Bipartisan Policy Center

Accelerating AI Sustainability and Innovation at the Department of Energy

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Introduction: What Does AI have to Do with Energy?

As a concept, artificial intelligence has existed since the 1950s. But the promise and perils of AI have only recently exploded in popular consciousness with the appearance of publicly available AI-based tools like ChatGPT and Google AI Overview. These tools are widely viewed as heralding the arrival of a new technological age in a way that earlier generations of AI—long embedded in smartphones, thermostats, search engines, navigation apps, and more—did not.

That the United States again finds itself at the forefront of developing a globally transformative new technology is no accident. As with previous innovations, U.S. leadership in AI owes much to the combination of an entrepreneurial and dynamic private sector, world-class academic and research institutions, and robust support from the federal government.

The U.S. government has played a key role in nurturing AI and the technologies that enable AI systems. Then-President Donald Trump recognized the growing importance of AI and its potential to accelerate federal decision-making processes with his Executive Order on Promoting the Use of Trustworthy Artificial Intelligence in the Federal Government. As a follow-up, President Joe Biden's Executive Order on the Safe, Secure, and Trustworthy Development and Use of Artificial Intelligence includes several agencies, such as the National Science Foundation (NSF), Department of Commerce, and NASA. Among the many policy positions being proposed by policymakers and thought leaders to advance national AI policy, the role of the Department of Energy (DOE) has been vastly understudied.

To address this gap, this report examines the ways that DOE has contributed to U.S. leadership on AI and explores ways that DOE should remain engaged with AI going forward. DOE's involvement spans several critical areas in AI development:

- Meeting the energy demands of the growing AI industry.
- Applying AI to a host of public policy challenges.
- Developing next-generation AI capabilities in collaboration with the private sector.
- Operating the world's most powerful supercomputers.

DOE is playing a critical role in ensuring that the United States and the world benefit from AI, while working with the private sector to effectively manage and minimize AI's potential risks.

This report begins by providing some background on AI and by describing DOE's AI-related activities and contributions to date. Subsequent sections focus on the department's efforts to improve the energy efficiency of AI technologies and operations, and on ways that AI tools are being deployed to advance energy technologies, national security, and scientific discovery. The report concludes with recommendations for the future of DOE's contributions to AI.

Background: Connections Between AI, Computing, and Data Centers

WHAT IS AI?

AI as a field of research has existed for a long time—the term was originally coined in 1956. Although no universally accepted definition exists, AI generally refers to machines that mimic human intelligence.[1] The National Artificial Intelligence Initiative Act of 2020, which was signed into law in 2021, defines AI as "a machine-based system that can, for a given set of human-defined objectives, make predictions, recommendations or decisions influencing real or virtual environments."[2]

HOW DOES AI WORK?

AI systems combine mathematical models or algorithms with large quantities of data to recognize patterns and make predictions or inform decisions. Earlier generations of AI systems relied on relatively simple rules (e.g., "if-then" relationships) to process information and automate decision-making. Newer generations of AI include machine learning and neural networks that enable more sophisticated data classification, process optimization, predictive modeling, and generative tools, such as ChatGPT. Figure 1 breaks down key steps in developing a generic AI application.[3]

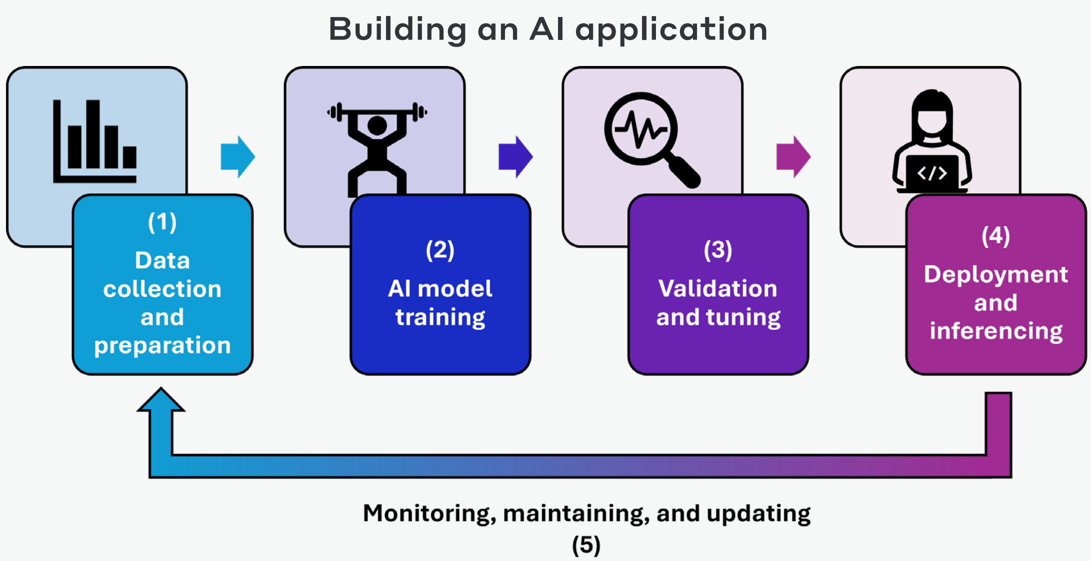


Figure 1. The process of AI model development

1. **Data collection and preparation.** Large amounts of data (e.g. speech, images, text, numbers) are gathered, cleaned, and organized to be suitable for use in training and testing. The data must be accurate with minimal errors.
2. **AI model training.** An appropriate algorithm is chosen and used to "train" the AI model using the data prepared in the first step. Training AI models requires processing massive amounts of data and significant computational resources, particularly for more sophisticated models, making it the most energy-intensive part of AI model development.
3. **Validation and tuning.** To assess its performance, the AI model is applied to new data it has not "seen" before. Based on the results, the model's parameters can be fine-tuned to improve the accuracy and reliability of its outcomes.
4. **Deployment and inferencing.** The AI model is integrated into an application or system and made available for use. The model performs inferences, and the application uses these inferences to make a prediction or generate an output based on new, real-time data such as inputs from a user.
5. **Monitoring, maintaining, and updating.** The AI model performance is monitored for accuracy and updated with new data as needed to address emerging issues or biases.

DATA CENTERS, COMPUTING, AND AI

Data centers serve many purposes, including hosting websites, storing data, streaming media content, and enabling AI applications. People rely on them every day without knowing it. Common physical elements of data centers include computing infrastructure (processing units, memory), data storage, and networking components to connect elements of the data center.[4]

DATA CENTERS SERVE MANY PURPOSES, INCLUDING HOSTING WEBSITES, STORING DATA, STREAMING MEDIA CONTENT, AND ENABLING AI APPLICATIONS.

To serve AI needs, AI data centers can be customized with (1) the ability to handle the high computational demands of training AI models; (2) the ability to quickly process, move, and store large amounts of data; and (3) specialized networking that efficiently connects different parts of the data center to each other.[5] Improvements in each of these elements—computing, data storage and processing, and networking—have been essential to unlocking rapid AI advances in recent decades.

UNDERSTANDING THE RELATIONSHIP BETWEEN SUPERCOMPUTING AND AI

Supercomputers are much faster than typical computers. They combine multiple computers to process data and perform computations in parallel, rather than sequentially, to model complex systems or solve data-intensive problems.[6,7] Because of their ability to quickly process and analyze large amounts of data, supercomputers are used to train and run AI models.

Figure 2. The Frontier Exascale computer at Oak Ridge National Lab, the most powerful supercomputer in the world as of June 2024.

