U.S. DEPARTMENT OF ENERGY

The U.S. Department of Energy's Ten-Year-Plans for the Office of Science National Laboratories FY 2024

Table of Contents

Front cover photo credits (left to right, first to third rows): Ames National Laboratory, Argonne National Laboratory, Princeton Plasma Physics Laboratory, Fermi National Accelerator Laboratory, Oak Ridge National Laboratory, Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, SLAC National Accelerator Laboratory

INTRODUCTION

The Department of Energy (DOE) is responsible for the effective stewardship of 17 national laboratories, of those ten are stewarded by the Office of Science and focus on discovery science. The DOE national laboratories were created as a means to an end: victory in World War II and national security in the face of the new atomic age. Since then, they have consistently responded to national priorities: first for national defense, but also in the space race and more recently in the search for new sources of energy, new energy-efficient materials, new methods for countering terrorism domestically and abroad, and addressing important critical national needs.

Today, the national laboratories comprise the most comprehensive research system of their kind in the world. In supporting DOE's mission and strategic goals, the SC national laboratories perform a pivotal function in the nation's research and development (R&D) efforts: increasingly the most interesting and important scientific questions fall at the intersections of scientific disciplines—chemistry, biology, physics, astronomy, mathematics—rather than within individual disciplines. The SC national laboratories are specifically designed and structured to pursue research at these intersections. Their history is replete with examples of multi-and inter-disciplinary research with far-reaching consequences. This kind of synergy, and the ability to transfer technology from one scientific field to another on a grand scale, is a unique feature of SC national laboratories that is not well-suited to university or private sector research facilities because of its scope, infrastructure needs or multidisciplinary nature.

As they have pursued solutions to our nation's technological challenges, the national laboratories have also shaped, and in many cases led, whole fields of science—high energy physics, solid state physics and materials science, nanotechnology, plasma science, nuclear medicine and radiobiology, and large-scale scientific computing, to name a few. This wide-ranging impact on the nation's scientific and technological achievement is due in large part to the fact that since their inception the DOE national laboratories have been home to many of the world's largest, most sophisticated research facilities. From the "atom smashers" which allow us to see back to the earliest moments of the Universe, to fusion containers that enable experiments on how to harness the power of the sun for commercial purposes, to nanoscience research facilities and scientific computing networks that support thousands of researchers, the national laboratories are the stewards of our country's "big science." As such, the national laboratories remain the best means the Laboratory knows of to foster multi-disciplinary, large-facility science to national ends.

In addition to serving as lynchpins for major laboratory research initiatives that support DOE missions, the scientific facilities at the SC national laboratories are also operated as a resource for the broader national research community. Collectively, the laboratories served over 37,000 facility users and more than 12,000 visiting scientists in Fiscal Year (FY) 2023, significant portions of which are from universities, other Federal agencies, and private companies.

DOE's challenge is to ensure that these institutions are oriented to focus, individually and collectively, on achieving the DOE mission, that Government resources and support are allocated to ensure their long-term scientific and technical excellence, and that a proper balance exists among them between competition and collaboration.

This year, DOE engaged its laboratories in a strategic planning activity that asked the laboratory leadership teams to define an exciting, yet realistic, long-range vision for their respective institutions based on agreed-upon core capabilities assigned to each.[1] This information provided the starting point for discussions between the DOE leadership and the laboratories about the laboratories' current strengths and weaknesses, future directions, immediate and long-range challenges, and resource needs, and for the development of a DOE plan for each laboratory. This document presents strategic plans for ten national laboratories for the period FY 2024-2034.

[1] A table depicting the distribution of core capabilities across the science and energy laboratories is provided in Appendix 1, along with the definitions for each core capability category.

AMES LABORATORY

Lab-at-a-Glance

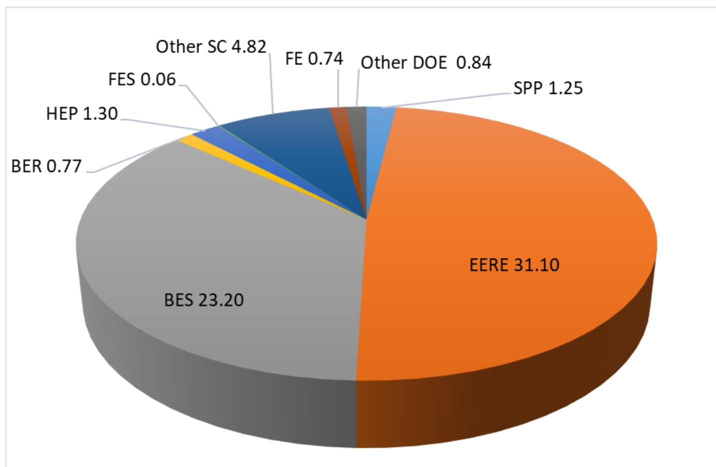
Location: Ames, IA
Type: Single-program Laboratory
Contractor: Iowa State University of Science and Technology
Site Office: Ames Site Office
Website: www.ameslab.gov

- **FY 2023 Lab Operating Costs:** $64.09 million
- **FY 2023 DOE/NNSA Costs:** $62.79 million
- **FY 2023 SPP (Non-DOE/Non-DHS) Costs:** $1.25 million
- **FY 2023 SPP as % Total Lab Operating Costs:** 1.9%

Physical Assets:
- 10 acres and 13 buildings
- 340,968 GSF in buildings
- Replacement Plant Value: $209.7M
- 0 GSF in 0 Excess Facilities
- 0 GSF in 0 Leased Facilities

Human Capital:
- 306 Full Time Equivalent Employees
- 39 Joint Faculty
- 47 Postdoctoral Researchers
- 126 Graduate Student
- 64 Undergraduate Students
- 0 Facility Users
- 58 Visiting Scientists

FY 2023 Costs by Funding Source ($M)



Mission and Overview

Ames National Laboratory delivers critical materials solutions to the nation. For over 75 years, Ames Lab has successfully partnered with Iowa State University of Science and Technology to lead in the discovery, synthesis, analysis, and use of new materials, novel chemistries, and transformational analytical tools. The Laboratory conducts fundamental research addressing critical chemistry and materials challenges, with a focus on three long-term strategic directions: critical materials and upcycling science, atomistic and molecular design and control for energy and chemical conversion, and novel synthesis to manufacturing. Each strategic direction has a particular focus on rare earth elements, sustainable chemistry, alloys, and compounds. Building upon our chemistry, physics, and materials sciences core strengths, and a proven track record of transitioning basic energy science through early-stage research to licensed technologies and commercialization, Ames Lab will lead the nation in translating foundational science for energy and chemical conversion into critical technology innovation. To address these challenges, the Laboratory focuses its fundamental research to: accelerate the discovery, design, and implementation of new chemistry, materials, and associated processes; create novel approaches for precision synthesis and chemical transformations across length scales; devise better ways to apply chemistry and materials for re-use, recovery, and efficient and clean conversion of end-of-life products; and integrate communication, computation, and artificial intelligence/machine learning across the basic and applied spectrum to optimize complex chemical and synthetic processes to enable rapid device integration and optimization.

Our goals are to transform the way we do science and to create next-generation materials and chemistry, enabling a more sustainable future. Our success results from a high-quality diverse workforce, modern business systems, safety-focused research and operations, renewed infrastructure and facilities, and a cultural ecosystem unique to Ames Lab and Iowa State University that is all rooted in our core values of creativity, collaboration, and community.

Core Capabilities

Ames National Laboratory's people and core capabilities represent the greatest strengths of the Laboratory. Ames Lab continually enhances each core capability through investments of LDRD funds, newly funded DOE programs, and strengthening our workforce. These core capabilities are comprised of interdisciplinary teams of world-leading researchers who utilize unique expertise and capabilities to address areas of national need and deliver on DOE's mission.

The Laboratory currently has three core capabilities. These include:

- Applied Materials Science and Engineering
- Chemical and Molecular Science
- Condensed Matter Physics and Materials Science

Ames Lab is proposing two new core capabilities. These new capabilities reflect and build on existing strengths in Ames Lab's programs, and are areas that we are investing in and supported by the Initiatives described in section 4. The proposed new emerging capabilities are:

- (Proposed New) Chemical Engineering
- (Proposed New) Computational Science

Applied Materials Science and Engineering

Ames Lab's core capability in *Applied Materials Science and Engineering* is underpinned through world-leading research in rare-earth science, high-temperature alloy development and synthesis, caloric materials, powder synthesis and advanced manufacturing, and foundational materials science.

Accelerated Alloy Discovery: Ames Lab is addressing materials challenges to support clean energy technologies by accelerating alloy development needed for harsh service environments. We leverage powerful modeling and computational approaches and couple them with advanced synthesis and characterization techniques. We are investing in new inert melting capabilities for processing refractory (e.g., Nb, Ta, W) and highly reactive (e.g., Ti) alloys for new materials for ultra-high temperatures.

Advanced Magnet Alloys: Ames Lab is commissioning a magnet fabrication prototyping facility that will serve as a National Resource for developing domestic magnet production. The flexible platform will enable rapid manufacturing of kg-scale magnets needed for rapid testing and validation of new magnet materials developed at Ames Lab, the Critical Materials Innovation (CMI) Hub, university, and industrial partners.

High Power Density Magnetocaloric and Elastocaloric Systems: Ames Lab has developed a testbed for magnetocaloric and elastocaloric colling systems to replace vapor compression cooling technology for the manufacturing and commercial and residential building climate control sectors.

Major Sources of Funding: Office of Energy Efficiency and Renewable Energy, Office of Fossil Energy and Carbon Management, Office of Advanced Research Projects Agency-Energy, Lab Directed Research and Development funds, and Strategic Partnership Projects.

Chemical and Molecular Science

Ames Lab's core capability in *Chemical and Molecular Science* is underpinned by catalysis and separation science aided by expertise in exascale computing, high-accuracy electronic structure methods, chemical characterization, and data-driven science.

Catalysis: Ames Lab combines concepts from homogeneous and heterogeneous catalysis in 3D environments to reveal new fundamental principles that enable selective conversions of underutilized hydrocarbons and oxygenates. Fundamental catalytic principles are being developed by iCOUP EFRC to move these novel plastic upcycling approaches from proof-of-principles to continuous processes.

Separations: Ames Lab is investigating fundamental principles that enable new methods for the separation of rare-earth elements. We devise new separation platforms with increased efficiency that are inspired by geo-chemical approaches and explore novel properties of solvents used for extraction.

Exascale Computing: Ames Lab is leading the development of highly scalable computational chemistry codes to take advantage of exascale computers, with application of the new codes to the simulation of heterogeneous catalysis and separation systems.

Solid-state NMR spectroscopy: Ames Lab is developing the next-generation instrument for dynamic nuclear polarization (DNP) that will greatly expand the classes of materials that can be studied and fundamentally change how we will do DNP in the future.

AI-driven Science: Ames Lab is developing AI-controlled reaction platforms that allow simultaneous co-optimization of multiple reaction parameters for smart and autonomous manufacturing and re-manufacturing of chemicals.

Primary Source of Funding: Office of Science, and Lab Directed Research and Development funds.

Condensed Matter Physics and Materials Science

Ames Lab's core capability in *Condensed Matter Physics and Materials Science* is underpinned through world-leading research in synthesis, quantum materials, rare earths, and interfaces. Ames Lab will enable a quantum future through new materials and new technologies.

Materials Synthesis and Discovery: Ames Lab can control chemistry, defects, and disorder for targeted functionality, particularly in rare-earth based systems. We can synthesize highly pure single crystals, thin films, multilayers, and nanoparticles of rare-earth materials. We can control intercalation processes to synthesize novel heterostructures with novel quantum properties.

Quantum Science: Ames Lab is involved in the *Superconducting Quantum Materials and Systems (SQMS) Center*, providing expertise to understand coherence in qubit materials. In the *Co-design Center for Quantum Advantage (C2QA)*, Ames Lab is using quantum computing to advance predictions of correlated materials behavior.

Advanced Characterization: Ames Lab's state-of-the-art microscopy facility allows the details of the defect structure to be visualized. We have recently added new capability in single crystal X-ray diffraction at high-pressure. We use solid-state NMR (SSNMR) and dynamical nuclear polarization (DNP) NMR for materials research to improve sensitivity beyond current technology by orders of magnitude. We have unique ARPES capabilities for probing electronic structure and have a unique low temperature laboratory for helium recovery that enables low-temperature and SSNMR measurements.

Computation and Theory: Ames Lab provides advanced theory to enable prediction and control for rare earth systems and their magnetic behavior. We are leveraging quantum computation to achieve highly accurate total energy calculations and to simulate quantum dynamics in correlated multi-orbital quantum materials. We combine computational tools with innovations in a variety of experimental techniques for probing correlated materials we will continue to advance our understanding and predictive capabilities for 4f-electron systems.

Major Sources of Funding*:* Office of Science and Lab Directed Research and Development funds.

(Proposed New) Chemical Engineering

Ames Lab is proposing a new emerging core capability in *Chemical Engineering* based on world leading research in separations, chemical conversions, catalysis, and the development of chemical processes. We invest in developing and sustaining these capabilities and expertise through LDRD funds to our initiatives as well as in development of facilities to support the work. Lab investments – including current LDRD investments listed below – are supporting this area significantly (>$1.3M/year in FY2024). Future investments in this area will be made, consistent with the three initiatives described in the lab plan, all of which will contribute to this emerging core capability.

Carbon Cycle Management: Ames Lab has expertise in understanding and designing the molecular function of both homogeneous and heterogeneous catalysts. The Laboratory is scaling up processes developed as part of the iCOUP EFRC, to efficiently convert polymer waste in a continuous process to clean burning, drop-in diesel fuel replacements.

Accelerated Optimization and Development of Separations: Ames Lab has decades of expertise in separations and is leading projects on the fundamental science of ionic liquid/deep eutectic solvent separations as well as rare earth separations in geoinspired systems. Ames Lab has pioneered the development of AI-driven automation algorithms and software, Rxn Rover, that accelerate research, development, and deployment of sustainable separation processes. Rxn Rover can automate experimental hardware to perform unassisted process optimization and achieve data-enabled prediction of process conditions.

High-purity Critical Materials Production: The Materials Preparation Center at Ames Lab has world-leading expertise and capabilities to convert REE oxides to ultra-high purity RE metals via fluorination and metallothermic reduction. Capabilities exist in synthesis of other high purity materials including alkaline and transition metals.

Critical Materials Recycling: Ames Lab has developed Acid-Free Dissolution Recycling (ADR), a hydrometallurgical technology that uses copper-based solutions for selective oxidative dissolution of REE-bearing e-waste components at neutral pH, which eliminates the hazards of using acids and generating environmentally polluting waste. This process does not limit the subsequent recycling of the other metals, e.g., Platinum Group Metals (PGMs), copper, and aluminum.

Critical Materials Refining: Through recently announced funding for the Critical Minerals Supply Chain Research Facility, Ames Lab will build a new Critical Materials Refining Center, which will enable the development of energy-efficient, and environmentally friendly critical materials refining technologies. We will integrate advanced diagnostics and data analytics into critical materials refining, and bridge mid-scale processing to commercial adoption.

