United States Government Accountability Office

Report to the Ranking Member, Committee on Commerce, Science, and Transportation, U.S. Senate

September 2021

HIGH-PERFORMANCE COMPUTING

Advances Made Towards Implementing the National Strategy, but Better Reporting and a More Detailed Plan Are Needed

A Century of Non-Partisan Fact-Based Work

GAO-21-104500

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Highlights

Highlights of GAO-21-104500, a report to the Ranking Member, Committee on Commerce, Science, and Transportation, U.S. Senate

Why GAO Did This Study

In 2015, Executive Order 13702 established the NSCI to maximize the benefits of high-performance computing for economic competitiveness and scientific discovery. The order directed 10 agencies to implement the NSCI and pursue five strategic objectives, including accelerating delivery of a capable exascale computing system, which is anticipated to be at least three times more powerful than the current top-ranked system. The NSCI Executive Council, established by the executive order and co-chaired by OSTP and the Office of Management and Budget, issued a strategic plan in 2016, which was updated in 2020.

GAO was asked to review the status of the NSCI. This report examines (1) agencies' efforts and OSTP's and agencies' reporting on progress towards meeting the objectives of the 2016 strategic plan and (2) the extent to which the 2020 strategic plan includes desirable characteristics of a national strategy. GAO analyzed key NSCI documents, administered a questionnaire to 10 NSCI agencies, and interviewed OSTP and other agency officials and nonfederal stakeholders.

What GAO Recommends

GAO is making two recommendations to OSTP, including that it annually report on progress in implementing the 2020 strategic plan and address each of the desirable characteristics of a national strategy, as practicable, in the upcoming implementation roadmap or through other means. OSTP concurred with both recommendations and stated it will annually report on progress towards the 2020 strategic plan.

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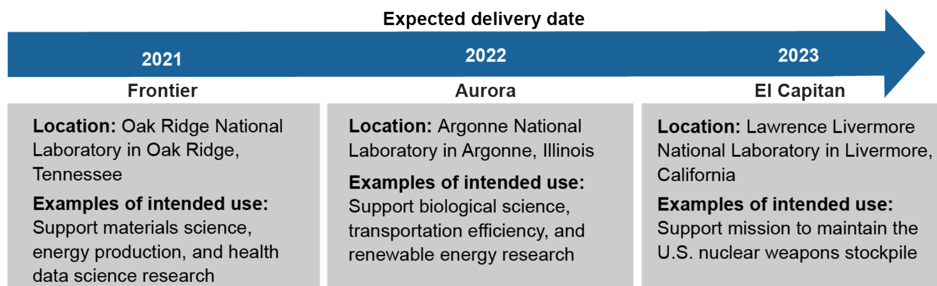
HIGH-PERFORMANCE COMPUTING

Advances Made Towards Implementing the National Strategy, but Better Reporting and a More Detailed Plan Are Needed

What GAO Found

Ten agencies took steps to implement all 71 efforts across the five objectives of the 2016 National Strategic Computing Initiative (NSCI) strategic plan and characterized most as ongoing. According to officials, agencies generally did not receive funding to implement the 2016 strategic plan and undertook efforts as part of existing programs or research that were aligned with the plan's objectives. As part of the largest NSCI investment, the Department of Energy (DOE) obligated $2.2 billion for exascale computing from fiscal years 2016 through 2020. This includes three exascale computing systems, which are expected to be among the most powerful computers in the world when completed (see figure). DOE also collaborated with other agencies to develop exascale-ready software applications for use on those systems to address problems beyond the capability of current high-performance computers. Other agency efforts include funding workforce development and conducting research on future computing technologies.

Figure: Department of Energy's Three Expected Exascale Computing Systems



Source: GAO analysis of Department of Energy documents. | GAO-21-104500

The Office of Science and Technology Policy (OSTP) and agencies inconsistently reported on progress towards the 2016 strategic plan's objectives. OSTP reported 2016 strategic plan accomplishments in a 2018 budget report but did not do so in subsequent years. It was also not aware of the NSCI executive council reporting on progress as called for by the NSCI executive order. Academic and industry stakeholders stated that a lack of progress reports limited their visibility into accomplishments and remaining work. Having such information could help them better align their activities with agency efforts.

The 2020 strategic plan—which superseded the 2016 strategic plan—fully or substantially addressed two desirable characteristics of a national strategy identified by GAO to help ensure accountability and more effective results. For example, the plan described how agencies will partner with academia and industry but partially addressed or did not address four other characteristics, such as the resources needed to implement it or a process for monitoring and reporting on progress. OSTP and agency officials said they plan to release a more detailed implementation roadmap later in 2021 but have not described what details this plan will include. By more fully addressing the desirable characteristics of a national strategy through the implementation plan or other means, including reporting on progress, OSTP and agencies could improve efforts to sustain and enhance U.S. leadership in high-performance computing.

Contents

Abbreviations

DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
FBI	Federal Bureau of Investigation
HPC	high-performance computing
IARPA	Intelligence Advanced Research Projects Activity
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NITRD	Networking and Information Technology Research and Development
NOAA	National Oceanic and Atmospheric Administration
NSCI	National Strategic Computing Initiative
NSTC	National Science and Technology Council
NSF	National Science Foundation
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
R&D	research and development
RFI	request for information

U.S. GOVERNMENT ACCOUNTABILITY OFFICE
A Century of Non-Partisan Fact-Based Work
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September 30, 2021

The Honorable Roger F. Wicker
Ranking Member
Committee on Commerce, Science, and Transportation
United States Senate

Dear Mr. Wicker:

High-performance computing (HPC)—the use of aggregated computing power to achieve much higher performance than that of typical desktop computers or workstations—is essential to the nation's security, global economic competitiveness, and scientific discovery. Researchers use high-performance computers to analyze massive amounts of data and use modeling and simulation to solve real-world problems. Issues of strategic importance, such as management of the national nuclear stockpile, research on Coronavirus Disease 2019 (COVID-19), development of climate models, and support for advances in commercial manufacturing, require HPC.

The United States has long held a leadership role in HPC, but it increasingly faces overseas competition. In 2016, China announced it had developed a new high-performance computer that nearly tripled the performance of the world's most powerful computer at the time (also from China). In 2021, the Top500 List ranked a Japanese high-performance computer as the world's most powerful computer system.[1] In addition, by 2021, the United States and China were both expected to build the world's first exascale high-performance computers, which were anticipated to be at least three times more powerful than the current top ranked system. An exascale computing system can perform at least 1 quintillion (or a billion billion) floating-point operations per second, which is a measure of computational power.

In 2015, Executive Order 13702 established the National Strategic Computing Initiative (NSCI), stating that it is the policy of the United

[1]The Top500 list ranks the 500 fastest computer systems in use based on self-reported information. The list has been released every six months since 1993 and is currently compiled by researchers from Lawrence Berkeley National Laboratory; the University of Tennessee, Knoxville; and Prometeus using a standard benchmark to measure performance.

States to sustain and enhance U.S. scientific, technological, and economic leadership in HPC through a coordinated federal strategy.[2] The executive order defined five strategic objectives, including accelerating delivery of a capable exascale system and developing an enduring public-private collaboration to ensure that the benefits of the research and development (R&D) advances are shared among government, industry, and academia. It outlined roles for 10 federal agencies engaged in HPC work and established the NSCI Executive Council co-chaired by the Directors of the Office of Science and Technology Policy (OSTP) and the Office of Management and Budget (OMB). The executive council's role was to ensure accountability for, and coordination of, HPC research, development, and deployment activities within the NSCI.[3]

To implement the executive order, the executive council issued an NSCI strategic plan in July 2016.[4] The plan included activities to be conducted by the 10 federal agencies to achieve the NSCI's strategic objectives. The plan was subsequently updated in 2019 and again in 2020 after receiving input from federal, industry, nonprofit, and academic stakeholders.

You requested that we review the status of the NSCI. This report examines (1) what steps agencies have taken to meet the objectives of the 2016 strategic plan and how OSTP and agencies reported on progress and (2) the extent to which the 2020 strategic plan includes desirable characteristics of a national strategy.

The scope of our review included OMB, OSTP, and the 10 federal agencies outlined in the 2016 strategic plan as lead, foundational R&D, and deployment agencies (see table 1).

[2]Executive Order 13702, *Creating a National Strategic Computing Initiative*, July 29, 2015.

[3]OSTP and OMB are both responsible for providing high-level oversight of federal R&D. In particular, OSTP serves as a primary advisor to the President regarding science and technology priorities. OSTP also leads interagency coordination efforts on science and technology policy. We asked OMB about actions it took to implement the NSCI; OMB responded that it deferred to OSTP to lead NSCI policy development.

[4]National Strategic Computing Initiative Executive Council, *National Strategic Computing Initiative Strategic Plan*, July 2016.

Table 1: National Strategic Computing Initiative Agency Roles

Type of agency	Agency
Lead	Department of Defense Department of Energy National Science Foundation
Foundational research and development	Intelligence Advanced Research Projects Activity National Institute of Standards and Technology
Deployment	Department of Homeland Security Federal Bureau of Investigation National Aeronautics and Space Administration National Institutes of Health National Oceanic and Atmospheric Administration

Source: GAO analysis of National Strategic Computing Initiative Strategic Plan, July 2016. | GAO-21-104500

To examine steps the agencies took to meet the strategic objectives of the 2016 strategic plan, we sent a questionnaire to all 10 federal agencies (NSCI agencies) in our scope and asked about the status of their efforts; specifically, implementation of specific activities that the 2016 strategic plan listed for each agency to conduct under each of the five objectives.[5] We also asked each agency to summarize the relevant programs, grants, contracts, and other efforts they undertook towards meeting the NSCI's strategic objectives since the issuance of the executive order establishing the NSCI in July 2015.