For a similar reason supercomputers are used in high-performance computing to perform the largest and most complex calculations in the world.[8] Exascale computing refers to the next generation of supercomputers, which achieve processing speeds on the order of 10^{18} operations per second and can support the massive workloads associated with scientific modeling and training AI systems.[9] Supercomputers are critical accelerants for large-scale AI applications, delivering the computational power and speed needed to handle very large datasets.

Data centers and supercomputers are built for different purposes. Data centers are intended to manage large amounts of data, while supercomputers are built to handle computationally intensive tasks.

DOE Leadership in AI and Advanced Computing

The Department of Energy played an important role in the development of modern AI and in reducing the energy use of AI systems. This section discusses DOE's pioneering contributions to advanced computing and to data center and computer chip efficiency. Much of DOE's efforts on AI and computing are carried out at the department's national laboratories, a network of 17 world-class scientific and engineering research institutions located across the country that helps deliver on DOE's mission to "to ensure America's security and prosperity by addressing its energy, environmental and nuclear challenges through transformative science and technology solutions."

DESIGNING, BUILDING, AND OPERATING SUPERCOMPUTERS[10]

DOE has a long history of supporting research to advance computing technologies, starting with the Manhattan Project in the 1940s, in which scientists used computational modeling to develop nuclear weapons and hydrogen bombs. Building on more than 60 years of sustained investment, DOE has pioneered the design, construction, operation, and maintenance of first-of-a-kind (FOAK) supercomputers, while also supporting research and development (R&D) in computer science that underpins modern AI methods and systems.

DOE investments have delivered key insights that are foundational to current AI and computing ecosystems including:

- Designing massively parallel processing computers, capable, for the first time, of executing many computations simultaneously.
- Developing methods to program parallel computers, which require new processes and deviations from existing practice.
- Developing methods to efficiently and quickly handle massive quantities of data.

DOE's contributions to supercomputing are analogous to FOAK energy projects: when the private sector views certain technology investments as too expensive or risky, DOE leads the way by building new systems that prove untested designs and solve complex scientific challenges to get the technology to function as intended. Importantly, the national labs have collaborated closely with the private sector on supercomputing projects, codesigning systems such that private companies can apply lessons learned to the design of "n^{th} of a kind" supercomputers and AI products.

Today, DOE operates many supercomputers, all built in collaboration with key private-sector partners and housed at the DOE's national labs (as shown in Figure 8). Since 1987, 10 DOE computers have been ranked as the world's most powerful supercomputer.[11] As of June 2024, DOE's Frontier system at Oak Ridge National Laboratory (ORNL) in Tennessee and Aurora system in Argonne National Laboratory (ANL) in Illinois held the No. 1 and 2 spots, respectively, as the most powerful supercomputers in the world.

> ACCELERATED COMPUTING IS AT THE HEART OF THE UNFOLDING AI REVOLUTION. ITS ORIGINS CAN BE TRACED TO ORNL SCIENTISTS IN THE LATE 2000S WHO HAD INNOVATIVE IDEAS ABOUT HARNESSING THE POWER OF GPUS.

Each DOE supercomputer has pushed the frontiers of advanced computing in ways that have transformed the industry. The national labs' close collaboration with companies like AMD, Hewlett Packard Enterprises (HPE), NVIDIA, Microsoft, and others, is mutually beneficial, allowing the labs access to the latest chips and computing technologies while enabling industry to accelerate the development of cutting-edge products that drive down cost and increase energy efficiency.

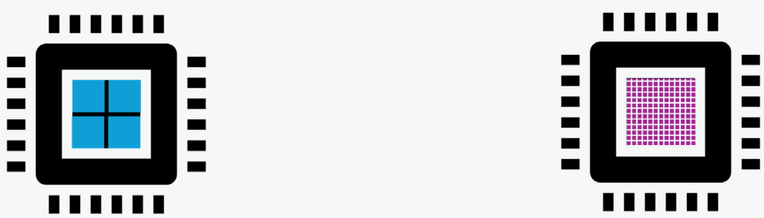
Examples of successful outcomes from these public-private partnerships include:

- **GPU-based computing:** The use of graphics processing units (GPUs) in supercomputers has irrevocably changed the AI landscape and enabled the current generation of AI applications. ORNL researchers were the first in the world to propose building a supercomputer that used GPUs; their partnership with AMD, NVIDIA, and Cray led to the successful delivery of the Titan supercomputer in 2012.[12]
- **NVLink:** AI systems require high-speed connections between central processing units (CPUs) and GPUs to rapidly send and receive data from shared stores of memory. DOE-funded research enabled development of NVIDIA's NVLink technology in partnership with DOE scientists. This high-speed interconnection system debuted in DOE's Summit supercomputer in 2018. Today, NVLink is one of NVIDIA's most valuable products.[13,14]
- **ChatGPT:** ORNL's latest supercomputer, Frontier, unveiled in 2022, was developed with private-sector partners, including AMD and HPE. Insights from Frontier informed the development of the computer that Microsoft built to train ChatGPT; that computer was very similar to Frontier.[15]

Accelerated Computing: Processing and Its Importance to Supercomputing

Processing units are the brains behind computing. Before transistors were invented, computers used large, inefficient, and unreliable vacuum-tube-based processing units. In this early era of computing, computers filled entire rooms and were available for use by only a privileged few. The invention of transistors opened the door to modern computing infrastructure, enabling miniaturization, dramatic improvements in energy efficiency of computing processes, and the democratization of computing.[16]

These gains were possible because transistors, in combination with other components, could be organized on a single computer chip called a central processing unit. CPUs perform most computational tasks and run operating systems and applications on laptops, desktop computers, and in data centers. CPUs excel at completing complex computational tasks in serial order.



Central Processing Unit (CPU)

- Handles main processing functions
- Designed for serial processing
- Best suited for general purpose computing applications

Graphics Processing Unit (GPU)

- Handles specialized processing functions
- Designed for parallel processing
- Best suited for supercomputing applications

Figure 3. Comparing CPUs and GPUs

Increasing reliance on computers for a wider set of applications led to the need for different processing units that could handle several specialized tasks simultaneously, or in parallel. Specifically, the quest for more sophisticated video game graphics and animation required processors that could conduct complex calculations to identify the correct color, intensity, and movement to display on thousands of pixels at the same time.[17] CPUs were not designed for this purpose and struggled to produce results quickly enough and with reasonable power consumption. These pressures led to the development of graphics processing units, or GPUs, which were designed to accelerate graphical workloads as they can handle many complex mathematical calculations in parallel.

Initially, GPUs were used exclusively for graphics processing and image generation. This changed when researchers at ORNL partnered with NVIDIA to design GPUs with features required for scientific computing and to build the Titan supercomputer. Debuting in 2012, Titan was ranked the most powerful supercomputer in the world that year and was the first to integrate GPUs.[18] As an added benefit, GPU-based computing is substantially more energy efficient than traditional designs. To foster use of the GPUs in supercomputers, ORNL started the Center for Accelerated Application Readiness[19] to help train the community. Five years later, NVIDIA added AI computing functions to GPUs, and these debuted in the Summit supercomputer at ORNL in 2017. Summit was the first large supercomputer with AI-enabled GPUs, a system that was quickly utilized by researchers for breakthrough insights.[20]

Today, additional types of specialized processors are being developed to increase computational speed, making accelerated computing the standard for modern and sustainable computing. **Accelerated computing** refers to an approach that separates the data-intensive parts of computing, which must be conducted in a massively parallel fashion, from the control functions, which are typically handled by a CPU.[21] Accelerated computing is at the heart of the unfolding AI revolution. Its origins can be traced to ORNL scientists in the late 2000s who had innovative ideas about harnessing the power of GPUs.