Major Sources of Funding: Office of Science, Office of Energy Efficiency and Renewable Energy (EERE), Office of Fossil Energy and Carbon Management (FECM), Lab Directed Research and Development funds, and Strategic Partnership Projects.

(Proposed New) Computational Science

Ames National Laboratory proposes a new emerging core capability in *Computational Science,* based on leading research in exascale computing and computationally-assisted scientific discovery. Through years of developing scientific software, particularly our 10-year involvement leading software development for two Exascale Computing Project (ECP) applications, we have a core set of researchers and exascale-capable expertise. We lead quantum computing efforts through BES-MSE funding and through the Superconducting Quantum Materials and Systems Center, led by Fermi National Laboratory.

As an emerging capability, we will support new efforts, including LDRD and other discretionary resources, in Computational Science and Applied Math, seeking to establish a core expertise and core efforts in these areas. Future investments in this area are consistent with the three initiatives described in the lab plan, all of which will contribute to this emerging core capability. In particular, the *Data-Driven Chemical, Materials, and Manufacturing Solutions* Initiative will focus on investments toward this area, building expertise and capabilities in computation and applied mathematics, and applying these to core and growing research areas within the Laboratory.

Exascale computing for chemical and molecular sciences: The Laboratory led efforts in development of two exascale-computing capable computational chemistry codes with efficient and portable implementations on heterogeneous architectures: the *General Atomic and Molecular Electronic Structure System (GAMESS)*, and *NWChemEx.* These codes support a broad range of chemistry research important to DOE Biological and Environmental Research and DOE Basic Energy Sciences on computing systems that range from petascale servers to exascale computers. Ames Lab has a core set of researchers continuing to work to develop these packages, and to demonstrate their value for chemical and molecular sciences.

Accelerated Optimization and Development of Molecular Synthesis: The Laboratory has pioneered the development of AI-driven laboratory scale optimization and automation algorithms and software, Rxn Rover. Rxn Rover can automate laboratory hardware to perform unassisted process optimization and achieve data-enabled prediction of process conditions to accelerate molecular synthesis. A large range of algorithms have been used and developed to facilitate the fastest time to solution.

Quantum computing for predicting correlated material behavior: The Laboratory leads efforts seeking to achieve practical quantum advantage by applying quantum algorithms to calculate properties of correlated multi-orbital quantum materials. The application of adaptive, variational quantum algorithms may provide a path to practical quantum advantage with an appropriate combination of problem formulation, algorithm, and hardware development.

AI-accelerated material and chemical discovery: Ames Lab is developing and applying a number of AI-accelerated approaches for materials discovery, ranging from physics-informed prediction of magnetic properties of novel compounds, to ML-accelerated genetic algorithm prediction of novel crystal structures in unexplored compositional space. We are utilizing AI-based molecular and protein design for rare earth separations, and developing new UQ approaches for integrating limited experimental data with simulations to optimize materials processing for efficient manufacturing.

Major Sources of Funding: Office of Science, Office of Energy Efficiency and Renewable Energy (EERE), Office of Fossil Energy and Carbon Management (FECM), Lab Directed Research and Development funds, and Strategic Partnership Projects.

Science and Technology Strategy for the Future/Major Initiatives

The mission of Ames National Laboratory is to deliver critical materials solutions to the nation. Our programs seek to provide and leverage the fundamental understanding of materials and chemistry in order to advance our nation's energy, economic, environmental, and national security. This is reflected in our strategy: *Today's fundamental science for tomorrow's critical chemistry and materials solutions*. We seek to transform the way we do science, to create next-generation materials and chemistry, and to enable these developments into manufacturing, to achieve a more sustainable future. Ames Lab focuses its priority research on the following strategic goals:

- *Discovery for a Sustainable Future – Critical Materials and Upcycling Science*: The Laboratory will create alternative materials from abundant resources, reduce use of strategically important materials, efficiently separate and create valuable resources from dilute sources and waste materials, and make every atom count.
- *Making Every Atom Count – Atomistic and molecular design and control for energy and chemical conversion:* The Laboratory masters interfacial, molecular, and electronic phenomena to create transformative capabilities in directing material and chemical behavior.
- *Innovating for Science and Industry – Novel Synthesis to Manufacturing:* The Laboratory precisely controls synthetic pathways and chemical transformations to fabricate materials across length scales and to accelerate the translation of fundamental science into new technologies.
- *Transitioning Fundamental Science – Chemistry and Materials for Clean Energy Technologies*: The Laboratory leverages its fundamental science to create and enable new technological approaches for a clean energy future.

Infrastructure

Overview of Site Facilities and Infrastructure

Ames Lab, with a mission to provide critical materials solutions to the nation, is located in Ames, Iowa, on the campus of Iowa State University (ISU). The Laboratory occupies 10 acres of land leased from ISU where 13 DOE-owned buildings reside (see the Ames Lab Land Use Plan). There are four research buildings, an administrative building, and eight support buildings on the campus, all of which are identified as "operating" in FIMS. The four research buildings are for general use and support research for all three of our core capabilities: applied materials science and engineering, chemical and molecular science, and condensed matter physics and materials science. The Laboratory has a replacement plant value (RPV) of \$209.7M (as captured in FIMS; actual RPV is likely ~\$500M-\$700M).

The three oldest buildings (Harley Wilhelm Hall, Spedding Hall, and Metals Development) serve as the Laboratory's research workhorses by supporting ~85% of research activity at the Laboratory and comprising ~70% of the overall square footage at the Laboratory. While solidly built for research needs of the mid-1900s, these buildings are rated substandard and require significant modernization to meet the research needs of today. In 2020, a Facilities Condition Assessment (FCA) was conducted of these three facilities. The FCA rated each of these facilities as below average (Spedding Hall) and poor condition (Harley Wilhelm Hall, Metals Development), highlighting the need for significant renovation investment in major infrastructure systems (electrical, HVAC, plumbing, building envelopes, and elevators).

Ames Lab has no utility-generating plants. Electricity is purchased through the local municipality (City of Ames). Water, steam, chilled water, and natural gas are purchased through ISU. Natural gas for the support buildings is purchased from Alliant Energy. ISU has updated utility systems that support Laboratory operations. Since 2015, ISU has upgraded its distribution systems for electricity and chilled water and upgraded some of its boilers from coal to natural gas. Future plans include updates to the storm and sanitary sewers, power, and the conversion to natural gas for more boilers. ISU has invested $75+M in infrastructure improvements that have had a positive impact across University Campus operations to include Ames Lab operations.

Campus Strategy

The future success of Ames Lab relies on outstanding scientific and operations staff, a strong partnership with ISU, and facilities and infrastructure that allow the Laboratory to advance its scientific directions for economic growth, environmental sustainability, and national security. The campus strategy establishes the framework to foster advancement. By aligning facility planning and design in support of current and future research needs through energy efficient, safe, secure, and optimized space utilization, the Laboratory will create the environment that ensures Ames Lab is a workplace of choice for great research.

Ames Lab facility planning and design partners closely with research divisions to identify plant and infrastructure investments for near and long-term needs. Ames Lab conducts a yearly examination of all research activities, research plans, and support function plans to determine the ability of the Laboratory's facilities to support our work now, in five-years and in 10-years. This mission readiness function ensures proper planning, prioritizing, and resources are secured, and future needs and capabilities are captured for longer-term investment planning. Ames Lab has increased its investment in the main research buildings, replacing 50+ year-old electrical and HVAC components, renovating individual laboratories, consolidating nuclear magnetic resonance (NMR) capabilities into a single modernized NMR laboratory, improving the Laboratory's capability to recover helium gas and compress it into a re-usable liquid form, and enhancing safety through a major upgrade to the Fire Alarm and notification system.

The COVID-19 pandemic has resulted in wider acceptance of virtual or hybrid work environments. The Laboratory currently allows for hybrid and remote work if the job functions do not require onsite activities. As a result, Ames Lab did convert a minimum number of spaces to hoteling configurations, allowing for generic desk spaces that can be used by multiple hybrid staff members for short visits to the Laboratory when they need to be onsite.

As Ames Lab focuses on its four key strategic scientific directions and strives to meet our mission to provide critical materials solutions to the nation, we must also optimize our infrastructure and facilities to accelerate progress. The Laboratory implements sustainability and energy conservation focused designs into all infrastructure modernization and upgrade projects. We are planning for future capabilities with the evolution of our research; for modern and flexible research space to advance DOE's and the nation's desire to reduce dependence on the supply of critical materials from foreign entities. Given the finite amount of existing research space, there is challenge in adapting existing operational research areas to meet emerging needs while research is in progress. However, with space utilization planning this challenge can be met to an extent, but as future research demands modernized capabilities and facilities the Laboratory also encourages investment for a new research facility. Additionally, we must continue to address the infrastructure capability gaps to continue to successfully sustain research operations and reduce deferred maintenance and repair needs.

Modification of Existing Research Areas

A major initiative which is underway and will continue over the next several years is transforming portions of Metals Development (MD) to ensure scientific capabilities are in place to support DOE mission needs in Critical Materials for Science, Energy, and Security.

Image 1: Advanced Magnet Facility (AMF)

Ames National Laboratory is undertaking large-scale facility upgrades in Metals Development (MD) to support DOE mission needs in Critical Materials for Science, Energy, and Security. Phase 1 of this five-year plan (started in FY 2022) was the renovation of ~1800 square feet of high-bay space in MD 160 that was previously part of a machine shop. Jointly funded with Lab discretionary funds, DOE Environmental Management funds, and AMMTO-EERE funds, the space was renovated (e.g., removal of contaminated equipment, upgraded utilities, casework, etc.) and new equipment was installed to construct the Advanced Magnet Facility (AMF). The AMF will serve as a key resource to stakeholders across National Laboratories, Universities, and industry for the mid-scale synthesis of advanced permanent magnets. In addition to the AMF, the newly renovated space in MD 160 will house a new gas atomization system (funded by ARPA-E) for reactive and refractory materials. This system will support mission needs in developing and synthesizing materials for extreme environments.

The second phase of the facility plan (FY 2024-2025) will focus on large-scale renovation of ~ 4000 square feet of space in MD 150. This space currently houses various thermo-mechanical processing equipment (e.g., rolling mills, hot presses, etc.) that will be relocated to another lab space in MD. The utilities will be upgraded to support the Critical Materials Refinery led by Ames Lab, which is part of the FECM funded Critical Materials Supply Chain Research Facility. The Refinery will build upon existing expertise and capabilities at Ames Lab to be a national resource for mid-scale processing (e.g., rare earth metal production) of critical materials.

The third phase (FY 2026-2027) of planned facility upgrades to support mission needs will involve renovation of ~3200 square feet of lab space in MD 131 and 135. This part of the facility plan will focus on building up capabilities in emerging initiatives to support mission space in the Office of Science. The renovated space will support new capabilities in data science, smart manufacturing, and next generation materials needed to support hydrogen and fusion energy.

New Construction: Critical Materials Research Facility (CMRF)

Image 2: Rendering of Supply Chain Research

Anticipating the need for future capabilities, expanded physical research space and eventual replacement of aging buildings, Ames Lab with an Architecture and Engineering partner completed a conceptual design for a new CMRF, that as designed, can be completed in multiple phases. Once complete the CMRF will provide a state-of-the-art research building that advances the DOE strategy to reduce dependence on the supply of critical materials from foreign entities and will support the accelerated advancement of the

DOE mission throughout the 21st century and meet the Nation's carbon free energy goals. This ~130,000 square foot facility is designed to provide an integrated platform that allows early-stage research, from fundamental science through applied technology, and development that spans the supply chain.

ISU recognizes the critical importance of this new facility and has designated a site adjacent to Ames Lab for its construction. Additionally, we are exploring the potential for ISU to formally lease this area to the DOE similarly to all other land which occupies DOE-owned facilities on the ISU campus further reflecting ISU's commitment to the DOE mission and the future sustainment of the Lab. Ames Lab will work with AMSO and DOE program sponsors on the strategy that will pave the way for this essential investment.

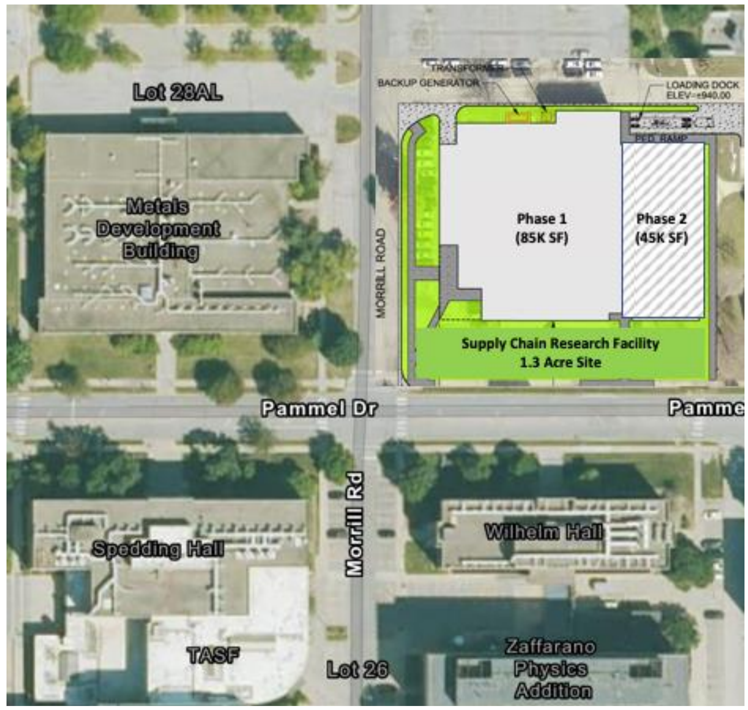


Image 3: Designated site for Supply Chain Research Facility

Infrastructure Capability Gaps

Through continued investment, we plan to fulfill our Strategic Plan objectives and goals to provide facilities that support scientific objectives, provide infrastructure that supports mission readiness, and pursue opportunities for future scientific capabilities. In the Infrastructure Investment Table (Enclosure 4), the Laboratory identifies several facility improvement projects, to continue to modernize infrastructure, upgrade facilities, and ensure safety at the Laboratory. These improvements total $191M in direct funded projects with starts through FY 2030, and $25M to $50M for those projects with starts in FY 2031 and beyond. Descriptions of significant gaps are provided below:

Ames Infrastructure Modernization (AIM)

To help address some of the needs of the Lab's aging facilities and with the restart of the $30M SLI Line-Item project, AIM in September 2022, the Laboratory is preparing for a CD2/3 decision so construction may commence in FY 2025. Given the delay in funding the AIM project and the significant increase in construction and equipment costs, the $30M budget allocated to this effort will be limited in its impact. It is anticipated that AIM will address the minimum threshold objectives currently identified for the project (limited plumbing, envelope replacement, standby power improvement, and minimal space renovations) but much more work is needed to address critical infrastructure needs.

To address the remaining critical infrastructure needs, the Laboratory recommends that DOE support two minor $30M construction projects; otherwise, critical infrastructure needs will go unattended and the risk of impact to research will increase. Areas to be addressed include:

Plumbing Systems: Most of the water supply piping and sewer drain piping are original to their respective buildings, and these systems are evaluated as deficient. Water leaks, complaints of sewer smells, and clogged drains have increased dramatically in recent years. The Laboratory inspected the sewer lines below the concrete floors utilizing cameras in FY 2016 and conducted surveys of pipe chases in FY 2018. The original sewer lines under the concrete floors and in the vertical pipe chases are deteriorating. Major cracks were found and repaired in several sewer drains behind vertical chase enclosures in FY 2017 and FY 2018. Current AIM project threshold objective will address water supply and sewer drain piping in one research building.

