercion (favorable treatment conditional on sexual activity) [18]. The detrimental impacts on women in STEM were highlighted in a 2020 documentary *Picture A Scientist* [19]. The documentary followed three women in their STEM careers as they sought gender equality, visibility, and diversity in their disciplines. The film showed that when women experience sexual harassment at work, they can suffer in multiple ways: by becoming less involved in the organization, leaving a job, or even leaving the field.

NIST wants to better understand its equity and inclusivity issues. NIST's culture has evolved from NIST's scientific roots – scientific excellence, and a strong belief in meritocracy. However, this culture can also contribute to a gendered social structure and outcomes that provide advantages and opportunities for men while erecting barriers for women, including isolation and exclusion [20-22]. These implications feed into the prevalence of women in lower-level positions ("sticky floor"), barriers to career advancement ("glass ceiling"), and even women being promoted into higher positions during times of crisis or when the chance of failure is highest ("glass cliff") [23]. It should be noted that women were also disproportionately impacted by extra caregiving duties during the COVID-19 pandemic [24], which may have further hindered their career advancement.

The issue of workplace diversity is an intersectional issue that includes factors of race and gender. Looking at pipeline issues, a landmark report published by the American Institute of Physics shows long-term systemic issues that have resulted in the underrepresentation of African Americans in the field of physics [25]. Across the STEM workforce, Black and Hispanic workers remain underrepresented [26]. Even though the number of STEM graduates has grown since 2010, this has not yet translated to increased diversity in related jobs. Hispanic workers make up only 8 % of the STEM workforce. Asian workers are 13 % of the STEM workforce, but American Indian or Alaska Native, Native Hawaiian or Other Pacific Islanders, and those that identify with two or more racial groups are only 3 % of the STEM workforce.

The 2020 pandemic has shifted the way we work and where we choose to work. Much of the STEM workforce had maximum telework, for at least a short period, in 2020. Now in 2023, even workers with a majority of their work time related to hands-on work (e.g., at the bench, in the field) can take advantage of the flexibility to work remotely to complete a portion of their duties. Workers who have health concerns returning to shared office spaces, who have immunosuppressed family members at home, and/or who have dependent care to coordinate all benefit from increased workplace flexibility. Fast Company notes that companies went from one extreme (i.e., working from 9 a.m. to 5 p.m. in an office) to the other (i.e., maximum telework) and now many companies) are trying to navigate something in between [27]. Future Forum data from 2021 shows that the majority of knowledge workers (63 %) expect to work in a hybrid environment. Only 17 % want to return full-time to an office and only 20 % want to work remotely full-time [28]. While there are risks to allowing decentralized coordination of work schedules (as opposed to top-down policies), Fast Company notes that the long-term gains include: access to a broader talent pool, empowered employees, and an organization that manages change more effectively in the future.

Digital Literacy

The National Association for Media Literacy Education (NAMLE) offers three definitions to describe media literacy: “Media refers to all electronic or digital means and print or artistic visuals used to transmit messages. Literacy is the ability to encode and decode symbols and to synthesize and analyze messages. Media literacy is the ability to encode and decode the symbols transmitted via media and synthesize, analyze, and produce mediated messages” [29].

In 2020, Pew Research Center reported that over half of U.S. adults get their news from social media [30]. The conflation of information and misinformation wreaks havoc on a society. The COVID-19 pandemic illustrated the challenges of misinformation propagated throughout social media – an “infodemic” [31]. The factors that contributed to the rapid spread of misinformation include the increased rate of social media usage during the pandemic (10.5 % more use) [32] and social media algorithms designed to reinforce the beliefs users already hold, creating an echo chamber [33]. During the pandemic, these types of posts included those with misinformation [34]. Though social media was supposed to help us connect, it has done the opposite in recent years. NBC News reported that 64 % of adults say that social media does more to divide us [35]. Misinformation coupled with this division has resulted in debates over vaccines, masks [36], and the validity of the U.S. electoral process [37, 38].

Widespread distrust in the United States is on the rise. For the past 20 years, the Edelman global communications firm has issued an assessment of trust around the globe. In 2021, the Edelman Trust Barometer trust index (the average percent of trust in four institutions: non-governmental organizations, business, government, and media) reported that trust in information sources was at a new record low. [39]. Edelman reported an 11-point gap in trust between those with good "information hygiene" (i.e., those that check their sources and ensure factual information is being shared) and those with poor information hygiene. Trust in science is also becoming more politicized [40].

Society is continuously connected to an influx of information while simultaneously generating and sharing new types of personal data. The European Union (EU)'s General Data Protection Regulation (GDPR) went into effect on May 25, 2018 [41] and was intended to protect the processing and sharing of personal data. A complaint was brought before the European Data Protection Board (EDPB) in 2022 against Meta Platforms Ireland Limited regarding their use of targeted ads using personal data [42]. In January 2023, Meta was fined €390 million ($414 million) for violating the GDPR [43]. In May 2023, Meta was again fined, at an even larger €1.2 billion ($1.3 billion) by Ireland's Data Protection Commission for violating the GDPR [44]. Increasingly, there is support for more privacy laws in the United States [45].

The current practice in the United States is to give users the choice to opt in or opt out of sharing their personal data. However, studies confirm that the majority of people do not read the terms of use (TOU) for websites and apps before using them [46]. Even if users read the TOUs terms, tech companies still misuse and sell their data (illegally in some instances) [47].

After Roe v. Wade was reversed on June 24, 2022, concerns began arising on the use of personal data by authorities to convict women seeking reproductive healthcare where abortion was now illegal [48]. In August 2022, officials in Nebraska became the first to use private Facebook data against a teenager accused of having an illegal abortion [49]. Executive Order 14076 *Protecting Access to Reproductive Health Care Services* was released on July 8, 2022, shortly after the reversal of Roe v. Wade in order to protect personal health information [50]. This however did not solve the issue. In February 2023, news was released about GoodRx, a drug discount app, sharing personal data on users' medications and illnesses to companies like Facebook and Google without the user's permission [51].

Implications for NIST

NIST faces many new challenges in delivering its mission in the face of societal trends in misinformation, politicization of science, public distrust in the United States, and information privacy concerns. With core values of perseverance, integrity, inclusivity, and excellence, NIST staff are dedicated to their work and feel that their work makes a difference to the Nation and within the world. As the next generation enters the workforce, NIST has the opportunity to attract new talent to NIST by utilizing its core values to integrate a variety of different staff backgrounds, including through understanding inter-generational differences in the workforce. Generational-based conflict in team environments stems from differing expectations around when and where to work (e.g., telework or flexible schedules), modes of communication (e.g., face-to-face meetings, voicemails, emails, instant messages), scheduling (e.g., use of calendar software) and obtaining new skills (e.g., taking a formal course or learning on the fly) [52].

Workplace biases and the hybrid work environment present many challenges to the collaborative team environment that NIST thrives upon. Nonetheless, NIST does not have to go it alone to navigate these challenges, as other organizations are actively working on best practices and solutions to these new workforce challenges.

Forthright and open discussions about workplace expectations can bring attention to biases caused by generational and cultural differences. For example, NIST offers training such as bystander intervention, identifying and addressing microaggressions, and having difficult conversations. NIST also established an Organizational Ombuds Program to provide support and assistance to members of the NIST community in addressing work-related conflicts.

During the pandemic, NIST staff were able to take advantage of Excused Absence for Dependent Care [53]. As caregiving duties for dependents did not end with the pandemic, the continued support of flexible work schedules (to include remote work) is needed to meet the needs of the current workforce. Support groups such as the Parents Network and Elder Care/Caregivers Support Group are also available to NIST staff. In January 2023, the National Academies project, *Policies and Practices for Supporting Family Caregivers Working in Science, Engineering, and Medicine*, kicked off with funding from several agencies, including NIST [54]. This project will produce evidence-based guidance to give leaders in academia and government information on how to implement policies and programs to support the retention, re-entry, and advancement of students and professionals working in STEM who have caregiving responsibilities, either for children or older adults.

The needs of NIST employees to fulfill roles as caregivers and their desire for workplace flexibility has resulted in an increase in requested routine telework and remote work. Moreover, the gradual shift in opinion about the ability to successfully accomplish work during the COVID-19 maximum telework environment using modern collaboration tools has changed attitudes towards these work arrangements. NIST may reevaluate use of remote duty stations to allow employees greater flexibility in where they choose to live. Increased location and telework flexibility may also help NIST recruit and retain talent from pools previously overlooked. As the hybrid work environment is most likely the new normal, NIST may also consider how to optimize the hybrid work environment, both from a technological as well as managerial perspective. NIST must consider what the workplace of the future will look like without compromising on its ability to effectively deliver on its mission.

Volunteer employee organizations (VEOs) and/or Employee Resource Groups (ERGs) play an important role in cultivating an inclusive workplace for NIST staff. They organize events for heritage months and have spearheaded long-lasting initiatives like the establishment of a childcare center onsite that opened in 1983. While VEOs and ERGs were active prior to the pandemic, they became even more accessible when they adopted the use of virtual platforms for meetings and hosting events.

In July 2022, NIST released an internal Diversity, Equity, Inclusion, and Accessibility (DEIA) Strategic Plan that outlined its DEIA goals for the institution but also for external engagement. Two objectives were developed for each goal and strategies for achieving each objective were identified. Over 130 NIST staff worked with the DEI Office to create quantifiable action items/milestones for strategy. Through inclusive and transparent processes like these, NIST hopes it will improve its DEIA posture and can live up to its core values.

The pipeline from student to a STEM career could be described as weak, leaky, or broken. NIST is taking action to become a more welcoming place for students, post-docs, and staff. It is also making progress in its outreach efforts, particularly to underserved communities and untapped talent pools. The Visiting Committee on Advanced Technologies (VCAT) formed subcommittees to develop recommendations on visibility and workforce developments that NIST could leverage. The passing of the CHIPS and Science Act also created opportunities for NIST to improve workforce development efforts. NIST may also have a role in minimizing the growing income and wealth gap through the hiring of diverse talent to meet mission needs. NIST currently has several organizations and activities that focus on workforce development, including the Hollings Manufacturing Extension Partnership (MEP), Manufacturing USA, and the National Initiative for Cybersecurity Education (NICE).

The general climate of distrust and skepticism, compounded by the information divide, could have far-reaching, harmful effects on the reputation and "brand" of NIST – a trusted organization within the scientific community [55]. However, NIST already has a legacy for defending scientific integrity. In May 2023, NIST released *The AD-X2 Controversy* [56] documentary about a salesman who sought to make his fortune with a chemical additive that he claimed would revolutionize the car battery business. When tests from NBS showed that the additive did not perform as claimed, NBS Director Allen Astin had to battle public opinion and political pressure, defending the importance of scientific integrity. NIST's commitment to scientific integrity still stands today. Now in 2023, there are new opportunities for NIST to step up and reassert its role as a "trusted" agency with strong scientific underpinnings that lack political bias or influence. With the passage of the CHIPS and Science Act in July 2022, NIST and the DOC were given the opportunity to regain the public's trust in its Government to responsibly implement $52 billion in programs to strengthen and revitalize the Nation's position in semiconductor research, development, and manufacturing [57].

3. Investment and Geopolitical Landscape

The current geopolitical landscape is extremely competitive along several critical dimensions, including research and development (R&D), investment, and innovation. The subtopics addressed include: global spending on R&D (public and private), global competition, and a trained workforce for Critical and Emerging Technologies (CETs).

The United States has long been recognized as a global science and technology (S&T) leader, with a budget reflecting this leadership stance. In 2018, U.S. spending on R&D accounted for approximately 40 % of the total Organization for Economic Co-operation and Development (OECD) countries' R&D expenditures ($555.1 billion across the 37 member countries). However, the U.S. position is not secure. The People's Republic of China (PRC) is rapidly growing its R&D capacities (Figure 2).

Over the next two decades, the United States and PRC will influence and drive global competition [58]. In 2019, the United States spent $656 billion on R&D and the PRC spent $526 billion; together, they account for 49 % of global R&D investment. The PRC has increased its R&D investments 10.6 % on average, year over year, between 2010 and 2019, whereas the United States has only increased investments an average of 5.4 % in the same time period [59]. As both nations compete for technological dominance, their actions will influence global relations and economies, increasing geopolitical volatility and uncertainty. Restrictions on U.S. entities working with individuals and companies from the PRC continue to increase. In March 2023, the DOC released proposed rules to prevent the PRC and other foreign countries of concern to benefit from the $39 billion CHIPS Incentives Program in the CHIPS and Science Act [60].