Today, accelerated computing advancements continue to be made to increase performance and energy efficiency. New types of processors, such as tensor processing units (TPUs) and data processing units (DPUs), are being developed to accelerate specific workloads. Future accelerated computing regimes could include quantum computing and architectures not yet invented. Further developments on software and algorithms are maximizing the benefits of accelerated hardware to unlock further efficiency and performance gains.

Designing, building, and operating supercomputers requires years of sustained investment, specialized talent, and effective partnerships with the private sector. Figure 4 shows historical funding and key accomplishments for DOE's Advanced Scientific Computing Research (ASCR) program, which peaked at approximately $1.1 billion in fiscal year 2023.

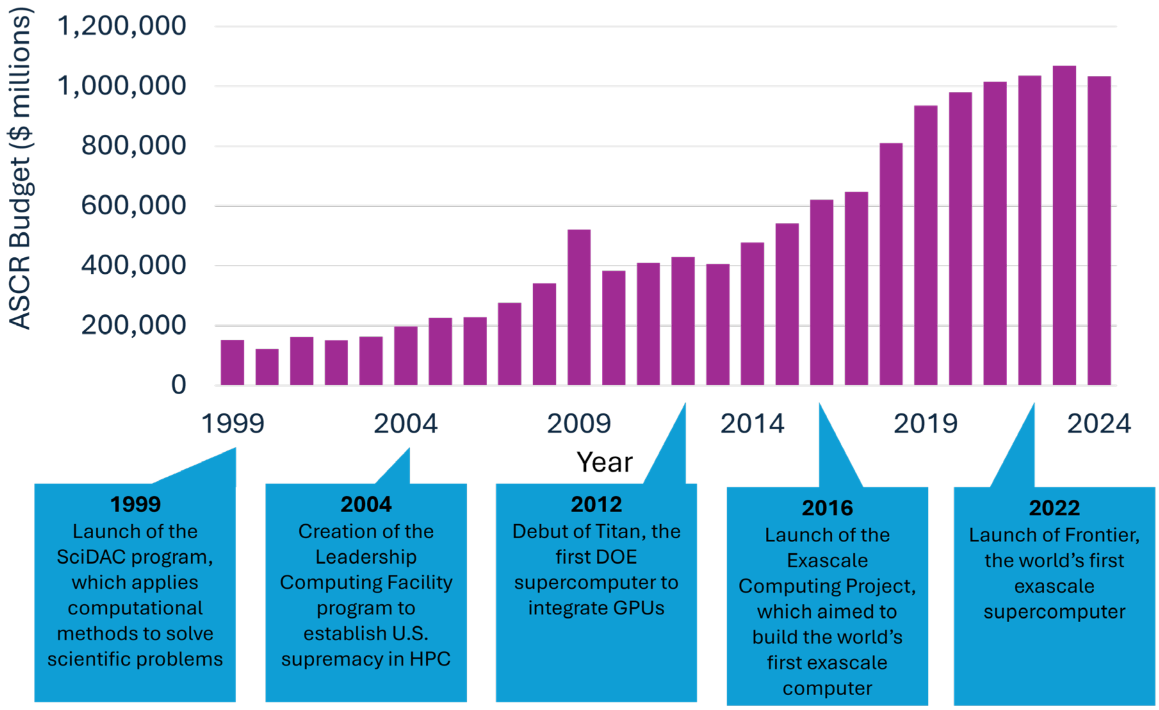


Figure 4. Historical funding and key accomplishments for DOE's Advanced Scientific Computing Research program (ASCR)

Computing and AI are inextricably linked. DOE's decades of investment in research breakthroughs and computing advancements have enabled the current AI revolution. As the future of AI unfolds, it will be imperative to rely on DOE's deep expertise to advance R&D in AI to ensure that our nation maintains its position at the forefront of this next technological revolution.

IMPROVING THE ENERGY EFFICIENCY OF DATA CENTERS, COMPUTING, AND CHIPS

Increased demand for electricity from high-powered computing facilities has emerged as a potentially concerning consequence of the AI revolution. The fear is that the rapidly growing energy use by data centers could overburden an already overstretched grid and hamper progress toward power-sector decarbonization, and these conversations are ongoing. Below, we review current DOE efforts to address these concerns by improving the energy efficiency of computers, computer chips, data centers, and other AI infrastructure.

Federal R&D investments play a critical role in improving the energy efficiency of AI, computing, and data centers. Work in this area dates to the Energy Independence and Security Act of 2007 (EISA07), which authorized DOE to coordinate with the Environmental Protection Agency on efforts to improve data center energy efficiency.[22] This included a voluntary program to identify best practices and efficiency benchmarks for data center operators and federal support for more efficient data center design, efficiency improvements at existing data centers, and government procurement of more efficient data servers.[23]