Building Envelopes: Building envelopes include roofs, exterior walls, windows, and other exterior building systems. The three general use research buildings require upgrades or repairs to their building envelopes. Future projects will need to add insulation to the roofs of the three primary research buildings to improve energy efficiency and improve each building's ability to protect people and equipment. A new white reflective roof system will increase energy efficiency, eliminate the need for ballast, and add at least 25 years to the life of the buildings. In addition, the Net Zero planning team came forward with a recommendation to add solar panels to the roofs, should funding be available. Current AIM project threshold objective will address building envelope for one research building.

Backup / Emergency Power and Uninterruptible Power Supply (UPS) Systems: The two existing diesel generators used for backup/emergency power on the main campus are past their useful life and do not have the capacity to add additional backup/emergency loads for new equipment. They can only handle 25% of the total electrical demand of the Laboratory, which is enough for life/safety systems only. Critical research equipment, information technology equipment, and operational equipment are protected by several smaller, decentralized UPS systems (most at point of use). These decentralized systems require various forms of maintenance, upkeep, and upgrades, which demands a great deal of effort and coordination. A centralized UPS system for each mission critical building would benefit the Laboratory by improving uptime and providing facility-wide protection for sensitive electronics. These larger UPS systems are also capable of ensuring critical systems will keep running during power disturbances such as blackouts, brownouts, sags, surges, or noise interference. Current AIM project threshold objective will provide for the replacement of two existing diesel generators.

Telecommunications Infrastructure: Most emerging technologies require the fast and efficient transmission of data from sensors and devices and greater bandwidth than is currently available. The Laboratory completed a feasibility study and is now proceeding with the planning and design to upgrade the physical telecommunications infrastructure needed for current and future computing needs. The Laboratory is creating a new IT room in Spedding Hall, with new telecommunications equipment, cabling, racking, and ventilation utilizing FY 2020 BES-GPP funding. Telecommunication updates are also needed in TASF, Wilhelm Hall, and Metals Development. This scope has been developed during a feasibility study and will be included in the Ames Infrastructure Modernization (AIM) SLI line-item project. Current AIM project threshold objective will allow for telecom infrastructure modernization in one research building.

Condition of Research Laboratories: The three oldest buildings (Harley Wilhelm Hall, Spedding Hall, and Metals Development) serve as the Lab's research workhorses by supporting ~85% of research activity at the Laboratory and comprising ~70% of the overall square footage at the Laboratory. While solidly built for research needs of the mid-1900s these buildings are rated substandard and require significant modernization to meet the research needs of today. Many of the research spaces within these buildings have original fixtures, rusted cabinets that are difficult to operate, pocked work surfaces from chemical exposure, asbestos-containing materials, and inadequate lighting. Over the last 10 years, the Laboratory has renovated 23,000 square feet of this space. Our capacity to renovate space is approximately 4,000 to 5,000 square feet per year. At the current pace, it will take the Laboratory approximately 15 to 20 years to renovate the substandard spaces. Current AIM project threshold objective will modernize at least 2,000 square feet in one research building.

Fire Alarm and Emergency Notification System (Phase 2): The Laboratory completed Phase 1 of this project in 2023 which included the replacement of the fire alarm system (detection devices and control panels) and mass notification signage in TASF, SH, and HWH and the replacement of only the fire alarm control panels in MD, the Maintenance Shop building, and the SIF. Phase 2 will replace fire alarm and detection devices, including photoelectric type detectors, in the remaining campus buildings: Storage Shed, Construction Shed, Warehouse, Maintenance Garage, Maintenance Shop, Paint & Air Conditioning, SIF, and MD. Phase 2 also includes adding additional fire alarm devices to a number of large bay spaces in HWH and SPH, and the customization of audio messages for mass communication devices.

Heating, Ventilation, and Air Conditioning (HVAC) Systems: The FY 2020 Facilities Condition Assessments (FCAs) completed for Harley Wilhelm Hall, Spedding Hall, and Metals Development identified some significant deficiencies in their HVAC systems. Though some HVAC updates have been completed by the Laboratory over the last 12 years utilizing GPP funds, the aging systems still require more resources to better support current and future research. The Laboratory completed a conceptual design in FY 2022 for the proposed HVAC upgrades in Wilhelm Hall and received $6.2M in IRA funding in September 2022 to proceed with this project. Construction bids were significantly higher than estimated and $1.3M in BES GPP funding was added to the project. The expected completion date is Dec 2025. Conceptual designs for HVAC upgrades in SH and MD are currently being developed. Initial estimates for these two projects are $24M and $21M, respectively. The Net Zero planning team has identified HVAC systems as the highest priority to reduce Scope 2 emissions.

Building Maintenance & Repair

The maintenance program, funded from overhead dollars, consists of activities necessary to keep the existing inventory of facilities in good working order and extend their service lives. It includes regularly scheduled maintenance, corrective repairs, and periodic replacement of components over the service life of the facility. It also includes facility management, engineering, documentation, and oversight required to carry out these functions. The condition of the research buildings has been maintained even as they age beyond normal service life. The Laboratory anticipates it will need to continue to operate in the older buildings over the 10-year window of this plan. Historically, the Laboratory has invested approximately 2.0% of Replacement Plant Value (RPV) per year into maintenance and repair activities. This level of resources has been able to control deferred maintenance in the buildings. However, the combination of limited capital improvements and aging facilities has placed a greater demand on maintenance resources. Maintaining the condition of the facilities does not ensure they will continue to meet the needs of research activities. In recent years, maintenance and repair expenditures have ranged from 2.0% to 2.8% of RPV.

Investment Summary

Over the last 10 years, $89M ($27M received at the end of FY 2022) has been invested from multiple sources to drive improvements at the Laboratory.

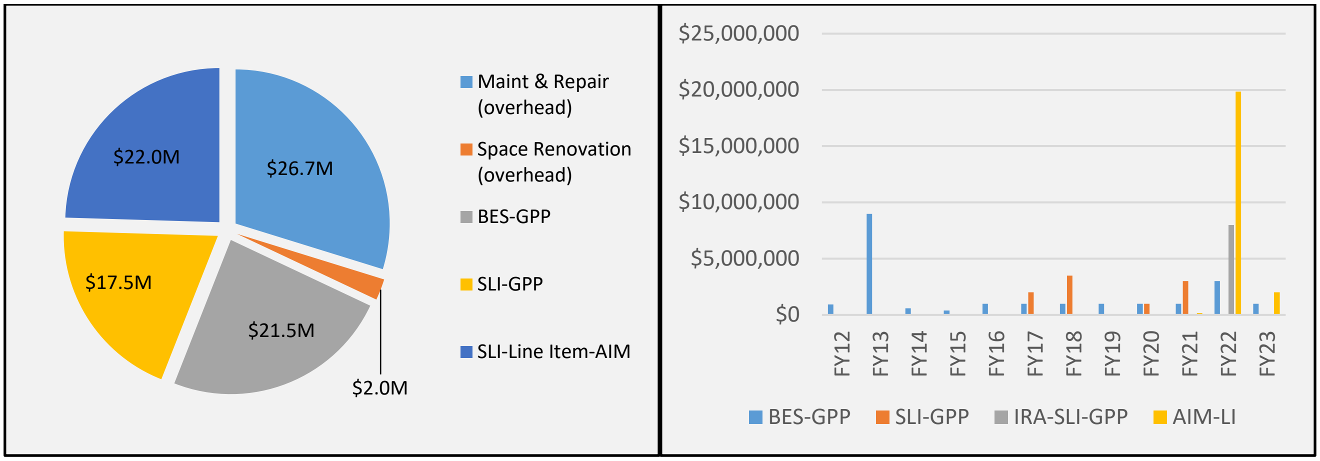


Image 4: Ames Lab Capital Funding Allocation

This past investment combined with the investments as outlined in this strategy will result in the three older research buildings moving from "Sub-Standard" to "Adequate" for their Overall Asset Condition and contribute to the success of the Laboratory's mission while also establishing a path to accelerate research capabilities through the construction of a new facility.

Repair Needs (RN) and Deferred Maintenance (DM)

Standard Repair Needs (RN) will continue to be addressed through maintenance and special project investments in annual overhead budgets. The highest priority RN that are impacting mission are categorized as Deferred Maintenance (DM). Deferred Maintenance deficiencies are primarily addressed through capital projects (i.e., AIM & GPP).

The AIM line-item project, and GPP projects like the fire alarm updates, elevator updates, and Wilhelm Hall HVAC replacement are funded and do have an impact on RN/DM. Though they do not significantly reduce RN/DM, they do prevent the Laboratory's major infrastructure systems from deteriorating, failing, and eventually impacting mission, resulting in increased DM.

Proposed GPP projects like AIM-Phase 2, Spedding Hall HVAC replacement, Metals Development HVAC replacement, AIM-Phase 3, fire alarm updates Phase 2, and TASF elevator updates will also have an impact on RN/DM. If not supported, the Laboratory's major infrastructure systems will continue to deteriorate, possibly fail, and impact mission, resulting in a significant increase in RN/DM.

This graph provides the DM projections based on the investment strategy that is able to be executed. To successfully maintain an acceptable level of DM continued infrastructure modernization, upgrades to HVAC systems and other identified infrastructure improvements will be necessary.

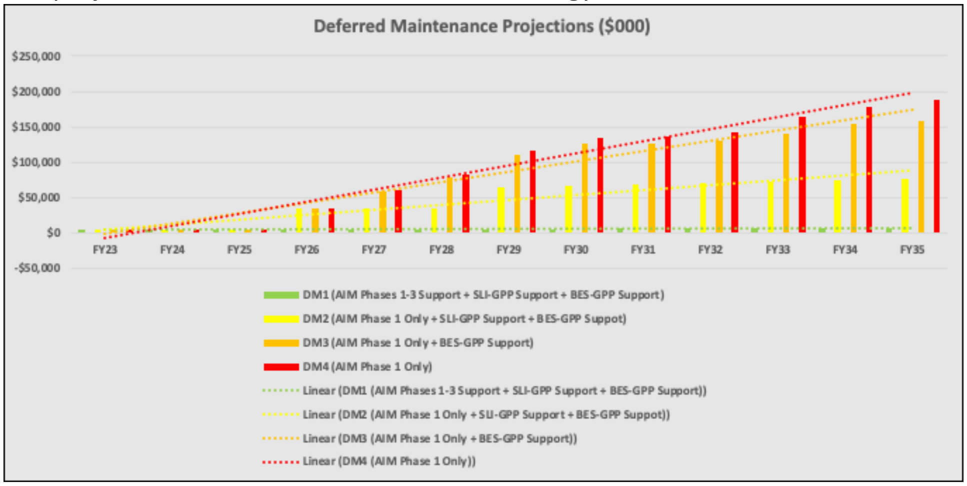


Image 5: Deferred Maintenance Projections

Project Execution Risk

Ames Lab is grateful for the recent significant infusion of infrastructure modernization investment made possible through the Bipartisan Infrastructure Law and the Inflation Reduction Act. The GANTT chart depicted below captures at a high-level the number of projects being planned and executed over the next several years. In response to this investment and to successfully and safely execute these critical projects, the Laboratory has doubled the number of its project execution staffing positions by adding two project managers, a scheduler/estimator, and a project coordinator. In addition, the following positions were added to the staff: Procurement Agent, Accountant, Construction Safety Specialist, Industrial Hygienist Specialist, and Health Physicist Specialist. The Laboratory took the added measure to create a Subcontractor Oversight Working Group that is focused on an integrated approach to all facets of construction project execution (contracting, pre-construction, construction, post construction). This group is comprised of project, procurement, safety, QA, and IT personnel who have vested interest in driving efficiency, ensuring safety, and building off of lessons learned in construction project execution.

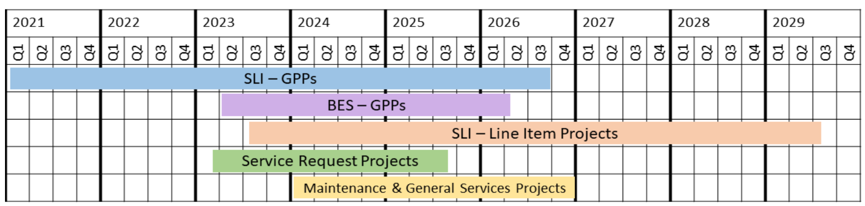


Image 6: Integrated Project Planning Schedule

Current Gaps

There is a significant need for intermediate "capacity" computing, which would allow for regular access to computing capabilities significantly larger than available on existing clusters, while also allowing for more rapid turn-around time than is currently available at DOE User Facilities. A "mid-level" capability would greatly enhance and more strongly support existing programs at Ames, across all of the research divisions. This would also enhance Ames Lab's ability to contribute to scientific computing within DOE: it would provide support for potential programs within the Advanced Scientific Computing Research (ASCR) Office, through Computational Chemical/Materials Sciences calls from Basic Energy Sciences, and to compete for other calls that require significant computing capabilities. The ideal capability would (presently) be ~10x current capabilities; reasonably, this should be targeting a 10 petaflop (or better) theoretical performance system. This order-of-magnitude expansion would greatly enhance local scientific and technical capabilities and provide a bridge to take advantage of the much larger (~100x) systems available at DOE user facilities. We also seek an expansion that would allow us to develop and test emerging computing hardware, both to ensure continued portability of our software and to prepare us as computing continues to evolve rapidly.

Ames Lab is presently evaluating the utility and space needs for this capability, in order to prepare for such a capability. There are some tentative spaces identified that have the power and weight capabilities, and we are examining costs of necessary renovations to make this fully suitable for the desired capability.

Ames Lab also notes that increasingly, applied projects require significant computation. In addition to the above computing capability that would help support such projects, we envision tighter integration of computing and experiment, which will require new computing and networking resources. Projects recently funded through FECM and through ARPA-E will result in new facilities at Ames Lab in the next few years, and we will seek to develop those with active monitoring, networking, and integrated modeling combined with machine learning techniques in order to rapidly adjust materials processing parameters to optimize material properties, minimize energy and other resource inputs, and to enable rapid larger-scale production of materials. We are presently using laboratory directed R&D (LDRD) funds to develop a unified data and machine learning framework that will support this work, with key demonstrations for powder metallurgy and for magnet manufacturing.

