# ENSURING U.S. LEADERSHIP IN A COMPETITIVE FUTURE

NATIONAL LABORATORY DIRECTORS COUNCIL

JULY 2024

# ENSURING U.S. LEADERSHIP IN A COMPETITIVE FUTURE

July 2024

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**Throughout the second half of the 20th century, the United States enjoyed an enviable position in the international sphere. As the undisputed global leader economically, technologically, and militarily, with firm commitments to democratic values and the free market, countries around the world looked to America as a shining example of freedom and opportunity. Many still do.**

In the first quarter of the 21st century, however, rivalries with nations that have different political and economic philosophies have created competition for ideas, facilities, technology, and talent. Hopes for a new, more stable and economically prosperous security environment have been undermined by an erosion of the rules-based international order and aggressive actions from historic adversaries like Russia and emerging peer competitors like China.

China presents a unique challenge; it has a far larger population than the United States and a comparable economic output. It also has significant and rapidly expanding military capability and a demonstrated willingness to invest heavily in science and technology (S&T) research and development with the goal of achieving global leadership in strategic areas.

They may be well on their way. The title of an article in the June 12, 2024 issue of The Economist asserts that "China has become a scientific superpower." In 2003, the United States produced 20 times more high-impact scientific papers than did China. By 2022, China achieved parity with the U.S. and has since surpassed it. China is already also home to some world-leading facilities as well, including the most sensitive ultra-high-energy cosmic ray detector and soon one of the world's most sensitive neutrino detectors. The U.S. must respond in such a way that ensures global leadership while striking an appropriate balance between robust international engagement and fostering a managed research ecosystem that is cognizant of research security risks.

The pace of scientific and technological discovery has never been faster. Today's new technologies will transform society, generate prosperity, and determine security. Mastery of these technologies is a prerequisite for future global leadership.

Thus, we are at a crucial moment in history, one that will determine whether the U.S. and its vision for prosperity and security remains at the forefront of innovation. To compete effectively and sustain and advance U.S. leadership, the nation must lean into its core strengths. These strengths include an unparalleled innovation ecosystem that has long attracted the best and brightest from around the world, fueled by major investments in fundamental and translational research to ensure leadership in strategic areas of S&T and collaboration among the country's strong private sector, academia, and government research laboratories. If we invest effectively in the pathways of discovery and redouble efforts to translate those discoveries to U.S.-led innovations, the nation will continue to prosper and have the capability to protect the values we hold dear.

The U.S. has a big advantage in the global push for new horizons of opportunity: the U.S. Department of Energy (DOE) national laboratories. National labs are critical strategic assets in this international competition. The excellent mission-focused multidisciplinary workforce and scientific infrastructure built out over last 80 years in the U.S. has been extremely successful—producing solutions to important national challenges, new ideas, innovative technologies, and world-class facilities and capabilities. The time has come for a renewed commitment and a future-focused strategy. We must think big about the challenges that face the nation and the world, and the most important questions in science that will continue to drive discovery, innovation, and positive societal impacts. The national labs are ready for the challenge, taking their efforts to the next level with greater strategic clarity, accelerated innovation, and a robust focus on research security.

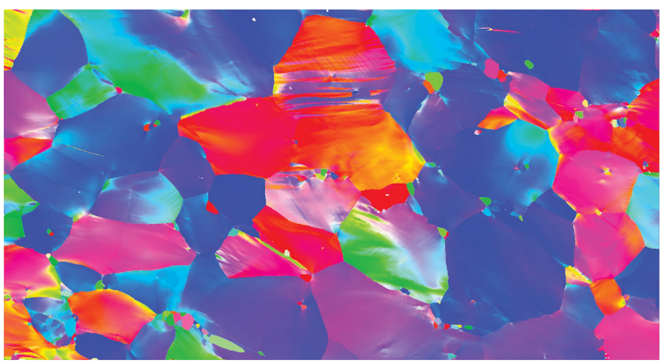
Together, the national labs work to achieve DOE's primary mission: to ensure America's security and prosperity by addressing its energy, environmental, and nuclear challenges through transformative S&T solutions. The national labs contain a cadre of researchers dedicated to fulfilling the DOE's mission. The scientific expertise that these researchers provide to agencies and missions across the government is an essential strength of the national lab system. National labs can convene multidisciplinary teams to focus on large-scale, complex challenges that often require years of focused effort to overcome.

The national labs are an important bridge between academic institutions, where education and advancing the frontiers of understanding are the goal, and industry, where new technologies can be quickly scaled and brought into the marketplace. These efforts also fuel the talent pipeline for the U.S. innovation ecosystem.

The scientific infrastructure developed and advanced by the national labs expands their reach. An important component of America's international competitiveness, this infrastructure provides powerful capabilities to academic and industrial researchers from around the nation and the world. The national labs also play an important role in training the S&T workforce of the future; together, they train thousands of students and postdoctoral researchers in key areas of S&T, building their expertise in areas relevant to the DOE missions, and providing opportunities to participate in multidisciplinary team science.

Nations around the world seek to emulate the DOE national lab system, a critical engine of innovation that drives world-leading S&T, economic competitiveness, and robust national security. Investing in this formidable innovation ecosystem will lay an essential foundation for U.S. leadership in the 21st century and beyond. Necessary investments include core infrastructure at the national labs, such as buildings and utilities, to support the sustained impact of the national labs and their contributions to continued U.S. innovation and competitiveness.

## ACCELERATING DISCOVERY AND ADVANCING TECHNOLOGY



**Crystal lattice of a "super alloy" made at Lawrence Berkeley National Lab with remarkable toughness at a wide range of temperatures, making it a candidate material for highly efficient next-generation aerospace engines**

### CURRENT STATE

The national laboratories pursue S&T goals that help to answer some of our biggest questions. "How do we get more energy from the sun?" leads to a technical challenge: "Can we control nuclear fusion, generating the sun's power, here on earth?" The question "can computers keep getting faster?" leads to investigations of quantum computing and better materials for classical computing. "When will I have a robot assistant?" leads us to questions of how artificial intelligence (AI) can be used to accelerate scientific endeavors, and how S&T can more quickly and accurately move from discovery science to applications that enhance the human condition. "What is the universe made of?" drives science in high-energy and nuclear physics, two of the core physics capabilities stewarded by the DOE, as research in those areas expands our understanding of the basic laws of nature.