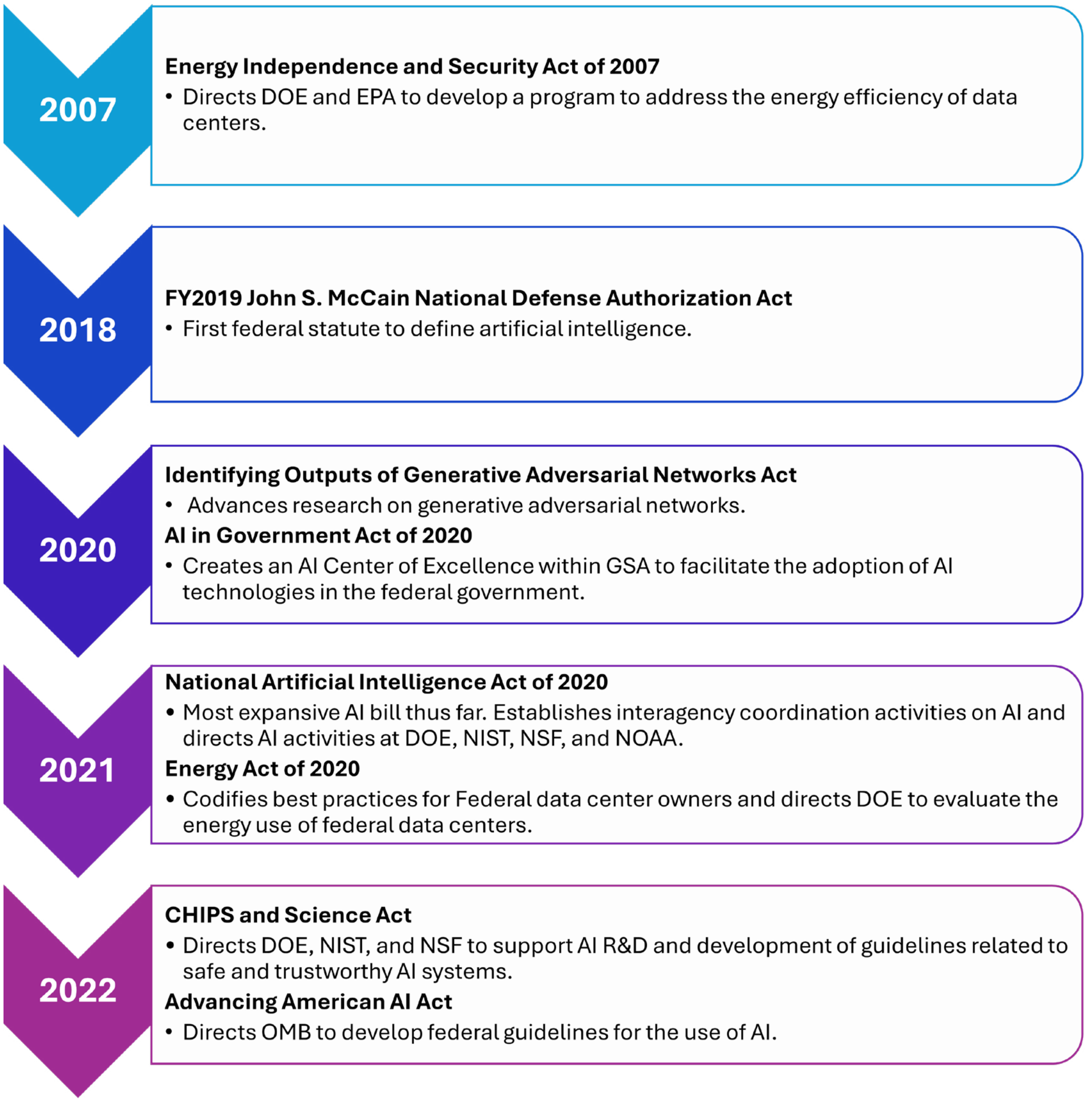


Figure 5. Timeline of key AI and data center legislation passed by Congress and signed into law

Following congressional direction in EISA07, DOE's Lawrence Berkeley National Laboratory (LBNL) has studied the energy efficiency of U.S. data centers. It presented its findings in a 2008 *Report to Congress on Server and Data Center Energy Efficiency*,[24] followed by a 2016 update, *United States Data Center Energy Usage Report*.[25] LBNL is currently developing an updated report on the status of data center energy use in the United States and recommendations for best practices that will be released at the end of 2024. The Energy Act of 2020[26] codified best practices for federal data center operators and directed DOE to establish a Data Center Practitioner Program[27] to evaluate the energy use of federal data centers. More recent legislative efforts are summarized in Figure 5.[28] Recent legislation introduced by Sens. Joe Manchin (I-WV) and Lisa Murkowski (R-AK), the Department of Energy Artificial Intelligence Act, would provide a much-needed update to DOE's AI mission.[29]

As the nation's largest energy consumer, the federal government is focused on reducing energy use in its more than 10,000 data centers. This includes efforts by DOE's Federal Energy Management Program (FEMP) to assist other agencies with improving data center energy and water use through training, technical support, energy assessments, and implementation of best practices.[30] Much of this work is carried out by LBNL's Center of Expertise for Energy Efficiency in Data Centers.[31]

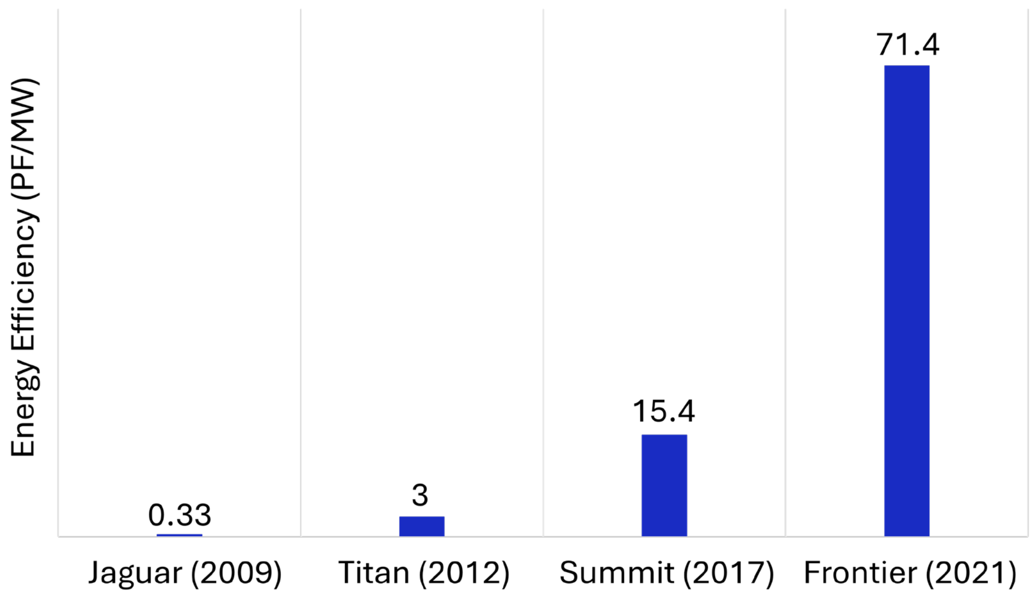


Figure 6. Energy efficiency of recent DOE supercomputers in petaflops/megawatt (PF/MW)

At the same time, DOE is focused on ways to improve the energy efficiency of computing. As noted already, DOE's largest contribution in this area was the advent of GPU accelerators for supercomputing. As seen in Figure 6, DOE's Titan supercomputer achieved a tenfold improvement in energy efficiency by using accelerated computing with GPUs for the first time in 2012. By 2021, this innovation had led to a two-hundredfold improvement in efficiency.

Currently, Lawrence Livermore National Laboratory (LLNL) convenes the Energy Efficient High Performance Computing Working Group, a coalition of more than 900 global companies that is implementing energy conservation and energy efficient design in high performance computing.[32] DOE is also investing in research to reduce energy and water use in supercomputer facilities, while addressing the energy efficiency of cooling technologies in data centers through a department-wide effort that includes investments from the DOE's Office of Science[33] and Advanced Research Projects Agency-Energy (ARPA-E).[34]

Applying AI for the Public Good

Previous sections have discussed DOE efforts to advance AI and supercomputing technology and to accelerate energy efficiency improvements in computers, computer chips, and data centers. This section focuses on a third important way that DOE engages with AI: advancing policy goals in multiple areas of vital national interest, from basic science, energy, and climate change to security and defense. These DOE efforts are delivering upon charges set forth in an executive order under then-President Trump, Promoting the Use of Trustworthy Artificial Intelligence in the Federal Government,[35] and an executive order under President Biden, Safe, Secure, and Trustworthy Development and Use of Artificial Intelligence.[36] DOE is fulfilling several aspects of these orders, including using AI in federal decision-making, supporting AI research to tackle major societal and global challenges, using AI to build a clean energy economy, training new AI talent, and managing AI in critical infrastructure.[37]

DOE's Frontiers in AI for Science Security and Technology (FASST) initiative,[38] summarized in Figure 7, is central to delivering on these goals by leveraging AI to further U.S. science, security, and energy needs. This includes:

- Revolutionizing scientific research by dramatically reducing the time to discovery.
- Leveraging the government's vast repositories of data to develop AI-ready datasets.[39]
- Using AI to speed up federal regulatory processes.
- Strengthening DOE's nuclear stockpile stewardship and strategic deterrence capabilities.
- Developing standards and regulations for safe, secure, and trustworthy AI.
- Building an AI-ready workforce.