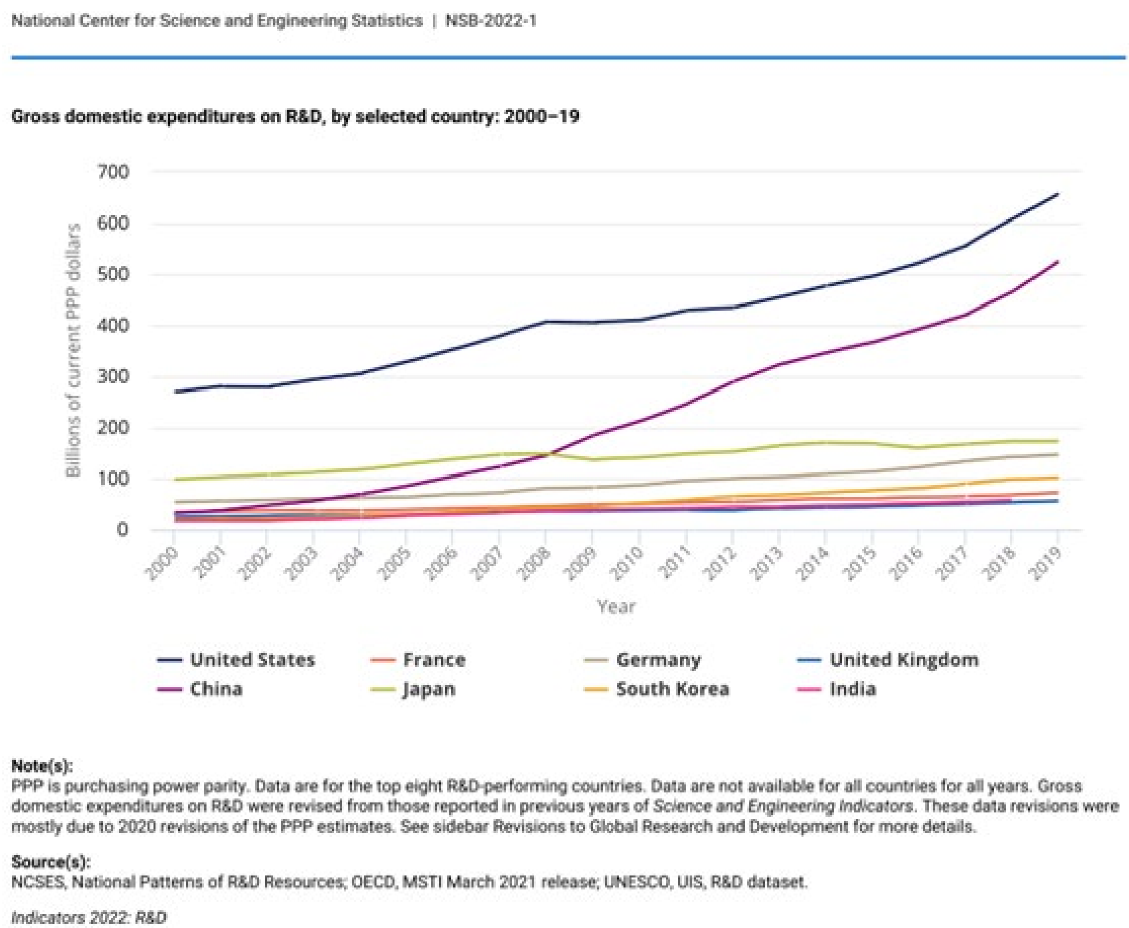

Figure 2. Gross domestic expenditures on R&D between 2000 and 2019 [59].

With increased public sector investment in private sector semiconductor production, there is a potential for conflicts of interest. Entities performing research, profiting from said research, or having undisclosed company affiliations could introduce a measure of bias and risk. Conducting unbiased research by third-party institutions can be leveraged to mitigate bias, while clear policies for the disclosure of funding and author affiliations can serve to mitigate risk. However, regardless of the steps used to address bias and risk, great power competition and challenges to U.S. leadership in CETs have already placed more controls around collaborative R&D between countries. NASEM reported that these restrictions will limit innovation and make research less attractive [61].

As geopolitical tensions rise, advances in technology that may make our lives easier might have the potential to be used by authoritarians for societal and political subversion [62]. In 2021, Georgetown University's Center for Security and Emerging Technology released a report that stated the PRC had surpassed the Unites States in the number of PhD degrees granted in STEM [63]. This amounts for three PhDs granted in the PRC for every two PhDs granted in the United States. As industries for CETs grow, competition for top talent is critical. The number of PhDs that drive innovation in CETs serves as an indicator for competitiveness.

U.S. Federal R&D funding was reported as $195 billion in FY 2023 [64]. Expenditures on R&D, however, should be presented within a macro view of federal budget discussions. The Congressional Budget Office (CBO) estimated a deficit of $1.4 trillion for 2023, and estimated the deficit to be $2.7 trillion by 2033 [65]. In recent years, Congress has rarely completed budget allocations prior to the October 1 start of the fiscal year and it has become even more challenging to come to bipartisan agreement on what will be funded in any given year. All these factors could mean that the U.S. position as a world leader in innovation and technology is at risk without certainty of R&D investments for sustained progress.

The Congressional Research Service outlined a set of science and technology policy issues that could potentially arise during the 118th Congress [66]. This document, which is not meant to be exhaustive, highlights the wide range of issues in which the federal government has a stake. Table 4 lists the eight categories discussed in this report along with examples of key technologies and topics in each category. While most topics have relevance, those that are particularly applicable to NIST are included below.

Table 4. Science and technology policy Issues for the 118th Congress that are relevant to NIST [66]

Category	Select Technologies and Topics
Overarching S&T Policy Issues	Federal R&D funding Interagency S&T coordination Domestic science and engineering workforce Patents and other intellectual property policies
Agriculture	Climate change science
Biotechnology and Biomedical Research	Bioeconomy Monitoring of environmental DNA and RNA Convergence of biotechnology, digital data, robotics, and artificial intelligence
Climate Change	Climate change-related science and the ocean-climate nexus Clean energy research, development, demonstration, and deployment S&T for adaptation and resilience to climate change Carbon capture, utilization, and sequestration
Energy	Biofuels Hydrogen pipelines
Information Technology and Social Media	Cybersecurity Law enforcement platforms/Facial recognition
Telecommunications	5G technologies
Water	Water use Water quality

Implications for NIST

The political and policy landscape carries with it significant implications for NIST from a budgetary, workforce, and programmatic perspective. These trends will force NIST to be flexible in pursuing new avenues of research and technology development while evaluating existing programs to ensure that NIST continues to help U.S. industry remain competitive in a global landscape.

Flat or decreasing levels of federal R&D funding are likely to impact resources available to NIST. Faced with uncertain levels of investment, NIST must continue to reprioritize program areas and projects on a yearly basis, especially with changing administration priorities. If NIST decides to address new areas of emerging technologies, it will leave less funding available for existing areas of strength including NIST's core metrology functions, which in turn could adversely impact NIST's ability to maintain long-term core competencies in measurement science. NIST is also facing the reality of its aging infrastructure negatively impacting scientific productivity across multiple campuses, with hundreds of millions of dollars annually needed to address its needs [67].

Beyond uncertain levels of federal R&D funding, NIST must also consider implications of rising levels of business sector R&D expenditures. As the business sector continues to invest in R&D, it is critical that NIST maintain credibility with the private sector to promote measurement science, guidance, and standards for meaningful adoption by industry. NIST must maintain and strengthen existing public-private partnerships and seek out new partnerships to continue to support American competitiveness. Balancing the needs of competing stakeholders and partners will continue to pose significant challenges for NIST. As such, NIST must maintain a careful and thoughtful balance between industry's research goals that are often driven by short-term profits, against the need for NIST to prioritize research based on the overall good of the U.S. economy and the American public.

Another consideration for NIST to manage is the importance of transitioning basic research from the government to industry. In addition to technology transfer for more mature research and technologies (already a NIST priority area), NIST must also work to transition basic research into more applied settings. NIST can do more in communicating its research to the public, helping to raise awareness about the bureau in general, and presenting itself as a trustworthy scientific organization.

Some members of Congress do not understand the voluntary consensus standards process that defines standards activities in the United States. Thus, the importance of NIST leading the implementation of the National Standards Strategy for Critical and Emerging Technology (NSSCET) [68, 69] must be communicated to Legislative Branch colleagues. Furthermore, not all members of Congress may fully comprehend the nuanced role that NIST plays in supporting those processes or the standards development ecosystem. This inconsistent understanding can manifest itself if Congress requests NIST to take on roles that are inconsistent with the consensus standards process and can result in misunderstanding about the non-regulatory role that NIST strives to maintain to continue its trusted role with industry. Congress is increasingly vocal about the need for U.S. leadership in global standards for emerging technology areas such as the fifth generation mobile network (5G), quantum information science (QIS), and AI. This recognition is partially brought about as it sees strategically competitive countries becoming more active in the standards arena, occasionally pushing solutions that have not been thoroughly vetted from a technical perspective or looking to exploit standards development processes to push their national priorities. Since some standards set the course of development for key technologies, Congress recognizes the importance of active engagement by federal staff to ensure continued competitiveness of U.S. industry.

NIST benefits from an open research environment that fosters close collaboration between talented international researchers and NIST scientists. However, the decrease in the number of post-docs and the restrictions on international collaboration will mean that NIST will have a smaller talent pool from which to recruit.

International guest researchers bring new areas of expertise to NIST and provide critical assistance for both R&D and service metrology programs. NIST is dedicated to building out its internal workforce development programs to attract both domestic and international talent. The International and Academic Affairs Office (IAAO) has outreach programs targeting students in elementary schools through post-doctoral programs, as well as university professors. NIST has joint programs with Sistema Interamericano de Metrología (SIM) and Asia-Pacific Economic Cooperation (APEC).

NIST has maintained its reputation as one of the leading global national metrology institutes (NMIs). However, the demand for R&D beyond traditional metrology efforts can dilute the measurement capabilities of NIST through reallocation of limited funding. As other countries invest further in their own NMIs, NIST may become less relevant in some critical metrology areas. Because Calibration and Measurement Capabilities (CMCs) form the basis of international trade, commerce, and regulatory affairs, they are essential for high-functioning trade relations. The need for new CMCs is apparent; however, participation in International Committee for Weights and Measures (CIPM) activities that produce CMCs will require NIST to make hard decisions about program engagement with limited available resources.

Similar considerations are necessary as NIST evaluates its standards development organization (SDO) activities. NIST participates in 112 SDOs, and the bureau's participation results in significant impacts on international technical standards adoption. With an increasing number of SDOs and activities within those organizations, it is essential to make strategic decisions about the bureau's participation to maximize impacts without spreading NIST expertise too thin in other strategic priority areas.

4. Technology and Science Landscape

Twelve technology drivers are highlighted in this section, from cybersecurity to sustainable innovations and advanced manufacturing, including several that are currently in the mainstream but still require further advancement. These technologies form the foundation for future innovation across the science and technology enterprise.

4.1. Standards Leadership

Market failures and supply chain issues resulting from semiconductor supply chain and manufacturing shortages that stem from global dependence on a single geographic location are driving a resurgence in international and industrial policy engagement. The U.S. government is positioning itself to mitigate market failures through strategic investments in CETs [70].

U.S. leadership in international standards development activities continues to be rivaled by its primary strategic competitor. The PRC has increased its international participation and leadership in a bid to influence outcomes through a coordinated government-driven approach. The international standards development process has shown resilience thus far. However, as the PRC continues to expand its activity, as articulated by the China Standards 2035 Strategy [71], the United States must continue to lead international standards development for the most critical areas of emerging technologies, including quantum information science, AI, advanced manufacturing, biotechnology, advanced telecommunications, and cybersecurity and privacy.

The new European Strategy on Standardisation and subsequent amendment to Regulation (EU) No 1025/2012 limits the voting rights of a standards participant if they are not a representative of an EU National Standards Body (NSB). This is a significant change for European Telecommunications Standards Institute (ETSI) members, applying to all requests for standards made by the European Commission (EC) in support of EU law, which is currently 3 % of ETSI's total standards work. The EU's motivation for the change is to: (1) ensure balanced representation from "relevant stakeholder" (e.g., small- and medium-enterprises (SMEs), environmental, social, and consumer) [72][2] interests; and (2) limit the ability of "third countries" (i.e., the PRC) to prevent the adoption of standards deliverables requested by the EC [72][3]. According to the EU, NSBs are best suited to ensure that the interests, policy objectives, and values of the Union are upheld [72][4]. When the EU uses the term "values," it is referring to those listed in Article 2 of the Treaty of Lisbon and the EU Charter of Fundamental Rights (human dignity, freedom, democracy, equality, rule of law, and human rights). These are binding agreements between EU member states [73].

The EU standardization system is led by the three European Standards Organizations (ESOs) – the European Committee for Standardization (CEN), the European Committee for

[2] (5) In line with Articles 5 and 6 of Regulation (EU) No 1025/2012, sound procedures and a balanced representation of relevant stakeholders' interests, including those stakeholders representing, inter alia, SMEs and environmental, social and consumer interests, are essential, and therefore should be ensured.

[3] (7) Participation by the national standardization organizations of third countries in the work of the European standardization organizations should not prevent the adoption of any decision concerning European standards and European standardization deliverables requested by the Commission where such decision has the support of the national standardization bodies from Member States and EEA countries only.

[4] (6). National standardization bodies are therefore best placed to ensure that the interests, policy objectives and values of the Union, as well as public interests in general, are duly taken into account in European standardization organizations.

Electrotechnical Standardization (CENELEC), and ETSI. These ESOs develop harmonized European standards (hENs) to meet the essential requirements of EU regulations. The subset of harmonized standards that are cited in the Official Journal of the European Union (OJEU) are recognized by the EC for use by manufacturers in demonstrating conformity with EU requirements. Prior to exporting, U.S. manufacturers must demonstrate that their products meet these standards. U.S. manufacturers can normally declare conformity to EU requirements by issuing a "Declaration of Conformity" (or placing a Conformité Européene (CE) mark on the product). Higher-risk products may require conformity assessment by EU Notified Bodies. Products that meet the OJEU cited harmonized standards have a "presumption of conformity" to applicable EU requirements.