The national labs have demonstrated leadership in many forefront areas of science, and in translating scientific discoveries to technical innovation. An expanding list of new and quickly developing technologies, such as quantum information science, AI, computing beyond exascale, microelectronics, fusion, advanced materials and manufacturing, bioengineering, and geoengineering, are quickly reshaping the global scientific landscape, and are emerging as contested domains of intellectual and economic leadership. Ceding leadership in these developing technologies would inevitably lead to a decline in U.S. global power. Accelerating progress in these scientific fields (and translating discoveries to impact), however, will take concerted efforts across the U.S. scientific ecosystem, with the DOE national labs providing unique capabilities through their distinct expertise and infrastructure, as highlighted below.

In many of these areas, this acceleration will also require focused R&D efforts to overcome key technical hurdles. Working closely with U.S. industry and the global scientific community, the DOE national labs play a unique role in keeping the U.S. at the forefront of these fields and preventing technological surprises that could impact national and economic security. To support American science leadership, it is important to adopt new modes of collaboration across sectors that unleash discovery and help to create impactful technological advances. Here we highlight seven areas where innovation is critical for the U.S. to succeed in today's highly competitive international landscape.

### OPPORTUNITIES

#### Energy-Efficient Post-Exascale Ecosystem

DOE has a congressionally mandated responsibility to drive the frontier of leadership computing for the nation, but current approaches are reaching the limits of computational performance per unit of power as Moore's law ends. The energy demands of algorithms (for example, for generative AI, large-language models, big data analytics, and high-fidelity modeling and simulation) require technical advances and the deployment of emerging, revolutionary, and energy-efficient computing technologies. This new and important technology will enable the expanded computational capabilities that underpin almost all aspects of the DOE mission. The national labs need to work with industry to tackle this pressing energy challenge. Advanced co-design and integration of energy-efficient hardware and software solutions will drive an energy-efficient computational ecosystem for the nation, which will include elements such as next-generation microelectronics and quantum computing.

### Semiconductors and Microelectronics

Features on advanced modern chips are only a few atoms across, which means we are reaching the fundamental limits of current microelectronics technology. To increase computing efficiency, we face the unprecedented challenge of redesigning the entire microelectronics innovation process, which has been based on a robust 70-year history of miniaturization in silicon. New devices, materials, and architectures that are capable of orders-of-magnitude improvements must be discovered and implemented over the next decade. Innovative nanoscale manufacturing techniques must be developed to commercialize these discoveries.

The national labs have a long history of being microelectronics innovators, co-designers with industry, and consumers. In the process, the labs have produced numerous technological breakthroughs, such as extreme ultraviolet lithography, that are now integral to the microelectronics industry. With their large scientific workforce with expertise across needed disciplines (such as computing, device physics, and materials), and an extensive network of powerful research capabilities, the national labs will develop new energy-efficient computing paradigms, including analog computing, non-volatile storage devices, domain-specific accelerators, and photonic interconnection networks.

### Quantum Information Science

Quantum information science (see sidebar on page 4) holds great promise to transform many fields of technology and innovation, including ultra-precise sensors, secure communications and networks, and extraordinarily fast, energy-efficient quantum computers.

### Artificial Intelligence (AI)

Generative AI capabilities (such as ChatGPT) have created new applications in many sectors, including finance, retail, entertainment, graphic design, and marketing. Generative AI also has the potential to confront challenges central to DOE efforts in scientific discovery, climate research, energy, and national security. Indeed, AI can significantly accelerate the pace of scientific discovery itself.

DOE has a world-leading research ecosystem that can develop trustworthy, secure, and energy-efficient AI systems that both advance the DOE mission and serve the national interest. This endeavor will build on national lab strengths in high-performance computing, unique and large scientific and classified datasets, and longstanding mission-driven industry partnerships.

### Scientific Laboratories of the Future

Accelerated S&T innovation is a key driver for U.S. global competitiveness. It requires sophisticated integration of scientific information from across diverse fields and from geographically distributed research facilities and data repositories. Today's research infrastructure is typically locally operated, producing heterogeneous datasets, and researchers lack tools to access and integrate across the diverse assets at scale. To overcome these challenges, DOE is developing a world-leading exemplar for "integrated scientific laboratories of the future." This integration will empower researchers to seamlessly and securely meld DOE's world-class research tools, infrastructure, experimental, computing, and networking facilities, and related data assets in novel ways to radically accelerate discovery and innovation.

Development of this scientific laboratory of the future concept will transform how investigators perform research. This new model for research will require advances and integration of a range of emerging technologies including AI, robotics, high-performance computing, large/heterogeneous data strategies, edge tools, and workflows. It is envisioned that the model will eventually extend beyond national labs to universities and industry.

### Fusion Energy

Fusion energy has the potential to be a scalable, on-demand, and zero-carbon source of primary energy. Recent breakthroughs at the national labs showcase the potential that fusion holds as an innovative energy security strategy for the nation, and these breakthroughs have attracted significant private investment. They have also inspired a national "bold decadal vision" for the achievement of commercial fusion energy.[1] However, although numerous companies and other organizations are pursuing various routes to fusion energy, none has the capacity to carry out the foundational research required for success. This is the role of the DOE. In fact, DOE fusion programs have developed an impressive science-based predictive capability that has powered the fusion breakthroughs. However, additional key S&T breakthroughs are still needed to enable fusion as a practical energy source.

The DOE is a world leader in fusion science both through the National Ignition Facility, the National Spherical Tokamak Experiment, and in partnership internationally through the ITER project. The goal of this work is to answer the remaining scientific questions that will enable the U.S. to design and build the first fusion pilot plant. AI trained on predictive models is already being used to search for

1 www.whitehouse.gov/ostp/news-updates/2022/04/19/readout-of-the-white-house-summit-on-developing-a-bold-decadal-vision-for-commercial-fusion-energy

the optimum fusion system. A successful fusion future will address an increasingly large fraction of the electricity market. DOE has a unique, timely, and important opportunity to ensure U.S. energy security in the coming decades by accelerating needed scientific advances across technical readiness levels and public-private partnerships.