ARGONNE NATIONAL LABORATORY

Lab-at-a-Glance

Location: Lemont, Illinois
Type: Multi-program Laboratory
Contractor: UChicago Argonne, LLC
Site Office: Argonne Site Office
Website: www.anl.gov

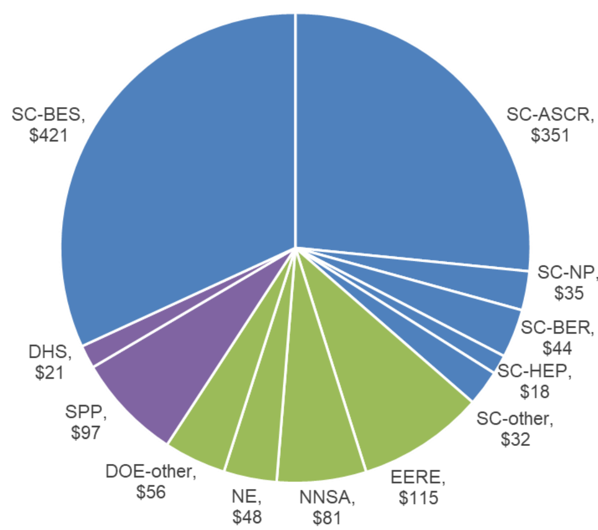
- **FY 2023 Lab Operating Costs:** $1,203 million
- **FY 2023 SPP (Non-DOE/Non-DHS) Costs:** $97 million
- **FY 2023 SPP as % Total Lab Operating Costs:** 9%
- **FY 2023 DHS Costs:** $21 million

Physical Assets:
- 1,517 acres and 157 buildings
- 5.2 million GSF in buildings
- Replacement Plant Value: $4.1B
- 0.3 million GSF in leased facilities
- 0.02 million GSF in 12 Excess Facilities

Human Capital:
- 3,944 Full Time Equivalent Employees (FTEs)
- 309 Outgoing Joint Appointees, 165 Incoming Joint Appointees
- 309 Joint Faculty
- 353 Postdoctoral Researchers
- 275 Graduate Students
- 415 Undergraduate Students
- 7,135 Facility Users of 6 research facilities*
- 2,030 Visiting Scientists

**Five of these facilities are supported by the DOE Office of Science and the sixth by the DOE Office of Nuclear Energy*

FY 2023 Costs by Funding Source ($1321 million total)



Mission and Overview

Argonne National Laboratory has long accelerated science and technology to drive American prosperity and security through transformative solutions to the nation's energy, environmental, and nuclear security challenges. We are recognized internationally for pioneering discoveries and technological innovations. We support the U.S. Department of Energy (DOE) mission through five signature contributions:

- Our discoveries solve the deepest mysteries in the physical and life sciences
- We build on our science to create energy and climate solutions with near- and long-term impact
- Our security advances protect society from diverse threats to health, infrastructure, and supply chains
- We design and operate research facilities that provide powerful tools for science and engineering, used by thousands of researchers each year
- We develop scientific leaders and help build a diverse STEM workforce for today and tomorrow

Two of our major facilities, the Advanced Photon Source and the Argonne Leadership Computing Facility, together provide unmatched opportunities for ultrafast research by both visiting and Argonne scientists and engineers.

Argonne's impact is amplified by extensive collaborations across the full spectrum from conducting fundamental research to supporting industry's deployment of advanced technologies. We lead multiple DOE research centers and consortia with members from academia, business, communities, and other national laboratories; together, we are advancing the frontiers of quantum and materials science, biofuel technology, electrification of steelmaking, and urban climate science. We are partners in DOE's Li-Bridge public-private alliance to strengthen the domestic supply chain for lithium batteries and in multiple efforts to accelerate decarbonization globally, through the Net Zero World initiative, and domestically, through state and municipal initiatives.

Since Argonne's founding, we have operated under the auspices of the University of Chicago, currently through UChicago Argonne, LLC. We have long conducted joint research with the University; current collaboration areas include quantum information science, microelectronics, molecular engineering, computing, and cosmology. Our main campus is about 30 miles outside Chicago, with a satellite center in the City of Chicago that supports our expanding role as a convener to drive regional economic growth. We also are proud to annually contribute more than $2.7 billion and 13,300+ jobs to the U.S. economy.

Core Capabilities

Argonne's broad base of expertise in science and engineering, which comprises 23 of the 25 core capabilities defined by DOE for its laboratories, is a powerful asset to meet national needs across the spectrum of discovery science to technology development.

We use these capabilities to advance the missions of our sponsors as we accelerate science and technology to drive U.S. prosperity and security. The expertise of our scientists and engineers both supports, and is supported by, our suite of large-scale experimental facilities that serve thousands of researchers from outside Argonne:

- Advanced Photon Source (APS)
- Argonne Leadership Computing Facility (ALCF)
- Argonne Tandem Linac Accelerator System (ATLAS)
- Atmospheric Radiation Measurement (ARM) user facilities
- Center for Nanoscale Materials (CNM)
- Intermediate Voltage Electron Microscope (IVEM)

The first five facilities are supported by DOE's Office of Science and the sixth by DOE's Office of Nuclear Energy.

Our collaborations with other research institutions and industry enrich our contributions to society. Across all of our core capabilities, we nurture the STEM workforce of the future, through undergraduate and graduate student appointments, post-doctoral appointments, and early-career researchers working under named fellowships. UChicago Argonne, LLC, supports our capabilities by leading the Joint Task Force Initiative, which pursues opportunities for Argonne, UChicago, and Fermilab to collaborate to drive breakthroughs in research and boost the efficiency of operations.

Accelerator science and technology

Argonne's core capability in accelerator and detector science and technology is foundational to the successful operation of accelerator-based user facilities at Argonne and other national laboratories and the development of critical technologies for future facilities across the DOE complex. We apply our multidisciplinary scientific and engineering expertise to develop diverse technologies for electron-based light sources, electron-positron colliders, radioisotope production and separation, and hadron accelerators for nuclear physics. This capability centers around our APS, ATLAS, Argonne Wakefield Accelerator (AWA), Low Energy Accelerator Facility (LEAF), and Argonne Accelerator Institute (AAI). Our expertise enables us to:

- Design, build, and test electron- and ion-beam accelerators. This work draws on our expertise in advanced beam-acceleration structures with conventional and superconducting radio-frequency cavities driven by high power sources, including two-beam acceleration technology; vacuum engineering; and beam diagnostics.
- Model linear electron and hadron accelerators, electron storage rings, and free electron lasers, including their beam dynamics and control systems, using our world-leading software tools.
- Offer unique instrumentation, at the AWA, to test novel electron sources, beam manipulation techniques, and state-of-the-art linear accelerator concepts, in support of high-energy physics research and future compact light sources. The AWA is open for R&D to the user community.
- Design and produce technologies vital to future light sources and colliders. Examples include magnetic systems and lattices to manipulate particle beams; insertion devices to generate X-ray light; optical systems to tailor light beams; and detector systems that include varied sensor types, materials and innovative chip integration for ultrafast signal processing and compression, for particle and nuclear physics and light experiments.

Argonne also supports accelerator outreach, training, and education via the U.S. Particle Accelerator School based at Fermilab, the summer undergraduate Lee Teng Fellowship in collaboration with Fermilab, and the DOE-funded graduate accelerator education program led by Michigan State University.

Looking ahead, our strategic focus is to demonstrate novel technology for compact and multiplexed X-ray free electron lasers and to play a leading role in the construction of critical detectors for DOE's Electron-Ion Collider and Argonne's ATLAS.

Advanced computer science, visualization, and data

Argonne is recognized for innovative contributions in extreme-scale systems software, scientific software productivity, distributed computing, and high-performance computing tools for data-intensive science and visualization. Through this core capability, we continue to pursue our focus on AI, extreme-scale computing, quantum computing, and co-design of microelectronics.

Our work in distributed computing underpins today's increasingly integrated research infrastructure, including via the Globus research acceleration tools used by hundreds of thousands across the globe. Production supercomputer systems worldwide use Argonne's research software tools, and we are highly regarded for our development of operating-system and runtime software for extreme-scale computing. Argonne-developed software is tested and deployed at the ALCF, Oak Ridge Leadership Computing Facility, and National Energy Research Scientific Computing Center at Lawrence Berkeley National Laboratory. Looking ahead, we will continue to help DOE scientists adopt computer science, data, and AI software through our leadership of the DOE SciDAC RAPIDS Institute.

We continue to leverage machine learning and AI in the sciences. Through development of trustworthy surrogate models, we accelerate simulations of climate processes, fusion and fission energy, and materials discovery. We are advancing the automation of scientific discovery to dramatically enhance the productivity of DOE scientists and key facilities such as our APS. We also participate in two recent DOE funding awards to develop quantum networks, and lead one, InterQnet, and are advancing the use of AI in the co-design of microelectronics.

A central pillar of our strategy is to advance research in large language models (LLMs) tailored for scientific and engineering applications. This endeavor includes the development of specialized generative pre-trained transformers (GPT) that harness the computational might of leading-edge systems like our Aurora supercomputer. Our AuroraGPT project represents a significant leap in applying LLM capabilities to scientific discovery.

We are deeply involved in framing and executing DOE's research plans for exascale computing and AI, in partnership with the other national laboratories; we recently hosted DOE's AI for Energy workshop. Our commitment to this field extends internationally as we collaborate with researchers from around the world in initiatives, like the Trillion Parameter Consortium, that aim to unlock the potential of LLMs to revolutionize research.

Applied materials science and engineering

Argonne drive advances in materials science and technology by applying internationally recognized expertise in materials design, development, synthesis, processing, and scale-up. This capability builds on discoveries in our core capabilities in materials science, chemical engineering, and microelectronics, with the goal of enhanced impact from accelerating the movement of those discoveries to market.

Applied and basic science teams from across Argonne use a broad suite of facilities in this work, including the ALCF for computational materials science; APS and CNM for materials characterization; ATLAS, IVEM, and APS for materials development; and Materials Engineering Research Facility (MERF) for scale-up. Collaborations with industry are a hallmark of our work in applied materials.

Argonne is committed to creating innovative materials and applying them to real-world needs. For example, we develop one-, two-, and three-dimensional nanomaterials – such as particles, powders, fibers, coatings, thin films, and membranes – using a wide range of scalable manufacturing-ready technologies for state-of-the-art synthesis and processing. We extend these technologies to demanding applications such as solid-state batteries; water treatment; catalysts for electrolyzers, fuel cells, and polymer upcycling; and emerging energy technologies.

We are expanding our efforts in materials for quantum and microelectronics applications. We are also increasing our efforts to develop membrane materials and systems for gas- and liquid-phase separation for uses such as hydrogen production, biofuels processing, lithium metal manufacturing, and water treatment. We are expanding our focus on supply chains for upstream and midstream processing of critical energy materials and on the upcycling of specialized materials, an example of which is the DOE/EERE-funded ReCell battery recycling center.

The integration of basic and applied materials science through diverse collaborative research efforts at Argonne has produced more-efficient batteries, high-performance sorbents, nanofiber magnets, heat exchangers for extreme applications, and materials for nuclear energy systems and solar receivers. Ongoing work shows promise for more-efficient nuclear fuel reprocessing; lighter-weight transportation alloys; advanced building materials; and higher-performance superconducting materials for use in detectors, accelerators, and energy transmission. Argonne's extensive experience in energy storage materials R&D has positioned us to make significant contributions to future storage solutions for stationary and mobile applications.

Applied mathematics

Our applied mathematics core capability supports DOE's mission to develop and deploy scalable software for scientific discovery using high-performance computing. We are recognized for leadership in mathematical optimization algorithms, modeling, software, and theory, implemented via scalable software for the world's largest computing systems. We excel in the scalable solution of partial differential equations (PDEs) and optimization tools for the design and control of complex systems, and we provide best-in-class expertise in automatic differentiation (AD). Impactful Argonne advances include:

- Scalable frameworks for modeling and solving large-scale-optimization-under-uncertainty problems
- Multimodal inverse problems, machine learning (ML), and statistical modeling for analyzing experimental, observational, and simulation data
- Fast algebra to enable accurate, extreme-scale simulation of atmospheric boundary layer flow and its interactions with wind turbines
- Automated ML, multi-objective optimization, and automatic differentiation algorithms applied to post-Moore architectural concepts and deployed for applications such as transportation modeling and autonomous scientific discovery

Argonne's advances are instantiated in varied state-of-the-art software packages. Examples of their capabilities include modeling complex physical phenomena as well as solving large computational fluid dynamics problems, discretized PDEs, optimization problems with discrete and continuous variables, and optimization problems with billions of variables and constraints. Our software makes it possible to answer a broad range of science and engineering questions, including how to upgrade the power grid, how to optimally design novel materials, how mantle convection affects the earth's geological evolution, and how to cool nuclear reactors efficiently.

Looking ahead, we are developing new models and numerical methods to enable digital twins of experimental facilities and complex interconnected systems, in a collaboration with universities and other national laboratories. We are devising techniques for automating data analysis and inference and conducting fundamental research in statistical and stochastic methods in the context of massive heterogeneous data sets for training AI/ML tools. We are committed to addressing emerging challenges in the development of rigorous AI/ML foundations that find widespread use in scientific applications and experiments.

Biological and bioprocess engineering

Argonne's approach to biological and bioprocess engineering incorporates methods from synthetic biology and synthetic chemistry to create systems and materials with tuned functionalities. We apply understanding of complex biological systems to design, test, and validate process components, technologies, and systems relevant to bioenergy and bioproduct production, environmental contaminant processing, and global carbon cycling and biosequestration. Further, we leverage Argonne's computational expertise and resources to develop bioinformatic tools and incorporate AI strategies for data analysis and biodesign.

This capability draws on APS and CNM tools for characterizing biomolecules, cells, proteins, and processes. We also have demonstrated the ability to predictively engineer microbes from the environment and design them for fundamental understanding.

To advance biotechnology and biomanufacturing innovation for a sustainable U.S. bioeconomy, we continue to harness the power of biology, increase piloting of new bioprocesses to accelerate the transition from basic research to demonstration, and develop climate-smart agriculture practices to boost sustainable biomass production. To support the missions of DOE and other sponsors, our current and future research focuses on:

- *Synthetic biology for biosystems design.* We analyze and model microbial and microbiome systems to predictively design strains and communities and understand their ecology.
- *Global carbon cycle and environmental chemical cycling.* We study elemental cycling in the biosphere to discover climate-resilient plant genes and agricultural practices.
- *Bioprocesses and biomanufacturing.* As the lead laboratory for the DOE/EERE Bioprocessing Separations Consortium, we have developed technologies and worked with industry to recover products from fermenters. We scale up bioprocesses from bench- to pilot-scale and contribute to DOE/EERE efforts such as the Agile BioFoundry and Feedstock-Conversion Interface Consortium. To support a circular economy, Argonne also develops and scales up bioprocesses to valorize waste streams. In addition, we use advanced analytical tools like the GREET model for life-cycle analyses of bioenergy-related processes.

Biological systems science

Argonne's core capability in biological systems science is focused on fundamental studies of information in biological systems and the use of generative, AI-based foundation models to design those systems. Such models are providing a new paradigm for designing biological systems. Knowledge gained through this research will identify new areas of study and drive solutions to challenges in bioenergy and environmental biology. Our strategy leverages Argonne's world-class computing and X-ray imaging capabilities for biology and our state-of-the-art automated laboratories focused on synthetic biology, radiation biology, and microbial ecology.

We draw on our computational science expertise and resources in developing bioinformatic tools and incorporating AI strategies to analyze and model microbial and microbiome systems. Our goal is to advance ecological understanding of these systems and inform the predictive design of microbial strains and communities. This effort supports basic science inquiry to understand the natural world, including wetland hydrobiogeochemical studies of how microbes mediate geochemical cycles. We are a major contributor to the DOE/SC-BER Systems Biology Knowledgebase (KBase), in collaboration with other national laboratories.