To examine the extent to which the 2020 strategic plan included the desirable characteristics of a national strategy, we assessed the plan against the elements of the six desirable characteristics for an effective national strategy that we identified in our past work.[6] We used a four-point scale to rate the degree to which each element was included.

For both objectives, we interviewed federal agency officials from the NSCI agencies about their implementation of the 2016 strategic plan and anticipated implementation of the 2020 strategic plan. We also interviewed OSTP officials on how OSTP reported on progress towards meeting the objectives of the 2016 strategic plan, and we interviewed a

[5]The scope of our work is limited to unclassified agency activities.

[6]GAO, *Combating Terrorism: Evaluation of Selected Characteristics in National Strategies Related to Terrorism*, GAO-04-408T (Washington, D.C.: Feb. 3, 2004). GAO has used these desirable characteristics to evaluate various national strategies, including those related to science and technology issues.

nongeneralizable sample of 10 nonfederal stakeholders to discuss their perspectives about OMB, OSTP, and federal agencies' implementation of the strategic plans. We also obtained written responses from OMB discussing its implementation of the strategic plans. When summarizing responses from the 10 NSCI agencies or the 10 nonfederal stakeholders, we use "some" to refer to 2 to 5 agencies or stakeholders and "most" to refer to 6 to 9.

For more information about our objectives, scope, and methodology, see appendix I.

We conducted this performance audit from August 2020 to September 2021 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Background

2015 Executive Order and 2016 Strategic Plan

The 2015 executive order establishing the NSCI, Executive Order 13702, directed 10 agencies to pursue five strategic objectives, and the 2016 strategic plan included descriptions of how the NSCI agencies would accomplish strategic objectives. The five objectives identified by the executive order were:[7]

1. *Accelerating delivery of a capable exascale computing system.* The 2016 strategic plan noted that capable exascale computing systems—that is, systems capable of performing a billion billion operations per second and with important characteristics such as affordable power consumption, programmability, reliability, and adequate memory and networking—were not projected to become available commercially until the mid- to late-2020s. The 2016 strategic plan set a goal of achieving capable exascale computing by the mid-2020s.
2. *Increasing coherence between the technology used for modeling and simulation and that used for data analytic computing.* According to the 2016 strategic plan, two types of computing—modeling and simulation, and data analytics—have traditionally relied on computing systems optimized for one type of computing or the other. According

[7]We summarized the full text of the objectives identified in the executive order.

to the 2016 strategic plan, because of increases in computing power, these two types of computing are merging, leading to the use of large-scale data analytics within modeling and simulation.[8] The plan cited a need for increased coherence between simulation and data analytic computing in HPC applications.

3. *Establishing, over the next 15 years, a viable path forward for future HPC systems even after the limits of current semiconductor technology are reached.* The 2016 strategic plan stated that current semiconductor approaches should be feasible at exascale but will eventually plateau because of the physical limitations inherent in semiconductor technologies. The 2016 strategic plan further stated that, given this anticipated development, the NSCI would pursue two parallel lines of efforts over a 10- to 20-year period: R&D to move past the theoretical limits of semiconductors and R&D on alternative computing paradigms, such as quantum computing.[9]

4. *Increasing the capacity and capability of an enduring national HPC ecosystem.* The 2016 strategic plan found that the current HPC ecosystem—which includes software, hardware, networks, and workforce—is not widely available or sufficiently flexible to support emerging opportunities in science and technology. According to the plan, making HPC easily accessible and usable by the broadest range of researchers requires increased investments in training and outreach to new users as well as in the development of innovative technologies.

5. *Developing an enduring public-private collaboration to ensure that the benefits of the research and development advances are, to the greatest extent, shared between the U.S. government and industrial and academic sectors.* According to the 2016 strategic plan, HPC developments in the United States historically derived from close collaboration between federal agencies, industry, and academia. The

[8]For example, researchers at a 2019 National Academies of Sciences, Engineering, and Medicine workshop on the use of data, modeling, and simulation for urban sustainability issues cited the need for studying real world problems like estimating methane leaks, disease forecasting, and transportation and traffic modeling that use large data sets as inputs for modeling and simulations. National Research Council, *Enhancing Urban Sustainability with Data, Modeling, and Simulation: Proceedings of a Workshop* (Washington, DC: 2019).

[9]Quantum technologies, which take advantage of properties such as entanglement (the ability of two particles to have correlated information, even at a distance), have the potential to revolutionize computing, making computers more powerful than the most advanced high-performance computers. However, many years of development may be required to do so. Also see GAO, *Science & Tech Spotlight on Quantum Technologies*, GAO-20-527SP (Washington: D.C.: May 2020).

2016 strategic plan stated that the NSCI will explore ways to optimize collaboration and benefit the public and private sectors across missions for scientific discovery, economic competitiveness, and national security.

The 2015 executive order identified 10 NSCI agencies under three categories—lead, foundational R&D, and deployment agencies—to pursue the five strategic objectives. The 2016 strategic plan further described these three categories and identified 71 activities across the five strategic objectives that the agencies would pursue.

- **Lead agencies.** Department of Defense (DOD), Department of Energy (DOE), and National Science Foundation (NSF) were to develop and deliver the next generation of integrated HPC capability, engage in mutually supportive R&D on hardware and software, and develop the HPC workforce. The 2016 strategic plan described 40 planned efforts for the lead agencies that span all five strategic objectives.
- **Foundational R&D agencies.** The executive order charged the Intelligence Advanced Research Projects Activity (IARPA) and National Institute of Standards and Technology (NIST) with fundamental scientific discovery work and associated advances in engineering. Specifically, the order called on IARPA to focus on future computing paradigms that offer an alternative to standard semiconductor computing technologies and NIST to focus on measurement science to support future computing technologies. The 2016 strategic plan described 19 planned efforts for IARPA and NIST, with most supporting more research in the first and third strategic objectives.
- **Deployment agencies.** Department of Homeland Security (DHS), Federal Bureau of Investigation (FBI), National Aeronautics and Space Administration (NASA), National Institutes of Health (NIH), and National Oceanic and Atmospheric Administration (NOAA) were to develop mission-based requirements to influence the early design stages of new HPC systems and seek viewpoints from the private sector and academia on requirements. The 2016 strategic plan described 12 efforts for the deployment agencies, with eight of those efforts under the fourth and fifth strategic objectives to build the HPC ecosystem and enhance public-private collaboration.

To ensure accountability for, and coordination of, the research, development, and deployment activities, the 2015 executive order designated the directors of OSTP and OMB as co-chairs of the executive council. In addition, the director of OSTP was to designate members of the executive council from within the executive branch, including representatives from NSCI agencies. The executive order directed the executive council to establish an implementation plan to support and align efforts among the 10 agencies in support of the order's five objectives, update the implementation plan as required, and document progress made in implementing the plan, among other things, annually for 5 years thereafter.[10] In addition, the executive order directed the co-chairs to prepare an annual report for 5 years from the date of the order on the status of the NSCI for the President.

The 2015 executive order further directed the executive council to coordinate and collaborate with OSTP's National Science and Technology Council (NSTC) and its subordinate entities as appropriate to ensure that HPC efforts across the federal government would align with the NSCI.[11] In particular, the NSTC's Subcommittee on Networking and Information Technology Research and Development (NITRD) provides for coordination among 23 member federal agencies and 50 other participating agencies that conduct or support R&D in advanced networking and information technologies. NITRD has 11 interagency working groups, including one on high-end computing, and issues an annual supplement to the President's Budget Request to Congress that reports on investments in NITRD research areas as well as key R&D programs and coordination activities by the federal agencies participating in NITRD.

2020 Strategic Plan

In November 2019, after seeking input from federal, industry, nonprofit, and academic stakeholders, OSTP and the NITRD Subcommittee's Fast Track Action Committee on Strategic Computing issued a report that included a set of refocused objectives that reflected advances in computer technology as well as recommendations for achieving the plan's updated objectives.[12] A June 2019 Federal Register notice seeking input from interested parties on ways to sustain and enhance U.S. leadership in strategic computing cited two reasons for reexamining the objectives:

[10]OSTP officials stated that the initial implementation plan in response to the executive order was issued in October 2015 as an official use only document and that the 2016 strategic plan updated that initial plan.

[11]NSTC coordinates science and technology policy across the various federal research and development agencies. Its membership includes the director of OSTP and cabinet secretaries and agency heads with significant science and technology responsibilities.

[12]OSTP, National Science and Technology Council, *National Strategic Computing Initiative Update: Pioneering the Future of Computing,* November 2019.

- significant near- and long-term advances that supported the efforts towards exascale computing; and
- changes in the technology landscape, including the increasing role of network-centric and edge computing and the need for improved software interoperability and sustainability.

The November 2019 report included a recommendation that, to enable effective use of the nation's computing ecosystem, the federal government embrace a diversity of hardware and software approaches for the future of computing. The report also included several recommendations to ensure effective coordination, including recommendations for an executive council and a new NSTC subcommittee that would, among other things, prepare yearly reports on progress towards meeting the strategic objectives.