### The Omics Revolution

The Human Genome Project launched the field of genomics, transformed medicine, and helped give birth to the modern biotechnology industry.[2] DOE national labs remain a major force in spurring the technology development and innovation that have transformed genomic sequencing into a routine tool of science, medicine, and industry. This created an explosion in "omics" techniques, gene-based metabolic analyses, design of new pathways, and a host of new systems approaches to understanding biology.

Genomic science is now an integral part of biological research, whether performed in a test tube, investigated in the environment, or used to improve industrial bioprocesses. In realizing the benefit of the next generation of synthetic biology tools, combined with the power of bioinformatics and advanced AI, simulation and modeling tools, the national labs provide a powerful suite of capabilities and a managed research approach essential to realizing benefits for the economy, while safeguarding against risks.

## FUTURE STATE

Part of the ebb and flow of history rests on the way S&T transforms societies. The 2007 study from the National Academies, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* described the status of S&T in the U.S. at that time: "Having reviewed trends in the United States and abroad, the committee is deeply concerned that the scientific and technological building blocks critical to our economic leadership are eroding at a time when many other nations are gathering strength."[3]

Today we stand at a critical crossroad where our leadership is threatened, and in some areas is slipping away; the storm in the title has arrived. For the U.S. to continue competing intellectually, technologically, and economically, we must rise to the challenges of leading across the broad spectrum of S&T—including the areas outlined above—that underlies *all* national competitiveness and security. If we are to compete today and into the future, we must be nimble in our approach to S&T, enabling multiple approaches to R&D; invest in our world-leading research facilities; foster an environment of transdisciplinary and large-team research to engage opportunities; enable broader laboratory-industry interactions; train early-career scientists and engineers to lead in their fields; and pursue the best and most compelling S&T in the world with a sense of urgency and vigor.

Finally, we must invest to advance S&T. As a recent report from the International Monetary Fund stated, "Basic scientific research is a key driver of innovation and productivity, and basic scientific knowledge diffuses internationally farther than applied knowledge. A 10 percent increase in domestic (foreign) basic research is estimated to raise productivity by about 0.3 (0.6) percent, on average."[4]

Our future depends on such investments.

### Quantum Information Science

In 1981, the profound shock of the first quantum revolution—the ingredient physicists call "entanglement"—led physicist Richard Feynman to suggest that a quantum computer could be developed. Today, after several decades of theory, experiments, and innovation, we are nearing the advent of practical, error-free, quantum computing.

Creating a useful quantum device takes a truly broad and transdisciplinary team, including computer scientists, device physicists, atomic physicists, materials scientists, and electrical engineers. All these talents come together in an integrated research effort to make progress. DOE's National Quantum Information Science Research Centers constitute the first large-scale quantum information system effort that fully utilizes the technical depth and breadth of the national labs. Each of the centers incorporates a collaborative research team that spans multiple scientific and engineering disciplines and multiple institutions.

Advances in quantum information science rely on research in foundational quantum materials science and on the ability to engineer quantum materials into functional, affordable devices such as quantum sensors, various forms of qubits, quantum transducers, quantum repeaters, and quantum-enabled microprocessors. In addition to the scientists, the DOE and its national labs have world-class quantum facilities and maintain quantum industry partnerships

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2 www.economist.com/science-and-technology/2023/04/08/how-the-human-genome-project-revolutionised-biology

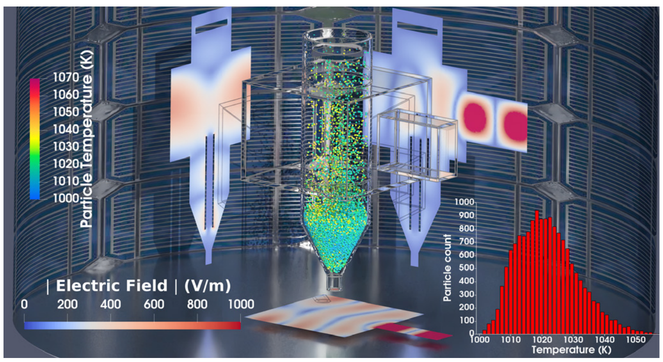
3 *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* National Academies Press (2007).

4 International Monetary Fund. 2021. World Economic Outlook: Recovery during a Pandemic—Health Concerns, Supply Disruptions, Price Pressures. Washington, DC, October, pg. 66.

that provide leadership to the nation and world in advancing the second quantum revolution and propelling national economic progress.

Research advances will lead to unbreakable encryption, a quantum internet, a secure and resilient electric grid, and quantum-enabled AI for applications, to name only a few.

## POWERING ECONOMIC PROSPERITY THROUGH FUTURE ENERGY SYSTEMS




**Simulation of heating of solid feedstock by microwave in a fluidized bed at National Energy Technology Laboratory**

### CURRENT STATE

America and many countries around the world are facing unprecedented energy and security challenges: a changing climate, aging energy infrastructure, and the need for a transition to cleaner, more reliable, and more resilient sources of energy. Historic growth in global energy demand is being driven by new technologies, such as hyperscale data centers, while millions of people around the world still live without reliable access to electricity. These challenges are formidable but can be addressed through R&D.

Our ability to maintain our standard of living, promote future growth in our economy, and ensure our national security depends upon having resilient energy systems that are clean, cost effective, and not dependent on other nations that may not share our objectives. Increasingly, energy systems have become central to national security, as critical infrastructure has been targeted with cyber- and physical attacks to achieve advantages during conflict by exploiting vulnerabilities.