Through our development of foundation models, we seek to mature the integration of synthetic biology, advanced computing, and imaging. One research example is analyzing the impact of low-dose radiation on biological systems. We also are training the next-generation workforce in the use of automated laboratories with generative AI with support from DOE-SC/ASCR.

Our Advanced Protein Characterization Facility at the APS produces and characterizes tens of thousands of proteins each year. We have been at the forefront of structural biology research using the APS, and DOE/SC-BER has supported our Structural Biology Center (SBC) since 1993. With the APS upgrade, the successor to the SBC – eBERlight – is poised to advance a new resource for DOE/SC-BER researchers by expanding macromolecular crystallography with other synchrotron imaging modalities. This aspect of our strategy in biological systems science will enable three-dimensional, multimodal, and multiscale imaging of centimeter-sized objects, as well as biological samples, with nanometer-scale spatial resolution. Macromolecular crystallography will advance to capture dynamic processes with milli- to microsecond temporal resolutions. This broader portfolio of imaging length scales and modalities will enable Argonne to address bioimaging needs beyond macromolecular structure.

Chemical and molecular science

Argonne's core capability in chemical and molecular science includes world-leading strengths in computational and theoretical chemistry, electrochemistry, actinide chemistry, interfacial chemistry and separations science, mechanistic chemistry, photosynthesis, molecular design and synthesis, and ultrafast molecular science. Our expertise in gas-phase, liquid-phase, and solid-state chemistries will continue to enable us deliver scientific discoveries relevant to understanding our physical world; improving synthetic methods, separations, and catalysis; and producing defossilized energy.

Our approach to chemical and molecular science integrates theoretical, experimental, and computational methods. We seek to unify understanding of the periodic table, taking advantage of our expertise in the chemistry of the light elements, transition metals, and heavy elements. We are enhancing our understanding of transient processes within molecules through our ultrafast chemistry and ion- and electron-transport expertise. We also use our expertise in photosynthetic systems to address quantum spin systems. These efforts will help to build the scientific foundation needed to address key energy, environmental, health, and economic issues.

Computational resources and characterization tools available through the ALCF, APS, and CNM are integral to this capability. The Aurora exascale computer will allow unprecedented detail and accuracy in simulations of complex molecular systems and will dramatically enhance the incorporation of AI into the solution of challenging chemical problems. The upgraded APS will enable the study of complex chemical processes in real time, under realistic conditions. Additional facilities important to this core capability include our High-Throughput Research Laboratory, Nuclear Magnetic Resonance Spectroscopy Laboratory, Advanced Electron Paramagnetic Resonance Facility, atomic layer deposition laboratories, and state-of-the-art radiological facilities for work in heavy-element chemistry and separations science.

Argonne's core capability in condensed matter physics and materials science complements these strengths through materials design and synthesis and functional material development. We advance our fundamental scientific discoveries by collaborating with industry and leveraging our core capabilities in chemical engineering and applied materials science. We lead the Energy Frontier Research Center on Advanced Materials for Energy-Water Systems (AMEWS), which continues to deliver breakthroughs in understanding of water/solid interfaces, and the new Energy Earthshot Research Center for Steel Electrification by Electrosynthesis (C-STEEL).

Chemical engineering

Through Argonne's core capability in chemical engineering, we build on and inform basic energy research efforts while developing break-through technologies for electrochemical energy storage, water cleanup, chemical and light energy conversion, hydrogen and other clean energy systems, radiochemical separations, and fuel cells. We address energy and security challenges by integrating our chemical engineering expertise with our capabilities in chemistry, materials science, biology, bioprocess engineering, and characterization at the APS.

We are globally recognized for our work in lithium-ion batteries, solar conversion, combustion and nuclear fuel cycle chemistry, and hydrogen; this work leverages our foundational knowledge of electro-, photo- and thermo-chemistry; catalysis; and engineering system analysis. We are at the forefront of next-generation energy storage and conversion science with our efforts to create and integrate solid-state electrolytes into storage systems, develop tailored cathode architectures, and identify direct lithium-ion battery recycling methods. Looking ahead, we will apply advanced tools at the upgraded APS and AI methods using the Aurora exascale computer. Close interactions among experimental, modeling, and theoretical researchers are core to our strategy.

In multidisciplinary and multilaboratory efforts, we develop electrocatalysts and electrode designs that reduce cost and improve the manufacturing of batteries, polymer-electrolyte-membrane fuel cells, and electrolyzers. We accelerate these efforts using high-throughput synthesis, characterization, and performance evaluation methods. These activities are the cornerstone of several DOE/EERE research consortia that we co-lead with other national laboratories, to find solutions to important energy problems. Our expertise in radiochemical separations supports radioisotope production and development of decarbonized, sustainable fuel cycles for nuclear energy.

An unmatched suite of facilities, including four funded by DOE/EERE, enables us to integrate experimental work with process, systems, cost, supply chain, techno-economic and life cycle modeling. All support DOE programs nationwide. They include our Cell Analysis, Modeling and Prototyping Facility, Electrochemical Analysis and Diagnostics Laboratory, Post-Test Facility, High-Throughput Research Laboratory, and Materials Engineering Research Facility. We lead development of novel process technologies to decarbonize steelmaking, including the Energy Earthshot Research Center for Steel Electrification by Electrosynthesis (C-STEEL), and the direct formation of iron using hydrogen plasma technologies, supported by ARPA-E.

Computational science

Computational science is a key Argonne strategic capability that advances the solution of critical problems in many scientific disciplines: More than 350 scientists and engineers work in interdisciplinary teams that include applied mathematicians, computer scientists, and computational scientists with expertise in various domains. ALCF resources strongly support these efforts.

Our computational science core capability leverages strong Laboratory-wide collaborations in modeling, simulation, data-intensive applications, software development, uncertainty quantification (UQ), and AI. We integrate domain science areas with methodological expertise: Computational scientists and engineers have ready access to broad, deep expertise in traditional and emerging scientific computing methods and tools. Focus areas include high-performance computing, data science, AI applications, and next-generation technologies such as quantum computing.

Examples of our computational science impact include major developments under DOE's recently concluded Exascale Computing Project, such as codes that model the detailed evolution of the universe over billions of years; machine learning approaches applied to cancer research; computational fluid dynamics software with applications in fluid flows, magnetohydrodynamics, thermal convection, and reacting flows; methods and codes for optimizing large-scale power system dynamics; and major contributions to community codes for precision computations in materials science and for neutron and photon transport, with applications in nuclear engineering and fusion energy science. More broadly, Argonne's computational science contributions cover a wide application spectrum, including support for accelerator simulation, decision science, earth system modeling, X-ray and electron tomographic analysis, power and energy system modeling, semiconductor properties, lattice quantum chromodynamics, and nuclear and particle physics. We also participate in SciDAC partnerships spanning environmental science, fusion, particle and nuclear physics, and nuclear engineering.

Our strategy for the future includes harnessing energy-efficient computational architectures for zettascale computing, building generative AI foundation models for scientific and engineering applications, creating large-scale surrogate models or "digital twins," and developing integrated approaches that seamlessly combine high-performance computing, large-scale data sets and UQ-enabled AI.

Condensed matter physics and materials science

Through Argonne's core capability in condensed matter physics and materials science (CMPMS), we predict, design, and create new materials and advance understanding of their behavior at a fundamental level, from nanoscale to macroscale systems. Our research strategy rests on understanding and exploiting the science of defects and interfaces and how they impact behavior in four areas: hidden and dynamic order in soft and hard matter; ionic and electronic dynamics and motion; science for microelectronics and quantum information science (QIS); AI and autonomous materials discovery.

Our strategy relies on the breadth and depth of our expertise in materials chemistry and physics, nanoscience, scattering and imaging, theoretical and computational science, and the integration of capabilities at the APS, CNM, and ALCF. Those capabilities include precision synthesis and *in situ* and *operando* coherent X-ray and electron studies. Through the Center for Molecular Engineering, Argonne leverages joint appointments with UChicago to enhance our expertise in soft matter, semiconductor-based QIS materials platforms, and computational materials science.

Our activities are synergistic with Argonne's goals in clean energy, sustainability, AI for science, autonomous discovery, hard x-ray sciences, microelectronics, and QIS. We lead DOE's Midwest Integrated Center for Computational Materials, our core materials science complements the work of the Q-NEXT national QIS center and the C-STEEL Energy Earthshot Research Center that we lead, and we play a principal role in several other DOE/SC materials-focused collaborations. We seek to transfer our fundamental materials discoveries to applied Argonne research for development and deployment.

Argonne's CMPMS research with recent impact in frontier areas of science includes developing a computational protocol to investigate the synthesis of point-defects at the atomistic level, explaining the origin of superconductivity at $KTaO_3$ interfaces, understanding the origins of site-selective atomic layer deposition on oxide surfaces, and exploring magnetic domains in 2D magnets using cryo-electron microscopy.

Looking ahead, we will take advantage of the upgraded APS to explore local behavior across timescales, expand our use of cryo-electron microscopy and autonomous discover to materials for energy-storage and QIS materials, develop and deploy exascale codes for data- and AI-driven materials discovery, and continue to refine plans for the co-location on our campus of advanced multimodal characterization tools.

Cyber and information sciences

Argonne's cyber and information sciences research bolsters the reliability of critical U.S. infrastructure and safeguards sensitive information that could harm the U.S. and its allies if not protected. We are a trusted partner to federal, state, and local agencies, and the international community, for developing and deploying innovative solutions to protect the integrity of information within complex vital systems and emerging technologies. Our strategy combines our expertise in information science and computing with our technical expertise in multiple domains, to achieve these goals:

- Evaluate the use of machine learning, AI, and autonomous systems to manage national and global security risks.
- Protect critical infrastructure by developing cybersecurity technology and standards for electric vehicle charging as well as novel systems to defend power distribution grids "at the edge."
- Characterize cyber-physical vulnerabilities by adapting testing and evaluation frameworks for advanced mobile sensor systems, including cellphone wireless interfaces and other user interfaces.
- Investigate emerging technologies to facilitate risk analysis, with advanced nuclear energy and fuel-cycle technology as a strategic focus. Other examples include quantum communications, distributed energy systems, and cloud-based computing platforms.
- Develop the future cybersecurity workforce in our role as lead laboratory for the DOE CyberForce® Program, in collaboration with industry and other national laboratories.
- Deliver training to enable global partners to protect themselves against cyberthreats and mitigate human-in-the-loop vulnerabilities.
- Raise threat awareness by focusing research on potentially illicit online activity related to proliferation of advanced technologies

Implementation of this strategy leverages an unmatched portfolio of capabilities, including the ALCF, Argonne Biomedical Learning Enclave, Argonne Smart Energy Plaza, and Argonne quantum network. Looking ahead, we will seek to improve resilience strategies by connecting synthetic simulation environments with cyber-physical system testbeds, including adaptable and validated autonomous agents, human-cyber behavioral predictions, and hybrid information processing architectures focused on the intersection of sensor edges and cloud.

Decision science and analysis

Argonne is recognized for developing and applying novel decision science and analysis approaches to inform decision makers as they address pressing national, cross-border, and global challenges in rapidly changing environments with incomplete and imperfect data. These approaches include agent-based modeling, complex adaptive system modeling, system dynamics, infrastructure modeling, life-cycle analysis, and network analyses that model parameters of dynamic, complex systems. This core capability – linked with Argonne's expertise in cyber and computing sciences and systems engineering – positions us to deliver impactful solutions to complex, multidisciplinary problems.

We are international recognized for our development of high-performance software tools, including their use in extreme-scale agent-based modeling applications. These tools include the publicly available Repast and EMEWS tool kits. We apply high-performance computing and AI capabilities to the analysis of social and behavioral systems to address problems such as the spread of misinformation and infectious disease and the effectiveness of interventions to mitigate both. UChicago epidemiologists are key partners in our work to model disease including COVID-19 and measles.

Examples of Argonne's decision science and analysis contributions include the following.

- Create assessment frameworks to inform decisions on the security and resilience of critical infrastructure.
- Minimize the vulnerabilities of infrastructure to natural or human disruptions.
- Assess the impact of cross-sector decarbonization strategies.
- Model and analyze global supply chains to Inform decisions affecting the U.S. stockpile of critical materials that support national security and energy technologies.
- Help policymakers evaluate the ability of proposed energy projects to support U.S. priorities as well as the goals of the U.S. Net Zero World initiative

Our future research will concentrate on model coupling, ensemble modeling, and uncertainty propagation to support decision making in dynamic hazard and policy environments. A near-term focus will continue to be integrating our decision science capabilities with our environmental and infrastructure science expertise for community evaluation of strategies to enhance resilience to climate change.

Earth, environmental, and atmospheric science

Through this core capability, Argonne advances basic scientific understanding and addresses climate-related energy, water, and security challenges. We make leading contributions in atmospheric and terrestrial measurement and analysis, earth science simulations, urban science, and soil and biogeochemical science. Our strategy is to integrate these areas to develop a predictive understanding of earth systems at relevant scales and to develop climate risk and adaptation data for the public and private sectors, as well as to provide a scientific basis for geoengineering.

We continue to apply Argonne's computational resources and expertise in support of multiple DOE climate, atmospheric, and environmental science efforts, including the Energy Exascale Earth System Model, and we are developing weather- and climate-scale AI foundation models. Through our Community Research on Climate and Urban Science urban integrated field laboratory, we are creating new insights into local-level urban climate challenges and options for overcoming them and developing the foundations of an urban digital twin. Our downscaled climate datasets for modeling support a growing number of local resilience planning efforts, including those of DOE's new climate resilience centers.

Our atmospheric science strengths are grounded in our operational leadership of ARM facilities, ability to make sophisticated atmospheric measurements, and leveraging of data from DOE's ARM observatories. We also provide the global scientific community with unique expertise and software to retrieve geophysical variables from atmospheric remote-sensing instruments. We are committed to continuing to pioneer edge-computing that uses AI and advanced wireless technology for agile and scale-relevant environmental sensing to benefit ARM and other DOE investments.

We apply our aerosol/cloud science along with ARM data to understand terrestrial-atmospheric coupling and the role of cloud processes in the hydrologic cycle. Our soil and biogeochemical scientists advance understanding of soil response to environmental change to produce high-resolution, spatially explicit estimates of organic carbon stocks in permafrost soils and wetlands.

Argonne is committed to continuing to build the future workforce in earth, environmental, and atmospheric science. For example, we operate DOE's National Virtual Climate Laboratory portal and help underrepresented students prepare for climate science careers through DOE's Reaching a New Energy Sciences Workforce Initiative and other opportunities.

Isotope science and engineering

Argonne develops radioisotopes that offer exceptional promise in both the diagnosis and treatment of diseases such as prostate and bone cancer. This work is grounded in our long-standing core capabilities in nuclear and physics, accelerator science and technology, nuclear and radiochemistry, analytical chemistry, applied materials science, chemical engineering, and mechanical design and engineering.

Our goals are to provide high-purity, high-specific-activity isotopes to the research and medical communities while minimizing secondary waste production and develop processes that enable recycling of valuable enriched target materials for continued radioisotope production. To achieve these goals, we conceive new radioisotope production pathways, develop target systems that safely produce desired isotopes while minimizing exposure to workers, and demonstrate economical radiochemical separations and purification technologies. Looking ahead, we are developing innovations that offer potential for improved operations and safety, such as automated target recovery using robotics.