In response to the 2019 report, the NSTC Subcommittee on Future Advanced Computing Ecosystem issued *Pioneering the Future Advanced Computing Ecosystem: A Strategic Plan* in November 2020 (the 2020 strategic plan).[13] Similar to the 2016 strategic plan, the 2020 strategic plan envisioned a future advanced computing ecosystem that would provide the foundation for continuing American leadership in science and engineering, economic competitiveness, and national security. The 2020 strategic plan outlined four strategic objectives summarized below, which broadly mirrored the 2015 executive order's strategic objectives:

- Utilize the future advanced computing ecosystem as a strategic resource spanning government, academia, nonprofits, and industry.
- Establish an innovative, trusted, verified, usable, and sustainable software and data ecosystem.
- Support foundational, applied, and translational research and development to drive the future of advanced computing and its applications.
- Expand the diverse, capable, and flexible workforce that is critically needed to build and sustain the advanced computing ecosystem.

Unlike the 2016 strategic plan, the 2020 strategic plan did not contain a separate strategic objective on exascale computing, but it did include exascale computing as part of its vision of a robust and sustainable software and data ecosystem. The 2020 strategic plan also maintained

[13]The 2020 strategic plan did not indicate how long it would guide high-performance computing efforts or when it would be updated or replaced.

the three categories of agencies identified in the 2015 executive order and 2016 strategic plan and added the Defense Advanced Research Projects Agency, which is part of DOD, to the foundational R&D agencies.

Agencies Took Steps to Implement the 2016 Strategic Plan but Reporting on Progress Was Inconsistent

The ten NSCI agencies took steps to implement all of the 71 efforts across the five objectives that the 2016 strategic plan called for and characterized most as ongoing. Agencies also cited challenges to achieving the objectives and noted that most challenges, such as lack of funding, continued to persist. However, OSTP and agencies inconsistently reported on overall progress made towards meeting the strategic plan's objectives.

Most Agency Efforts Remain Ongoing

According to their responses to our questionnaires, the 10 agencies took steps to implement all 71 efforts that the 2016 strategic plan called for and characterized 69 out of 71 of those efforts as ongoing.[14] Agency officials stated that, for the most part, they undertook these efforts as part of existing programs or research efforts that were aligned with the 2016 strategic plan objectives. These efforts also varied by size of investments and scope of the objectives each agency was responsible for supporting. For example, NOAA, a deployment agency, cited investments of nearly $3.8 million from fiscal years 2016 through 2020 on efforts such as software development and analytic improvements of large datasets to support its mission. NIH, another deployment agency, cited funding obligations to use HPC to accelerate cancer research for a total of about $50 million from fiscal years 2016 through 2020. To support capable exascale efforts, lead agencies cited obligated or enacted funds ranging from about $169 million for DOD, $461 million for NSF, and $2.2 billion for DOE from fiscal years 2016 through 2020. We highlight key agency efforts for each 2016 strategic plan objective below.

Strategic Objective 1: Capable Exascale

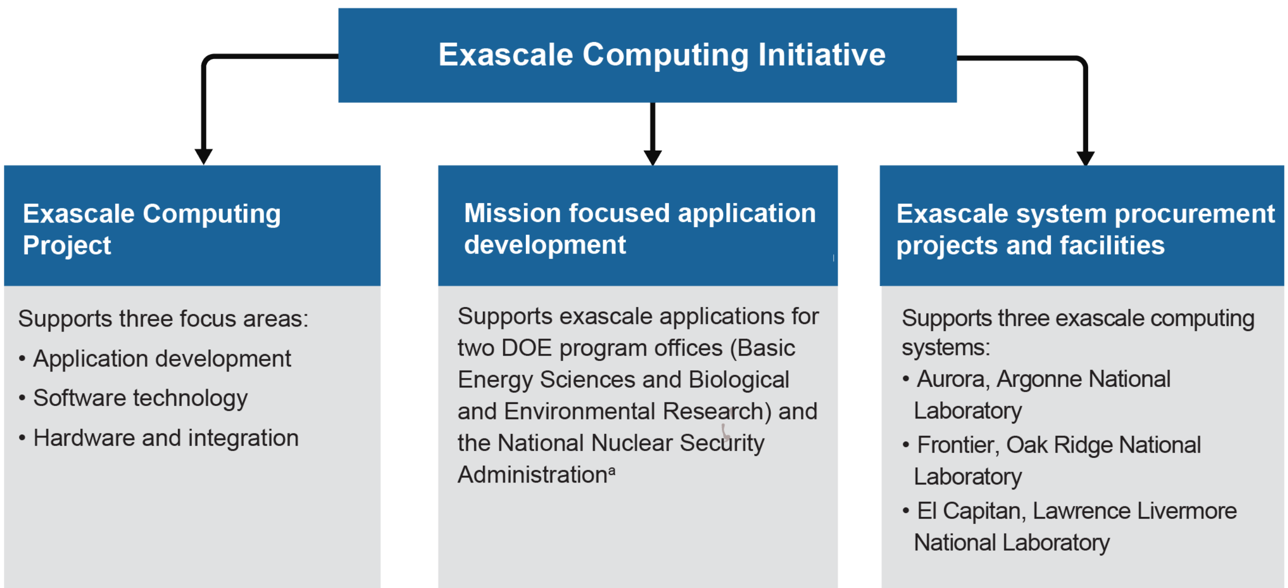
DOE made substantial progress toward the objective to accelerate the delivery of a capable exascale computing system by the mid-2020s, according to OSTP officials, most agency officials and nonfederal stakeholders we interviewed.[15] The 2016 strategic plan identified DOE as leading the capable exascale effort. DOE expects to deliver the first of its three exascale systems in 2021 and, according to data DOE provided to

[14]DOE reported one effort as mostly complete and one effort as partially complete.

[15]DOE officials stated that, upon delivery, rigorous acceptance testing will be conducted before the systems are ready to be used.

us, obligated about $2.2 billion from fiscal year 2016 through fiscal year 2020 to support its exascale efforts. DOE supported exascale efforts primarily through the Exascale Computing Initiative, a partnership between DOE's Office of Science and National Nuclear Security Administration. The initiative consists of three major components: the Exascale Computing Project, mission-focused application development, and exascale system procurement projects and facilities (see fig. 1).

Figure 1: Department of Energy's Exascale Computing Initiative



Source: GAO analysis of Department of Energy (DOE) documents. | GAO-21-104500

[a]Note: According to DOE officials, DOE's National Nuclear Security Administration also conducts software development in addition to application development.

- **Exascale Computing Project.** The Exascale Computing Project underpins all of DOE's other exascale efforts and focuses on three major technical areas: application development, hardware and integration, and software technology. For example, the Exascale Computing Project aims to develop and deliver exascale-ready applications that address high-priority strategic problems of national interest.[16] According to DOE and responses to our questionnaire, the project supported 30 application development projects related to high-priority strategic problems including those related to chemistry, materials, energy, earth and space science, data analytics and optimization, and national security. DOE officials cited the PathForward program, which aims to support and accelerate industry partners' hardware innovations needed for exascale systems, as another area of significant progress. According to DOE documents and officials, the PathForward program awarded contracts to six industry partners in order to support and accelerate hardware innovations that could be included in proposals for exascale systems. Specifically, industry partner projects completed 80 percent of the total milestones across their projects as of fiscal year 2020 and expect to complete all remaining milestones in fiscal year 2021. According to DOE, as of November 2020, DOE's software technology focus area supported about 70 software products spanning areas such as data visualization and mathematical libraries.