DOE Frontiers in Artificial Intelligence for Science, Security and Technology (FASST)

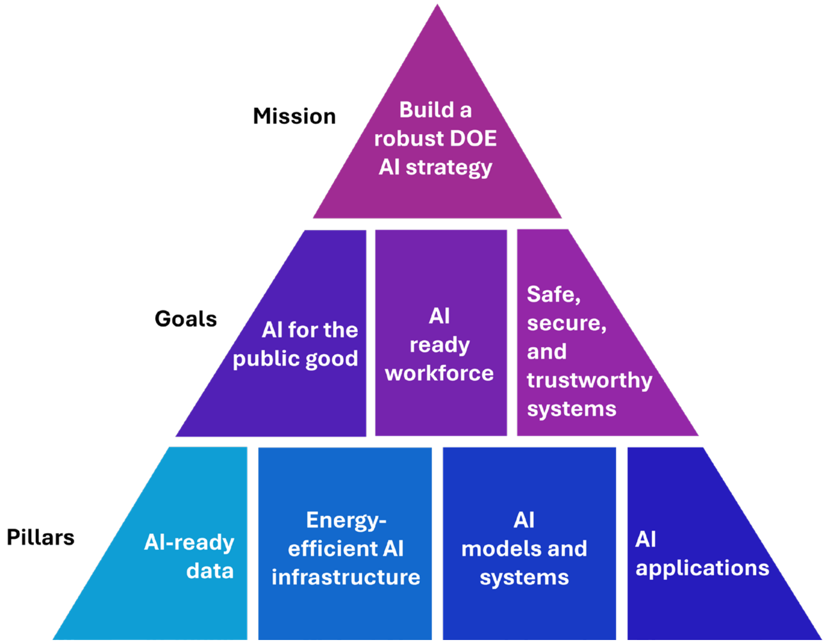


Figure 7. DOE's national AI strategy through the Frontiers in AI for Science Security and Technology (FASST) initiative

DOE'S AI PARTNERSHIPS: FEDERAL AND EXTERNAL

To stay at the forefront of AI, our nation requires access to the fastest supercomputers and the smartest scientists, as well as strategic R&D investments. DOE can contribute to all three. The department's AI expertise and facilities are used by entities across the federal government as well as private-sector partners to advance applications for the public good.

By leading in the design, construction, and maintenance of supercomputing facilities—and giving other federal agencies and external users access to DOE supercomputers—DOE enables the development of new AI applications on its own supercomputers. Figure 8 shows the location of DOE supercomputers and highlights several DOE facilities included in the June 2024 TOP500 list of the most powerful computer systems globally.[40] All of these facilities were co-designed with private sector partners.

Importantly, other agencies' AI initiatives rely on the use of DOE facilities. For example, the NSF's new National Artificial Intelligence Research Resource (NAIRR) pilot program gives researchers access to advanced computing facilities. ANL's AI Testbed and ORNL's Summit supercomputer are donating computing resources to support the NAIRR pilot.[41] Summit is currently the single most powerful supercomputer supporting NAIRR, enabling the most demanding AI calculations as well as projects with sensitive data that require a secure computing environment. According to recent estimates, DOE is providing about 90% of the NAIRR pilot's computing capacity.[42]

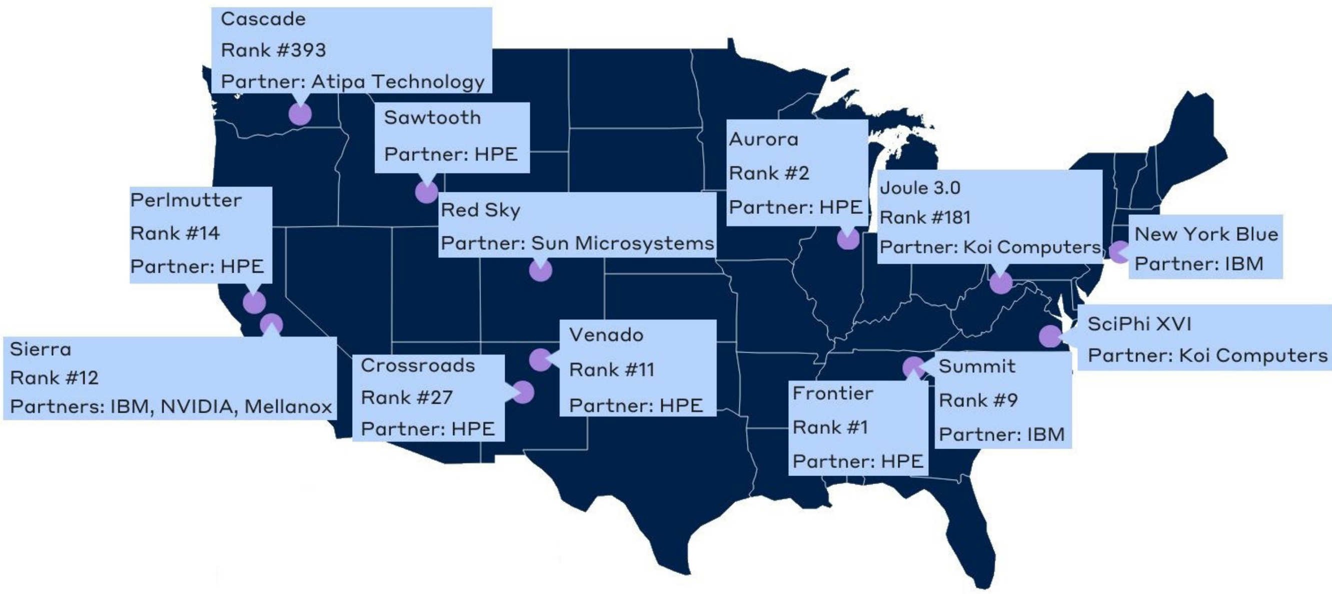


Figure 8. Map of top performing DOE supercomputers, 2024

In a prominent example of impactful interagency partnership on AI, DOE has been collaborating with the National Cancer Institute (NCI) since 2016 to accelerate advances in the diagnosis and treatment of cancer using AI and supercomputing. The National Institutes of Health (NIH), which includes the NCI, is collaborating with four DOE national labs on this project, which is improving scientists' understanding of cancer's initiation and its growth, accelerating drug discovery, and helping to model drug responses.[43]

In addition to its interagency partnerships, DOE supports dozens of academic and industry partners through access to its supercomputing facilities to solve a myriad of scientific and technological problems.[44] DOE has numerous programs for making its computing resources available, including:

- Innovative & Novel Computational Impact on Theory & Experiment (INCITE)
- ASCR Leadership Computing Challenge (ALCC)
- High Performance Computing for Energy Innovation (HPC4EI)
- High Performance Computing for Advanced Manufacturing (HPC4Mfg)

Access to these resources has been transformational for the scientific community and for advancing private-sector AI applications. In fiscal year 2023, DOE facilities served nearly 40,000 individual users.[45]

An effective national strategy for AI requires sustained and robust partnerships across academia, industry, and the federal government to leverage existing resources and facilities while making new investments that draw on the strengths of each of these sectors. Alongside world-leading academics and companies, DOE continues to have a role to play as a thought-leader on computing and AI.

AI FOR SCIENCE

DOE is deploying AI to enable breakthroughs in key mission areas, including science, energy, and national security. The department's unique position in American scientific enterprise rests on three main pillars:

- Funding external R&D performed by academic and private-sector entities.
- Advancing original research through the DOE national lab system.
- Building and maintaining world-class facilities that can be used by lab scientists and external researchers to advance cutting-edge insights and technologies.

In each of these areas, DOE is supporting progress at the intersection of AI and science. These topics are covered in detail in the national labs' 2020 *AI for Science* report.[46]

DOE's investments in scientific use cases for AI are crucial in that they address areas that the private sector is uninterested in pursuing. Without federal support, AI applications for the public good will not advance at the same rate as commercial AI applications. DOE's AI assets and capabilities provide scaffolding for research efforts to advance the frontiers of human knowledge.