NIST attends the General Conference on Weights and Measures (CGPM) which was held in November 2022. The International Bureau of Weights and Measures (BIPM) 2022 Strategic Plan [74] was approved at the meeting, which highlighted the future role of BIPM since the redefinition of the système international d'unités (or in English, the International System of Units (SI)) will no longer require maintaining physical artifacts. The redefinition of the SI represents a paradigm shift in the dissemination of the SI. It is now possible to do accurate and precise measurement science anytime and anywhere in the world without needing calibration to a specific artifact. This 'democratization' of the SI is leading to new interest in broader deployment of NIST-on-a-Chip types of technologies and may also lead to new roles for NMIs and BIPM related to new practical realizations of units and validating traceability and uncertainties of these measurements. Concurrently with the redefinition of the SI, another revolution in SI dissemination is developing, as global attention on digital metrology is growing. Digital transformation of measurement services and the use of "digital twins" in metrology is a growing topic for many NMIs.

On May 4, 2023, President Biden released the NSSCET [68, 69]. The strategy identifies specific actions designed to ensure that the United States will be the world leader in innovation and research in critical and emerging technologies. NIST will lead the federal government's implementation of the strategy.

Implications for NIST

NIST coordinates U.S. engagement in key standards areas. For example, NIST chairs the Interagency Committee on Standards Policy (ICSP) and is taking steps to ensure that the United States is influential in areas of quantum science standardization by leveraging its private sector partners like the Quantum Economic Development Consortium (QED-C). NIST also chairs the Interagency International Cybersecurity Standards Working Group (IICSWG) to coordinate cybersecurity standards needs among its member agencies.

NIST is currently leading lines of effort in multilateral CET policy-focused fora. These include the U.S.-EU Trade and Technology Council (TTC), Quad (Australia, India, Japan, and the United States), international Group of Seven (G7), Ottawa 5 (O5), OECD, 3rd Generation Partnership Project (3GPP), Internet Engineering Task Force (IETF), and the O-RAN (Open Radio Access Network) Alliance. NIST participates in trade policy fora such as the Indo-Pacific Economic Framework (IPEF) [75] and United Nations (UN) fora such as the Department of State-led International Telecommunication Union (ITU).

The U.S. implementation of the NSSCET will require NIST to take a proactive approach to coordinate U.S. representation and leadership of international standards development, pre-standardization R&D, and workforce training to accomplish economic and national security policy goals.[5] Stakeholder engagement and coordination across international standards organizations and policy development bodies will be critical to its implementation. NIST will coordinate federal agency engagement in standards activities and collaborate with the American National Standards Institute (ANSI), and other ANSI-accredited SDOs, to develop standards to solve the most pressing CET challenges. NIST is already doing work that is aligned with the Strategy by leading the R&D that underpins and benchmarks novel technologies. The NSSCET offers NIST immense opportunities for leadership in research and standards, leading to an even greater impact for NIST products and services.

In response to the European Strategy on Standardisation and subsequent amendment to Regulation (EU) No 1025/2012, NIST advocates for the development of international standards in a process that is open to all materially interested parties. The U.S. private sector companies have not indicated a willingness to forgo their participation in ETSI; however, they continue to message concerns with ETSI's new voting restrictions. NIST supports a diversified approach to standards development and can recommend additional ways of incorporating the work of international SDOs (such as the American Society of Mechanical Engineers (ASME) and ASTM International (formerly known as the American Society for Testing and Materials) into the ESO's work through agreements and other mechanisms (e.g., tri-labeling, etc.).

The redefinition of the kilogram, kelvin, ampere and mole in 2018 marked the beginning of the end for physical artifacts as ground truth. Physical artifacts will still prove to be the most practical way to perform calibrations on a day-to-day basis. But the difference now is that the new SI units are based on a kilogram standard that is defined by fundamental constants of nature, and not a physical artifact. NIST, which maintains and disseminates the SI units for the United States, will continue to play a major role in the realization of the new kilogram. In parallel, NIST will need to consider how it can bring calibrations to its stakeholders in ways that are faster and cheaper than currently possible. For example, the NIST-on-a-Chip program was designed to deploy calibration services nearly anywhere and at anytime [76].

NIST is expanding efforts to digitally transform NIST's measurement services, looking at creating digital calibration reports for measurement services and digital certificates of analysis for reference materials. Issues such as format, accessibility, digital traceability, digital security, and international compatibility all require consideration. The next step in the digital transformation process may include considering the use of digital twins in metrology and standards, particularly for complex sensors to deploy the new SI units in remote or harsh environments.

4.2. Semiconductors and Hardware Supply Chains

Geopolitical tensions, natural disasters, and logistical challenges are consistent strains that can affect the stability of domestic and global supply chains. These issues, in combination with the

[5] CHIPS and Science Act of 2022 reiterates NIST's standards leadership role in the USG. NIST will lead information exchange and coordination among Federal agencies and communication from Federal agencies to the private sector to guide effective Federal engagement in the development and use of international technical standards.

major impacts of lockdowns from the COVID-19 pandemic, heavily disrupted supply chains, particularly for semiconductors [77, 78]. A clear example of the impact of the semiconductor shortage was seen in the automotive industry. When COVID lockdowns resulted in the closing of semiconductor manufacturing facilities overseas, the United States was left vulnerable due to insufficient domestic semiconductor manufacturing capability. With more people working from home, the demand for electronics amplified the shortages. Automotive factories that shut down in the early days of the pandemic found an insufficient supply of semiconductors when they restarted, resulting in a shortage of new automobiles and higher prices for both new and used vehicles [79]. Semiconductor shortages will continue to be an issue unless steps are taken to increase domestic production [79].

While semiconductor innovation is strong in the United States, manufacturing mainly has been conducted overseas. Major segments of the semiconductor ecosystem include design, fabrication, (assembly, testing, and packaging – ATP), equipment, and materials. To establish a resilient domestic supply chain, investment into the weakest parts of that chain, such as domestic fabrication and ATP, will be required [80].

The lack of a strong domestic supply chain for semiconductors and microelectronics also has significant national security implications. Semiconductor and microelectronics security challenges include malicious insertions, counterfeiting, side-channel attacks, extraction and bypass of roots of trust, and supply chain assurance challenges that can occur during chip design, manufacturing, and throughout the system's lifecycle. Although many microelectronics have supply-chain security challenges, such as counterfeit or out-of-specification components originating from commercial entities, product design and supply chain vulnerabilities can be exploited by state-sponsored bad actors [81] hoping to gain technological advantage or access to state secrets. Without domestic or friend-shored production of semiconductors and a secure supply chain, tracking counterfeits and preventing product tampering are difficult, if not impossible.

In 2022, President Biden signed the CHIPS and Science Act [82] into law. It is a vital first step that provides the DOC with $50 billion for a suite of programs to strengthen and revitalize the U.S. position in semiconductor research, development, and manufacturing, while also investing in American workers.

These programs seek to restore U.S. leadership in semiconductor manufacturing by providing incentives and encouraging investments to expand the domestic manufacturing capacity necessary to produce the most advanced semiconductors for applications in AI and high-performance computing, as well as less advanced semiconductors that remain critical components of everything from automobiles to microwave ovens. In addition to major manufacturing investments, these programs will also make substantial investments in research and development, laying the groundwork for the creation of next-generation industries [57].

Roughly $39 billion is to be directed toward the construction or modernization of U.S. facilities for semiconductor fabrication, assembly, testing, packaging, or R&D. Funding would be applied to supporting multiple market segments and to meeting the semiconductor needs of critical sectors, including commercial requirements as well as requirements of the U.S. Department of Defense (DoD) and the broader intelligence community.

Another $11 billion supports critical R&D and infrastructure investments to help protect and extend U.S. technological leadership, including: the establishment of a National Semiconductor Technology Center (NSTC); the establishment of a National Advanced Packaging and Manufacturing Program (NAPMP) to strengthen semiconductor advanced test, assembly, and packaging capability in the domestic ecosystem; the establishment of one or more Manufacturing USA institutes targeting the manufacturing R&D needs of the semiconductor industry; and increased investment and expansion of NIST's metrology R&D in support of semiconductor and microelectronics [57]. NIST was charged with implementing the CHIPS Act through the newly created CHIPS Program Office and CHIPS R&D Office.

This approach by the U.S. government to reshore critical aspects of the semiconductor industry has many challenges ahead, as manufacturing facilities and R&D are only parts of a larger supply chain. Currently, domestic mining of critical minerals used in semiconductor manufacturing is insufficient. Investments into circular technologies such as those that reclaim critical minerals from electronic waste could return these commodities to the economy rather than creating burdens on the environment [83]. Additionally, the use of biotechnology to harvest critical minerals from mining waste streams or even from celestial bodies at a commercial level are a near-term reality that could help alleviate the domestic critical mineral gap [84].

The 2020 semiconductor workforce in the United States was estimated to be approximately 277,000 people, and it is estimated that the CHIPS Act will create an additional 185,000 temporary jobs annually from 2021 to 2026 (not including R&D personnel) [85]. These jobs range from construction to operations to R&D. Preparing the next generation of workers and helping existing workers learn new skills will be one of the challenges the country will face during the implementation of CHIPS. In the longer term, it is estimated that there will be a shortage of as many as 165,000 people if the number of people entering STEM fields does not increase.

Implications for NIST

The passage in August 2022 of the CHIPS and Science Act ushered in a new era at NIST. Implementing the CHIPS Act is an unprecedented task for NIST that brings great opportunity to develop partnerships with the semiconductor industry, develop innovative measurements and technologies in support of the semiconductor industry, and support the manufacturing and supply chain landscape. However, it also creates great challenges that include balancing the immense efforts of implementing the CHIPS Act with maintaining the health of NIST's other mission priorities and quickly growing the NIST workforce.

NIST is already experiencing new opportunities to interact with and develop new partnerships with industry as a result of the CHIPS and Science Act and can expect these opportunities to increase by, for example, establishing working groups like the existing Extreme Ultraviolet (EUV) working group, where members of industry present and discuss top-priority technical problems and their metrology needs. The establishment of the NSTC will greatly increase and accelerate such opportunities. The new interactions should lead to more targeted insight into the important manufacturing challenges that would benefit from innovation in measurement science. However, it will be a challenge for NIST to identify research areas that benefit the entire U.S. semiconductor ecosystem. NIST researchers will also need to navigate industry concerns to protect proprietary information and intellectual property, and may need to work to earn the trust of companies in order to create productive collaborations.

NIST's extramural programs will also see increased opportunities for engagement with the semiconductor industry. One component of the $11 billion R&D effort called out in the CHIPS and Science Act is the Manufacturing USA semiconductor institute program. Even though this program will provide funding and other opportunities for Manufacturing USA Institutes to contribute to the health of the U.S. semiconductor industry, NIST will need to ensure that adequate staffing is available and that dedicated focus is provided to other manufacturing areas.

Existing bottlenecks in the semiconductor supply chain are also likely to negatively impact research across every part of NIST through the reduced availability of new technologies and equipment, and other delays in shipments. Even with careful planning, this will likely cause delays in research.

4.3. Health and Pandemic Preparedness

Most of the top 10 emerging technologies highlighted by the World Economic Forum in 2018 were related to healthcare. They included augmented reality, personalized medicine, AI-led molecular design, more capable digital helpers, implantable drug-making cells, gene drives, plasmonic materials, and electroceuticals [86]. In 2019, almost half of the Forum's top 10 were health-related and included disordered proteins as drug targets, DNA data storage, miniature device lenses, and collaborative telepresence [87].

Precision medicine considers each person's individual variability in genes, environment, and lifestyle. It could change every aspect of modern healthcare; however, many of the technologies needed to fulfill the promise of precision medicine have yet to be developed or are in the early stages of development. Nonetheless, precision medicine continues to evolve, as demonstrated by the use of cell and gene therapy (CGT) for cancer treatment. The global market for precision medicine is expected to reach $254 billion by 2023 at a compound annual growth rate of 12.1 % from 2023 to 2032 [88].

The popularity of using genomic tools to investigate health through at-home testing has opened the door to include other -omics capabilities beyond genomics, such as metabolomics [89] and microbiome measurements [90]. These tools are of increasing interest, not only for personalized medicine, but also as a new direction in healthcare. This represents a departure from treating a disease to stopping a disease before it develops. Much like genomics, there are still issues in how to interpret data and with quality assurance, but as AI technologies advance and standards are developed, these areas have the potential to broaden the capabilities of the healthcare system.

In addition to patients processing their own data through AI, the number of people comfortable with using at-home medical tests is increasing. As of 2019, more than 26 million people have taken DNA tests from companies to get their genetic information and health reports; this number is expected to hit 100 million within two years [91]. At-home flu tests are in development and the latest Apple Watch contains an electrocardiogram app that alerts users when irregular heartbeats are detected [92]. The COVID-19 pandemic greatly accelerated the use of at-home testing due to several factors, including the FDA emergency-use approval and the reluctance of patients to visit care providers in-person [93]. In January 2022, the Biden Administration pledged to supply one billion tests to the public [94]. Well into the pandemic, COVID tests were still being provided free of charge by the U.S. government to slow the spread of COVID-19 during the fall cold season [95]. The adoption of at-home tests is beneficial because the tests are relatively inexpensive, do not require professional application, can improve health access to rural communities, and in the case of a health emergency, can provide rapid diagnostics when the healthcare community is strained. Additionally, the use of telehealth increased as a result of the COVID-19 pandemic. The American Medical Association (AMA) surveyed 1800 physicians, and 80 % reported they utilized telehealth in 2022 [96], compared to only 14 % of physicians who used telehealth in 2016. Despite more people being able to access healthcare through telehealth, concerns still remain about the quality of care and those who cannot access telehealth because they do not have broadband internet [97].