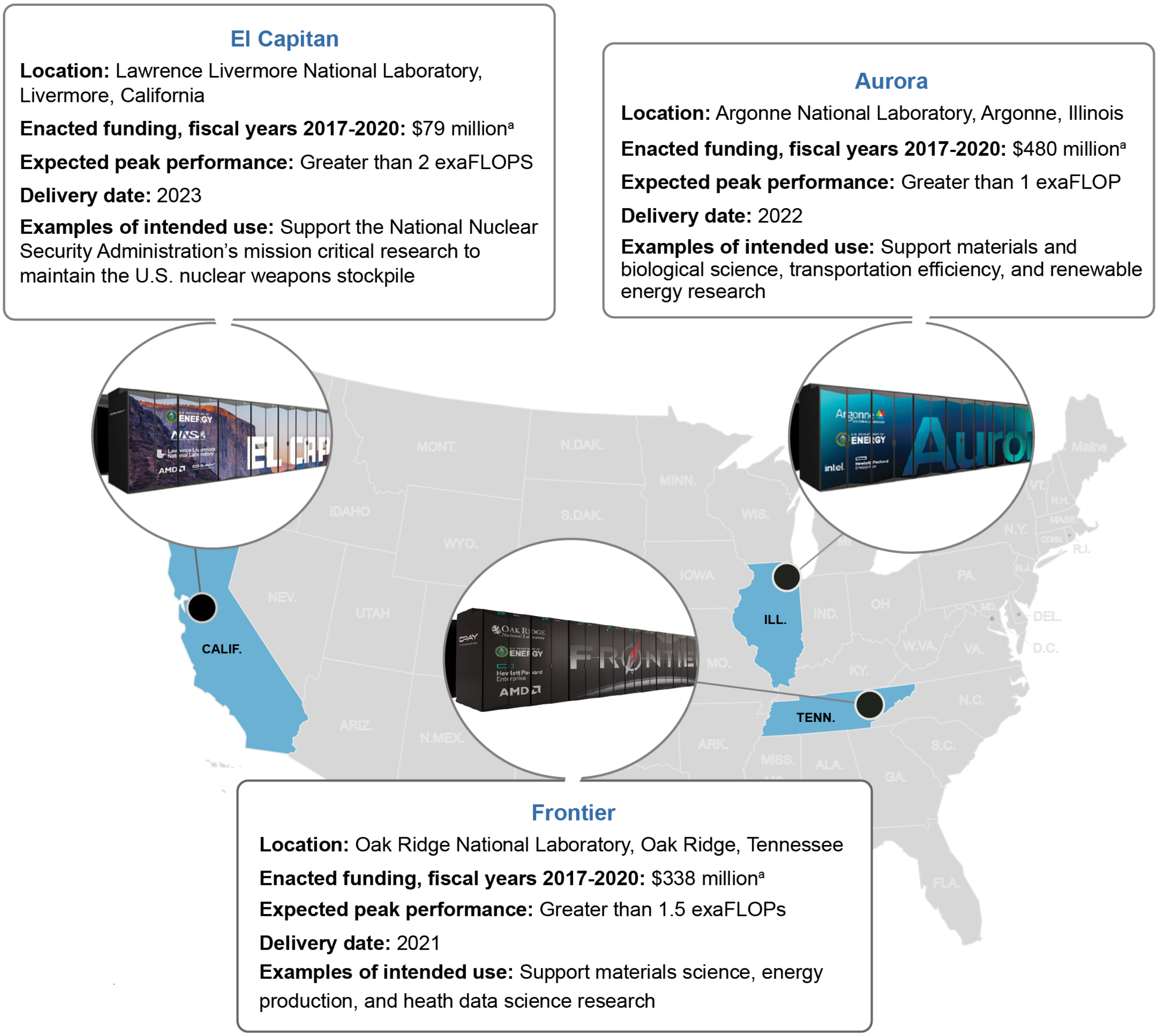
- **Mission focused application and software development.** This component of the Exascale Computing Initiative includes application and software development for DOE's missions related to two program offices and the National Nuclear Security Administration. In particular, this component provides support for DOE's Basic Energy Science program's development of computational materials and chemistry applications related to exascale computing; DOE's Biological and Environmental Research program's development of a state-of-the-science Earth system modeling, simulation, and prediction project; and the National Nuclear Security Administration's weapons mission.
- **Exascale system procurement projects and facilities.** According to DOE officials, DOE began planning for three exascale systems in 2017, each developed and built in collaboration with industry partners. DOE expects that the Frontier system at Oak Ridge National Laboratory—the first system scheduled to be delivered later in 2021—will be able to solve calculations over 6 times faster than current top high-performance computers in the United States. For example, Frontier will be able to simulate the life cycle of a nuclear reactor and help perform research on the genetics of complex diseases. According to its questionnaire response, DOE plans to deliver the second and third systems—Aurora at Argonne National Laboratory

[16]According to DOE, the Exascale Computing Project distinguishes between code, which is typically a general capability, and an application. An application uses code to address a specific scientific or engineering question. DOE's application code team must then define an application challenge that is scientifically impactful and requires exascale resources.

and El Capitan at Lawrence Livermore National Laboratory—in 2022 and 2023, respectively (see fig. 2). According to DOE, Aurora will be used for materials, biological, transportation, and renewable energy research—for example, to help design new classes of materials used to create more efficient and powerful batteries and solar panels. El Capitan will support the National Nuclear Security Administration's research to maintain the U.S. nuclear weapons stockpile. OSTP officials cited the expected delivery of these systems as evidence of the success of the 2016 strategic plan. According to DOE, total funding enacted to support the exascale facilities was about $897 million from fiscal years 2017 through 2020—$338 million for Frontier, $480 million for Aurora, and $79 million for El Capitan—with higher amounts for Frontier and Aurora because they were further along in the construction process.[17]

[17]According to DOE officials, these funding estimates include site preparation and non-recurring engineering costs.

Figure 2: Department of Energy’s Exascale Computer Systems Scheduled to Be Delivered in 2021–2023



Source: GAO Analysis of Department (DOE) documents (text), DOE/Lawrence Livermore National Laboratory, courtesy of Hewlett Packard Enterprise (El Capitan image), Argonne National Laboratory (Aurora image), Hewlett Packard Enterprise (Frontier image), Map Resources (map). | GAO-21-104500

[a]Note: According to DOE officials, these funding estimates include site preparation and non-recurring engineering costs.

The two other lead agencies (DOD and NSF) and the two foundational R&D agencies (IARPA and NIST) were also responsible for contributing to exascale computing. As part of these contributions, DOD and DOE participated in each other's programs and cost reviews, such as DOE's Exascale Computing Project evaluations, and formed partnerships to develop software products. According to DOD's questionnaire response, it contracted with DOE's Sandia National Laboratories to develop and align the laboratory's software products for modelling and simulation of classes of weapons systems. For example, DOD used advanced computer modeling methods, testing, and analysis to ensure that ships are hardened to withstand battle conditions. According to information provided in its questionnaire response, NSF invested $461 million from fiscal years 2016 through 2020 to support this strategic objective. These efforts included 446 software development awards totaling $300 million during that period ranging from less than $50,000 to support students, conferences, and workshops to awards of up to $20 million to address issues like software sustainability.

IARPA and NIST also supported exascale computing efforts. IARPA cited five of its programs as examples of contributions to exascale computing. For example, IARPA supports R&D on alternative options to address the power and cooling challenges of large-scale computing systems and supports another program that seeks to reverse engineer the algorithms of the brain to advance machine learning.[18] Among other efforts, NIST was responsible for addressing potential logic, memory, storage, and systems technologies needed for an exascale HPC platform. To support this effort, NIST researchers are currently developing methods to improve the use of silicon in HPC platforms.

Strategic Objective 2: Technology Coherence

Two lead agencies (DOD and NSF) and three deployment agencies (NASA, NIH, and NOAA) made efforts to increase coherence between modeling and simulation and data analytic computing. According to responses to our questionnaires and agency documents, examples of agency efforts included supporting programs to meet mission needs through HPC, investing in software and data analytics systems, using cloud computing to lower the barrier to entry for researchers to use HPC,

[18]Machine learning begins with data—generally in large amounts—and infers rules or decision procedures that aim to predict specified outcomes. This inference happens when the system is able to train itself using the data to increase the accuracy of its predictions. According to DOE documents, exascale computers were once projected to need their own dedicated power plants. The three exascale systems under development will not need dedicated power plants, but challenges related to power persist.

and issuing funding opportunity announcements for grants and small business awards.[19] Table 2 highlights examples of efforts that agencies implemented to support this objective, all of which the agencies characterized as ongoing in their questionnaire responses.

Table 2: Examples of Agency Efforts Implemented to Support Increased Technology Coherence

Agency	Examples of efforts
Lead	
Department of Defense	Funded 18 research, development, test, and evaluation projects, which provided competitively selected projects with high amounts of high-performance computing resources, such as increased hours, that would otherwise not be available to meet mission needs as demand for high-performance computing exceeds resources
National Science Foundation	Invested in software and data analytics systems at the academic campus, regional, and national levels which led to the deployment of the Frontera high-performance computer at the University of Texas at Austin's Texas Advanced Computing Center in October 2019
Deployment	
National Aeronautics and Space Administration	Engineered a cloud computing solution for its user community that lowers the barriers to large scale computing and storage and enhances capabilities in Earth science, including weather and climate prediction
National Institutes of Health	Issued funding opportunity announcements for grants and small business awards—including 418 grants, or supplements to grants, to support sustainable and scalable biomedical research software tools resulting in seven patents and more than 3,400 publications
National Oceanic and Atmospheric Administration	Increased the availability of datasets to the public by moving over 130 datasets, such as historical weather and lightning observation data, to industry partners' cloud-based systems

Source: GAO analysis of agencies' responses to questionnaires and agency documents. | GAO-21-104500

Strategic Objective 3: Future Computing Technologies

To establish a viable path forward for future HPC systems after the physical limitations of current semiconductor technology are reached, all three lead agencies (DOD, DOE, and NSF), both foundational R&D agencies (IARPA and NIST), and one deployment agency (NASA) were responsible for researching alternative computing technologies. For example, NSF, IARPA, NIST, and NASA conducted research related to quantum computing, which is the manipulation of bits of data using the behavior of individual atoms, molecules, or other quantum systems to potentially outperform high-performance computers. According to responses to questionnaires, NSF, IARPA, and NASA also conducted research on machine learning and artificial intelligence.

[19]NIST defines cloud computing as a means for enabling on-demand access to shared pools of configurable computing resources that can be rapidly provisioned and released. This approach offers federal agencies a way to buy computing services more quickly and possibly at a lower cost than building, operating, and maintaining computing resources themselves.

Some nonfederal stakeholders familiar with and some agencies responsible for this objective stated it is challenging to determine progress made towards the objective because the technologies are currently in early phases of development and will require years of R&D. According to the 2016 strategic plan, agencies will support R&D related to this objective over the next 10 to 20 years. Table 3 highlights examples of efforts that agencies implemented to support this objective. All efforts remain ongoing.