Globally, we are also experiencing a consequential increase in frequency and intensity of extreme weather events—including droughts, heat, precipitation, and sea level rise—engendered by the increased warming of the planet. During the last four decades, within the U.S, the number of severe weather events each resulting in over a billion dollars in damages has increased by more than an order of magnitude. In total this cost has exceeded $2.5 trillion, according to the National Oceanic and Atmospheric Administration. Greenhouse gas (GHG) emissions responsible for the warming have arisen mostly from electricity generation, transportation, and industrial, residential, and commercial energy uses. These have major implications on our water supply, food security, and health, as well as on our nation's infrastructure and economy. In addition to improving and rebuilding our now vulnerable infrastructure to adapt to this new reality, we must design and build a future energy system that is reliable, resilient, and secure in both the cyber and physical realms.

To create this future energy system, clean power sources including wind, solar, nuclear energy (both fission and fusion), geothermal, biomass, and marine will form major parts of the U.S. energy mix. Steady and reliable power from clean energy sources such as nuclear will be critical in achieving grid reliability. Solutions, including small modular nuclear reactors and marine (rivers) energy, will also be needed for remote communities and installations where grid access is limited. The continued use of fossil sources requires the development and deployment of carbon-capture management technologies, for which additional S&T advances are necessary.

Another requirement of the future energy system is the electrification of end-use technologies. However, not everything can be electrified; biotic and abiotic processes can be exploited to convert captured carbon dioxide ($CO_2$), or other simple gases, together with green hydrogen, to make chemicals, high-energy-density fuels, and materials. Improvements in efficiencies and decarbonization of buildings and industrial processes will be essential. Various energy storage technologies, including pumped hydropower, electrochemical battery storage, and thermal storage, require further development to achieve cost reductions and scale. A highly distributed power-generation and energy-storage system is more resilient than the conventional grid, in which power generation is centralized. However, such a distributed system increases the number of digital interfaces, and hence increases vulnerability to cyberattacks.

Additionally, the U.S. high-voltage transmission system must be expanded and enhanced to facilitate the performance of this more distributed energy system. A future grid with cheap electricity will lead to lower operational costs for all sectors, including buildings, industry, and transportation.

## OPPORTUNITIES

The DOE has recognized for some time that the original power grid of the 20th century, designed to generate power centrally and distribute it to customers, with little communication, must evolve into a more distributed system of power generation and storage. This will rely on sophisticated sensors and control systems and advances in machine learning (ML) and AI. This future system will necessarily be autonomous. A prototypical future American city of a million people will include buildings and homes with electric vehicle(s) and charging infrastructure, power generation (e.g., rooftop solar), energy storage device(s), smart sensors, and appliances, all interacting with the grid. Hence, there will be millions of devices that will require control to ensure grid stability. Grid operation will be largely autonomous, relying on massive amounts of data management, real-time control systems, and AI/ML.

Based on technoeconomic analysis, lifecycle assessment, and conversations with stakeholders, grand challenges to achieving this future energy system have been identified. These grand challenges include clean hydrogen cost reductions; long-duration energy storage cost reductions; major expansion of U.S. nuclear energy capacity; carbon removal from the atmosphere; producing clean fuels and products to achieve significantly lower carbon and energy footprints; significant reductions in the costs of offshore wind and of geothermal energy; reduction of emissions from industrial heat decarbonization technologies; reduction in the cost of upgrading residential infrastructure to take advantage of advances in energy technologies; and reduction in the GHG emissions of industry (e.g., steel, cement, ammonia).

These are difficult challenges, and they are complicated further by the fact that entities in this sector, particularly utilities, have been hesitant to embrace new technologies that have not previously been demonstrated at the relevant scale. Therefore, in addition to R&D, investments in facilities and capabilities to demonstrate these technologies at relevant scales and in effective public-private partnerships are essential to hasten commercial adoption.

## FUTURE STATE

The energy system of the future will be clean, resilient, cost effective, and not subject to unacceptable foreign dependencies. Developing future energy systems will require trillions of dollars of investments from government and industry, with eventual returns that far exceed the investments. The DOE national laboratories play a leading role in creating this clean, resilient, cost-effective, and secure energy system. To modernize and decarbonize the energy system, the national labs should work in concert with partners from industry (including major oil companies), academia, and communities to take full advantage of the capabilities and expertise that reside within the labs. These broad-based partnerships will be critical to proving and derisking nascent energy technologies so they move up the technology readiness level (TRL) scale toward the market.

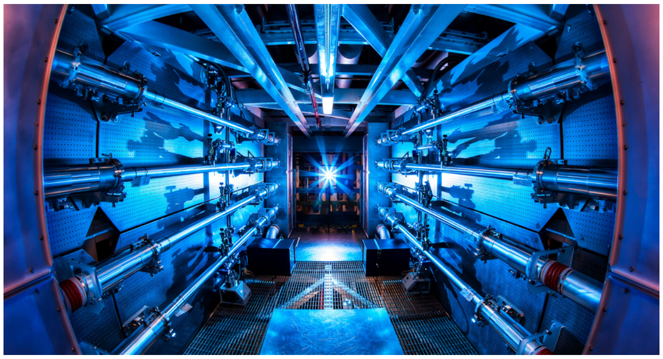
### Nuclear

The U.S. has declared the target of tripling nuclear capacity by 2050, greatly expanding the domestic capacity to produce clean, reliable power. Part of this expansion will involve the deployment of advanced nuclear reactors which build upon decades of research conducted by the national laboratories. One such example is accident-tolerant tristructural isotropic (TRISO) fuel particles, developed as a collaboration between two national laboratories. The national labs have performed two decades of uranium oxycarbide TRISO fuel fabrication and performance testing under a wide range of conditions. These tests generated a large database of fuel performance data that reactor developers have leveraged in their license applications. Multiple advanced reactor developers, including Kairos and X-energy, are incorporating TRISO fuel particles as a critical component of their reactor designs and continue to collaborate with the national labs to leverage their expertise.