The impacts of COVID-19 will ripple far into the future on personal, national, and global levels. Vaccines are now available for children as young as six months and boosters for children as young as five years old. Nonetheless, equitable access to vaccines is still an issue [98] and the effects of long-COVID can be devastating [99]. Infection-fighting antivirals are now available for those at risk for serious complications due to COVID-19 and who have tested positive for SARS-CoV-2 [100]. However, every fall and winter, hospitals must still brace for a rise in both COVID-19 and flu cases that may overwhelm already-stressed health systems [101].

On a national and global level, efforts are underway to prepare for the inevitable next pandemic. In September 2021, The White House released *American Pandemic Preparedness: Transforming Our Capabilities* to review whole-of-government national biopreparedness policies to prepare the United States to rapidly and effectively respond to future pandemics or biological threats [102]. In March 2022, The White House released the *National COVID-19 Preparedness Plan* that had four goals: (1) protect against and treat COVID-19; (2) prepare for new variants; (3) prevent economic and educational shutdowns; and (4) continue to lead the efforts to vaccinate the world and save lives [103].

In September 2022, the *First Annual Report on Progress Towards Implementation of the American Pandemic Preparedness Plan* was released [104], which outlines priority areas for investment and highlights existing work to prepare for future pandemics. The U.S. Centers for Disease Control and Prevention (CDC) Home Ventilation Tool was highlighted, which was a joint effort among NIST, CDC, and the CDC Foundation. The NIST-funded Manufacturing USA Institute, National Institute for Innovation in Manufacturing Biopharmaceuticals (NIIMBL), was highlighted for its Vaccine Analytics and Assays Center of Excellence that supports vaccine manufacturing. Other Manufacturing USA Institutes were also mentioned, as manufacturing innovation will only enhance and help scale pandemic responses in the future. In October 2022, The White House released the *National Biodefense Strategy and Implementation Plan for Countering Biological Threats, Enhancing Pandemic Preparedness, and Achieving Global Health Security* [105] to protect the American people from biological threats, whether they are naturally occurring (e.g., infectious outbreak), accidental, or deliberate threats.

These preparedness efforts were already tested. In July 2022 during the COVID-19 pandemic, the World Health Organization (WHO) declared monkeypox (mpox) a public health emergency of international concern [106]. In the United States, the number of cases declined after the peak in late July 2022 [107] due to public education and increased availability of vaccines.

In December 2022, the White House published a Fact Sheet to prioritize improved indoor air quality (IAQ) as an effective tool for reducing the spread of airborne diseases [108]. Strategies to do so included enhancing filtration, funding research related to disease transmission and effective interventions, providing guidance and funding for institutions to improve their IAQ, and incentivizing IAQ improvements in new residential buildings.

The flow of electronic health data creates risks, including the potential for healthcare providers to become high-value targets in cyber-attacks, leading to corresponding increases in cybersecurity costs. In 2017, a global cyber-attack crippled the National Health System (NHS) in the United Kingdom, holding computer systems hostage for bitcoin ransom [109]. Along with preventing health professionals from accessing information, vulnerable instruments can also be hacked for patient data. Therefore, all Internet of Things (IoT)-enabled instruments must be secured properly. *Implementing the Health Insurance Portability and Accountability Act (HIPAA) Security Rule: A Cybersecurity Resource Guide* is designed to help the industry maintain the confidentiality, integrity, and availability of electronic protected health information [110].

Implications for NIST

NIST is currently working to address inconsistent standards for genomic tests. Current genomic diagnostic tests are evaluated for their "clinical utility," a metric that is neither clear nor predictable. Objective and reliable standards for the evaluation processes are needed for results of genomic tests to be trusted. To support the future endeavors in the use of –omics in healthcare, NIST also develops and maintains Standard Reference Materials and Standard Reference Data for quality assurance in metabolomics, proteomics, and microbiome measurements. Future advances in molecular profiling technology and analysis, combined with genetic clinical information, promise unprecedented advances in precision medicine. However, the challenges in application of –omics to healthcare stretch beyond the precision measurements, as sampling, processing, and data handling can influence the results when dealing with extensive biological data sets, particularly those strongly affected by sample treatment such as metabolomics. NIST is currently working not only to improve the measurements for -omics, but also to create the pre- and post- analytical tools and workflows necessary to ensure comparable quality data for healthcare and other applications. Data privacy policies and the cybersecurity of medical technologies are also areas in which NIST can provide added value.

As the world transitions to precision medicine, NIST can contribute to sensor development required for research in devices that track individual health and monitor target molecules. NIST's manufacturing and research expertise is well-positioned to develop automation methods for high-throughput screening, as well as new methods for manufacturing the scale-up of gene therapies.

NIST has leading experts in the field of high-performance buildings and community resilience who can support efforts at the White House and other agencies to design and operate buildings of the future to withstand biological threats, natural disasters, and other hazards. The challenge is to conduct research and then provide guidance to diverse communities with individual needs and socioeconomic drivers. The use of advanced modeling tools and the collaboration with utility companies, local and regional authorities, and individual community members will be key in making sure that solutions generated at NIST have the largest impact.

4.4. Advanced Communications

Fifth generation (5G) cellular networking technology has already enabled dramatically faster connectivity for smart machines, autonomous driving, and media consumption. Key features of 5G include high throughput, low latency, high mobility, and high connection density. Since 2020, the United States has achieved parity with South Korea and exceeds the PRC, Europe, and Japan with respect to this coverage metric. However, the United States lags the PRC and South Korea with respect to average mobile downlink speeds [111].

As the 5G rollout continues, the world is already preparing for the advent of 6G cellular systems. They will offer speed increases of two orders of magnitude compared to 5G. They will enable new immersive virtual applications that may radically transform how people work and live [112]. In the meantime, the widespread use of 5G technologies is expected to produce $3.5 trillion in output and 22 million jobs globally by 2035 [113].

Developments in 5G networking include the rapid creation of software-defined services, support for a greatly expanded IoT, the proliferation of cashier-less stores, the use of AI to enhance communications, and the use of cellular radios for police and other emergency services [114]. 5G can enable edge computing[6] because it supports enhanced connectivity and enhances computing power, and allows for better performance of devices at lower energies [115]. However, technical impediments remain. Use cases for 5G will bring new requirements for storage, computation, and network domains, and will introduce new risks to the confidentiality, integrity, and availability of enterprise and user data.

Even though 5G systems represent a significant improvement in performance over their 4G predecessors, it is not clear that they are going to be adequate for handling the kinds of application traffic that would result from the massively connected networks of the near future, using Ultra Reliable Low Latency Communications (URLLC) [116]. Previous evolutions of wireless networks involved transitioning away from a world where most carried traffic was encoded voice with a small amount of data. The next revolution will be one that takes the world from networks full of data traffic between people to networks full of data traffic between machines, with traffic originating from or ending at a personal device comprising a small fraction of the total network load. Predictions for the types of data traffic that will comprise this load include virtual/augmented/extended reality (VR/AR/XR) applications, autonomous systems (including autonomous vehicles but also encompassing industrial systems and controls), and computationally intensive applications such as blockchain and machine learning (ML) systems.

Because URLLC traffic has very stringent requirements for low delay and low packet loss rates, 6G networks will need to provision resources to meet these requirements. Equipment manufacturers and telecommunications service providers are turning to artificial intelligence (AI) and ML to give the next generation of wireless networks the agility that they will need to support large volumes of URLLC traffic. While there have been numerous innovations in the United States and the EU with respect to AI for wireless networks, Chinese researchers are also examining how deep learning can be used to better manage wireless communications networks, and appear to be strongly interested in the areas of cognitive radio, edge computing, channel

[6] Edge computing is an emerging technology that aims to allow cloud processing of large amounts of data at or near where the data is being generated, allowing faster processing the more efficient day-to-day operations https://www.accenture.com/bg-en/insights/cloud/edge-computing-index#:~:text=Edge%20computing%20is%20an%20emerging,led%20results%20in%20real%20time.

measurement, end-to-end encoder/decoder and visible light communication [117]. Interestingly, another Chinese survey paper examining areas of future research notes that a challenge is the lack of standardized, accurate wireless network-related training data compared with other types of training sets, such as images or text, which are sufficiently abundant to enable the kinds of powerful classification and prediction algorithms that are becoming widespread [118]. Also, AI applications are power-intensive, and there is a need to increase their energy efficiency; some proposed solutions in this area include using distributed AI/ML controllers [119]. Distributed AI/ML can be implemented in multiple ways, such as transfer learning, where a centrally trained model is sent to local controllers and updated as necessary. A variation on this approach is federated learning, where the local nodes send the parameter sets for their updated models back to the central node, combining the parameter sets to produce an updated global model.

Implications for NIST

For the design, evaluation, and deployment of future wireless communications networks, it is essential to have channel models that are well-supported by diverse measurements across different frequency bands, deployment scenarios, and geographical areas. This need presents opportunities for NIST to make significant contributions to international standards in this area. The NextG Channel Model Alliance (CMA), which is led by NIST, provides a venue to promote fundamental research into measurement, analysis, identification of physical parameters, and statistical representations of millimeter-wave propagation channels. In establishing the alliance, NIST brought together more than 130 participants to solve the most pressing modeling and measurement challenges facing the deployment of wireless communications systems. The output of the alliance will be incorporated into new standards, specifications, and best practices benefitting the entire industry. As a national leader in cybersecurity, NIST will be asked to take a lead role in helping to secure this massive IoT ecosystem. In addition, how to use AI in combination with next-generation channel models will be critical to optimizing wireless network performance. Future systems will use more elaborate and sophisticated approaches that include the ability to predict changes in the channel, which would improve the communications system's ability to rapidly adapt to variations in the channel environment.

As an example, of some of the opportunities that NIST is pursuing, the agency is working with the Alliance for Telecommunications Industry Solutions (ATIS) through the NextG CMA to develop measurement data, channel models, and simulation tools for Joint Communications and Sensing (JCAS) applications in the (7 to 15) GHz, 28 GHz, and 140 GHz frequency bands, as contributions to the Release 19 cellular telephony standard, which will define 6G cellular communications systems. This work is part of the agency's efforts to increase U.S. participation in, and contributions to, international standards development.

There are also multiple measurement challenges related to 5G and beyond wireless technologies. These challenges span a broad set of technical areas, including device-to-device communications, channel modeling and sounding, channel resource allocation, antenna field pattern measurements, advanced wireless communications for IoT networks, AI for wireless network control, and research into how to build reliable and secure supply chains for next-generation wireless systems. Because these networks will rely on high-density deployments of devices, one challenge area is interference of wireless signals. 5G and 6G systems will utilize higher-frequency spectrum bands, which have different (and less studied) propagation properties than lower-frequency bands on which current networks operate. New antenna systems will need to be built and calibrated to accommodate 5G networks, and there is still work to be done in using telemetry and measurements for autonomous control of communications systems [115].

NIST has been actively involved with standards development organizations, particularly 3GPP, which is currently in the study phase of Release 19 of the cellular standard, with Release 18 expected in early 2024 with the final protocol coding freeze. NIST is also a member of the O-RAN Alliance, which is a nonprofit organization whose members include mobile network operators, mobile equipment vendors, and academic and government institutions. The O-RAN Alliance's goal is to make RAN technologies more open, more capable of supporting next-generation intelligent control systems that use AI to make RANs more flexible and autonomous, more virtualized, and more supportive of interoperability between many different vendors' products.

4.5. Artificial Intelligence

The most recent surge in interest in AI has produced systems that are sufficiently robust that they are being employed to solve a wide range of problems across a broad swath of economic sectors. Much of the current acceptance of AI systems is due to the continuous improvement in computing power and memory storage, which has allowed the hardware's capabilities to finally "catch up" with the algorithms running on such hardware. This surge in AI interest has fueled an explosion in the varieties of neural network architectures and algorithms. Convolutional neural networks (CNNs) are being used for tasks such as classifying images, but they can be used to process other data sets that can be represented as groups of arrays of values. Reinforcement learning can be used to train control systems by representing the operational scenario as a game where each of the possible actions by the controller has a cost or reward associated with it, which the algorithm uses to train the controller to "play" the game to obtain the highest possible reward.

On November 30, 2022, OpenAI launched an AI tool known as Chat Generative Pre-trained Transformer (ChatGPT). ChatGPT is an example of generative AI, which are algorithms trained on vast amounts of written text to predict "next letter" or "next word" given a new text string. Additionally, ChatGPT uses reinforcement learning to improve by interacting with human users. Initial news reports on the tool included samples of generated text that appeared indistinguishable from text produced by humans. This drove interest in the tool, with more than 100 million users interacting with ChatGPT by January 2023 [120]. Multiple stories about the algorithm's ability to produce text output that reads like it was generated by a human have led to suggestions that students will no longer write anything themselves but simply generate essays with AI [121, 122], and that there was a coming wave of AI-generated prose [123, 124]. The field of writing is on the cusp of a period of seismic change as powerful content-generation tools replace human writers on mundane writing tasks such as producing content for news outlets, writing manuals or other technical documents, or even writing code. However, there are worries about the negative effects of algorithms that can produce long-form text that is difficult to distinguish from the output of a human author.

AI image generators can generate authentic-looking photographs and award-winning art [125]. This raises concerns that image generators may perpetuate the spread of misinformation and erode public trust in the media [126].