Table 3: Examples of Agency Efforts Implemented to Support Future Computing Technologies

Agency	Examples of efforts
Lead	
Department of Energy (DOE)	NSF and DOE signed a memorandum of understanding in 2019 to coordinate NSF's Quantum Leap Challenge Institutes and the DOE's National Quantum Information Science Research Centers in support of the National Quantum Initiative Act
National Science Foundation (NSF)	Supported a program that applies machine learning and artificial intelligence to better understand the impacts of urbanization, natural disasters, and climate change on natural ecosystems and city infrastructure
Foundational R&D agencies	
Intelligence Advanced Research Projects Activity	Conducted research across three programs, one of which explored ways to reduce the physical footprint, power, and cost required for conventional computing storage technologies
National Institute of Standards and Technology	Established a consortium of federal, academic, and industry partners to enable and grow a robust commercial quantum-based industry and associated supply chain in the United States
Deployment agencies	
National Aeronautics and Space Administration	Used quantum computing and other technologies with the potential to improve astronauts' ability to perform activities on the International Space Station and to support communication with unmanned aircraft systems

Source: GAO analysis of agencies' responses to questionnaires and agency documents. | GAO-21-104500

Strategic Objective 4: An Enduring HPC Ecosystem

According to the 2016 strategic plan, all three lead agencies (DOD, DOE, and NSF) and three of the five deployment agencies (NASA, NIH, and NOAA) were responsible for supporting efforts to increase the capacity and capability of an enduring national HPC ecosystem. According to responses to our questionnaires and agency documents, agency efforts included developing and investing in software and R&D, increasing availability of data and tools to the public, investing in workforce development, and creating interagency partnerships. Table 4 highlights examples of efforts that agencies implemented to support this objective, all of which agencies characterized as ongoing.

Table 4: Examples of Agency Efforts Implemented to Support an Enduring High-Performance Computing Ecosystem

Agency	Examples of efforts
Lead	
Department of Defense (DOD)	Funded the development, use, and maintenance of software to support its mission needs, which had impact on 100 air, land, and sea weapon system classes
Department of Energy (DOE)	Supported 34 projects to develop a new high-performance computing software ecosystem under its Exascale Computing Project, some of which is also used by the NSF-supported Texas Advanced Computer Center
National Science Foundation (NSF)	Launched a training program in fiscal year 2017 to prepare and grow the workforce for careers in cyberinfrastructure and, by fiscal year 2020, made 75 awards in addition to providing support for early career faculty and undergraduate researchers
Deployment	
National Aeronautics and Space Administration (NASA)	Collaborated with other agencies, such as DOE, NSF, and NOAA, on software ecosystem development to identify solutions that allow earth scientists to analyze and visualize large datasets associated with climate model outputs
National Institutes of Health (NIH)	Made publicly available the data, computational models, and software developed in partnership between NIH's National Cancer Institute and DOE, which led to the development of an open-source software platform that provides deep learning methodologies to accelerate cancer research, among other things
National Oceanic and Atmospheric Administration (NOAA)	Identified short and long-term needs to meet high-performance computing requirements and provided the high-performance computing infrastructure to meet its mission goals

Source: GAO analysis of agencies' responses to questionnaires and agency documents. | GAO-21-104500

Strategic Objective 5: Public-Private Collaboration

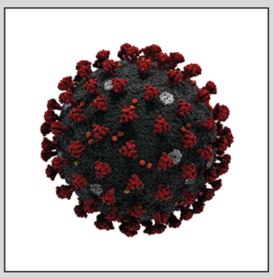
According to responses to our questionnaires, all 10 agencies identified in the 2016 strategic plan supported efforts to develop public-private collaboration. Under the 2016 strategic plan, the lead agencies' efforts could include efforts such as coordinating with other agencies on their 2016 strategic plan-related mission needs, convening technical exchanges, and issuing requests for information. Table 5 highlights examples of efforts implemented by lead agencies to support this objective.

Table 5: Examples of Lead Agency Efforts to Support Public-Private Collaboration under the 2016 Strategic Plan for the National Strategic Computing Initiative

Lead Agency	Example of efforts
Department of Defense	Created a suite of software tools for teaching the concepts of design and computational aerodynamic analysis, which over 120 companies and 20 academic institutions used as of 2021
Department of Energy	Partnered with National Institutes of Health's National Cancer Institute on a program to use high-performance computing and artificial intelligence to accelerate specific areas of cancer research, and participated in a public-private partnership that uses computational approaches to reduce the time needed to discover and develop new cancer medicines
National Science Foundation	Awarded graduate research students with internships to acquire the professional competencies and skills needed for careers in science, technology, engineering and mathematics

Source: GAO analysis of agencies' responses to questionnaires and agency document. | GAO-21-104500

The COVID-19 High Performance Computing Consortium



The Office of Science and Technology Policy and three of the National Strategic Computing Initiative agencies, including Department of Energy, National Science Foundation, and National Aeronautics and Space Administration, helped form the Coronavirus Disease 2019 (COVID-19) High Performance Computing (HPC) Consortium in March 2020. The consortium brought together more than 40 domestic and international members from the federal government, industry, and academia to provide researchers with free access to 600 petaflops of compute power to support COVID-19 research and develop methods to combat it. As of April 2021, the consortium had received applications for over 190 proposals and supported 100 projects such as using quantum simulation to identify and repurpose Food and Drug Administration-approved drugs to fight against COVID-19, and modeling the impact of public health measures on the COVID-19 variants.

Source: GAO analysis of agency documents and dehweh/stock.adobe.com (photo). | GAO-21-104500

According to the 2016 strategic plan, as part of their public-private collaboration, all agencies could participate in convening technical exchange forums, conferences, and panels with members of industry and academia. Besides participating in NITRD subcommittee and interagency working groups that led to the 2019 update to the NSCI and the 2020 strategic plan, agencies collaborated through workshops, used solicitations through the Small Business Innovation Research program to fund industry R&D, and issued requests for information (RFIs) to inform agency efforts, among others. For example, IARPA issued eight RFIs from fiscal years 2015 through 2019 on areas ranging from artificial intelligence and deep learning to future computing systems. According to the questionnaire responses and agency documents, OSTP and agencies such as DOE, NASA, and NSF formed the COVID-19 HPC Consortium with partners from industry and academia in direct response to the coronavirus pandemic. Similarly, as mentioned in table 3, NIST established a consortium of federal, academic, and industry partners to enable and grow a robust commercial quantum-based industry and associated supply chain in the United States.

Agencies Cited Challenges in Implementing 2016 Strategic Plan

Agencies cited challenges across the 2016 strategic plan's five strategic objectives related to COVID-19, funding, workforce, technology development, and industry partners and procurement. Agencies stated that they were able to overcome a few challenges but that most persist. According to interviews with officials and responses from questionnaires, COVID-19 created ongoing challenges for six of the 10 agencies because of travel restrictions, the need for remote work, human capital disruptions, and supply chain delays.[20] Multiple agencies cited COVID-19 as a challenge across all five objectives, and some agencies' efforts were affected more than others. For example, according to agency officials, COVID-19 had no effect on NIST's efforts but caused six months of delays at IARPA and required contract extensions and adjustments to testing schedules. To address COVID-19 challenges, NSF-funded laboratories enabled remote access to labs and changed the scope or timelines of research, and NASA rescheduled an in-person event to be held virtually. According to NIH officials, COVID-19 originally limited researchers' ability to enter labs but also helped to accelerate scientific discoveries. For example, agencies such as DOE, NASA, and NSF collaborated with industry and academic partners to provide researchers with free access to HPC resources to conduct research to fight COVID-19.

Most agencies cited lack of funding as a challenge across all five objectives in their responses to our questionnaires. According to agency officials, other than DOE's exascale efforts and an increase in funding for NSF that was not specific to any particular effort called for in the 2016 strategic plan, agencies did not receive additional funding to implement the strategic plan objectives. To help mitigate this challenge, agencies instead relied on existing funding to support the efforts called for in the 2016 strategic plan. Six agencies—DOE, DHS, IARPA, NASA, NIST, and NOAA—cited lack of funding as the greatest challenge to implementing the 2016 strategic plan objectives. For example, according to DOE officials, lack of funding for other agencies to do technology transfer of DOE's Exascale Computing Project to their mission work remains the greatest overall challenge. In addition, according to NIST officials, when they did not receive the funding they anticipated, the agency's R&D into alternative materials for chips slowed down.

[20]Specifically, DOD, DOE, NIH, NASA, NSF, and IARPA cited challenges related to COVID-19. NIST, DHS, FBI, and NOAA stated either that COVID-19 was not a particular challenge for their agency or did not list it as a challenge.

DOE, NASA, NIH, NIST, and NOAA cited challenges related to uncertainty over how to meet future funding needs across four objectives (all except public-private collaboration). For example, in their questionnaire responses, DOE, NASA, and NIST cited the need to fund long-term software maintenance at their agencies. To help address these challenges, DOE identified key elements in its Exascale Computing Project that will need to transition into other initiatives within DOE at the end of the project in 2024. According to NASA officials, NASA started an effort with scientists collaborating with each other to develop application software on new computing architectures to better maintain the software into the future.