### Grid Modernization Initiative and Grid Modernization Lab Consortium

During the last two administrations, the DOE established the Grid Modernization Initiative (GMI), and the Grid Modernization Lab Consortium (GMLC) to articulate and address key challenges involved in achieving a future energy system. GMI provides evolving management and insights for the initial steps toward the grid of the future, while GMLC is a national laboratory-led collaboration among the labs, industry, and academia. These efforts include preparing comprehensive plans to address resilience, reliability, security, affordability, flexibility, and sustainability. DOE also established the Office of Cybersecurity, Energy Security, and Emergency Response, which engages the national labs, industry, and other government agencies.

## ASSURING OUR NATIONAL SECURITY



National Ignition Facility at Lawrence Livermore National Laboratory

Assurance of U.S. national and energy security are central to the mission of the DOE national laboratories. Since the founding of the first national labs in the 1940s, this system of laboratories has delivered scientific discoveries and innovation that influence and impact national priorities, including the use of S&T to sustain and modernize the U.S. nuclear deterrent, support nuclear non-proliferation and threat reduction worldwide, and to support broader national security strategic objectives enabled by lab capabilities.

### CURRENT STATE

The global security environment is complex and continues to evolve at an ever-more-rapid pace; it has changed substantially even from a decade ago. Increasingly, key national priorities center around meeting threats to the well-being of U.S. citizens, from bouts of extreme weather and a changing climate to threats arising from technological competition as well as militant actions carried out by non-state actors, rogue behavior by nation-states, and ongoing conflicts. The global COVID-19 pandemic highlighted how vulnerable we are to both naturally occurring and bioengineered pathogens in a highly interconne cted world, bringing biosecurity concerns to the fore.

Another growing concern in this global security environment is the return of a Great Power competition and the unprecedented national security challenge of facing two major nuclear-armed national adversaries, a situation made even more complex by technology advances that will affect that competition and also enable other actors. The recent report of the Strategic Posture Commission noted that in the current environment, the program of record to modernize the U.S. nuclear deterrent and the infrastructure that supports it is "necessary but not sufficient" and that the U.S. will most likely require new and/or different nuclear capabilities than was envisioned only a few years ago.

Finally, the commercialization and militarization of outer space is a rapidly evolving situation that could represent additional threats to national and global security.

### OPPORTUNITIES

New technologies like AI, advanced semiconductors and networks, new materials and manufacturing approaches, space-based communications and sensors, and biotechnology are central to meeting these global challenges. Many of these technologies are key to ongoing and planned work in support of the U.S. nuclear weapons stockpile, its manufacturing enterprise, formal assessments of the quality of the nuclear deterrent, and ongoing efforts to curb nuclear proliferation and establish robust counter-proliferation and counterterrorism capabilities.

The DOE National Nuclear Security Administration (NNSA) laboratories have been responsible for the creation and stewardship of the safe, secure, and effective nuclear deterrent that underpins the security of the U.S. and our allies. Since the end of nuclear explosive testing in 1992, the NNSA labs have succeeded in developing a remarkable suite of scientific tools to sustain the nation's nuclear weapons stockpile. These tools—unique facilities for precision experimentation and world-class high-performance computing systems for state-of-the-art computation—have transformed the nuclear security scientific and engineering enterprise, built a talented workforce, enabled the modernization of the nuclear deterrent and provided responsive support for nuclear proliferation issues. They are, however, in need of updating.

If we are to succeed in modernization and respond to the changing geopolitical landscape and emerging deterrence gaps, the tools of science-based stockpile stewardship must be renewed and advanced to allow for more rapid, cost-effective, and high-confidence development of the future nuclear deterrent.

Unfortunately, many of these same technologies also result in raised concerns about malevolent actions by diverse adversaries. New challenges have arisen due to nuclear threats and increases in nuclear weapons capabilities in other nations, as well have as the escalation of cyber threats that can damage critical infrastructure, the commercialization and militarization of space, and the rapid acceleration of emerging and disruptive technologies like biotech and AI.

DOE national laboratories are a critical asset to agencies across the government, providing expertise and capabilities to address this full spectrum of national security challenges. The new multipolar security environment and the multi-domain character of conflict demands detailed exploration of new S&T, understanding of options and implications, and the creation of additional tools for the U.S. and allied nations.

## FUTURE STATE

The ongoing delivery of research insights and technological tools to meet global challenges enriches the lives of people. U.S. security and national competitiveness will continue to support the values of our citizens and our democracy. Competitiveness in S&T will also benefit our allies and partners with shared values; together we will work to use advanced scientific research and technological development to strengthen global stability and prosperity. With these opportunities met, the future state will be one with a vibrant national laboratory ecosystem—together with partners in the broader national and international scientific community—that enables progress, increased productivity, and well-being.

For nuclear security, the future state will be a modernized deterrent that is fit for purpose, supported by a modern, agile, and resilient nuclear security enterprise with a talented and dedicated workforce that continues to deter our adversaries, assure our allies, and be a force for good in the world. In the continued absence of explosive nuclear testing, state-of-the-art experimental and computational facilities will be developed and employed to ensure the safety, security, and effectiveness of the active stockpile, enable advanced manufacturing of essential components for the modernization programs, and prepare for future threats and possibilities. Our deterrent will adapt to emerging deterrence gaps and evolving adversarial capabilities at pace with the threat.

With an enduring and healthy innovation ecosystem in which the national lab system operates, new scientific understanding, experiments, and prototype manufacturing approaches will enable sustainable energy production and use; access to and prudent use of critical materials; design and synthesis of new materials and chemicals; rapid design and optimization of bioengineered products including drugs and vaccines; AI-enabled analyses and roboticized laboratories; new tools for a strong national defense; and robust efforts supporting access to space for travel, residence, and work.

It is important to note that the international competitive landscape, particularly with respect to China, is not just one of Great Power competition in the military domain; it is also scientific, technological, and economic. Historically, investment on national-security-focused S&T has allowed us to both outstrip competitors militarily and outdo them economically through broader application of defense-related R&D.

### Understanding Threats as a Member of the Intelligence Community

The DOE is the only federal R&D agency that is a formal member of the U.S. Intelligence Community. At DOE headquarters, the Office of Intelligence and Counterintelligence is responsible for all intelligence and counterintelligence activities throughout the DOE complex, including nearly 30 intelligence and counterintelligence offices located at several of the national laboratories and at other distributed site offices nationwide.