Bias in AI systems is a major concern that can have negative impacts and outcomes [127]. A recent *Science* article highlighted racial bias in a widely used medical algorithm that determined which patients needed more care [128]. Bias in AI systems is often thought of as the statistical or computational bias, in which predictions made by the AI system are flawed because of characteristics of the datasets and algorithmic processes used to train AI systems that do not represent the true population of interest [129]. However, AI systems are also prone to errors due to human bias and systemic bias [129]. Human bias refers to the cognitive or perceptual biases in human decision-making. Because humans at the individual, group, and institutional level are involved in the AI lifecycle and use AI applications, AI systems can have these human biases. Systemic bias results from societal patterns in practices and procedures that favor certain social groups over others, such as institutional racism and sexism. Systematic biases may be present in the training datasets underlying an AI system or be introduced during the AI lifecycle.

A second major AI-related problem relates to digital privacy and the ability of content creators to control how their work is used [130]. Generative AI programs produce their output by training on, for example, images on the internet, which are the kind of vast data corpus that make such powerful AI systems possible. Content creators and the entire creative industry are most immediately affected because the scraping of online image databases has allowed AI programs to render new images based on user prompts. Others affected include voice actors and audiobook narrators because of the relative simplicity of synthesizing realistic voices. The impact extends to AI-generated music that is trained on a vast set of recorded audio in many genres, such as OpenAI's Jukebox AI [131]. While the Jukebox AI program has limitations (the creators note that the music is locally coherent but longer-duration themes are absent), it is likely that they will be resolved in the coming years. At present, artists are actively opting out of having their work used in training, but on the Internet, where original works are repeatedly copied and can end up in multiple places, fully opting out may be difficult, unless there are changes to how intellectual property online is handled.

The current concerns surrounding AI are serious and need to be addressed. A delay in addressing issues of AI bias, impact on privacy, or impact on intellectual property could lead to negative societal effects that are more challenging to mitigate than to prevent.

Implications for NIST

NIST has already positioned itself as a leader in the AI space: NIST is engaged in many national and international efforts, groups, and fora seeking to develop trustworthy and responsible AI. NIST is the Federal AI Standards Coordinator and is vice-chair of the OECD working party on AI Governance. NIST is also a leader in AI R&D and is actively engaged in fundamental research on the design, development, and use of AI [132]. Due to NIST's expertise and leadership in AI, in Executive Order 13859 *Maintaining American Leadership in AI*, NIST was tasked to assist with the development of the technical standards and related tools needed for trustworthy and responsible AI. Through a transparent and robust stakeholder engagement process, in January 2023, NIST released the AI Risk Management Framework (RMF) as a resource for organizations to understand and manage the complex risks of AI systems [133].

The framework is intended to empower individuals and organizations to harness the great benefits of AI systems, but to also make them trustworthy and responsible in their impact on society. The AI RMF specifically outlines several characteristics of trustworthy AI systems: valid and reliable; safe, secure and resilient; accountable and transparent; explainable and interpretable; privacy enhancing; and fair with biases managed. Organizations can use the framework as a tool to think critically about the context and impacts of AI system use. NIST is also in the process of developing crosswalks with other international AI documents, including the EU AI Act [134]. NIST will continue to seek partnerships for applying the AI RMF, as well as continuing to produce guidance and case studies for applying the AI RMF.

NIST has many opportunities to build upon the momentum of the AI RMF. NIST's continued role as a leader in AI R&D will be critical as AI systems continue to expand and overlap with other technologies, including genomics, image and video processing, robotics, and wireless spectrum monitoring. As these technologies are developed and deployed so rapidly, there is great need for testing, evaluating, verifying, and validating AI technologies. NIST is poised to provide the base AI metrology that industry needs for developing and deploying trustworthy and responsible AI. NIST is also looking to the future, and has prioritized developing guidance for balancing trade-offs in AI system trustworthiness characteristics, human factors, and human-AI teaming [135]. NIST continues to conduct research on harnessing the AI in hardware to accelerate computing speeds and efficiencies [136].

Although the future of AI technologies poses many exciting opportunities and questions, there are two challenges NIST will face. First, AI technologies are evolving very quickly, and NIST will need to balance conducting its rigorous research and development processes with keeping pace with the demands of industry and the world in understanding the risks and impacts of AI. Second, NIST will need to expand its current expertise to fully combat the challenges of AI. Although AI and ML problems have typically been approached by computer scientists, the risk and impacts of AI go beyond the technical scope of computers; thus, NIST will need sociotechnical expertise in the social sciences and humanities as well as in the physical sciences.

4.6. Quantum Information Science & Technology

Quantum technologies (computing, sensing, and networking) represent emerging markets with enormous potential. Quantum sensors, for example, have already shown utility in medical imaging and navigation, but estimates of the global market for quantum technologies vary by hundreds of millions of dollars [137]. The quantum sensor market is projected to grow, with one estimate placing the value at $585 million by 2027 [138]. The quantum computing market is also projected to grow from an estimated $614 million in 2022 to a projected annual growth rate of 25.3 % by 2025 [137].

Beyond economic opportunities, quantum computers pose a direct concern for U.S. economic and national security because of Shor's algorithm [139]. Shor's algorithm, when run on a quantum computer of sufficient scale and sophistication, is expected to be capable of breaking existing encryption methods. This poses a substantial threat to cybersecurity and necessitates the timely standardization and deployment of quantum-resistant cryptographic algorithms.

In December 2018, the U.S. Congress passed the National Quantum Initiative (NQI) Act to advance U.S. leadership in quantum information science and technology (QIST) for the economic and national security of the United States [140]. The NQI Act called for a national approach to QIST R&D by authorizing a range of quantum activities at several agencies, establishing interagency subcommittees to develop and coordinate the national efforts, and creating the National Quantum Coordination Office (NQCO) in the Office of Science and Technology Policy (OSTP) at the White House to provide overall support and leadership. Subsequently, Congress expanded the roles and activities of the DoD and the Intelligence Community through the National Defense Authorization Acts (NDAA) of Fiscal Year (FY) 2019 to FY2022 [141, 142] and civilian agencies through the CHIPS and Science Act of 2022 [82].

The 2018 National Strategic Overview for QIS has guided U.S. quantum policy. The strategic overview emphasized: (1) a science-first approach, (2) building the workforce, (3) engaging industry, (4) building right-sized infrastructure, (5) maintaining economic and national security, and (6) international collaboration and cooperation. Quantum.gov, maintained by the NQCO, hosts reports and strategies that augment the strategic overview and support coordination across the federal quantum enterprise.

On May 4, 2022, President Biden signed a National Security Memorandum on *Promoting United States Leadership in Quantum Computing While Mitigating Risks to Vulnerable Cryptographic Systems (NSM-10)* [143] and Executive Order 13885 *Enhancing the National Quantum Initiative Advisory Committee* [144]. Together, these orders reaffirmed that the NQI is a whole-of-government effort, and the United States must continue to promote and accelerate R&D in quantum while ensuring a timely transition to post-quantum cryptography (PQC) to mitigate the risk posed to modern information technology infrastructure.

The United States is not alone in targeting quantum science as a priority. Over a dozen countries have developed national strategies, and even more have launched programs focused on QIST [145]. Over the last three years, the United States has signed quantum cooperation agreements with several countries, and in May of 2022, the White House and State Department held a multilateral dialog with a dozen countries that focused on quantum cooperation. A driving factor in these discussions is a recognition that the supply chains needed for developing quantum technologies are global, with many of the most critical components being manufactured by a small number of vendors located in just a handful of countries.

As fields leveraging QIST mature into engineering disciplines, a broad range of opportunities and challenges are being created. Many of the underlying technologies still need fundamental science research and measurement to support their advancement. Standards that can support the commercialization of quantum products and services, engineering and production of components, hardware and software, training a quantum workforce, and maturing the quantum supply chain are all growing in importance to the quantum landscape [146].

Implications for NIST

The first five years of the NQI have focused on advancing basic science, enabling people, and ensuring the United States is competitive. NIST, which has a long history of leading quantum research, has been involved in each of these facets: continuing world-leading R&D in quantum, training students in NIST labs and through NIST joint institutes, standing up a quantum industry consortium (e.g., QED-C), and supporting the whole-of-government initiative by detailing a staff member to the NQCO.

Moving forward, NIST has both the challenge of maintaining its world-class research, innovation, and technical leadership in QIST while taking advantage of the opportunity to grow that work. This includes: a broad range of qubit platforms, benchmarking, transduction between electrical, nano-mechanical and optical regimes, scalability of quantum systems, single-photon metrology and integrated photonics, quantum simulation and many-body physics, PQC, and quantum-enhanced precision measurement based on non-classical states. NIST has new opportunities for engagement with the National Science Foundation (NSF), U.S. Department of Energy (DOE), and the DoD along with the ability to expand its engagement with joint institutes and external stakeholders such as JILA (formerly the Joint Institute for Laboratory Astrophysics), Joint Quantum Institute (JQI), Joint Center for Quantum Information and Computer Science (QuICS), and the QED-C. Global NMIs have also expressed interest in increased ties and collaboration with NIST in the QIST arena.

A growing focus will be on understanding the big applications of quantum that will benefit society, especially those that will provide economic gains and provide the needed technologies to support our national security. There is a need to accelerate the translation from the lab to final product and to ensure that we are preparing students to have the right skills to carry out critical efforts in QIST. NIST's continued work with the QED-C will provide early insight into potential applications that support industry, along with areas for improvement in supporting technologies like cryogenics, control and readout electronics, and environmental and vacuum components.

Quantum workforce shortages create specific challenges to NIST. To date, NIST has provided a critical talent development pipeline for industry and government efforts. NIST will need to grow its activities to support the expanding needs of the quantum industry and increase recruiting efforts. Given its research portfolio, NIST has an opportunity to help define the field of quantum engineering and begin developing the relevant workforce. NIST can expect to expand its leadership in international quantum standards, with continued prominence in PQC standardization and a continuing and growing role in coordinating and contributing to standards development in quantum networks, algorithms, and the emerging industry of suppliers of quantum-specific products.

The MEP and Manufacturing USA's American Institute for Manufacturing Integrated Photonics (AIM Photonics) can expect more interaction with quantum manufacturers and U.S. manufacturers as quantum companies seek to mitigate causes of delays at key chokepoints, such as access to new raw materials and manufacturing/assembly equipment [146].

4.7. Cybersecurity and Privacy

In the past ten years, there have been several high-profile online security breaches leading to exposure of billions of data records from large, well-known companies and the U.S. Office of Personnel Management [147, 148]. New risks have emerged as a consequence of technology development, and as the personal and professional lives of Americans become increasingly connected to the internet [149].

Increased use of technology and connectivity across sectors has also made cybersecurity important and relevant in fields where it was not a concern before, such as in the automotive industry. Many vehicles now use significant software and information technology (IT) hardware for their operation and can be connected to the internet for both safety-critical and non-safety features, which may leave these systems vulnerable to attacks [150]. Utilities and critical infrastructure are additional areas where connected technology has brought many benefits but also has created new opportunities for attackers to target these important systems [149]. In 2019, the U.S. electric grid was the target of an attack, underscoring the need to protect critical infrastructure and utilities [151]. Ensuring critical infrastructure is well-protected is vital, especially as upcoming initiatives such as Smart Grid [152] continue to connect important parts of the Nation's infrastructure. Satellite-based global positioning systems (GPS) that are used to meet positioning, navigation, and timing (PNT) needs represent potential attack targets, especially since GPS supports crucial infrastructure sectors including finance, energy, agriculture, and telecommunications. Securing PNT is also essential when considering the future needs for space satellites. As private companies continue to invest in the space ecosystem, there is a need to secure satellites from a number of threats [153].

Just as the internet and connectivity have brought both benefits and risks to society, the technology of the future, such as AI systems and quantum computing, may be exploited. While some believe AI systems can be used to assist with cybersecurity training and policy development [154], others see AI systems as tools attackers will use. There is concern that generative AI like ChatGPT can be used to develop ransomware and phishing attempts [155]. Quantum computing may also bring great societal benefits, but it poses great risks to individuals and organizations. If quantum computers can be used to break existing algorithms, individuals and organizations may become victims of data breaches, and communication disruptions, and lose data integrity and privacy [156]. Although quantum computing is still largely theoretical, there is a need to begin investigating how to protect systems of the future. The World Economic Forum estimates that 20 billion digital devices will need to be replaced or updated in the next 20 years to be protected from the threat of algorithm-breaking quantum computers [156]. There is great interest in developing new tools to thwart attacks from quantum computers, but also a need for solutions now to protect the vast amount of data gathered and stored by individuals and organizations.

Technology development has also spurred the need to consider privacy in tandem with cybersecurity. Privacy is becoming a complex and all-encompassing concept impacting core values of human autonomy and dignity, with consequences for both individuals and organizations [157]. Despite the concerns and attention of many, achieving privacy with technology can be difficult to accomplish. With more information being stored online, there is a great need for individuals and organizations to decide when, where, and how information should be shared and protected. The rapid shifts in technology require tracking of new threats, understanding of short- and long-term solutions, and deploying resources and staff to support security measures. Certain groups may encounter obstacles to ensuring they are protected and thus may disproportionately fall victim to threats. For example, there is increasing pressure for small businesses to prioritize cybersecurity and use the latest solutions for protecting themselves from outside attackers. However, small companies may have neither the staff with the depth of knowledge to implement current solutions, nor the financial resources to obtain the best hardware and software to protect themselves. Certain user populations may also face inequities in accessing and using technology in safe and secure ways. In the realm of digital identity, image capture technology can present challenges with identity verification for users with certain skin tones or facial features [158].