According to questionnaire responses, DHS, NASA, NIST, NOAA, and NSF experienced workforce and human capital challenges across a combination of the five objectives. For example, NASA stated that finding qualified staff with experience in both quantum computing and earth science was a challenge. NIST stated that recruiting staff is challenging because academia and industry compete for the same pool of applicants with specialized expertise. Two nonfederal stakeholders stated that the broader field of HPC has an aging workforce and needs more training for the next generation of researchers. According to its questionnaire response, NASA currently conducts outreach to academic institutions to mitigate its workforce recruitment challenges.

NASA, NOAA, DOE, and NIST also cited technology development challenges across a combination of all of the 2016 strategic plan’s objectives except for the public-private collaboration objective. For example, DOE planned for Aurora to be the first exascale system delivered in 2021 but delayed it until 2022 because of technical problems. Specifically, according to DOE officials, an industry partner experienced technical challenges in manufacturing microprocessor chips. In addition, NASA cited challenges with the adoption of cloud computing, which required applications to be re-engineered. To mitigate this challenge, NASA is exploring applications that can leverage the advantages of the cloud computing model (that is, applications that are cloud native).

DOD, DOE, and NASA also cited challenges related to working with industry partners, such as the use of non-disclosure agreements limiting the flow of information and changes in industry partners’ technology roadmaps. For example, NASA cited numerous delays in hardware procurement for its long-term storage environments, including HPC, because of changing supply chain and country of origin requirements.

OSTP and Agencies Inconsistently Reported on Overall Progress Made towards Meeting the Objectives of the 2016 Strategic Plan

The executive order establishing NSCI required the executive council, co-chaired by the Directors of OMB and OSTP and including members from NSCI agencies, to document progress made in implementing the plan annually for five years from 2016 through 2020. OSTP officials stated that they were not aware of any reports prepared by the executive council that documented progress in accordance with this provision of the executive order. Instead, OSTP and agency officials described various other means they used to track or report on progress towards activities that align with the objectives of the 2016 strategic plan.

- **Joint Program Office.** OSTP officials stated that the executive council developed the NSCI governance model that created the joint program office to help facilitate the execution of the NSCI. According to OSTP officials, agencies initially tracked progress through the joint program office during monthly meetings where agencies were able to present on progress and achievements. According to officials from DOE and NSF, the joint program office exercised some oversight over agency efforts but stopped convening regularly after January 2017.[21] According to questionnaire responses and interviews with officials, agency involvement in the joint program office varied. For example, NASA stated that it presented on 2016 strategic plan progress to the joint program office two or three times, but DHS stated it was not involved.
- **NITRD budget supplement.** OSTP officials said they also tracked progress towards meeting the strategic plan's five objectives in an appendix in NITRD's annual supplement to the president's budget in fiscal year 2018. For instance, the 2018 supplement described 14 efforts made by DOD, DOE, IARPA, NASA, NIST, and NSF to support research on future computing technologies. It also described IARPA's demonstration of increased working memory technology related to its research into power and cooling technologies. However, subsequent NITRD supplements to the president's budget from fiscal year 2019 on did not include similar information, and OSTP officials stated that they were not aware of any other documentation of agencies' progress towards meeting the objectives of the 2016 strategic plan.
- **Internal agency program reviews and budgets**. According to questionnaire responses and our interviews with agency officials, NIH, NSF, and DOE reported progress of agency programs aligned with

[21]OSTP officials stated that the joint program office last met in June 2019 and subsequent meetings were cancelled in light of the NITRD Fast Track Action Committee on Strategic Computing meetings to support the writing of the *National Strategic Computing Initiative Update: Pioneering the Future of Computing*.

the 2016 strategic plan through program and project reviews and budget documents, but did not specifically report on agency progress towards meeting the objectives of the 2016 strategic plan. For example, in their questionnaire response, DOE provided progress reports on the Exascale Computing Project, which supports the 2016 strategic plan's exascale objective. NSF told us that they included updates on existing and new programs in their annual budget requests. NSF also tracked awards made to support the 2016 strategic plan, but stated that it had no formal report summarizing its efforts towards meeting the objectives of the strategic plan.

- **Working group presentations.** Agency officials stated that they shared information about their progress regarding high-end computing during NITRD working group meetings. According to responses to our questionnaires and interviews with agency officials, DOD, DOE, NSF, IARPA, NIST, NASA, NIH, and NOAA participated in NITRD's High End Computing Interagency Working Group where they shared information about their progress and plans each year, some of which could have included progress toward 2016 strategic plan objectives.

Some nonfederal stakeholders from academia and industry told us the lack of progress reports limited their visibility into the accomplishments achieved under the 2016 strategic plan and remaining work. As discussed further below, having a process for monitoring and reporting on progress is part of the desirable characteristics we have identified for an effective national strategy. By regularly reporting on progress and making such reports available to the public, OSTP, in its role leading interagency coordination efforts on science and technology policy, could help members of industry and academia better align their activities with agency efforts. Such reporting could also keep Congress informed of federal agency activities to sustain and enhance U.S. scientific, technological, and economic leadership in high-performance computing.

The 2020 Strategic Plan Addressed Few of the Desirable Characteristics of a National Strategy

As previously discussed, in November 2020, the NSTC Subcommittee on Future Advanced Computing Ecosystem issued "*Pioneering the Future Advanced Computing Ecosystem: A Strategic Plan*" (the 2020 strategic plan). The 2020 strategic plan, developed by the NSTC Subcommittee on Future Advanced Computing Ecosystem, outlined four objectives that broadly mirrored the 2015 executive order's strategic objectives. In our assessment of the plan, we found that it fully or substantially addressed two of the six desirable characteristics of a national strategy. Of the remaining four desirable characteristics, the plan partially addressed two and did not address the other two (see table 6).

Table 6: Extent to Which the 2020 Strategic Plan Addresses GAO Desirable Characteristics of a National Strategy

Desirable characteristic	Elements of the desirable characteristic	GAO assessment of the 2020 strategic plan against the elements of the desirable characteristic
Organizational roles, responsibilities, and coordination	Who will implement the strategy, what their roles will be, and mechanisms to coordinate their efforts	Fully addressed
Purpose, scope, and methodology	Why the strategy was produced, the scope of its coverage, the process by which it was developed, and how it compares and contrasts with other national strategies	Substantially addressed
Goals, subordinate objectives, activities, and performance measures	What the strategy is trying to achieve, steps to achieve those results; the priorities, milestones, and performance measures that include targets to measure results and help ensure accountability; and a process for monitoring and reporting on progress	Partially addressed
Problem definition and risk assessment	What the particular national problems are, assessments of the risks to critical assets and operations—including the threats to, and vulnerabilities of, critical operations—and discussion of the quality of the risk assessment data	Partially addressed
Resources, investments, and risk management	What the strategy will cost, the types of resources and investments needed, and where resources and investments should be targeted based on balancing risk reductions with costs	Did not address
Integration and implementation	How a national strategy relates to other strategies' goals, objectives, and activities and to subordinate levels of government and their plans to implement the strategy	Did not address

Legend:

Fully addressed = Addressed all of the elements of the desirable characteristic

Substantially addressed = Addressed more than half of the elements of the desirable characteristic

Partially addressed = Addressed half or less than half of the elements of the desirable characteristic

Did not address = Addressed none of the elements of the desirable characteristic

Sources: GAO analysis of agency document. | GAO-21-104500

Note: We assessed the National Science and Technology Council's *Pioneering the Future Advanced Computing Ecosystem: A Strategic Plan* (Washington, D.C.: 2020) against the elements of the desirable characteristics in GAO-04-408T.

In previous work, we identified six desirable characteristics of an effective national strategy.[22] These six characteristics consist of elements such as scope and mechanisms for coordination that, when included in a national strategy, help federal agencies implement the strategy and achieve its goals. By their nature, national strategies aim to provide broad direction and guidance rather than prescriptive, detailed mandates to the relevant implementing parties. Nonetheless, as previously reported, the more

[22] GAO-04-408T.

detail a strategy provides, the easier it is for the responsible parties to implement and achieve its goals.

2020 Plan Fully or Substantially Addressed Two Characteristics

The 2020 strategic plan fully addressed organizational roles, responsibilities, and coordination and substantially addressed purpose, scope, and methodology.[23]

Organizational roles, responsibilities, and coordination—fully addressed. The 2020 strategic plan included all of the elements that make up this desirable characteristic. In particular, it fully described who will implement the strategy, what their roles will be, and mechanisms to coordinate their efforts. The plan defined three types of agencies participating in HPC development—lead, foundational R&D, and deployment agencies—and assigned to them the roles and responsibilities consistent with those assigned in the 2016 strategic plan. Further, the plan described how each type of agency should work together, such as lead agencies collaborating with foundational R&D agencies to develop and deploy future advanced computing technologies. It also described lead agencies developing the workforce to support the objectives of the strategic plan and how foundational R&D and deployment agencies will partner with academia and industry to address goals such as workforce development and commercialization of technology.

Purpose, scope, and methodology—substantially addressed. The 2020 strategic plan described why the plan was produced, stating it envisions a future advanced computing ecosystem that provides the foundation for continuing American leadership in science and engineering, economic competitiveness, and national security. In addition, the plan clearly outlined major function and mission areas and activities that are within its scope. For example, according to the plan, NASA's program for landing American astronauts, including the first woman, on the moon by 2024 and sending American astronauts to Mars requires a future advanced computing ecosystem to enable the next generation of human space exploration.