Research capabilities and facilities that enable this work include the Low-Energy Accelerator Facility (LEAF), APS, ATLAS, and ALCF. LEAF comprises Argonne's electron linear accelerator, one of the most powerful electron accelerators in the DOE complex, and a Van de Graaff accelerator; the two accelerators are used, respectively, for radioisotope production via photonuclear reactions and for radiation damage studies. The APS and ATLAS provide specialized capabilities that enable, for example, R&D on auger emitters of medical interest. Computational research using the ALCF allows us to compare measured and theoretical isotope yields and determine nuclear reaction cross-sections for less-studied isotopes. Our extensive radiological laboratories support the development and demonstration of innovative separation processes for radioisotope recovery and purification.

We apply these facilities and our associated expertise to perform R&D on, and reliably produce, medical radioisotopes such as scandium-47 and actinium-225 via photonuclear reactions. We make these and other new isotopes available to researchers at universities, industry and medical centers for evaluation. As production of the new radioisotopes become routine, we provide them to the National Isotope Distribution Center for extended distribution.

Large-scale user facilities/R&D facilities/advanced instrumentation

Argonne designs, builds, and operates world-leading scientific user facilities, which are elements of nationwide DOE networks. We collaborate closely with other research institutions that operate user facilities, to deliver complementary value users. Our facilities are strongly integrated with our research programs and reflect our commitment to nurture diverse and vibrant user communities. Two of the six facilities described here, the APS and ALCF, will together spur revolutionary science by collecting and analyzing imaging data at unprecedented speeds.

The APS, funded primarily by DOE/SC-BES, produces high-energy X-rays for scattering, spectroscopy, and imaging studies over a wide range of length and time scales. The upgraded APS will be the world's brightest hard X-ray storage-ring light source, with an unmatched suite of characterization capabilities.

The ALCF, funded by DOE/SC-ASCR, offers powerful computing resources for open scientific research. Current resources include Aurora, set to be fully operational in 2024 with peak performance of >2 exaflops, and the 44-petaflop Polaris. ALCF also hosts a dedicated testbed of AI-accelerated systems available to the DOE community.

The ATLAS, funded by DOE/SC-NP, is a superconducting linear accelerator and one of two DOE user facilities for low-energy nuclear research. It provides high-intensity heavy-ion beams in the energy domain best suited to study the properties of the nucleus. ATLAS offers its users an array of one-of-a-kind experimental systems.

Argonne oversees operations and provides instrument and measurement expertise to all ARM user facility sites, funded by DOE/SC-BER. We also manage the Southern Great Plains and Bankhead National Forest sites. The former is the world's largest and most extensively instrumented field site for atmospheric research.

The CNM, funded by DOE/SC-BES, enables interdisciplinary nanoscience research, with emphasis on clean energy, microelectronics, and quantum information science. CNM's tools enable synthesis, characterization, nanofabrication, modeling, theoretical studies, and AI-assisted autonomous synthesis and characterization.

Our IVEM is one of the Nuclear Science User Facilities funded by DOE/NE. It produces high-dose ion damage to materials and enables direct, real-time observation of the response of nuclear energy materials to extreme conditions like irradiation, temperature, and stress

Mechanical design and engineering

Through Argonne's mechanical design and engineering core capability, we identify and optimize critical decarbonization technologies for the transportation, energy, industry, and building sectors. In addressing national needs, we apply this capability in concert with our core capabilities in chemical and nuclear engineering, computing sciences, and systems engineering and integration, and with large-scale facilities such as the APS and ALCF. Our high-throughput, rapid prototyping, autonomous research and similar laboratories leverage machine learning and robotics in the discovery of new materials for clean energy. Our expertise in energy storge includes optimization and design of porous electrode systems.

In our growing carbon management portfolio, we are developing computational and experimental tools for carbon capture and conversion systems. Our research into net-zero carbon fuels is accelerating their incorporation into next-generation turbines, engine systems, and large-scale industrial burners. We generate datasets for components of interest and collaborate actively with DOE/FECM-funded entities to generate high-fidelity experimental data and simulations. These tools and data are then transferred to industry to accelerate the design of next-generation energy-conversion devices.

Argonne's design expertise and fabrication capabilities support medical radioisotope production R&D by providing target systems, material transport systems, advanced nuclear systems, and chemical separations equipment designed for safe operation in high-radiation environments and with dispersible radioactive materials.

We also design and investigate heating and cooling systems, envelopes, integrated photovoltaics and energy storage, and control systems for buildings. We develop high-fidelity and reduced-order component and whole-building models, as well as urban-scale collections of buildings, for model-based design, system optimization, and techno-economic analysis (TEA). Our multidisciplinary efforts model and simulate hydropower operations, including pumped storage hydropower (PSH) plants, and optimize hydropower turbine and reservoir operations to increase water-use efficiency for electricity generation and other purposes. We conduct TEA of new PSH projects and perform valuation assessments in vertically integrated and competitive electricity markets.

Looking ahead, our strategy is to leverage advances across Argonne – notably the upgraded APS, Aurora supercomputer, and the application of AI – to accelerate design and optimization of decarbonization technologies.

Microelectronics

Argonne's microelectronics research links fundamental science with manufacturing, guided by our unique set of computational and characterization capabilities and an overarching focus on supply-chain, environmental, and energy challenges. We support technology development in multiple areas that are driving the changing landscape in microelectronics, with heterogeneous integration of chiplets being a prime example. Our microelectronics work involves discovery science that spans the co-design framework, from new materials, chemistries, and phenomena to devices, higher-level microelectronic systems, algorithms, programming paradigms, and applications. It is synergistic with our core capabilities in the physical and computational sciences.

We apply unmatched experimental and computational expertise to the design and discovery of new materials and chemistries, such as 3D fabrication using "direct-write''; atomic layer deposition; and incorporation of emergent materials in technologies that include high-frequency devices, radiation-hard detectors, and thermal management systems. Recent examples include developing co-design-guided approaches for new nonvolatile memory, spin-based memory, neuromorphic approaches, and organic electrochemical transistor learning circuits; pushing computing onto detector silicon to manage high data rates; and developing interconnect layers to limit electromigration.

Our research leverages capabilities at the APS and CNM for synthesis, patterning, and advanced characterization. We will use the capabilities of the upgraded APS to extend our success in 3D imaging of integrated circuits to dense, highly integrated chiplet stacks. Our advanced capabilities in time-resolved ultrafast electron and X-ray microscopy will allow us to understand *operando* material and device behavior on a nanosecond timescale. The ALCF is critical for modeling across the co-design framework and for applying AI approaches to complex data analysis and accelerated hardware optimization and design. To meet energy-efficiency targets for next-generation high-performance computing, we will pursue a co-design approach for algorithms, compiler optimization and possible hardware solutions.

We will further leverage capabilities at our Materials Engineering Research Facility to apply new additive-manufacturing approaches to microelectronics, informed by supply chain modeling. We will pursue this research through collaboration with national laboratories including Fermilab, universities, and industry partners, with the goal of establishing a Midwest center for research on energy-efficient microelectronics.

Nuclear and radio chemistry

We apply our core capability in nuclear and radio chemistry to conduct pioneering work in nuclear chemical engineering, chemical separations, and the materials and chemical science of actinides, radioisotopes, and the nuclear fuel cycle. Our strategy to enable next-generation technologies is to enhance this capability by gaining new understanding in five areas: (1) chemical and thermophysical properties of actinides in extreme environments, like those encountered in advanced nuclear energy systems; (2) production and chemical separation of radioisotopes for medical and national security technologies; (3) structure-property relationships foundational to actinide and radioisotope chemical separations across energy-related processes; (4) correlations between ion- and neutron-radiation damage to nuclear fuels and structural materials, needed to enhance their performance in advanced energy; and (5) technical foundations that enhance material security and nonproliferation.

A distinctive portfolio of research facilities enables this work, including Argonne's APS, ATLAS, ALCF, and electron microscopy tools such as the IVEM. In addition, we use purpose-built radiological facilities to extend understanding of the pure and applied chemistry of the actinide elements. In these facilities, we develop and test advanced electrochemical and aqueous separation processes and nuclear fuels, nuclear fuel cycle and safeguards technologies for advanced nuclear energy systems, and recovery and purification technologies for advanced radioisotope production systems.

We leverage our facilities and apply AI/ML to produce novel approaches to synthesizing actinide-bearing materials and characterizing and modeling their properties. We develop predictive bonding and energetics models, within the context of nuclear fuel development and chemical separations relevant to nuclear energy, by using Argonne computational facilities to interpret characterization results from the APS. We are applying insights from this modeling to develop efficient separations processes and associated safeguards technologies that enable cost-effective advanced nuclear technologies with enhanced nuclear material security as well as innovative detection and analysis methods for nuclear forensics provenance determinations.

We actively collaborate with national and international research and industrial partners to accelerate the development of these technologies. Looking ahead, we are focused on developing innovative technologies that address emerging, strategic needs in nuclear energy and national security.

Nuclear engineering

Argonne pioneered nuclear energy systems and remains a world leader in advancing nuclear energy science and technology. Our goal is to sustain the benefits of nuclear energy generation; develop new and innovative nuclear energy systems, including advanced testing facilities that support development of future nuclear systems and components; use advanced modeling, simulation, and AI capabilities in reactor design; enhance the security of nuclear technology applications worldwide; and develop the next-generation nuclear engineering workforce for analytical and experimental research and development.

Our nuclear engineering capability supports national goals in nuclear-reactor and fuel-cycle development, expanded use of nuclear energy to supply clean energy, nuclear nonproliferation, and nuclear materials security. We draw on a distinguishing suite of Argonne capabilities in nuclear and neutron physics, thermal-hydraulics, instrumentation and control, mechanical design and engineering, materials science, nuclear and radio chemistry, X-ray imaging, computational science, advanced nondestructive examination techniques, advanced fuels research, and advanced reactor coolant handling techniques.

Key facilities that support this work include the APS, ALCF, ATLAS, and IVEM, which has distinctive capabilities to image changes in materials during irradiation. Our Activated Materials Laboratory will soon become operational at the APS to enable powerful X-ray analyses of radioactive samples. We use specialized engineering laboratories to study nuclear reactor materials and components under extreme conditions like those encountered in nuclear energy systems. Throughout our history, we have enhanced the impact of our research through national and international collaboration with research and industrial partners seeking to deploy advanced nuclear energy systems, under various U.S. government programs. Such partnerships are an essential element of our future strategy.

We will continue to build on our core strengths in neutron physics and advanced reactor plant design and safety analysis. Our nuclear fuel cycle expertise, along with our nuclear and radio chemistry capabilities, allows us to develop methods for separating radioisotopes and recycling actinides from used nuclear fuel to reduce nuclear waste generation. We also apply our expertise to convert fuel in research and test reactors around the world from highly enriched to low-enriched uranium, to help reduce proliferation risk, and to analyze global nuclear energy and material production developments.

Nuclear physics

Argonne is a global leader in the study of nuclear structure and reactions, astrophysics, hadron physics, and fundamental symmetries. We enable advances in nuclear physics instrumentation and accelerator development. Our national user facility, ATLAS, is at the cutting edge of discovery science in nuclear physics, and each year we collaborate with 300-500 ATLAS users from academia, industry, and other national laboratories. We also make major contributions in science and instrumentation through a partnership with the Facility for Rare Isotope Beams.

Our physicists are leaders in theoretical and experimental quantum chromodynamics (QCD), the fundamental theory that describes the binding of quarks and gluons into protons, neutrons, and nuclei. They design, construct, and operate detectors at multiple facilities to carry out these investigations. For the future Electron Ion Collider, we are making major contributions to the science program and the design and simulation of the detectors and accelerator. We also test the limits of the Standard Model in on-site labs used for experiments that search for violation of time reversal symmetry. Furthermore, we provide a testbed for new methods to aid in the search for neutrinoless double beta decay, a process that, if observed, would establish that neutrinos are their own anti-particles.

Argonne’s experimental nuclear physics research is supported by our work in accelerator science and by theory efforts that make significant use of the ALCF. We are world leaders in quantum Monte Carlo calculations of nuclear structure and reactions, lattice QCD, and predictions of hadron and nuclear properties using nonperturbative methods in QCD. This research is key to several DOE Scientific Discovery through Advanced Computing (SciDAC) projects and is at the forefront of AI and machine-learning methods for nuclear physics.

Our physicists support applications of nuclear technology, such as characterization of spent nuclear fuel; medical radioisotope R&D; nonproliferation; and atom trap trace analysis for geophysics, oceanography, and national security. We are expanding our capabilities by leveraging Argonne’s expertise in materials science, particle physics, accelerator and hard X-ray science, and advanced computing. In quantum science, our physicists are building a program in quantum information science in partnership with materials and computational scientists.

Particle physics

Through Argonne’s core capability in particle physics, we carry out cutting-edge research aligned with the national high energy physics roadmap. Our vision is to be a hub of innovation in computing, detector, and accelerator technologies.

Physics studies for the Large Hadron Collider (LHC) focus on beyond-standard-model (BSM) searches and precision standard model measurements. We support LHC ATLAS detector operation, software, and computing, with an emphasis on high-performance computing and machine learning, building on the ALCF. We are contributing to the high-luminosity LHC upgrade, including construction of the silicon pixel detector and development of the trigger and readout systems. Our strategy for theoretical high-energy physics research focuses on quantum chromodynamics and BSM physics with emphasis on interpretations of, and predictions for, experimental results.

Argonne deployed the largest focal plane to date of transition edge sensors (TES) for the South Pole Telescope and will provide detectors for the CMB-S4 experiment. Ultrasensitive superconducting sensors are being developed for potential use in future dark matter detectors. We also draw on our strengths in superconducting devices for quantum science as part of the Argonne-led Q-NEXT center and collaborations via the Chicago Quantum Exchange.

In addition to operating the Argonne Wakefield Accelerator, we participate in the construction of Fermilab's muon-to-electron-conversion experiment and provide the precision magnetic field map for the muon g-2 experiment. For the Deep Underground Neutrino Experiment, we lead the design and engineering of the high-voltage system and the production and installation of the cathode-plane assemblies for the Far-Detector.

The multilaboratory DOE/SC-HEP Center for Computational Excellence (HEP-CCE), co-led by Argonne, develops approaches to enable the use of exascale computing resources for experimental high-energy physics. We are a leader in extreme-scale cosmological simulations and provide some of the largest simulations to support DOE-led optical and cosmic microwave background (CMB) cosmological surveys. Results are shared worldwide via a data portal. As part of a new effort, a compute portal is being developed to provide access to analysis tools and compute resources to enable direct interaction with the data. Other future activities supported under HEP-CCE include complex workflows on exascale systems, optimization of data storage and movement, and large-scale AI/ML applications.