WITHOUT FEDERAL SUPPORT, AI APPLICATIONS FOR THE PUBLIC GOOD WILL NOT ADVANCE AT THE SAME RATE AS COMMERCIAL AI APPLICATIONS.

As an example, LBNL launched the Materials Project in 2011 to develop an open-source database with information on thousands of materials and molecules that provide the building blocks for modern infrastructure and technologies.[47] Researchers can use the database to simulate and search materials properties in a virtual environment instead of synthesizing materials in a lab first, which can save thousands of hours of research and lower the costs of discovery. Recently, Google used AI methods that built on computational models used in the Materials Project to discover hundreds of thousands more materials that will be added to the database.[48]

AI FOR ENERGY AND CLIMATE

DOE has a long history of supporting advances in basic science, but it is best known today for its contributions in the field of energy. DOE's energy mission focuses on investments in critical areas, including energy technology development, electric infrastructure upgrades, energy efficiency standards, cybersecurity for energy systems, and securing energy manufacturing and supply chains, among other topics. This section focuses on the ways DOE and other technologists are deploying AI to accelerate energy technology development.

AI can be used to accelerate every step of the energy technology development process shown in Figure 9, and to facilitate innovations that reduce costs, materials requirements, labor demands, and emissions.

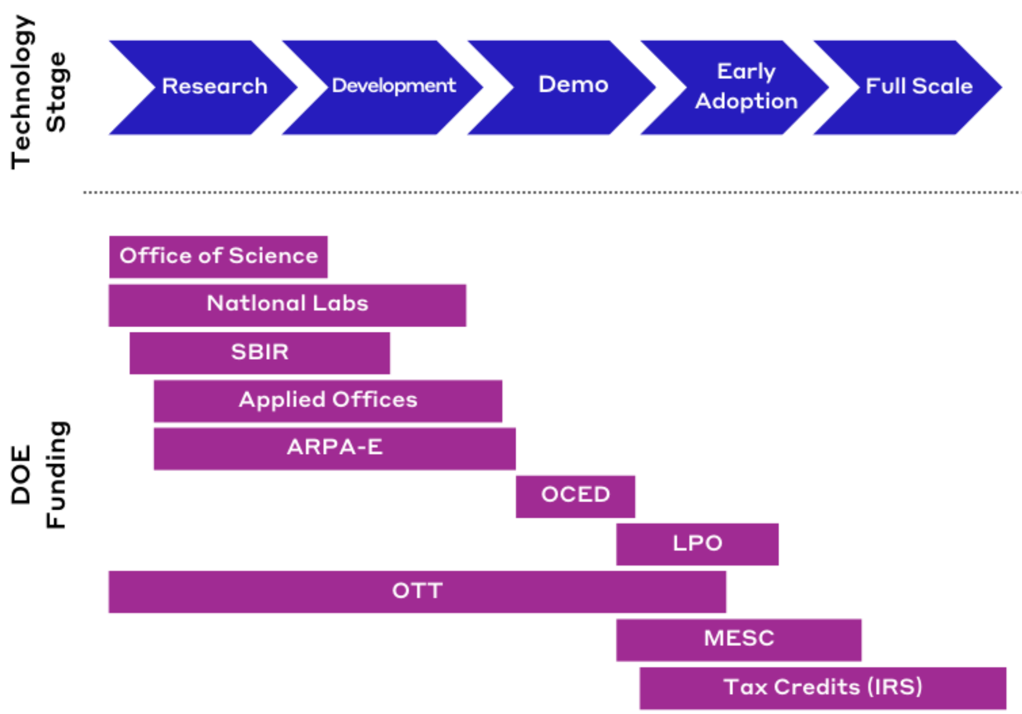


Figure 9. The energy innovation process and associated DOE programs[49]

- **Research.** At the very start of the innovation process, AI can help generate scientific hypotheses, distill information from a vast number of sources, and develop strategies for testing hypotheses. DOE is utilizing AI in these ways to advance fusion energy development.[50] Additional examples are covered in the section on AI for Science.
- **Development and demonstration.** AI is being used to accelerate development timelines for new energy technologies. As an example, ARPA-E is funding research through its DIFFERENTIATE program that will use machine learning to reduce time spent on design iteration.[51] Iowa State University researchers received a grant under this program to use an “inverse design” process to more quickly develop novel, manufacturable structures for more efficient solar cells.
- **Early adoption.** As the scientific and technical merits of a technology are proven and companies start to move to scale, cost-effective manufacturing techniques are needed to bring technologies to market. AI tools are being used to simulate and optimize product design and manufacturing processes, resulting in significant time and cost savings.[52] Much of this learning can take place in virtual environments, allowing innovators to model manufacturing processes without building costly prototype facilities. Technologies cannot scale unless they can be cost-effectively produced—AI can help make that happen.
- **Full-scale commercialization.** A critical step in the pathway to commercialization involves navigating regulations that govern permitting processes for new energy generation facilities. DOE has launched an initiative to use AI to synthesize information from thousands of environmental review documents to speed up National Environmental Policy Act (NEPA) reviews through the VoltAIc initiative.[53] DOE is uniquely positioned to leverage its AI expertise to speed up regulatory processes across the government, which could include permitting and nuclear reactor licensing.