Further, the 2020 strategic plan detailed the process agencies used to develop it and described the executive order, the 2019 update, and

[23]We determined that the 2020 strategic plan fully addressed a desirable characteristic if it included all of the elements that make up the characteristic and substantially addressed a desirable characteristic if it included a majority of the elements.

committees that were fundamental in shaping the plan's objectives.[24] For example, the plan described how it incorporated input from government, academia, nonprofits, and industry sectors. According to nonfederal stakeholders we interviewed, the interagency working group responsible for producing the 2020 strategic plan provided opportunities for all involved sectors including those from academia and industry to provide input on the creation of the plan. These opportunities included workshops, RFIs, and opportunities for providing comments directly to the interagency working group on the draft of the plan.

However, according to our analysis, the 2020 strategic plan did not fully address the purpose, scope, and methodology characteristic because it did not compare or contrast its purpose with that of other national strategies, such as the American Artificial Intelligence Initiative and the National Quantum Initiative. A national strategy that compares and contrasts to other related strategies can help ensure agencies will collaborate on common areas of interest and activity.

2020 Plan Partially Addressed Two Characteristics

The 2020 strategic plan partially addressed the characteristics of goals, subordinate objectives and performance measures, as well as problem definition and risk assessment.[25]

Goals, subordinate objectives and performance measures—partially addressed. The 2020 strategic plan stated its overall goals, subordinate objectives, and the activities that will be undertaken to achieve those outcomes. For example, the plan's strategic objectives included promotion of a robust, sustainable software and data ecosystem and a subordinate objective to promote and practice robust, proactive information-security procedures. Establishing clear desired results can help implementing agencies track progress towards meeting the goals of a national strategy.

However, we determined some elements of this desirable characteristic were not included in the plan. Specifically, the plan did not contain performance measures or a process for monitoring and reporting on progress, which are two elements of this desirable characteristic. OSTP officials told us the 2020 strategic plan did not include a process for

[24]Executive Order No. 13702; OSTP, National Science and Technology Council, *National Strategic Computing Initiative Update: Pioneering the Future of Computing,* November 2019.

[25]We determined that the 2020 strategic plan partially addressed a desirable characteristic if it included less than a majority of the elements that make up the characteristic.

monitoring because the agencies' focus when drafting the plan was on the high-level strategic goals and that they planned to provide implementation details in a later document. According to OSTP officials, as of July 2021, the NITRD High End Computing Interagency Working Group was developing a supplemental implementation roadmap. Officials told us they expected to complete the roadmap later in 2021 but did not anticipate this plan would include performance measures or a process for monitoring.

Without the 2020 strategic plan including provisions for monitoring and reporting on progress, Congress, federal agencies, industry, and academia may not have full visibility into the completed activities and remaining work to achieve the objectives of the strategic plan. In particular, as noted previously, NITRD's annual Supplement to the President's Budget in fiscal year 2018 provided a summary of NSCI accomplishments in fiscal year 2016 but did not include similar information in subsequent years. Stakeholders from academia and industry told us the lack of progress reports limited their visibility on accomplishments achieved under the 2016 strategic plan. Having progress reports would help stakeholders coordinate and align their activities with federal efforts.

Problem definition and risk assessment—partially addressed. The 2020 strategic plan defined challenges to the continuation of U.S. leadership in HPC, such as growth in the scale and availability of data and the resulting need for data-intensive computing. However, the plan did not discuss elements of risk assessment, such as consideration of the vulnerabilities of an advanced computing ecosystem to cybersecurity attacks or other threats that could take advantage of those vulnerabilities.

National strategies that do not analyze threats and risks can limit management decisions about resource allocations required to minimize risks and maximize returns on resources expended. If the details of these analyses are classified, an unclassified version of the strategy could include a broad description of the analyses and stress the importance of risk assessment to implementing parties. By including a risk assessment in a strategic plan or its supplemental documents, agencies are better positioned to take specific actions to allocate and manage the appropriate resources to minimize risks and therefore enhance the ability of agencies to achieve the objectives of the strategy.

2020 Plan Did Not Address Two Characteristics

The 2020 strategic plan did not address the characteristics of resources, investments, and risk management, or integration and implementation.[26]

Resources, investments, and risk management desirable characteristic—did not address. The 2020 strategic plan did not describe resources or investments needed. For example, it did not provide a cost estimate for its overall implementation, define funding needs, or provide cost estimates for its specific proposed objectives or activities. In general, we found that the plan did not include details, such as the level of agency resources and investments needed to support proposed actions. As a result, it is not clear how proposed actions will be funded and sustained in the future, which was one of the challenges to implementation of the 2016 plan that agencies cited. OSTP and many agency officials told us that the nature of R&D makes it difficult to understand and anticipate costs and that it is therefore difficult to include costs and resources in a strategic plan.

Nevertheless, without some cost estimates, it is impossible to perform a cost-benefit analysis or provide Congress with the necessary information to understand the full amount of funding needed. NITRD budget supplements provided an overview of costs associated with certain programs. For example, agencies report to NITRD budget amounts related to high-end computing. However, NITRD budget supplements for fiscal years 2019 through 2021 did not discuss how the high-end computing budget amounts related to the NSCI.

The plan did not address how, or whether, agencies will implement risk management strategies. We have reported on enterprise risk management principles that can support enterprise-wide decision-making under complex and uncertain conditions.[27] For areas like HPC, where activities cut across multiple federal and nonfederal entities, risk management becomes more challenging but is still important for

[26]We determined that the 2020 strategic plan did not address a desirable characteristic if it did not include any of the elements that make up the characteristic.

[27]GAO, *National Biodefense Strategy: Additional Efforts Would Enhance Likelihood of Effective Implementation,* GAO-20-273 (Washington, DC: Feb. 19, 2020). GAO, *Enterprise Risk Management: Selected Agencies' Experiences Illustrate Good Practices in Managing Risk,* GAO-17-63 (Washington, D.C.: Dec. 1, 2016). The basic elements of enterprise risk management are (1) aligning the enterprise risk management process to goals and objectives, (2) identifying risks, (3) assessing risks, (4) selecting a risk response, (5) monitoring risks, and (6) communicating and reporting risks.

responsible parties to be able to make decisions that help to ensure effectiveness and maximize opportunities to better manage risk.

Integration and implementation—did not address. The 2020 strategic plan stated that it was intended to complement the objectives and activities of other initiatives and national priorities, such as the American Artificial Intelligence Initiative and National Quantum Initiative. However, it did not describe how these related initiatives and priorities are to work with the plan, such as how the interrelated initiatives will share funding or other resources.

In addition, the 2020 strategic plan described, at a high-level, the plan's implementation and the NSCI agencies that will implement it, but did not assign specific activities to agencies, as the 2016 strategic plan had done. Officials from DOE, who served on the Subcommittee on Future Advanced Computing Ecosystem and were involved in drafting the 2020 strategic plan, told us they deliberately left the discussion of implementation broad to elicit initial interagency buy-in for the plan. As discussed earlier, OSTP officials told us that agencies were focused on the high-level strategic objectives when developing the 2020 strategic plan and planned to focus on the implementation steps in an implementation roadmap to be issued later in 2021.

National strategies that do not include details on the relationships among various related initiatives and national strategies, and the agencies responsible for implementing those strategies, run the risk of not being able to foster effective implementation and accountability. Including details about how a national strategy compares and contrasts with other national strategies can help ensure that agencies work together in achieving outcomes and avoid unnecessary overlap or duplication of efforts.

Conclusions

Federal agencies charged with implementing the NSCI made significant advances toward implementing the objectives of the original strategic plan from 2016. In particular, DOE expects to deliver the first of its three exascale systems in 2021—a step toward achieving the strategic plan's objective to accelerate the delivery of a capable exascale computing system by the mid-2020s. In collaborating on the November 2020 update to the strategic plan, the NSTC Subcommittee on Future Advanced Computing Ecosystem, which includes representatives from OSTP, all NSCI agencies, and OMB, developed a vision of a future advanced computing ecosystem and American leadership to achieve priorities in science and engineering, economic competitiveness, and national security.

As of July 2021, OSTP and all NSCI agencies were working on an implementation roadmap for the 2020 strategic plan. By including desirable characteristics of a national strategy in the upcoming implementation roadmap or in future iterations of the 2020 strategic plan, the agencies can improve their ability to achieve the 2020 plan's goals. The implementation roadmap could address elements that the 2020 plan partially addressed or did not address, such as how it integrates with related national strategies, the resources needed to implement it, or a process for monitoring and reporting on progress. OSTP is well-positioned to lead such an effort because it leads interagency coordination efforts on science and technology policy. Similarly, OSTP is well-positioned to coordinate agencies to provide annual reporting on implementation of the 2020 plan. For example, OSTP reported on progress toward meeting the objectives of the 2016 strategic plan in its fiscal year 2018 budget supplement and could provide similar information for the 2020 strategic plan in future budget supplements. Such information could help Congress and the public gain a better understanding of the efforts made by federal agencies to sustain and enhance U.S. scientific, technological, and economic leadership in high-performance computing.