With increased public concern in these topics coupled with the potential dangers of ignoring them, a final challenge in this space is determining the place of government oversight in cybersecurity and privacy issues. Recent legislation proposes to take a stronger approach to cybersecurity and privacy. In 2018, the California Consumer Privacy Act was passed to protect consumer's rights regarding what information is collected and stored by businesses [159]. Most recently, in 2023, the Biden Administration released its National Cybersecurity Strategy [149] which may catalyze new regulations and requirements in the future for cybersecurity.

Implications for NIST

NIST has the opportunity to leverage its research, standards, guidance, and practical applications to drive cybersecurity and privacy both in the United States and globally. NIST is a trusted leader in cybersecurity and privacy, producing the Cybersecurity Framework (CSF), Privacy Framework, cryptographic standards, and numerous other resources [160-162]. NIST is meeting the need for quantum-resistant cryptography by developing a post-quantum encryption standard that will be finalized in the coming years [163]. Ultimately, this standard will be used to protect infrastructure, the government, and industry from threats. NIST will also have the opportunity to provide guidance for managing risk as well as implementing post-quantum encryption. NIST is also in the process of updating its guidance to keep pace with the changing digital landscape. NIST is updating the CSF [164] to address new threats and include lessons learned and new best practices. The new "CSF 2.0," along with the NIST Privacy Framework, will continue to help organizations manage risks in new technological areas. NIST also had the opportunity to apply its research, frameworks and expertise to managing cybersecurity and privacy risks in the real world. NIST is working in areas such as PNT capabilities [165], IoT devices [166], 5G [167], genomic data [168], and automated vehicles [169], and can expand this work to other topics and technologies. Additionally, NIST is conducting work AI systems' impact on cybersecurity and privacy may be impacted. NIST recently opened a public comment period for developing "a taxonomy and terminology of attacks and mitigations" for adversarial machine learning (AML) [170].

NIST has the opportunity to leverage its expertise and frameworks, guides, research, and partnerships with industry to work with the federal government to implement the National Cybersecurity Strategy [149]. The strategy emphasizes the urgent need to secure supply chains and names several NIST frameworks, such as NIST's CSF [160] and Secure Software Development Framework [171], as critical for the work to defend critical infrastructure and invest in a resilient future. NIST's digital identity research program will be another key area to implement as part of the strategy. NIST is currently revising the digital identity guidelines to address the new landscape of digital identity, and, for the first time, providing equity considerations [172]. NIST's NICE will also be leveraged to meet the strategy's goal of developing the cybersecurity workforce [173]. NIST will continue its efforts to promote rigorous training in cybersecurity education as well as provide resources specifically for small businesses to obtain the experts and understanding they need.

4.8. Bioeconomy

With the White House release of Executive Order 14081 *Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure American Bioeconomy*, there is a renewed interest in the potential for innovation through this cutting-edge field. For the bioeconomy to grow both domestically and globally, innovations in biotechnology discovery, production, and manufacturing capacity need to accelerate. Once achieved, biotechnology and biomanufacturing will be used to advance the development of medicines and therapeutics, to achieve U.S. climate and energy goals, to improve food security and sustainability, to secure our supply chains, and to grow the overall American economy.

Through biology, products that modern chemistry have been unable to replicate can be synthesized or grown. For example, spider silk strength is superior to Kevlar or steel, but chemistry has been unable to replicate these proteins that can contain over 20,000 amino acids. Interestingly, biology has generated multiple sources of lightweight strong materials, and using biotechnology to harness these products is now within reach if biomanufacturing innovations can be realized at sufficient scale and cost competitiveness compared with traditional production routes. Manufactured spider silk is one product that could be available to consumers in the near future, but companies have already started generating new materials just as strong and lightweight from other biological sources, such as the proteins found in squid teeth [174] or wood from trees that is as strong as steel [175].

Advances that accelerate growth of the bioeconomy could provide more sustainable products compared with other feedstocks, with the added benefit of positively advancing goals of the circular economy as well. Pulling reusable commodities out of waste streams and degrading pollutants into elemental components are already being demonstrated at limited scale. Microbes are being designed to clean chlorinated or even radioactive hazardous wastes, fungi are being cultivated to dissolve plastics, and bone waste has been repurposed to reclaim critical mineral-like cobalt [176-179]. Additionally, waste streams can be used as feedstocks or the energy sources to fuel reactors, like using human waste to generate fertilizer [180-182]. To support more sustainable practices, microbes can produce products that have controversial production processes. For example, a cosmetics company has released the first products that otherwise contain synthetic palm oil produced by yeast cells [183]. These technologies for a sustainable bioeconomy already exist, but developing the manufacturing capabilities to sustain these technologies at the scale needed to efficiently and cost effectively produce commodities at the level of commercial demand still needs development.

However, what commercial scale looks like could be very different for commodities produced within the growing bioeconomy. Small-scale bioreactors can be set up with little infrastructure and could even be mobilized to regions with high demand or an abundance of feedstocks. Many microbes can be engineered to produce different products, meaning that the equipment needed for one commodity could quickly be switched to produce a different commodity should demand change or supply chains be strained. To create this agile biomanufacturing reality, more standardized platform technologies for flexible production are required. The potential for every home to have a bioreactor to use microbes to recycle or create on-demand commodities could be a future reality.

Implications for NIST

NIST recognizes that biotechnology and biomanufacturing are critical emerging technologies and is already working to support the needs of the American economy to position the nation as a world leader in this burgeoning field. The White House stated in *Bold Goals for U.S. Biotechnology and Biomanufacturing: Harnessing Research and Development to Further Societal Goals* how biotechnology and biomanufacturing R&D can stimulate the advancement of the bioeconomy, which cited a report authored by NIST for the DOC to highlight key developments where NIST can positively impact U.S. industry [184].

Just as standards foster competition in multiple sectors by allowing manufacturers, including startups, to demonstrate the performance of their products using agreed-upon metrics, the growth of the U.S. bioeconomy needs a comprehensive standards approach to realize what is believed to be achievable through biotechnology and biomanufacturing. NIST can act as a neutral party through its relevant consortia (such as Genome in a Bottle, Genome Editing, Flow Cytometry, and Rapid Microbial Test Methods), providing technical guidance and leadership in standards development while helping industry safely engineer new microbes, design new reactors, and understand how to accurately measure synthesized DNA and engineered cells. NIST is already contributing through developing standards and technologies such as: a baseline for commonly discussing and measuring bioeconomy terms through the NIST Bioeconomy Lexicon [185]; documentary standards through leadership in the International Organization for Standardization Technical Committee (ISO TC) 276 on Biotechnology; well-characterized physical standards such as the new NISTCHO cell line for benchmarking current pharmaceutical production technologies such as those for monoclonal antibodies (mAbs); and fundamental engineering biology research outputs such as identification of the minimum number of genes needed to reproducibly produce a standard cell line with specific attributes.

The potential impact of the bioeconomy across so many sectors is both an opportunity and a challenge for NIST. While NIST, and the DOC more broadly, is not sector-specific as other federal departments and agencies are, it can be a theoretical mismatch of NIST's limited resources to be responsive within the unique NIST mission to the pharmaceutical, agricultural, industrial chemical, and energy sectors while aligning with circular economy sustainability goals. Even the pharmaceutical industry alone has multiple segments such as large-molecule biologic drugs like mAbs, small-molecule therapeutics, generic drugs and biosimilars, and emerging CGTs. Likewise, the industrial chemical enterprise has different biotechnology and biomanufacturing quality and scale goals depending on the predicted demand of the biomanufactured product. For example, 100,000 L and larger bioreactors may be required to satisfy the demand for butanol, while a specific, custom-scent molecule for the cosmetic industry might be needed in a significantly smaller scale. However, there are opportunities for NIST to provide measurement science and standards for platform technologies that are consistent regardless of the end product within the bioeconomy. For many biomanufactured products using precision fermentation technology, NIST can bring industry together to develop pre-competitive voluntary consensus standards for upstream biotechnology and data needs that can help harmonize the bioeconomy innovators. Similarly, for enzymatic-based and other emerging cell-free technologies, providing measurements and standards for key attributes of biomanufactured product quality can result in broad NIST impact.

Even if NIST can find the right balance of investments with limited resources vs. the high demand for NIST's mission in accelerating the bioeconomy, the organization faces the same competitive workforce challenges of other critical and emerging technology areas. This includes a need to continue to implement strategic recruitment and retention strategies to maximize the potential to deliver impact in biotechnology and biomanufacturing.

4.9. Climate Change and Sustainable Innovations

Energy is recognized as a basic human need. The UN Sustainable Development Goal 7 is to "ensure access to affordable, reliable, sustainable, and modern energy for all" by 2030 [186]. Access to energy has also been used as a social and economic indicator [187]. Energy powers the systems that provide food and potable water. It supports economic development, with clean energy being crucial for improved IAQ, especially in homes. Those who do not have access to modern, "clean" energy, typically use firewood or other solid fuel sources. WHO reported that the burning of these solid fuels indoors is the largest single environmental health risk, and it affects the poorest people in the world the most [188]. Lack of access to reliable energy also has negative impacts on the environment (e.g., deforestation) and the global economy (e.g., reduced work hours and access to education because there is no indoor lighting) [189]. It is no surprise that the wealthiest nations, with reliable access to energy, produce the most greenhouse gas.

There is consensus that modernization of the grid (i.e., integrating renewable energy into existing infrastructure and incorporating distributed energy resources) will support decarbonization (i.e., reducing or eliminating carbon emissions) and slow down climate change, but only if there are enough clean energy sources like solar and wind [190] to supplement or replace fossil fuels. Decarbonization of buildings can play a major role since the building sector accounts for about 40 % of the global energy-related carbon emissions [191]. This includes increasing building energy efficiency, transitioning to low global warming potential (GWP) refrigerants, increasing the use of renewable energy, and reducing embodied carbon in building materials. In the transportation sector, decarbonization is mostly likely to occur in the near term with electric vehicles (EVs), and the popularity of EVs continues to increase with EVs making up 7.5 % of all new car purchases in the United States in 2022 [192]. The tax breaks of up to $7,500 for qualifying purchases of EVs in the Inflation Reduction Act of 2022 [193] have encouraged more drivers to choose EVs over internal combustion vehicles.

Solutions for increasing the availability of "clean" energy sources need to be developed in parallel with solutions for decreasing global energy consumption. In 2022, energy use in buildings accounted for 39 % of the total energy used in the United States [194], which was more than the industrial (33 %) and transportation (28 %) sectors. Globally, buildings account for 30 % of the total energy use [195]. One of the five Grand Challenges identified by the National Academy of Engineering in their 2018 report on Environmental Challenges for the 21st Century was to "Create Efficient, Healthy, Resilient Cities." Improvements in efficiency can be gained through "smart" technologies that leverage sensing technology, data, connectivity, AI, and participatory governance [196]. However, rising global temperatures inevitably cause greater use of heating, ventilating, and air-conditioning (HVAC) systems which increases the energy use in buildings, thus causing a self-reinforcing loop – greater use of AC causes global temperature rise, which causes greater use of AC [197].

The Bipartisan Infrastructure Investment and Jobs Act of 2021 included two programs to advance carbon capture technologies with the goal of decreasing carbon dioxide (CO_2) emissions from electricity generation and achieving net-zero emissions in the United States by 2050 [198]. It is funding commercial-scale carbon capture technologies and providing tax incentives for companies to reduce carbon emissions.

Resilient communities not only need reliable energy but also safe shelter. The wildland-urban interface (WUI) is defined as the location where structures and communities meet or intermingle with undeveloped wildland [199]. In 2022, the National Interagency Fire Center reported almost twice the number of wildfires (11,663) than in 2021 (5,398) [200]. There have already been 5,431 wildfires from January 2023 to March 2023. Places like California, which have been devasted by recent wildfires, suffer from major droughts. Even when rain comes, it means more fuel load for the impending wildfire season [201]. Homeowners are advised to replace their roofs with non-combustible or fire-resistant materials, keep embers out of their homes by covering exterior air vents, reduce or remove flammable vegetation close to their homes, and install sprinkler systems [202]. The CDC has guidance on how people can protect themselves from wildfire smoke that includes staying indoors and using portable air cleaners [203]. Residents impacted by wildfire smoke have been using consumer-grade sensors measuring particulate matter smaller than 2.5 µm (PM2.5) to monitor their IAQ since a large component of wildfire smoke particles is in this size range. Consumer-grade sensors have performed acceptably tracking the relative changes in PM2.5 but are, unsurprisingly, not very accurate [204]. Consumers should be aware of the limitations of such sensors that are marketed for home use.

In 2022, tropical cyclones (or hurricanes) and severe convective storms (or thunderstorms) contributed to over $133 million in losses in the United States [205]. High winds from these events are major drivers for damage to the built environment. In 2021, the American Society for Civil Engineers (ASCE) published ASCE/SEI 7-22 *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* [206], which included first-of-their-kind tornado hazard maps developed with the help of NIST scientists. These, and other design standards, are evolving over time to meet the ever-increasing risks to communities.
The cost of not finding solutions to sustainability could result in millions more people displaced from their homes and places of work [207]. Communities ravaged by disasters also need time to recover with an acknowledgement that some communities will recover more slowly than others and other communities may never recover. These delays will negatively impact U.S. gross domestic product (GDP) and national security [208].