Power systems and electrical engineering

Through this core capability, we apply comprehensive expertise and analytical and experimental tools to improve technologies used to produce and transfer electrical power. Our work supports the modernization and resiliency of the U.S. electric grid and identifies the impacts of grid coupling with other critical infrastructure. Argonne plays an integral role in national grid planning for greater use of decarbonized energy. This work builds on our strengths in energy systems, computational science and AI, and materials science. Our suite of engineering-based computational tools gives insight into the life cycle of the grid and relevant technologies; we use these tools in many ways, including to:

- Integrate capacity expansion, unit commitment, and economic dispatch models; simulate markets using agent-based models; identify clean generation and transmission corridors; and analyze the life-cycle carbon impacts of grid technologies.
- Analyze emerging grid dynamics, design microgrids, optimize grid performance, and co-simulate power transmission and distribution.
- Perform valuation, market analysis, and technoeconomic studies of energy storage, hydropower, and pumped-storage operations.
- Assess grid resilience and strengthen cybersecurity for distributed energy resources (DERs), smart inverters, and electric vehicle supply equipment.
- Develop and integrate multi-sector models for interdependency analysis, including models of building-to-grid connectivity, transportation systems, and natural gas and hydrogen systems.

Our work uses Argonne's ALCF and AI to model power systems, APS to characterize materials, Materials Engineering Research Facility to scale up new energy materials and technologies, and Smart Energy Plaza to test vehicle-to-grid integration. Supporting experimental equipment includes a hardware-in-the-loop system to evaluate grid edge technologies and lab facilities for compact low-cost power meter development and *in-situ* failure testing of power electronics. We collaborate extensively with the power industry on demonstrating and transitioning research for applications such as resilience analysis for ERCOT, climate adaptation for Ameren, and power asset management for ComEd.

Moving forward, we will further develop and apply our tools for accelerating grid expansion to accommodate deep electrification.

Systems engineering and integration

Through this core capability, we bring together multiple engineering disciplines to integrate scientific discoveries into technological solutions that improve energy systems and U.S. economic competitiveness. Our work enables deployment of clean energy technologies at scale, thereby accelerating the energy transition both in the U.S. and abroad. We are active contributors to multilaboratory, multi-agency international initiatives, including Net Zero World, that support adoption of clean energy by partner nations on multiple continents. Argonne solves problems holistically and develop optimal solutions, enabling us to.

- Perform life-cycle analysis of energy systems, vehicle technologies, and building and industrial technologies to quantify energy, air emissions, and water-use impacts using the GREET model, which has nearly 60,000 users worldwide; its use is mandated by the Inflation Reduction Act of 2022 for some transportation fuel analyses.
- Advance energy storage deployment through material and process R&D for batteries and analysis of supply-chain, economic, and environmental impacts. We play a key role in DOE's Li-Bridge, a public-private partnership focused on strengthening the supply chain for lithium-ion batteries.
- Assess the impact of advanced transportation technologies and policies on metrics such as energy consumption, costs, mobility, behavior, equity, and environmental effects, through modeling, simulation, and experimental testing from the component level to large-scale transportation systems.
- Develop and use process simulations and techno-economic models to address cost implications of R&D progress in emerging energy technologies and infrastructure ramp-up for clean energy and sustainable transportation deployment.
- Conduct integrated analyses of nuclear energy deployment in deep-decarbonization energy systems, including coal-to-nuclear energy site transitions, nuclear energy coupled with direct air capture systems, and application of nuclear energy in integrated energy systems.
- Analyze environmental impacts of renewable energy and other energy-related technologies, including the environmental behavior of novel polymers.

Looking ahead, our strategy is to expand and apply these competencies to advance deep decarbonization of all U.S. economic sectors, by enabling system-level predictable outcomes from energy technologies.

Science Strategy for the Future / Major Initiatives

Throughout Argonne's history, our research capabilities have grown to enhance our service to science and society. Today, our laboratory is distinguished by the combined breadth and depth of our capabilities in both basic and applied research, combined with exceptional experimental and computational facilities. Our strategy for the future is grounded in those strengths. To achieve our strategic goals, we leverage our core capabilities, sponsored programs, S&T initiatives, and research institutes.

Discovery science is at the heart of our strategy, with a focus on materials and chemical science, nuclear and particle physics, environmental science, and biology. It will continue to provide the foundation for applied research that takes on critical societal challenges.

We are committed to continuing to advance clean energy technologies and carbon management across all sectors of the economy, drawing on our capabilities in energy storage science and the engineering of renewable, chemical, and nuclear energy systems. We also will expand our efforts to improve understanding of climate processes and needs for human adaptation to climate change.

Drawing on our expertise in computational, decision, and cyber sciences, as well as in nuclear science and engineering, we will continue to identify pathways to protect against threats to critical infrastructure and supply chains, counter the spread of infectious disease, and support nuclear nonproliferation goals.

We will continue to enhance our user research facilities, which will drive progress across our entire S&T enterprise and benefit thousands of external users: In FY23, half of our users accessed these facilities remotely, without the need to travel to our campus. Our user facilities are anchored by the recently upgraded Advanced Photon Source and the new Aurora exascale computer at the Argonne Leadership Computing Facility.

We also remain committed to building the STEM workforce, through development of our staff, student internships, and educational outreach. In particular, we intend to carry forward the principles of DOE's Fostering Great Minds and Great Ideas initiative through targeted engagement with emerging research institutions with potential to bring new people and ideas to our science.

External partnerships will continue to be key elements of our strategy, and we will seek additional opportunities to support DOE priorities through centers and consortia like the ones we lead today.

Table 4.1 DOE user facilities operated or supported by Argonne*

ALCF	Argonne Leadership Computing Facility
APS	Advanced Photon Source
ARM	Atmospheric Radiation Measurement user facilities
ATLAS	Argonne Tandem Linac Accelerator System
CNM	Center for Nanoscale Materials
IVEM	Intermediate Voltage Electron Microscope

*Sponsored by DOE Office of Science except for IVEM, which is sponsored by the DOE Office of Nuclear Energy.

Table 4.2 Key multi-institution DOE collaborations led by Argonne*

AMEWS	Advanced Materials for Energy-Water Systems Center, an Energy Frontier Research Center
SEPCON	Bioprocessing Separations Consortium, an industry-advised national laboratory collaboration
CROCUS	Community Research on Climate and Urban Science, an Urban Integrated Field Laboratory
C-STEEL	Center for Steel Electrification by Electrosynthesis, an Energy Earthshot Research Center

MICCoM	Midwest Integrated Center for Computational Materials, a collaboration with research universities
Q-NEXT	A National Quantum Information Science Research Center

*Sponsored by DOE Office of Science except for SEPCON which is sponsored by the DOE Office of Energy Efficiency and Renewable Energy.

Infrastructure

Argonne Facilities and Infrastructure

Argonne's campus in Lemont, Illinois, a suburb of Chicago, is stewarded by DOE/SC. The average age of the Argonne-operated (DOE-owned and contractor-leased) buildings and infrastructure is 50 years, with 57% of the buildings being more than 50 years old. Our facilities are roughly 83% utilized (calculated as utilized space / total space). Tables 6.1, 6.2, and 6.3 summarize the type and condition of Argonne's facilities and utilities.

We maintain 5.1 million square feet of space for DOE on our 1,517-acre campus. Argonne-operated buildings average 47 years old and 35% of all building repair needs are identified as deferred maintenance.

In addition to buildings operated by Argonne, our campus includes three privately operated buildings. The Howard T. Ricketts Regional Biocontainment Laboratory is operated by UChicago; Argonne does not occupy space in that structure. The Theory and Computing Sciences (TCS) office building, and the TCS "powered shell" data-center addition, are both operated by the TCS Trust, and Argonne leases space in these buildings.

We also continue to lease or license off-campus space for other Laboratory needs, such as those in support of the APS Upgrade project or Radiological Assistance Program (RAP) team. Real estate actions conducted in FY24 include ending a 14,735-square-foot lease for Washington, D.C., office space and replacing it with a significantly reduced footprint in the D.C. area through an annual license agreement.

We reduce operational risks and potential impacts by targeting investments to improve substandard infrastructure and utilities, which account for most of our deferred maintenance (DM), and to address potential failure modes in our utility systems. In FY23, Argonne spent $54.2 million on maintenance using Laboratory-indirect funds. Despite these significant investments in infrastructure, we carried $121.2 million in DM costs for DOE-owned assets at the end of FY23. Sixty percent of our total DM costs are tied to substandard assets. Deferred maintenance accounts for a portion of Argonne's Repair Need (RN) FY23 year-end total of $347.67 million. See Sec. 6.2 for a discussion of our strategy to reduce RN.

We identify risk-reduction measures in our ten-year plan for campus modernization, titled *Facility and Infrastructure Strategic Investment Plan*, which aligns with the Annual Laboratory Plan and details our intended facility operations portfolio and future campus vision. The Facility and Infrastructure Strategic Investment plan will be updated in FY24.

Campus Strategy

Overview of 10-year plan

Our vision for the future is to provide a resilient site with energy-efficient, hybrid-workforce-supportive, sustainable facilities and infrastructure to enable mission readiness and continuous operations, while supporting federal goals for net-zero-carbon ("net-zero") emissions. Our 10-year plan for modernization establishes a roadmap for advancing this vision, with enabling investments aligned to support our multiprogram S&T missions and position Argonne to prepare for, adapt to, withstand, and recover rapidly from adverse events that affect our facilities and infrastructure.

Support and advancement of Argonne's S&T strategy is foundational to all infrastructure investment decisions. Four goals guide our campus strategy to assure facility and infrastructure readiness in a net-zero future:

- Renovate existing facilities and construct modern facilities
- Repair and modernize utilities and support infrastructure
- Eliminate legacy waste and excess facilities
- Decarbonize campus and operations.

Crosscutting themes include strengthening our operational resilience through enhanced, data-driven decision-making capabilities. Each goal is evaluated against a set of metrics and objectives and is expanded upon in the following sections.

We continue to adjust our space planning and utilization assignment approaches to incorporate lessons learned from the unprecedented levels of telecommuting by our workforce during the COVID-19 pandemic. We have increased hybrid conferencing infrastructure and reservable office/workstation options to accommodate our workforce. We have also reallocated existing space to provide daily reservable desks, with a focus on the primary office-use buildings.

To advance Argonne's science strategy and manage operational risks, we take an integrated planning approach that analyzes infrastructure gaps, establishes a comprehensive portfolio of facility and infrastructure needs, aligns necessary investments, and sets associated timeframes for completion.

Our infrastructure investment plan includes estimated total capital investments in buildings and utility systems across the Argonne campus of $1,245 million during the time period FY24-FY35. This total does not include Utility Energy Service Performance Contracts or the campus-wide decarbonization plan. The $1,245 million consists of:

- $289 million in Argonne indirect funds
- $562 million in proposed DOE funds (line items, program funds, scientific laboratories infrastructure [SLI], and general plant projects [GPP])
- $342 million in proposed DOE/EM clean-up funds
- $52 million in potential State of Illinois funding

Over the FY24-FY35 planning period, the DOE investments listed above would reduce our DOE-owned space by an estimated 500,000+ gross square feet.

In addition to our capital investments, we will also maintain our robust operations maintenance and repair program with planned spending of $932 million during that period. We optimize our Laboratory-indirect investments in this program to perform preventive maintenance and repairs before capital investment is required.

Our DM reduction profile relies on all investments, including our maintenance and repair investments, occurring as planned. Delays in investment or execution of the infrastructure investment strategy will result in more DM carried per fiscal year than projected.

We intend to build on our sustainability accomplishments to date to move Argonne toward net-zero emissions in alignment with the federal sustainability plan.

Site Sustainability Plan Summary

As noted in Argonne's annual site sustainability plan, our sustainability program is an integral part of our campus strategy, leading efforts to meet DOE's sustainability and resilience goals. We realigned our sustainability plan and program over the last year to address key federal sustainability requirements: the Energy Act of 2020, Guiding Principles for Sustainable Federal Buildings 2020, Executive Order 14008 - Tackling the Climate Crisis at Home and Abroad, and Executive Order 14057 - Catalyzing Clean Energy Industries and Jobs through Federal Sustainability. We are taking a Laboratory-wide approach to reduce greenhouse gas (GHG) emissions and improve resilience. We have incorporated these goals into our long-range plans while also dramatically increasing our near-term efforts for energy-reducing facility and infrastructure renovations, green fleet management, and sustainable product acquisitions in commercial contracts and construction.

Energy Management

DOE goals: (1) Reduce energy intensity (Btu per gross square foot) in goal-subject buildings by 50% on an hourly basis by the end of FY30. (2) Achieve a net-zero-emissions building portfolio by 2045 through building electrification and other efforts. (3) Energy Independence and Security Act (EISA) Section 432 continuous (4-year cycle) energy and water evaluations. (4) Meter individual buildings for electricity, natural gas, steam, and water to adhere to federal metering guidance.

FY24 Argonne efforts

Measures currently being implemented include multiple lighting retrofit projects, controls upgrades, and multiple exterior door replacements.

We are working to transition the electric supply to carbon-free sources and convert heating from natural-gas-based to heat-recovery systems and/or electrification. To support this transition, we have developed sustainability requirements specifications that we will implement in our future infrastructure projects.

Energy conservation measures (ECMs) identified include controls upgrades, envelope upgrades, on-campus solar, and potable/domestic water to canal (industrial) water conversions. Potential investment value is unknown at this time. In compliance with the Energy Act of 2020, which requires Argonne to address issues of energy production, distribution, consumption, and modes of use, we are preparing to use performance contracting to meet at least 50% of life-cycle cost-effective ECMs.

Review existing metering infrastructure to verify its accuracy and recalibrate or replace meters as necessary. In FY23, we developed a Microsoft Access "Meter Tracking Database" to better manage 1,400 meter assets and we installed new meters in three buildings.

Planned Argonne efforts

Continue to work to formalize a campus decarbonization strategy. New buildings and building renovations target high-performance sustainable buildings (HPSBs) and/or Leadership in Energy and Environmental Design (LEED) certification.

Continue to leverage the Council on Environmental Quality's *Guiding Principles for Sustainable Federal Buildings* workbook to require Argonne's design and construction subcontractors to incorporate these principles into their construction proposals and work.

Continue to pursue project funding through a Utility Energy Service Performance Contract (UESC). We anticipate that both the preliminary and investment-grade audits, required to secure this contract and funding, will occur in FY24. We will use UESC funding to make progress toward meeting our decarbonization strategy and net-zero goals and implementing energy conservation measures. We are focusing our efforts on six buildings with a total area of nearly 1.1 million gross square feet.

Continue installing advanced metering and add chilled-water meters at buildings, leveraging planned investments for campus-wide utility system upgrades.

Overall risk of nonattainment: Moderate

Clean and renewable energy

DOE goals: (1) Achieve 100% carbon pollution-free electricity on a net annual basis by 2030, including 50% 24/7 carbon pollution-free electricity. (2) Increase consumption of clean and renewable and non-electric thermal energy.

FY24 Argonne efforts

We are updating our calculation methodology to take credit for the more than 80% CFE provided currently through the regional grid.

Argonne currently meets these goals by purchasing Renewable Energy Certificates/Energy Attribute Certificates (EACs) and maintaining onsite clean and renewable energy infrastructure.

Planned Argonne efforts

Electricity and natural gas utility contract negotiations will commence in FY24, as the contracts expire in December 2024. Argonne will work with the Defense Logistics Agency (DLA) to include federal sustainability requirements in the procurement. We will consider both Power Purchase Agreement and EAC purchases.

We are completing a final design to install ground-mounted solar panels in the 400 Area, including battery storage. Our goal is to use the UESC described above, currently in process, to fund some or all of this installation.