A distinctive contribution of the national laboratories to national security is the ability to leverage the DOE's S&T expertise directly in support of policymakers as well as national security missions in defense, homeland security, cybersecurity, intelligence, and energy security.

Deep understanding of frontier science at the national labs and this ongoing engagement benefits the nation by enabling a role in reducing the global security threat, strengthening the nuclear security infrastructure, and buttressing America's economic prosperity.

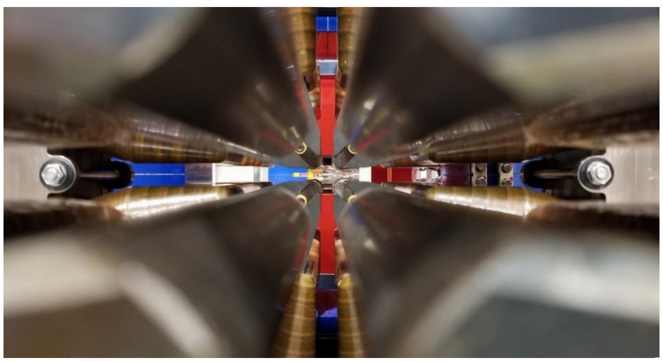
### Assessing Dual-Use Implications of Convergent S&T

DOE national labs have a deep heritage of working with scientists from all over the world, especially via collaborative work at the major DOE user facilities including synchrotrons, particle accelerators, and high-performance computing facilities. More and more, the ability to make exquisite measurements and to couple that understanding with precision computation, ML, and other analytical approaches enables understanding of convergence in 21st-century S&T. Collaboration and the promotion of innovation in S&T must be carried out with an eye to protecting the economic potential and impact of new inventions. This balancing of benefits and dangers is an ongoing capability in the national labs and in the DOE.

For example, AI and advanced computing—together with deeper understanding of biological systems and mechanisms—are enabling better optimization, design, and production of new drugs, medicines, and biomaterials. Concerns have been raised about the ability of these powerful new design tools to be used in harmful ways. AI safety and security approaches in a range of application areas are needed to assure the benefits of new drugs and materials.

In the energy sector, advances in dynamic control systems for energy distribution, coupled with diverse energy generation and use technologies, are enabling enhanced energy system reliability and comfort. However, these advances have also made energy systems more vulnerable to cyberattacks, including ransomware attacks, denial-of-service attacks, phishing campaigns, insider threats, and attacks targeting industrial control systems and supervisory control and data acquisition (SCADA) systems. Cybersecurity research coupled with deep understanding of energy system operations can ensure the security, resiliency, and survivability of key energy assets and the critical energy infrastructure at home and abroad.

## ENSURING U.S. S&T LEADERSHIP THROUGH WORLD-CLASS RESEARCH FACILITIES



**Center view of a quadrupole magnet in the upgraded Advanced Photon Source (APS) electron storage ring at Argonne National Laboratory—quadrupole magnets focus the electron beam into a tighter shape, decreasing the beam emittance and increasing the brightness of the X-rays**

### CURRENT STATE

The large-scale research infrastructure in the national laboratories is unique, meeting DOE mission requirements and providing U.S. industry and academia with capabilities and expertise that is, collectively, unmatched in the world and, individually, frequently world-leading. Driven by the DOE mission of providing transformative S&T for the nation's security and prosperity, these facilities include light and neutron sources, research reactors, lasers, pulsed power facilities, particle accelerators, and high-performance computers. They are made available to researchers at national labs, industry, and academia and allow over 40,000 users each year to make advances across a broad swath of discovery science and applied technology that enriches our lives and transforms the economy. Examples range from fundamental science discoveries such as the demonstration of fusion ignition, to technological applications, such as the work on antiviral drugs and vaccines for COVID-19, to the national security arena, including stewarding the nation's stockpile. Indeed, research across the national labs provided a foundation for many of the 118 Nobel Prizes associated with the DOE and is critical for advancing the DOE mission and associated priorities.

The national labs' current leadership role for many, but not all, areas of science that rely on major facilities has its origin in long-term plans developed in the 2000s for open science and the 1990s for national-security science. These blueprints were sustained through multiple administrations and succeeded in meeting the objectives identified at their inception. However, their future relevance will be threatened if they are not updated, because other countries seek to exceed our capabilities and new possibilities have emerged as S&T has advanced.

In addition, these national lab facilities are engines for economic growth: The stewardship mission means that the DOE is the national custodian of expertise in technological areas such as accelerators, high-performance computing, detectors, and radiation-hardened electronics. Further, the need for these facilities to be cutting-edge drives engineering innovation across a range of disciplines. This, in turn, establishes supply chains and one-off engineering capabilities in the U.S. that promote economic innovation and growth in many disparate sectors. Many new technologies have been invented and spun out of the national labs into U.S. industry as a result of this mission.

The construction, operation, and use of these facilities also provide drivers for the production of the nation's next-generation technical workforce, training scientists, engineers, and technicians in a wide range of disciplines. On the research side, many of the nation's doctoral degrees are awarded each year based on work done at these facilities. In addition, these facilities also attract the best and the brightest to come to the U.S., further boosting the workforce and the talent pool here.

Finally, these facilities directly support and enable much of the work described in the rest of this document, including work in accelerating S&T, in energy systems, in national security, and in workforce development. Indeed, these research facilities enable a wide range of discoveries that form the S&T foundation of this country, as outlined in this report.

### OPPORTUNITIES

In most cases, DOE national laboratory large-scale facilities are the best in the world or world-class. Examples include the world's fastest open-science and classified supercomputers, the highest-peak-brightness pulsed neutron source, high-brightness X-ray light sources, and the only facility to demonstrate nuclear fusion ignition. As a collection, these facilities are unparalleled. This is a direct result of the DOE's long-term stewardship of such facilities. Many of today's most important discoveries and technologies relied upon powerful research tools that were developed in previous decades. However, today countries around the world are developing new capabilities that will potentially challenge American technological leadership. We have the opportunity now to continue to secure our position at the forefront and to re-establish U.S. leadership in the highest priority areas. This should be accomplished by continuing the DOE tradition of long-range strategic planning, carrying this out in the context of the international landscape and with attention to national priorities. The plan should seek to both build new facilities in select areas and upgrade and maintain existing facilities. The national labs have the expertise to help shape this vision and to execute it.