Implications for NIST

There is a clear role for NIST in developing innovative energy solutions. Access to accurate, internationally recognized measurements and standards is required for the implementation of sustainable solutions and climate change-related policies around the globe. NIST's roles in carbon capture and sequestration, greenhouse gas measurements, building decarbonization, sensors, advanced materials, engineering, and community resilience are all critical to the success of sustainable innovations [209].

Decarbonization will rely on access to clean energy and a smart grid, which is often driven by the availability of distributed energy resources. To best integrate with these new sources of electricity, building controls and localized energy storage need to be expanded to use electricity when its carbon impact is the least [210]. Additionally, multiple approaches can be a part of slowing the impacts of climate change by reducing greenhouse gas emissions and adopting green technologies.

Challenges to advancing solutions include aging infrastructure that will be costly to modernize. The continental U.S. power grid is also fragmented into three regions (Eastern, Western, and Electric Reliability Council of Texas (ERCOT)), making inter-regional transmission challenging [211], and inhibiting the sharing of resources on a national level. Thus, any solutions improving the resilience of U.S. energy systems may need to be tailored to the needs and constraints by state and utility.

Much of the research in energy and resilience is incorporated into standards and follows the ANSI process to ensure that all standard-making protects the rights and interests of all participants. This process is transparent and ensures consensus but may also mean latency between the availability of solutions, their adoption, and their impact.

NIST can continue to play a critical role in understanding how to reduce the impact of wildfires on the built environment and increase its footprint in the measurement, characterization, and modeling of smoke produced by prescribed fires used to reduce wildfire hazard to communities.

4.10. Big Data

It is estimated that by 2025, the entire digital universe will reach 181 zettabytes (or 10^{21} bytes) [212], which equates to about 20 terabytes (TB) of data for every person on Earth, or double the printed collection of the U.S. Library of Congress per person[7]. Data sharing can have positive impacts on society, such as driving innovation, advancing discoveries, and helping the economy [213] but its use has to be balanced with protecting privacy and minimizing other risks [214].

Section 4.7 on Cybersecurity and Privacy focused on how data can present risks to individuals and organizations. This section will focus on how data is being managed. Data Management Association (DAMA) International, a community of global data management experts, outlines data management into 10 areas [215]:

1. Governance
2. Architecture
3. Analytics
4. Storage and operations
5. Security
6. Integration and interoperability
7. Unstructured data – documents and content
8. References and standard data
9. Metadata
10. Quality

[7] *What is a Terabyte?* from https://www.teradata.com/Glossary/What-is-a-Terabyte#:~:text=A%20relatively%20large%20unit%20of,copies%20of%20the%20Encyclopedia%20Brittanica.

Data mining techniques can be used to uncover important trends in large datasets that are difficult to perceive with traditional data analysis methods; however, how to mine the data to untap these benefits is one of the biggest hurdles – "the biggest problem in the analysis process is having no idea what you are looking for in the data" [216]. This referenced article proposed shifting to a top-down, solutions-driven strategy as opposed to one that is disjointed when those with the data develop a local data management strategy. The use of AI for data management is also gaining momentum [217]. AI can handle more data faster and at a lower cost. Nonetheless, building AI that is responsible, secure, and trustworthy still requires expertise.

In August 2022, OSTP delivered guidance to agencies to make results of taxpayer-supported research free and publicly accessible without delay [218]. The *Department of Commerce Strategic Plan 2022-2026* is also focused on effectively using data for evidence-based decision making, using economic data better to meet the needs of business owners and other stakeholders, and improving how others use Commerce data [219]. The Commerce Data Governance Board (CDGB) supports activities such as the one outlined in the Commerce Strategic Plan [220]. Federal agencies can demonstrate leadership in managing the demands of big data – how to optimize its use, how to secure it, and how to ensure its quality. Such agencies have the advantage of breadth when piloting approaches across agencies with diverse datasets and needs, as well as the advantage of scale when implementing hardware and software to manage big data.

Implications for NIST

In the context of research, advances in laboratory instruments, sensors, and modeling/simulation systems are generating data at unprecedented levels and require new approaches for storing massive quantities of data intelligently and economically. The types of data are also more diverse than ever before – experimental data, text, photographs, images, and others. Beyond intelligent storage, there is also the problem of managing the information that describes the origin, experimental conditions, purpose/context, structure, and many other specific characteristics of the data for it to be useful now and into the future. For NIST to maintain its role in enabling advancement of U.S. industries, NIST's world-class research staff require data management and storage capabilities that meet the requirements, scale, and pace of their work. These are not struggles unique to NIST, so there are opportunities to work with other government agencies and large organizations to develop solutions collaboratively. NIST's Research Data Framework (RDaF), including the new release of RDaF version 1.5, provides stakeholders with a structured approach to develop a customizable strategy for the management of research data [221]. NIST's expertise in cybersecurity is also needed in the data storage space to prevent unauthorized data exploitation and protect user privacy. Finally, as ML and AI are increasingly used to analyze large sets of data, NIST can provide algorithm standards and training to help eliminate bias and identify techniques for the smart use of data.

Open-source software has transformed the programming landscape. Parallel benefits could be realized for open data. NIST supports the FAIR (findable, accessible, interoperable, reusable) data principles, and hosts public databases and a NIST Science Data Portal in fulfillment of the OSTP memo [218]. The secure sharing of quality research data could lead to innovations and new technologies across many sectors. Required guidance will need to be developed so that challenges with interoperability and secure sharing can be overcome. In the age where "data is the new gold," a balance will also have to be struck between data sharing for the common good and proprietary interests.

NIST's Open Access to Research (OAR) project works to develop the data sharing infrastructure, identify tools for intramural and extramural collaboration, and provides training to NIST staff. A Research Computing Advisory Committee (RCAC) was recently stood up to assess the data needs (across the 10 areas listed earlier) of NIST and to recommend solutions.

4.11. Advanced Manufacturing

The industrial and information revolutions have given way to Industry 4.0, the next phase of digital and distributed manufacturing [222]. It will include increased use of data and analytics, connectivity, and advancements in manufacturing automation and robotics [223].

Digital twins can optimize manufacturing by using data and analytics. They do this by combining validated real-time simulation of a system. In addition to real-time response, digital twins can be used for product design, quality management, supply chain management, predictive maintenance, collaboration, and analysis of customer and product performance [224].

Supply chain disruptions in the United States during the COVD-19 pandemic involve underlying issues that still need to be addressed [225]. We can avoid another major disruption by building in supply chain resilience. This can be done by increasing inventory of raw materials and adding manufacturing surge capacity [226].

Traditional manufacturing is "linear" – raw materials are received and made into products at a plant, components are assembled into larger products, and then distributed across the country and around the world. After the products have outlived their use, the products are disposed of. The circular economy is based on product design and manufacturing that enables future repair, recycling, and/or reuse. Parts would be made by "microfactories" on a local scale using additive manufacturing (or 3D printing) and other advanced manufacturing processes [227]. A microfactory can be small-to-medium scale, is typically highly automated, and can accommodate a wide range of capabilities. This type of manufacturing allows for localization of supply-demand markets (e.g., production of raw materials matching demand for products), customization, and reduces greenhouse gas emissions since parts and products do not need to be driven, shipped, or flown long distances. Biomanufacturing (discussed in Section 4.8) has similar advantages to 3D printing, where small-scale bioreactors can be set up with little infrastructure and even mobilized to regional areas of need. Bioreactors also can be quickly adapted to produce a different commodity by growing the same microorganism that has been engineered to produce a different product.

Additive manufacturing (AM) can be performed using plastics, ceramics, metals, biomaterials, concretes, or edible materials. This type of manufacturing can reduce supply chain disruptions, adapt to changes more rapidly than traditional manufacturing methods, save costs, and be more environmentally friendly. It is flexible, allows for rapid prototyping, can print on demand, and can produce strong and lightweight customizable parts. However, AM has several limitations, particularly on the types of materials that can be printed, the size of the final product, and the repeatability of the manufacturing process [228]. Nevertheless, large-scale items such as high-precision aerospace parts, homes [229], and foot bridges have all been 3D-printed. The White House launched AM Forward [230, 231] in May 2022 to encourage the use of AM by small- and medium-sized manufacturers to build more resilient supply chains, grow industries of the future, and encourage more investment in regional manufacturing ecosystems. Companies like GE Aviation, Raytheon, Siemens Energy, Lockheed Martin, and Honeywell pledged to purchase additively manufactured parts from smaller suppliers, train the workforce in AM, and engage in standards development and certification for additive products.

Advanced materials used in manufacturing are being developed that can possess specific qualities, outperforming traditional materials [232]. In addition to the novel materials created using biomanufacturing, there are materials that have better conduction properties, self-healing ones, and ones stronger than steel. Using AI and ML, material development can be done faster, more precisely, and at a lower cost.

Agile and collaborative robotic systems are a disruptive technology essential to achieving a new vision of manufacturing because of their inherent flexibility coupled with tirelessness, high-precision, and repeatability. Shorter product lifecycles coupled with just-in-time manufacturing make robotic flexibility and responsiveness highly beneficial [233]. More than two million industrial robots are in daily operation around the world, and the market for industrial robots continues to increase. However, it is estimated that only a fraction of potential users in the manufacturing domain have adopted robotic systems. This is often because there is a lack of measurement science infrastructure to assure manufacturers that robotic components and systems can be readily integrated into their operations and will perform as needed under dynamic unstructured shop floor conditions. The next advancement in this field will focus on more adaptable and flexible robot programming as well as on human-robot collaboration (HRC). This will involve creative uses of AI and ML, as well as paradigms where robots and humans can work closely side by side, and where the robot will adapt to human behaviors [234].

Implications for NIST

Manufacturing has gone through an evolution of niche production (i.e., in an individual shop) to mass production. Now, customers want customization but for the price of mass quantities. This is where AM can provide the solution. Although AM has recently experienced considerable growth and publicity for its potential to transform the manufacturing sector, its promise is limited due to a lack of confidence in part quality. Improvements in material properties, consistency, and process control are necessary for companies and consumers to realize the potential of enhanced performance, reduced cost, and increased manufacturing speed. These can be done through testbeds, benchmarking data, and the development of standards at NIST [235-239]. Standards need to be developed for materials, process control, personnel training, inspection, and acceptance requirements [240]. NIST is strongly positioned with its current programs to help address these needs, even though market drivers will ultimately decide the success of goods produced using AM techniques.

Digital twin simulations have many potential applications, but also have significant technical, economic, and social limitations that inhibit widespread implementation. They include: the need to determine what information is needed for decision making (and how often); how to determine the proper level of fidelity for the simulations; methods to validate probabilistic simulations; and inevitably noisy input data from the real world. NIST provides important resources to the manufacturing community through engagement in standards development organizations and publishing the scope and requirements for a digital twin in manufacturing framework [241, 242]. This includes how digital twins can be used to protect manufacturers from cyberattacks [243]. NIST has the opportunity to help characterize noisy, physical systems in order to build trust in the digital twins that are supposed to mirror actual operation.

Due to their tireless flexibility and reusability, robotic systems are an essential tool in strengthening U.S. manufacturing competitiveness by enabling dramatically greater responsiveness and innovation. To attain these gains, robotic systems need to be highly capable, perceptive, dexterous, and mobile systems that can operate safely in collaboration with humans, are easily tasked, can learn, and can be quickly integrated into the rest of the enterprise. NIST can advance this effort through development of methods, protocols, and metrics necessary to evaluate the interactive and teaming capabilities of robot systems and advance their adaptability and flexibility, and to ensure the systems are safe for operation with humans [244-246].

NIST is researching the use of AI systems to autonomously optimize new materials faster and more efficiently than traditional experimentation. NIST is combining its expertise and experience in materials science, materials characterization, reference data, and standards with leading research capabilities for designing, producing, and processing advanced materials. CHiMaD is developing the next generation of computational tools, databases, and experimental techniques to enable "Materials by Design," one of the primary goals of the Materials Genome Initiative (MGI) [247, 248].

4.12. Space

There are now multiple countries and commercial organizations, rather than a few large governments, operating missions in space. Technological advances that have allowed miniaturization of many applications have led to a low-cost entry in space through the use of SmallSats (small spacecraft), opening the arena to new players. This has been particularly fueled by the electronics industry meeting this demand with miniaturized components playing crucial roles in navigation, radar, guidance and communication systems, among others [249]. Hundreds of private companies have invested in the space exploration enterprise, with $18 billion of investment from 2009 to 2018 and $3.25 billion in 2018 alone [250, 251]. In 2019, the DOC Bureau of Economic Analysis noted the U.S. space economy accounted for $194.4 billion of real gross output, $125.9 billion of real GDP (translating to 0.6 % of U.S. GDP), $42.4 billion of private industry compensation, and 354,000 private sector jobs [252]. In 2021, the global space economy grew to reach a record $469 billion, and 1,022 spacecraft were placed in orbit during the first six months of 2022 [253]. The DOC identified advancing U.S. leadership in the global commercial space industry as a Strategic Objective in its 2022-2026 Strategic Plan [254]. The coming years hold great potential to reach new heights and bolster the U.S. space ecosystem, but international cooperation will be necessary as we continue to explore and expand into the universe.