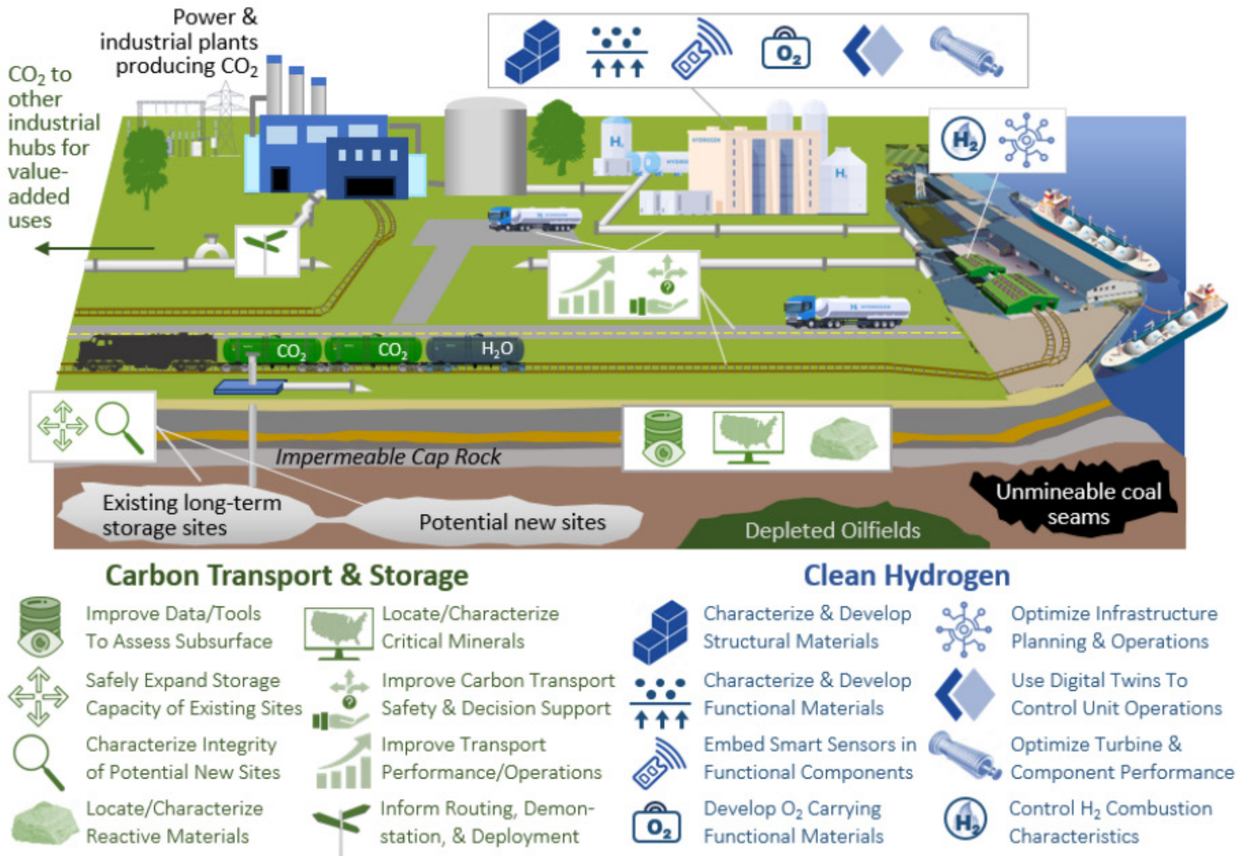


Figure 10. Examples of how AI can accelerate the full innovation pipeline for carbon capture and clean hydrogen technologies[54]

- **Operation.** Once a new technology has been developed, AI can help enhance its operations in the field to lower costs and optimize system operation. For example, AI is being used to increase outputs from geothermal energy facilities, including improving subterranean resource characterization, geothermal system power outputs, and geothermal system operations.[55] AI is also benefitting the wind industry. Researchers demonstrated recently that AI can be used to optimize the design of a wind farm to ensure that power output from downstream turbines is not negatively affected by wake effects from upstream turbines.[56]

Beyond accelerating the innovation process, AI is being used to improve the resilience and reliability of existing energy systems. As highlighted in a recent national labs report, AI is helping to manage energy load and match supply to load, including through tools for optimizing power flow from smart devices at the grid edge.[57] This is a growing problem, as the number of residential solar installations, electric vehicles, and other customer assets increases.[58] ARPA-E is supporting a company known as Utilidata that is helping utilities anticipate and solve power flow challenges in real time.[59]

DOE is also helping companies use AI to protect infrastructure against the effects of weather and a changing climate. In 2019, ANL partnered with AT&T to develop a model for predicting local impacts of climate change that informs AT&T's infrastructure planning, including sea-level rise and wildfire risk.[60] The product of this collaboration, known as the Climate Risk and Resilience Portal (ClimbRR), was made available to the public in 2022.

DOE's "AI for Energy" effort is a department-wide initiative that draws on the expertise of the national labs and relevant DOE program offices. AI's major promise is as an accelerant. AI can speed up timelines for all stages of the innovation process, as well as improving the overall resilience and reliability of the nation's energy infrastructure. Additional ways in which AI is supporting the energy system are explored in DOE's report, *AI for Energy: Opportunities for a Modern Grid and Clean Energy Economy.*[61] Although AI is raising electricity demand in the United States, AI tools and systems are helping to reduce emissions in a variety of ways. These additional effects should be considered to accurately discuss the effects of AI on the nation's energy system.

AI FOR NATIONAL SECURITY

DOE has a strong national security mission as the lead department for maintaining the U.S. stockpile of nuclear weapons, overseeing nuclear weapons nonproliferation, responding to nuclear-related terrorist activity, and supporting the Navy's use of nuclear power. This work is carried out by DOE's National Nuclear Security Administration (NNSA).[62]

For nearly 30 years, the NNSA's Advanced Simulation and Computing (ASC) program has developed tools to support nuclear deterrence. In the coming decade, NNSA will use AI to accelerate the development of new nuclear warheads from discovery to design, manufacturing, and maintenance.

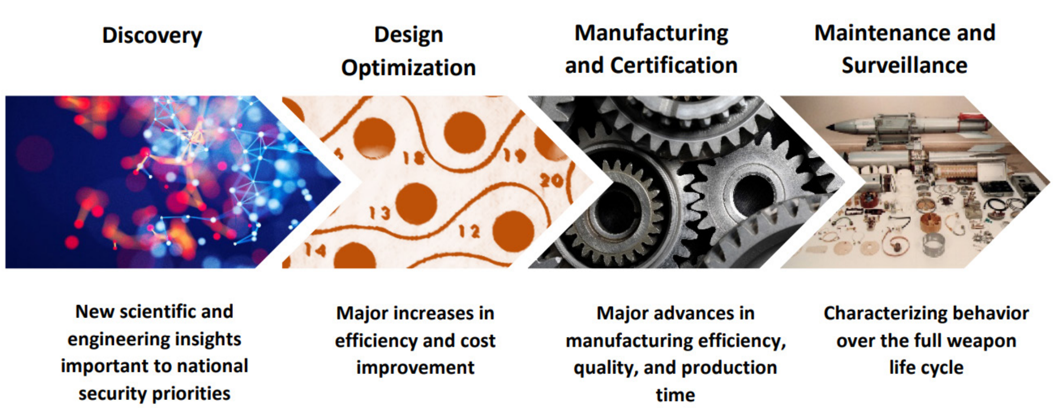


Figure 11. Life cycle of a nuclear warhead system[63]

BUILDING SECURE, SAFE, TRUSTWORTHY, AND RESPONSIBLE AI SYSTEMS

While AI has many potentially beneficial applications, it also poses risks. DOE's Office of Cybersecurity, Energy Security, and Emergency Response (CESER) has identified four risks that apply to energy systems:[64]

1. **Unintentional failure modes** due to training AI on data that do not represent real-world scenarios or misalignment between the implicit goals of an AI model and its intended use.
2. **Adversarial attacks** in which bad actors exploit system vulnerabilities to manipulate an AI model such that it produces inaccurate results.
3. **Hostile applications** in which bad actors use AI for nefarious purposes, such as to plan and execute cyber or physical attacks on energy infrastructure.
4. **Compromised supply chain**, which refers to cybersecurity risks for software-based systems, including the digital systems currently used to operate energy infrastructure.

Federal agencies are investigating strategies for managing these risks and enhancing AI security, including the AI Risk Management Framework developed by the National Institute of Standards and Technology.[65] The White House has issued several directives aimed at addressing AI-related vulnerabilities. In response, DOE established the Center for AI Security Research (CAISER) in 2023 at ORNL, which is collaborating with national security and industry partners to study AI implications and risks for cybersecurity, biometrics, geospatial intelligence, and nuclear nonproliferation.[66] This work is initially focused on AI risks related to national security but could expand to other areas in the future. NNSA is also conducting exercises to stress test DOE's cybersecurity enterprise, including 'red teaming' to uncover possible AI risks.[67]

Educating a National AI Workforce

According to one recent analysis, AI workers comprised about 10% of the overall U.S. workforce in 2022, with demand continuing to increase.[68] As AI applications are used more widely, companies will seek to ensure that their employees are prepared to deliver AI solutions, leverage AI tools that can enhance their performance, and adjust as tasks for human workers shift.[69] DOE's national labs are helping train a national AI workforce through programs targeted to a range of education levels, from kindergarten to college.[70] These efforts deliver on President Biden's direction to DOE and NSF to establish a pilot program to train 500 new AI scientists by 2025.[71] DOE's AI workforce programs include:

- **K-12 students.** The national labs' K-12 programs are designed to help students learn about the fundamentals of coding, data science, and computer science. Students are exposed to real-world problems that the national labs are working on. One example is the CodeGirls@Argonne Camp at ANL which teaches middle-school girls the fundamentals of coding.
- **Undergraduate students.** Every summer, the national labs offer learning opportunities to hundreds of undergraduate students in machine learning, AI, high performance computing, and other related fields through internships and collaborations on research projects. For example, ORNL's AI Summer Institute trains students, working alongside ORNL mentors, to solve scientific challenges using AI.
- **Graduate students.** The national labs provide a variety of AI research and training programs for graduate students. This includes summer internships, research partnerships, introductory courses, and graduate fellowships. For example, DOE's Computational Graduate Fellowship allows graduate students to spend three months at a national lab, accessing world-class facilities and learning from DOE lab scientists to advance research on a computer science topic of their choosing.