Recommendations for Executive Action

We are making two recommendations to OSTP:

The Director of OSTP should address each of the desirable characteristics of a national strategy, as practicable, in the implementation roadmap for the 2020 strategic plan or through other means. (Recommendation 1)

The Director of OSTP, in consultation with the 10 NSCI agencies, should prepare publically available annual reports assessing progress made in implementing the 2020 strategic plan on the future advanced computing ecosystem. (Recommendation 2)

Agency Comments and Our Evaluation

We provided a draft of this report to OSTP, OMB, and the 10 NSCI agencies for their review and comment. We received comments via email from OSTP that are summarized below. OSTP, OMB, DOE, NASA, NIST, and NOAA also provided technical comments, which we incorporated as appropriate. The remaining agencies stated that they had no comments.

In its emailed comments, OSTP concurred with our recommendations. In response to our first recommendation, OSTP stated that it will address the desirable characteristics of a national strategy, as practicable, in the upcoming implementation roadmap for the 2020 strategic plan, with the exception of characteristics that it considers to not be reasonable for inclusion in federal strategies. In particular, OSTP stated that within the federal government, the strategy development process is separate from and takes place in advance of the budget formulation and appropriations process and that as a result, federal strategies do not include proposed costs or levels of investment. OSTP also stated that agencies do not typically commit to specific milestones or objectives until they have a budget and that it is difficult for agencies to make multiyear commitments because of how the budget and appropriations process is implemented. OSTP stated that details on milestones and objectives are therefore best left to an implementation plan once agency appropriations are known. In response to our second recommendation, OSTP stated that it will publish an annual report on progress toward implementing the 2020 strategic plan on the future advanced computing ecosystem.

We recognize the limitations on the ability of federal agencies to commit to levels of investment and specific milestones and objectives in a national strategy. Nevertheless, we believe we have addressed OSTP's concerns regarding the desirable characteristics for an effective national strategy by allowing for flexibility in how OSTP can implement our recommendation. In particular, we recommended that the Director of OSTP should address each of the desirable characteristics of a national strategy *as practicable*, giving the Director flexibility regarding the type of information and level of detail required. In addition, our recommendation allows OSTP to address it through the implementation roadmap for the 2020 strategic plan or through other means, and does not specify a timeframe for OSTP to address the recommendation. We encourage OSTP to use this flexibility to address each of the six desirable characteristics to the extent practicable in the upcoming implementation roadmap for the 2020 strategic plan.

We are sending copies of this report to the appropriate congressional committees, the Directors of the OSTP, FBI, IARPA, and NSF; acting Director of OMB; the Secretaries of Commerce, Defense, Energy, Health and Human Services, and Homeland Security; the Administrator of NASA; and other interested parties. In addition, the report is available at no charge on the GAO website at http://www.gao.gov.

If you or your staff have any questions about this report, please contact me at (202) 512-6888 or wrightc@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix II.

Sincerely yours,

Candice N. Wright

Candice N. Wright
Director, Science, Technology Assessment,
and Analytics

Appendix I: Objectives, Scope, Methodology

Our objectives were to examine (1) what steps agencies have taken to meet the objectives of the 2016 strategic plan and how OSTP and agencies reported on progress; and (2) the extent to which the "*Pioneering the Future Advanced Computing Ecosystem: A Strategic Plan*" (2020 strategic plan) includes desirable characteristics of a national strategy.

The scope of our review included the Office of Management and Budget (OMB) and the Office of Science and Technology Policy (OSTP), as co-chairs of the National Strategic Computing Initiative (NSCI) Executive Council, and the 10 federal agencies listed in the 2015 executive order:

- Three lead agencies—Department of Defense (DOD), Department of Energy (DOE), and National Science Foundation (NSF);
- Two foundational research and development (R&D) agencies—Intelligence Advanced Research Projects Activity (IARPA) and National Institute of Standards and Technology (NIST); and
- Five deployment agencies—Department of Homeland Security (DHS), Federal Bureau of Investigation (FBI), National Aeronautics and Space Administration (NASA), National Institutes of Health (NIH), and National Oceanic and Atmospheric Administration (NOAA).[1]

To examine the steps agencies took and how OSTP and agencies reported on progress towards meeting the objectives of the 2016 strategic plan, we sent a questionnaire to all 10 federal agencies (or NSCI agencies) in our scope and asked them about the status of their efforts to meet the strategic objectives of the NSCI. The questionnaire included questions for each of the five strategic objectives and the specific activities that the 2016 strategic plan listed for the federal agencies to conduct under each strategic objective. We asked each agency to summarize the programs, grants, contracts, and other efforts that they undertook toward implementing the strategic objectives from July 2015 through March 2021. We also asked agencies to identify funds obligated, accomplishments, collaboration with other entities, and challenges associated with their activities under each strategic objective. To assess the reliability of funding amounts we asked the agencies to provide documentation to corroborate their funding amounts. We also examined fiscal years 2017 through 2020 budget information submitted as part of the president's budget request to further corroborate agency reported funding. We determined that the reliability of the provided data was

[1]The scope of our work is limited to unclassified agency activities.

sufficient to illustrate the size and scope of those efforts. We asked the agencies to identify what activities conducted by the agency fell within the scope of the 2016 strategic plan. We pretested the questionnaire with two lead agencies (DOD and DOE), one foundational R&D agency (NIST), and one deployment agency (NASA), and modified the questionnaire as appropriate to help ensure that the questions were clear and that agency officials could provide the information within requested timeframes.

To obtain additional information about agency efforts identified in the questionnaire responses, we reviewed documentation, such as agency websites and reports, and interviewed agency officials. For each strategic objective in the 2016 strategic plan, we identified illustrative examples of selected agency efforts to highlight in our report based on factors such as the size and scope of the effort and the variation in stakeholders involved in the effort.

To examine the extent to which the 2020 strategic plan includes desirable characteristics of a national strategy, we reviewed the contents of the *Pioneering the Future Advance Computing Ecosystem: A Strategic Plan* issued in November 2020 (2020 strategic plan) to determine the extent to which it addresses the elements of a set of six desirable characteristics for an effective national strategy that we identified in our past work.[2] We have previously assessed the extent to which a variety of national strategies, including those for advancing science and technology, addressed these desirable characteristics.[3] For our review of the 2020 strategic plan, two analysts conducted separate assessments of the 2020 strategic plan using a four-point scale to rate the inclusion of each element of the desirable characteristic in the strategy. We determined that the plan fully addressed a characteristic when it included all elements of that characteristic; substantially addressed a characteristic when it addressed a majority of the elements of that characteristic; partially addressed a characteristic when it included some, but less than a majority of elements of the characteristic; and did not address a characteristic when it did not include any elements of the characteristic. The two analysts met to determine whether their individual assessments were in

[2]GAO, *Combating Terrorism: Evaluation of Selected Characteristics in National Strategies Related to Terrorism*, GAO-04-408T (Washington, D.C.: Feb. 3, 2004).

[3]For example, in October 2020, we reported that the national strategy for securing the infrastructure for the fifth generation of mobile communication networks (5G) partially addressed five of the desirable characteristics but did not discuss what it would cost. See: GAO, *National Security: Additional Actions Needed to Ensure Effectiveness of 5G Strategy*, GAO-21-155R (Washington, D.C.: Oct. 7, 2020).

agreement with each other. In cases where the first two analysts differed, a third analyst reviewed the assessments and made an independent assessment of any elements where the first two analysts were not in agreement. Finally, all three analysts reached consensus on the assessments of each desirable characteristic.

For both objectives, we interviewed federal agency officials and reviewed federal laws relating to high-performance computing, Executive Order 13702 establishing the NSCI, and agency documentation, such as agencies' congressional budget requests, project progress reports, the 2016 and 2020 strategic plans, and the 2019 update to the 2016 strategic plan. We interviewed officials from OSTP and the 10 NSCI agencies listed in the 2016 strategic plan about the creation of both the 2016 and 2020 strategic plans as well as follow-up questions related to progress towards the 2016 strategic plan objectives. We obtained written responses from OMB discussing its implementation of the strategic plans. We also interviewed a nongeneralizable sample of 10 nonfederal stakeholders to discuss their perspectives about federal agencies' implementation of the strategic plans. We selected these nonfederal stakeholders to represent a diversity of viewpoints from individuals who had participated in planning meetings regarding high performance computing (HPC) that led up to the November 2019 update and 2020 strategic plan, respectively. Six of the 10 nonfederal stakeholders were from academia and their research encompassed hardware and software, including HPC architecture, software applications, and workforce issues. Three of the 10 nonfederal stakeholders represented companies that manufactured semiconductor chips and systems for HPC. We also interviewed a representative of an electrical engineering trade association. The views of these stakeholders are not generalizable to all nonfederal stakeholders that participated in the HPC planning meetings but provide a variety of viewpoints and knowledgeable opinions. When summarizing responses from the 10 NSCI agencies or the 10 nonfederal stakeholders, we used "some" to refer to two to five agencies or stakeholders and "most" to refer to six to nine.

We conducted this performance audit from August 2020 to September 2021 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Appendix II: GAO Contact and Staff Acknowledgments

GAO Contact

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Staff Acknowledgments

In addition to the contact named above, Joseph Cook (Assistant Director), Arvin Wu (Analyst in Charge), Lauren Lochocki, and Calaera Powroznik made key contributions to this report. Also contributing to this work were Cheron Brooks, Virginia Chanley, Louise Fickel, Amy Pereira, and Sarah Veale.

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