There are over 20,000 artificial objects orbiting Earth, including 1500 satellites [255]. In 2021, the National Aeronautics and Space Administration (NASA) reported more than 27,000 pieces of orbital debris, or “space junk,” as being tracked by the DoD’s global Space Surveillance Network (SSN) sensors, [256] with the UN Office of Outer Space Affairs reporting over 2,000 satellite registrations in 2022 alone. Thirty-five percent of all satellites were launched over the past three years [257], demonstrating a tremendous growth in the deployment and use of space assets by spacefaring nations. With an increased number of stakeholders in the space biosphere, the number of space assets and the amount of space debris in low Earth orbit are also growing. Human-generated objects, including parts of rockets and non-functioning satellites, or accidental explosions or collisions of high-speed objects contribute to space debris [258]. Global space traffic monitoring is necessary, but there are currently few internationally accepted rules or standards in this area; the committee draft (CD) standard ISO/CD 9490 is under development by ISO to help meet this need [259].

Today, the U.S. government provides space situational awareness support to commercial and civilian operators through the DoD, using sensors from their SSN. In 2018, Space Policy Directive 3 (SPD-3) directed DoD to transfer its public space situational awareness (SSA) support functions to DOC, which is better positioned to support industry needs, so that DoD can focus its resources on its national security mission [260]. In response, DOC and DoD signed a Memorandum of Agreement (MOA) formalizing the organizations' relationship for basic SSA, space traffic management (STM), and coordination for civil and commercial entities. The agreement defines how the two departments will work cooperatively to implement SPD-3. SPD-3 seeks to advance SSA and STM science and technology; provide federally supported basic SSA data and STM services; and improve SSA data interoperability for SSA data sharing [261]. The National Oceanic and Atmospheric Administration (NOAA) and the Office of Space Commerce (OSC) are leading development of the Traffic Coordination System for Space (TraCSS) for civil and commercial SSA [262].

SPD-3 also called on the government to develop standards and best practices relevant to space situational awareness, data and information sharing, RF spectrum sharing, and orbiting debris mitigation [260], as well as cybersecurity. In 2020, a White House presidential memorandum on cybersecurity for space systems provided guidance on the protection of space assets and supporting infrastructure from evolving cyber threats [263]. In 2021, in response to the growing need to examine cybersecurity and space assets, NIST, OSC, and the U.S. Department of Homeland Security (DHS) convened three separate one-day symposia [264-266]. More recently, NIST and Red Hat co-sponsored a half-day open forum to provide an opportunity for the public to discuss the evolution of information systems and its impact on cybersecurity [267]. It became clear that public and private stakeholders must work together to address cybersecurity challenges [268].

While space asset numbers are increasing, astronomers and environmentalists are raising concerns over the impact of man-made satellite constellations and orbital debris on radio interference and increased sky brightness [269]. In 2022, NIST held a workshop specifically to address this issue [270], in collaboration with the Satellite Industry Association, the American Astronomical Society, the International Astronomy Union Center for the Protection of Dark and Quiet Skies, and the NSF. [271]

To accomplish NASA's lofty goal of getting humans to Mars, rockets and spaceships must go further and faster. Crews must be able to repair anything that goes wrong during a mission, which may require parts produced by 3D printers. AM aerospace technologies could also enhance production of materials used on Earth in unique conditions [272]. Materials for spaceships and satellites are not the only parts needed. Being able to grow food in space could reduce cargo loads and costs required to feed astronauts; it currently costs $2,000 to ship a lemon to the International Space Station. Synthetic biology offers promising technologies through cellular agriculture where meats like beef and poultry can be grown in a lab. Textiles from microbial production would allow astronauts to recycle old materials and grow new ones [273].

Implications for NIST

NIST contributes to space technologies and the aerospace and space economy in many ways. As the commercial space economy grows rapidly, NIST will be challenged to embark on work more specifically targeted towards commercial space endeavors and may discover that the existing, technically broad, efforts supporting space commerce may benefit from greater internal coordination. With these challenges, NIST gains the opportunity to explore new R&D efforts focused specifically on space; expand leadership in areas such as advanced manufacturing, documentary standards, and space cybersecurity; expand engagement in research related to SSA; and enhance interactions with the new space commerce industry. Examples of technologies that support the needs of a commercial space sector include new spectrum analysis capabilities and optical and infrared spectrum options to address the growing number of satellites needed for communication bandwidth; space-qualification of components; better measurements to support orbit trajectory predictions; improvement and resiliency of precision navigation and timing (PNT); and managing data for space traffic management.

With an increased number of satellites and space missions, advanced manufacturing for materials production and research for development of new aerospace materials will drive innovation forward, while making these launches more efficient and decreasing the amount of waste left behind in the process. NIST is currently contributing to R&D of aerospace materials through several public-private partnerships and regional manufacturing networks including Manufacturing USA and MEP [274]. Measurements of materials properties for reflectance and emissivity are useful for informing how materials may be applied to aerospace applications, such as satellite design and for tracking technologies to support SSA capabilities and to address the brightness mitigation as described above. NIST can anticipate increasing interest in these efforts.

As a safer and more sustainable space environment emerges, standards analysis and advancement for space safety are needed. NIST’s Standards Coordination Office and Information Technology Laboratory are already working with the OSC, and requests for additional engagement are likely to continue and expand. NIST’s unique expertise in cybersecurity can aid this effort [264-266, 275]. At NIST, experts from government, the research community, and industry collaborate to produce standards, recommendations, and other tools to achieving effective cybersecurity. The NIST CSF – and the information systems controls outlined in NIST Special Publications, such as Special Publication 800-53 – are useful building blocks to manage cybersecurity risk. Recent NIST publications on the application of the NIST CSF to space systems are important tools for the community to use and share for greater risk management and risk mitigation [276-279].

NIST will also contribute to the aerospace ecosystem through the development of physical standards and sensors for space measurements. Sensors in satellites are calibrated by NIST to ensure that measurements taken are accurate and can be compared to observations from other sources [280]. As more satellite constellations are placed in the lower orbit, physical standards will need to be modernized to ensure continued accurate measurements, but at lower cost.

NIST has engaged in interagency efforts such as the National Executive Committee for Space-Based PNT; working groups led by the White House National Space Council, National Security Council, and OSTP in the areas of strategy for Near-Earth Object Hazards, Low Earth Orbit Research and Development strategy, Orbital Debris Implementation Plan; the national spaceport strategy; and development of standards for reliable and secure space commerce. With the growing interest and commerce in space, NIST will likely have more requests for increases in these and related areas. This provides both an opportunity for increased leadership and a challenge, as many requests may not be accompanied by additional funding.

5. Conclusion

The 2023 NIST Environmental Scan provides insight into factors that will continue to impact NIST in its mission "to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life." This analysis examines the landscape through three specific lenses: societal and political; investment and geopolitical; and technology and science.

The future brings both great opportunities for NIST as well as significant challenges. As the COVID-19 pandemic has wound down, there are opportunities for NIST to reexamine how work is done and who the NIST workforce is. NIST can emerge into the "new normal" to meet staff's needs for flexibility and leverage technology to conduct work efficiently, effectively, and collaboratively. However, NIST must chart a course forward that harnesses the benefits of the new nature of work without compromising on its mission and collaborative culture. There is also opportunity for NIST to be thoughtful in how biases are managed and how diversity can be celebrated and equity improved in the workforce. One area NIST should pursue is addressing the underrepresentation of women and people of color in STEM. By increasing diversity, NIST will be better prepared to continue research and standards work with perseverance, integrity, inclusivity, and excellence.

The CHIPS and Science Act is a huge opportunity for NIST to significantly impact the U.S. economy and the future of semiconductor R&D. NIST must take full advantage of this opportunity to leverage its expertise in this area of great need and showcase NIST as a trusted premier research and standards institution. Although this is a great opportunity for NIST to shine, there are also concerns about how this endeavor will impact NIST's existing work and staff. NIST's role in research and standards is essential and critical as emerging technologies become increasingly important in the United States and globally. AI, quantum information systems, advanced communications, biotechnology, sustainability, and other areas are rapidly changing the world. To keep up with its competitors, NIST must remain on the cutting edge of these and other emerging technologies with the resources to deliver impact within its unique mission space for the Nation.

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Appendix A. List of Abbreviations and Acronyms

3GPP
3rd Generation Partnership Project

5G
fifth generation mobile network

AAPI
Asian American and Pacific Islander

AC
air-conditioning

ACLU
American Civil Liberties Union

AI
artificial intelligence

AI RMF
AI Risk Management Framework

AIM Photonics
American Institute for Manufacturing Integrated Photonics

AM
additive manufacturing or 3D printing

AMA
American Medical Association

AML
adversarial machine learning

ANSI
American National Standards Institute

APEC
Asia-Pacific Economic Cooperation

ASCE
American Society for Civil Engineers

ASME
American Society of Mechanical Engineers

ASTM International
formerly known as the American Society for Testing and Materials

ATP
assembly, testing, and packaging

information technology

BIPM
International Bureau of Weights and Measures

CBO
Congressional Budget Office

CD
committee draft

CDC
U.S. Centers for Disease Control and Prevention

CDGB
Commerce Data Governance Board

CENELEC
European Committee for Electrotechnical Standardization

CE
Conformité Europóene

CEN
European Committee for Standardization

CETs
critical and emerging technologies

CGPM
General Conference on Weights and Measures

CGT
cell and gene therapy

ChatGPT
Chat Generative Pre-trained Transformer

CHIPS
Creating Helpful Incentives to Produce Semiconductors

CIPM
International Committee for Weights and Measures

CMCs
Calibration and Measurement Capabilities

CNNs
Convolutional neural networks

CO_2
carbon dioxide

CSF
Cybersecurity Framework

D&I
diversity and inclusion

DAMA International
Data Management Association International

DEIA
Diversity, Equity, Inclusion, and Accessibility

DOC
U.S. Department of Commerce

DoD
U.S. Department of Defense

DOE
U.S. Department of Energy

DHS
U.S. Department of Homeland Security

EC
European Commission

EDPB
European Data Protection Board

ERCOT
Electric Reliability Council of Texas

ERG
employee resource group

ESOs
European Standards Organizations

ETSI
European Telecommunications Standards Institute

EU
European Union

EUV
Extreme Ultraviolet

EVs
electric vehicles

FAIR
findable, accessible, interoperable, reusable

G7
International Group of Seven

GDP
gross domestic product

GDPR
General Data Protection Regulation

GPS
global positioning systems

GWP
global warming potential

hENs
harmonized European standards

HIPAA
Health Insurance Portability and Accountability Act

HRC
human-robot collaboration

HVAC
heating, ventilating, and air-conditioning

IAAO
International and Academic Affairs Office

IAQ
indoor air quality

ICSP
Interagency Committee on Standards Policy

IETF
Internet Engineering Task Force

IICSWG
Interagency International Cybersecurity Standards Working Group

IoT
Internet of Things

IPEF
Indo-Pacific Economic Framework

ISO
International Organization for Standardization

IT
information technology

ITU
International Telecommunication Union

JCAS
Joint Communications and Sensing

JILA
formerly the Joint Institute for Laboratory Astrophysics

JQI
Joint Quantum Institute

mAbs
monoclonal antibodies

MEP
Hollings Manufacturing Extension Partnership

MGI
Materials Genome Initiative

ML
machine learning

MOA
Memorandum of Agreement

mpox
monkeypox

NAMLE
National Association for Media Literacy Education

NAPMP
National Advanced Packaging and Manufacturing Program

NASA
National Aeronautics and Space Administration

NASEM
National Academies of Science, Engineering, and Medicine (or "National Academies")

NDAA
National Defense Authorization Act

NextG CMA
Next generation mobile network Channel Model Alliance

NHS
National Health System

NICE
National Initiative for Cybersecurity Education

NIIMBL
National Institute for Innovation in Manufacturing Biopharmaceuticals

NIST
National Institute of Standards and Technology

NMI
national metrology institute

NOAA
National Oceanic and Atmospheric Administration

NQCO
National Quantum Coordination Office

NQI
National Quantum Initiative

NSF
National Science Foundation

NSB
National Standards Body

NSSCET
National Standards Strategy for Critical and Emerging Technology

NSTC
National Semiconductor Technology Center

O5
Ottawa 5

O-RAN Alliance
Open Radio Access Network Alliance

OAR
Open Access to Research

OECD
Organization for Economic Co-operation and Development

OJEU
Official Journal of the European Union

OSC
Office of Space Commerce

OSTP
Office of Science and Technology Policy

PM2.5
particulate matter smaller than 2.5 μm

PNT
positioning, navigation, and timing

PQC
post-quantum cryptography

PRC
People's Republic of China

QED-C
Quantum Economic Development Consortium

QIS
quantum information science

QIST
quantum information science and technology

Quad
Australia, India, Japan, and the United States

QuICS
Joint Center for Quantum Information and Computer Science

R&D
research and development

RAN
Radio Access Network

RCAC
Research Computing Advisory Committee

RDaF
Research Data Framework

S&T
science and technology

SDO
standards development organization

SI
système international d'unités, or in English, the International System of Units

SIM
Sistema Interamericano de Metrología

SME
small- and medium-enterprise

SmallSats
small spacecraft

SPD-3
Space Policy Directive 3

SSA
space situational awareness

SSN
Space Surveillance Network

STEM
science, technology, engineering, and math

STM
space traffic management

TC
technical committee

TOU
terms of use

TraCSS
Traffic Coordination System for Space

TTC
U.S.-EU Trade and Technology Council

UN
United Nations

URLLC
Ultra Reliable Low Latency Communications

VCAT
Visiting Committee on Advanced Technologies

VEO
volunteer employee organization

VR/AR/XR
virtual/augmented/extended reality

WHO
World Health Organization

WUI
Wildland-Urban Interface