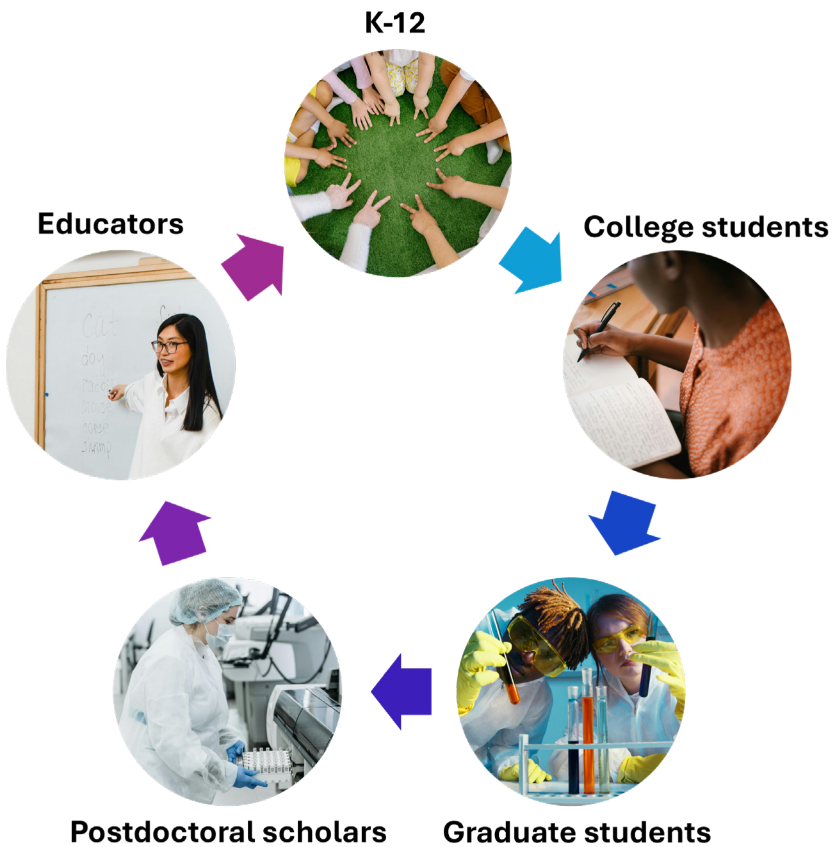


Figure 12. From K-12 students and educators to postdocs, DOE is helping build AI talent in the U.S. workforce

- **Postdoctoral scholars.** In addition to hosting interested scholars at the labs for long-term research projects, the national labs train postdocs who are seeking to understand and incorporate AI, machine learning, and data science into their work. For example, Brookhaven National Lab's AI and Machine Learning for Scientists (AIMS) program of seminars and tutorials highlights cutting-edge research in AI and machine learning.
- **Educators.** The national labs offer summer programs for college and university faculty to help improve their STEM teaching, to better inspire students, and to collaborate on AI research projects. The DOE Office of Science's Visiting Faculty Program supports this work.

The federal government needs to increase the number of AI experts in its own workforce, both to improve the effectiveness and performance of federal agencies and to build capacity for thoughtful AI oversight. With the national lab ecosystem's large scientific workforce, DOE is home to one of the biggest groups of in-house federal AI experts. Agencies must capitalize on this talent to ensure they have the technical expertise to integrate AI to improve the functionality of the federal government and to understand how to govern AI as the technology spreads.

Recommendations

The United States is in a position of global leadership with respect to AI and supercomputing thanks to more than 60 years of sustained federal investment. Within the federal government, DOE has unique expertise in AI as a department that studies, uses, and develops AI applications. This cross-cutting knowledge will be essential as the federal government seeks to develop its own use cases for AI. Building upon the vision presented in DOE's FASST proposal, DOE can shape the future of AI and promote responsible deployment of AI tools and systems through its work in several key areas:

Advancing the U.S. energy system

- **Advancing data center and chip efficiency.** Although the overall impact of AI on future energy demand remains uncertain, an increasingly digitized economy can be expected to become even more dependent on data centers and AI tools. DOE has already made significant contributions to advancing the energy efficiency of data centers and computer chips. Continuing this work is essential.
- **Meeting U.S. electricity needs**. With the U.S. entering a period of load growth, DOE is the central federal agency providing tools and support to meet our nation's electricity needs. DOE can help meet load growth through federal interventions including AI-powered permitting, accelerating commercialization of clean, firm power, and informing policymakers about expected data center energy use.

Building AI applications

- **Investing in AI for the public good.** The DOE has a long history of organizing large, interdisciplinary projects to advance public-sector missions. Looking forward, DOE can leverage its expertise on solving big problems at scale to advance AI applications that will benefit the public. This should include applying AI to speed up regulatory processes in energy, accelerate clean technology development, and enhance national security.
- **Supporting long-term AI R&D programs that fill gaps in the private sector.** DOE's past investments in AI and supercomputing have been successful largely because they have been sustained over many years and benefited from strong partnerships with industry. Continued collaboration with industry will be important to ensure federal resources are directed to areas lacking private-sector expertise or interest. DOE should maintain leadership in R&D and computing in a way that complements rather than replicates private-sector resources and expertise.

Ensuring widespread benefits of AI

- **Enabling secure, safe, and trustworthy AI applications.** AI technologies can be vulnerable to adversarial attacks, data breaches, and systemic biases. DOE expertise can help mitigate these risks while also ensuring that AI is used in ways that strengthen national security, economic stability, and public safety. Additionally, DOE should ensure that data produced by its user facilities are AI-ready and should adopt clear standards on data quality to more easily enable AI applications.
- **Enabling AI accessibility.** DOE's model of stewardship for the national lab enterprise is built on making its expertise and facilities available to a wide range of external users nationwide. As AI tools become more widely studied and used, researchers at institutions that do not have the resources to build, operate, and maintain supercomputers of their own will benefit from access to DOE's vast network of AI and computing facilities.
- **Training a national AI workforce.** Federal support for the training of a national AI workforce is essential to harness AI's full potential and address the complex challenges AI presents. Several DOE programs are already investing in AI education and training for the next generation of workers while also equipping young people for productive and innovative careers in sectors such as health care, manufacturing, and defense.

Supporting federal use of AI

- **Enabling partnerships with the DOE national labs.** At a time when preserving America's global leadership in science and technology is more difficult and consequential than ever, DOE's lab network stands out as a national treasure without parallel. The national labs have been pioneering computing and AI advances for decades, and they are vital to maintaining U.S. competitiveness in these critical industries.
- **Supporting interagency partnerships**. DOE resources and expertise are already helping many other federal agencies advance AI applications relevant to their own mission areas. This support must continue to maximize the federal government's capacity to address a broad range of objectives and challenges.

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