There is also the opportunity to accomplish this vision through increased use of partnerships. These can come in the form of international partnerships, following existing examples in high-energy physics and fusion science, and in industrial partnerships such as those in high-performance computing and microelectronics. Well-developed partnership models can yield many benefits, including melding diverse partner expertise in co-design/development, engagement and development of the U.S. workforce, and sharing of costs associated with major infrastructure development.

## FUTURE STATE

Facility development and upgrades are critical to provide the infrastructure necessary for ensuring U.S. S&T leadership. A renewed focus on modernizing core physical and research infrastructure at the national laboratories will support the work of the major facilities and lead to new discoveries.

With the DOE Office of Science facility road-mapping exercise and the NNSA facility Blueprint currently underway, the current fleet of large-scale facilities within the DOE can be maintained, upgraded, and augmented to a ensure a position of world-leadership in areas of national priority. New facilities must be developed to address emerging scientific challenges and opportunities. The revamped fleet will capitalize on the AI/ML revolution, which will be fully integrated into every aspect of facility operation, along with the data infrastructure and robotics to support this approach. Researchers will carry out their research within a system of facilities, data infrastructure, interoperable datasets, and computational resources that will enable new ways of doing science. This will bring about transformational opportunities for scientific research, with the U.S. at the leading edge. Such an approach will allow the facilities to, collectively, be optimally utilized and maximally productive, contributing to the "integrated scientific laboratories of the future" vision described above.

Such a renewed fleet will have great scientific impact in a range of disciplines, from high-performance computing to fusion science, clean energy, microelectronics, and quantum information science. It will also come with an associated boost in economic capabilities in the most technologically advanced sectors and in the training of the next-generation workforce.

### DOE Facilities Play a Crucial Role in Advancing Microelectronics

DOE facilities offer unprecedented capabilities in leadership computing, in X-ray and neutron sources, in nanocenters, in accelerators, and more. These are brought to bear on a range of scientific problems, including critical emerging technologies such as AI, quantum information science, and microelectronics. In this last, X-ray light sources play a particularly prominent role. Examples include work at National Synchrotron Light Source-II with IBM to enable the development of the 1-nanometer node technology, and work using the dramatically increased brightness of the Advanced Photon Source's new upgraded X-ray beams to perform extraordinarily detailed three-dimensional imaging of even the smallest potential fault areas of microchips. In addition, decades-long work at the Advanced Light Source in conjunction with industry has led to the development and testing of extreme ultraviolet photolithography for the most advanced chips, including for the latest generation of iPhones, and work at the Stanford Synchrotron Radiation Lightsource has mapped new microelectronic materials as they form and operate. Collectively, the five DOE light sources offer world-leading resolution and sensitivity to materials properties and will play a central role in developing next-generation microelectronics for the U.S.

## TRAINING AND SCALING THE S&T WORKFORCE OF THE FUTURE

**Innovation Crossroads awardee and former GEM Fellow, Shantonio Birch, at Oak Ridge National Laboratory**

### CURRENT STATE

The nation's competitiveness in the global science, technology and innovation ecosystem is based on a combination of STEM-trained talent, R&D-driven discovery, and translation of knowledge into economic and societal benefits through innovation. The U.S. remains a global leader in performing R&D, but now trails in other measures of research output. China is now the top overall producer of science and engineering publications and awards more science and engineering doctoral degrees each year than does the U.S.; it also leads in knowledge- and technology-intensive manufacturing output. This is occurring at a time when technology sectors in the U.S. face a deficit of workers.

Significant shortfalls exist in the workforce for semiconductor manufacturing, and labor shortages also exist for positions requiring information technology and data skills, as well as in engineering fields. This slows progress in efforts to build capability for critical domestic supply chains and new sectors of innovation. Through the efforts of DOE's national laboratories, there is an opportunity to support the development of needed talent in new and innovative ways, both for the DOE's missions and for partners in the U.S. R&D ecosystem. America's continued leadership in innovation, particularly in emerging technologies, will require attention to the expansion and development of this future workforce, for which the national labs can play a unique role.

### OPPORTUNITIES

The national laboratories represent one of the largest technical workforces dedicated to U.S. scientific leadership. Collectively, they employ nearly 80,000 people working to support international leadership, including in key areas of S&T identified earlier. As managed research environments, the national labs steward the products of R&D, and develop the standards and practices required to realize economically the benefits of these technologies. As an integral part of their work, the national labs continually seek to recruit, develop, and retain the dedicated talent required to advance the DOE's missions and focus on world-class science and innovation to benefit the nation. In addition, they host nearly 60,000 visiting scientists, students, and users of their scientific facilities each year.

Through collaborations and access to specialized facilities, national labs introduce a broader science and engineering workforce to research in important sectors, often providing first experiences to early-career researchers. Importantly, the national labs enable faculty and students at institutions with limited resources to contribute to world-class science, thereby broadening participation and opportunity. Inspiring and building a pipeline of talent from high school onward forms a central element of national labs' success and will create the breakthroughs of the future. By opening pathways for community college, university, industry, and international collaboration, the DOE national labs are well positioned to deliver science (and scientists) with the greatest possible impact.

The national labs provide an environment particularly well suited to the development of S&T talent. The labs have a long history of offering collaborators and students opportunities for research experiences involving unique facilities and first-of-a-kind instrumentation and computational capabilities, plus the opportunity to work in multidisciplinary teams with leading researchers who facilitate their science. To create and maintain their world-class facilities, the national laboratories must nurture unique skills in first-of-a-kind engineering and technology not available at most universities. For early-career researchers, this engagement provides critical experience and an introduction to multidisciplinary science.

In recognition of the national labs' unique environments and capabilities, the DOE has been encouraged to incorporate engagement with academia in fashioning workforce-development curricula in fields such as quantum information science and AI, often in collaboration with other agencies. In addition to the students and postdocs the national labs employ directly, these institutions host tens of thousands of scientists (including both users and collaborators) from around the world. The labs introduce them to the most recent innovations and research approaches and, by doing so, they multiply the impact of the labs across the nation's S&T ecosystem. The national labs ultimately contribute to the development of well-trained researchers at all degree levels, many of whom will move on to work in other technology sectors.

For global competitiveness, we also need to recruit the best and brightest from around the world. This will pay off by strengthening America's talent pipeline, in which we must continue to invest, and will create more opportunities for collaboration and innovation.

## FUTURE STATE

A concerted approach to cultivating talent will be a key element of future U.S. technology leadership. The national laboratories, with their mix of fundamental science and applied research, as well as their environment of collaborative team science focused on national interests, will continue to present unique development environments for the nation's skilled technical workforce. The national labs will:

- **Provide supported access to world-leading research facilities and unique tools and testbeds:** The full potential of the national labs' premier research tools must be unleashed to serve the S&T community. In the future, this will be possible through expanded remote mechanisms and broader access.
- **Create distinct multidisciplinary research environments that bring innovators together to create "team science":** Acceleration of scientific discovery and translation to innovation will be realized through the efforts of multidisciplinary teams. Working with partners in academia and the commercial sector through novel partnerships will speed development.
- **Support entrepreneurial efforts, creating return on the government's investment in technology and jobs:** Innovation can be more quickly translated to impact through the creation of new U.S. companies and jobs in emerging technologies. In the future, the national labs will provide expanded opportunities to support entrepreneurs in commercializing technology, furthering U.S. intellectual and economic leadership.
- **Collaborate with international partners to leverage the best tools and talent:** The national labs will collaborate with international partners and researchers in managed research environments in the service of U.S. interests. Examples include sharing the cost of major collaborative experiments and facilities, accelerating innovation to tackle global challenges, and attracting the right global talent.
- **Engage in outreach in educational programs to inspire students:** Local communities already benefit from the engagement of tens of thousands of educators and students in programs in support of cultivating awareness of and interest in STEM careers. The national labs will be active partners in a broader set of communities, using strategies such as virtual outreach and coordinated programs.
- **Support internships and training opportunities for scientists and engineers:** Building on the success of existing early-career research programs, the national labs will expand programs (in partnership with the DOE) to attract and retain top talent in support of all DOE missions and U.S. S&T leadership. They will expand career development beyond the early-career stage to retain and enable our highly skilled workforce.
- **Provide technical assistance to community partners:** The national labs will serve as a significant resource to local and regional stakeholders. They will provide technical assistance in designing, implementing, executing, and evaluating new technologies.

All these efforts are conducted in the context of world-leading basic and applied research programs focused on the national interest. The national labs are an integral component of developing and supporting the uniquely skilled workforce required for stewardship of U.S. S&T interests. This both supports future mission success, and contributes to broader intellectual, economic, and security leadership required for the future.

### The Faces of Our Early-Career Researchers

The 17 DOE national laboratories are focused on inspiring, attracting, and developing science and engineering talent. The emerging workforce must tackle the most challenging science questions, serve the missions of the DOE, and drive key innovations required to serve the nation's economic and security interests. Intentional development of early-career researchers makes our research environment stronger. Nowhere is this more on display than at the National Lab Research SLAM. The SLAM is a competition in which contestants are challenged to present a compelling three-minute presentation of their research in language appropriate to a non-specialist audience. The first ever 17-lab SLAM (sponsored by the House Science & National Labs Caucus and the Senate National Labs Caucus) was held in 2023 in Washington, DC, and served to highlight the key role national labs play in the nation's innovation ecosystem and their impact on the nation. Building on the momentum from the first SLAM in 2023, plans are underway to make the SLAM a recurring event.

## WHY US?

The proven quality and impact of innovation from the DOE national laboratories underscore their role as key pillars of the U.S. and global innovation ecosystem. Collaboration is an important feature of the national labs' approach, manifested by the large number of effective partnerships—among labs, with academic institutions, with small and large industrial firms, and with nongovernmental institutions—all carried out regionally, nationally, and globally. Such partnerships are central to the labs' delivery of solutions to problems of national interest. With these partners, the work of the national labs enables the delivery of capabilities and solutions for national security that generate knowledge in new domains designated as important in this century: materials, energy systems, information (computing, data, AI), and sustainability.

The national labs have their roots in the early days of nuclear physics and the creation of large experimental facilities together with the practice of team science. The 17 DOE national labs have honed the discipline of big-team science and have delivered impactful S&T outcomes over the past nearly 80 years. These labs, with close to 80,000 employees, have expertise and capabilities that are unique, currently unmatched, and critical to supporting national missions such as national security, economic security, and energy security. The DOE national lab system collectively represents unparalleled intellectual prowess that exists nowhere else.

Each national lab carries out its work as a managed research enterprise with explicitly negotiated deliverables and outcomes. Access control and training are required to ensure safe operation of experimental research facilities. Similarly, access controls are a part of visiting national lab facilities and collaborating with scientists. The operational approach and laboratory culture makes it possible to fulfill the guidance on research from Presidential Memorandum 33, which directs that U.S. S&T be guided by the precept to both promote research collaborations with international collaborators and also to protect the technological outcomes for economic benefit as well as national security.

NATIONAL
LABORATORY
DIRECTORS
COUNCIL

## OUR NATIONAL LABORATORIES

- Ames National Laboratory
- Argonne National Laboratory
- Brookhaven National Laboratory
- Fermi National Accelerator Laboratory
- Idaho National Laboratory
- Lawrence Berkeley National Laboratory
- Lawrence Livermore National Laboratory
- Los Alamos National Laboratory
- National Energy Technology Laboratory
- National Renewable Energy Laboratory
- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory
- Princeton Plasma Physics Laboratory
- Sandia National Laboratories
- Savannah River National Laboratory
- SLAC National Accelerator Laboratory
- Thomas Jefferson National Accelerator Facility