Overall risk of nonattainment: Moderate

Efficiency and conservation measure investments

DOE goals: Implement life-cycle cost-effective efficiency and conservation measures with appropriate funds and/or performance contracts.

FY24 Argonne efforts: Continue to implement projects through Argonne's in-house energy and water reinvestment program, other indirect operations funds, and current Energy Savings Performance Contracts (ESPCs).

Planned Argonne efforts: Argonne anticipates entering the UESC preliminary assessment and investment-grade audit phases of the performance contracting process in FY24 to meet EISA ECM funding requirements.

Overall risk of nonattainment: Low

Climate adaptation and resilience

DOE goals: Implement climate adaptation and resilience measures.

FY24 Argonne efforts: Prioritize implementation for key climate adaptation and resilience measures that provide the most cross benefit to all areas of the Laboratory. As we are able, we are building resilience measures into existing projects.

Planned Argonne efforts: Continue to implement planned actions identified in Argonne's 2022 Vulnerability Assessment and Resilience Plan and continue to make progress on key infrastructure projects that support climate adaptation and resilience.

Overall risk of nonattainment: Low

BROOKHAVEN NATIONAL LABORATORY

Lab-at-a-Glance

Location: Upton, New York
Type: Multi-program Laboratory
Contractor: Brookhaven Science Associates
Site Office: Brookhaven Site Office
Website: www.bnl.gov

- **FY 2023 Lab Operating Costs:** $752.3 million
- **FY 2023 DOE/NNSA Costs:** $709.9 million
- **FY 2023 SPP (Non-DOE/Non-DHS) Costs:** $41.7 million
- **FY 2023 SPP as % Total Lab Operating Costs:** 5.6%
- **FY 2023 DHS Costs:** $0.7 million

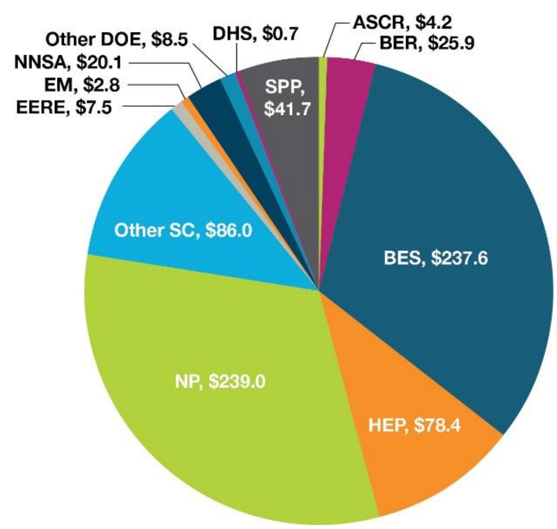
Physical Assets:

- 5,322 acres and 316 buildings
- 4.8 million GSF in buildings
- Replacement Plant Value: $6.93 B
- 200,016 GSF in 28 Excess Facilities
- 0 GSF in Leased Facilities

Human Capital:

- 2,754 Full Time Equivalent Employees (FTEs)
- 86 Outgoing Joint Appointees
- 64 Incoming Joint Appointees
- 174 Postdoctoral Researchers
- 261 Graduate Student
- 312 Undergraduate Students
- 3,583 Facility Users
- 2,734 Visiting Scientists

FY 2023 Costs by Funding Source ($M)



Mission and Overview

Brookhaven National Laboratory (BNL) and its people are driven by a common vision to accelerate pathways to scientific discovery and technological innovation that transform the world. Brookhaven is a multi-program laboratory with seven Nobel Prize-winning discoveries and 77 years of pioneering research. Established in 1947, BNL brings unique strengths and exceptional capabilities to the DOE laboratory system.

Its nearly 3,000 science and operations staff work together to advance the Lab's mission – to drive fundamental science by discovering and exploring forms of matter to gain a deeper understanding of the universe, by understanding and controlling electronic and materials properties down to the nanoscale, by employing capabilities to advance emergent information science, and by addressing environmental and societal challenges. BNL carries out its mission safely, securely, and environmentally responsibly, with a commitment to diversity, equity, inclusion, and accessibility, and with the partnership of local, state, national, and international communities.

Over the next decade, the Lab will build the Electron-Ion Collider – the only new collider to be constructed worldwide during the next decade – for the pursuit of knowledge about the basic building blocks of matter; lead in discovery with light-enabled science at the National Synchrotron Light Source II and a future build out of its beamline suite and a possible upgrade to the accelerator to drive advances in a broad range of science disciplines; enable an interdisciplinary approach to emergent information science and technology by taking advantage of the Lab's core capabilities; and foster programs that address environmental and societal changes.

These four initiatives are enabled by BNL's suite of powerful facilities and capabilities which serve DOE's basic research needs and reflect BNL/DOE stewardship of national research infrastructure critical for university, industry, and government researchers.

BNL is managed by Brookhaven Science Associates (BSA), a partnership between Stony Brook University and Battelle, and six core universities: Columbia, Cornell, Harvard, MIT, Princeton, and Yale. BSA works to advance BNL's strategic initiatives, from basic research to technology deployment. BSA and its partners oversee BNL's growing impact, including its vital relationship with New York State.

Core Capabilities

Eighteen existing and two emerging core technical capabilities underpin all activities at Brookhaven National Laboratory. Each one is comprised of a substantial combination of facilities, teams of people, and equipment that has a unique and often world-leading component and relevance to national needs, as well as to the education of the next generation of scientists from grades K – 12 and through graduate school. They arise from long-standing strengths and synergies in fundamental nuclear and particle physics, in chemical, materials, biological, environmental, isotope, and data sciences with applications to today's problems; in developing and operating major user facilities; and in targeted applications in national security. These core capabilities enable BNL to deliver transformative science and technology (S&T) that is relevant to the DOE (including the National Nuclear Security Administration) and the Department of Homeland Security (DHS) missions and external partners.

BNL has updated its core capabilities to reflect recent efforts in each capability area. The revisions are not major changes in focus. In FY 2022, BNL was assigned three new capabilities in Isotope Science and Engineering, Mechanical Design and Engineering, and Microelectronics after the Office of Science (SC) conducted an exercise to validate and map the list of core capabilities. BNL still considers its capabilities in Nuclear Engineering and in Power Systems and Electrical Engineering as "emerging."

Accelerator Science and Technology

Accelerator science and technology development has been central to BNL's mission since the construction of the Cosmotron in 1948. The Laboratory operates three Office of Science User Facilities based on its accelerator capabilities – the Relativistic Heavy Ion collider (RHIC), the National Synchrotron Light Source II (NSLS-II), and the Accelerator Test Facility (ATF) – and several smaller accelerators that provide unique platforms for specialized applications. BNL expertise spans the delivery of electron and hadron beams over a wide range of parameters. Core technology areas include the design and construction of magnets (from permanent to superconducting), including the unique direct-wind technology for complex field profiles developed in the Magnet Division and the "complex bend" design for the proposed NSLS-II upgrade; high-intensity high-brightness electron and hadron beam sources (unpolarized and polarized); high-power mid- and long-wave infrared laser systems; development of radiofrequency (RF) and superconducting RF components and systems; beam instrumentation; beam vacuum systems (including coating capabilities); power supply systems; cryogenic systems; and control systems. Expertise in beam dynamics ranges from low-emittance beams at NSLS-II that produce some of the brightest X-ray beams in the world, to the unique electron and laser interactions at the ATF, to multiple hadron beam cooling techniques implemented in RHIC. This expertise drives critical advances for accelerator-based science and technology in the U.S. and around the world.

BNL has pioneered some of the most innovative detectors that are the cornerstone of scientific experiments. BNL's research seeks to extend capabilities and develop technologies to advance programs in science, energy, security, and industry. BNL's detector research and development (R&D) covers a broad range of technologies from silicon and other solid-state materials to gas, liquid scintillators, and noble liquid detectors. Integral to these developments is microelectronics, particularly operating in extreme environments, and signal processing using the most modern techniques (e.g., Machine Learning/Artificial Intelligence [ML/AI]). BNL's unique facilities and expertise are key to the development of state-of-the-art detectors. Synergistic developments and collaborations with other laboratories and universities enable innovation and implementation of new concepts and technologies.

DOE support for BNL's accelerator capabilities comes from the Offices of Nuclear Physics (NP), Basic Energy Sciences (BES), Fusion Energy Sciences (FES), High Energy Physics (HEP), and Accelerator R&D and Production (ARDAP), and Laboratory Discretionary Funds. Support for BNL's detector R&D also comes from DOE and Other Government Agencies (OGA) and industrial partners.

Advanced Computer Science, Visualization & Data

BNL has long-standing research, development, and operational programs in advanced computer and data science methods, applied mathematics, algorithms, tools, and infrastructures — particularly in support of experimental facilities - making it one of the largest data science Labs in the DOE complex. Scientists have built an extensive research program in ML and AI that focuses on scalable, robust, trustworthy, streaming, and foundation ML algorithms beyond deep learning, including causal analysis, manifold learning, and natural language processing. The technologies developed are applied to projects in other DOE offices, such as the Office of Biological and Environmental Research (BER) RadBio and low-dose (LUCID), two Biopreparedness Research Virtual Environment (BRaVE) centers, and the BES Automated Sorting of High Repetition Rate Coherent Diffraction Data from X-ray Free Electron Lasers and the Angstrom Era Semiconductor Patterning Material Development Accelerator. This program is complemented by research into AI explainability and reproducibility and supported by research into programming models, runtime systems for ML, and new performance portability approaches that provide a capability to enable the effective use of novel architectures. Advanced workflow management tool concepts including the Exascale Computing Project (ECP) ExaWorks are used to create high throughput workflows that can effectively leverage exascale systems in projects, such as CANDLE, ExaLearn, the completed award winning BER National Virtual Biotechnology Laboratory Medical Therapeutics project, and the HEP Center for Computational Excellence. The Office of Advanced Scientific Computing Research (ASCR) REDWOOD project addresses efficiently managing extreme volumes of data as part of complex workflows in a distributed heterogeneous computing infrastructure. The research is supported by a state-of-the-art 60,000 sf data center. BNL is a leading computing center for high-throughput and data-intensive computing, supporting HEP and NP experiments, (ATLAS, Belle II, Deep Underground Neutrino Experiment [DUNE], STAR, sPHENIX) and BNL, U.S., and international efforts: Lattice Quantum Chromodynamics (LQCD), National Synchrotron Light Source II (NSLS-II), the Center for Functional Nanomaterials (CFN), the Nonproliferation and National Security Department, the Energy and Photon Sciences Directorate, the Worldwide LHC Computing Grid, and the Open Science Grid. BNL operates one of the top ten archives in the world, with over 255 PB of actively managed data and 1.2 EB were analyzed in 2023. Data traffic exceeds 200 PB/year. The primary sources of funding are from ASCR, HEP, NP, BES, BER, the Office of Electricity (OE), the Office of Energy Efficiency and Renewable Energy (EERE), NNSA, New York State, OGA, and Laboratory Discretionary Funds.

Applied Materials Science and Engineering

BNL capabilities in applied materials encompass materials for energy storage and growing capabilities for studies of materials in extreme environments for nuclear applications, as well as applications in catalysis, and solar energy conversion (3.7), molten salts for energy applications (3.7), fuel cells and electrolyzers (3.8), quantum information science (3.10), and microelectronics (3.18). Capabilities in energy storage include materials synthesis, characterization and functional electrochemical evaluation, high energy density cell technology, evaluation of thermal stability and functional limits of battery materials, fundamental studies of charge and discharge mechanisms and the associated material-structure evolution. BNL has established expertise and capabilities for in-situ and spatio-temporal characterization under operando conditions of energy storage materials by X-ray methods at NSLS-II and electron microscopy at the CFN. BNL has capabilities to study materials in extreme environments for nuclear applications that include a specialized robotic system at NSLS-II for the rapid characterization of radioactive materials, X-ray diffraction computed tomography, which enables three-dimensional (3D) imaging of the microstructure of engineering-scale samples, and a unique suite of environmental cells for the in-situ characterization of highly corrosive reactor materials and molten salt samples. The 200 MeV proton beam of the Linac and the Brookhaven Linac Isotope Producer (BLIP) target facility allow for the investigation of radiation damage of beam collimators, beam windows, and high-power targets, and have been used by the RaDIATE collaboration. The primary sources of funding are BES, the EERE Vehicle Technologies Program (VTO), the Office of Electricity (OE), the Office of Nuclear Energy (NE), New York State, and Laboratory Discretionary Funds.

Applied Mathematics

Over BNL's long history, its mathematics research has traditionally focused on areas relevant to HEP, NP, synchrotron science (BES), and accelerator physics. Today BNL emphasizes a number of cross cutting themes such as optimal experimental design under uncertainty and broader decision making and optimization of complex systems under uncertainty. The Lab is a partner in ASCR's Mathematical Multifaceted Integrated Capabilities Center, called Multifaceted Mathematics for Digital Twins (M2dt), two ASCR epidemiological decision making projects (EMERGE and RADIUM), the BER RadBio and LUCID projects on low-dose radiation biology that include experimental design, and an NP project on AI for accelerator control, with the CFN and NSLS-II in a Laboratory Directed Research and Development (LDRD) project, which develops new optimal experimental design concepts in autonomous systems, and an LDRD with the Environmental and Climate Sciences Department on optimal observing system design. A second theme centers on multiscale modeling and digital twins that address the bridging of scales and integration of data from experiments/observations and from simulations. Initial focus areas are nuclear physics, climate, biology, and chemical processes, including partnerships on a BER/ASCR Scientific Discovery through Advanced Computing (SciDAC) project Framework for Antarctic System Science in E3SM, M2dt, LDRD investment in a Digital Twin for a new BER Cloud Chamber, and the development of a digital twin for plants. Applied math for scalable AI and ML that will provide key foundations needed for BNL's AI research program is another cross-cutting theme. An added focus involves exploring how to achieve AI explainability through foundational applied mathematics work. BNL's ASCR-funded Noether Fellowship in Applied Mathematics supports work in AI uncertainty quantification, digital twins, and generative modeling. Additional work is being carried out on the development of numerical methods for solving functional renormalization group equations for strongly coupled physics problems. Support comes primarily from ASCR, BER, and Laboratory Discretionary Funds.

Biological Systems Science

The goal of BNL's program is to develop a systems-level understanding of complex biological processes relevant to the DOE mission. This involves generating and testing hypotheses using approaches that include genomics, molecular biology, biochemistry, structural biology, computation, imaging, and biosystems design. This capability lays the foundation for desired manipulations of growth rates, biomass accumulation, resistance to stresses, and the accumulation of desired products that constitute feedstocks for biofuel and bioproduct production in bioenergy crops relevant to the BER mission. This program is synergistic with programs in physical biosciences (funded by BES, Core Capability [CC] 7). BNL is a major contributor to DOE's BRaVE program with a focus on developing molecular-level insights into the interactions between pathogens and plants to lay the foundation for improved resilience of bioenergy crops to biothreats. BNL also contributes to three Bioenergy Research Centers and participates in ECON, a component of the BER Sustainability Research for Bioenergy program. Biological Systems Science research at BNL drives and enhances the biomolecular characterization and imaging user facilities, through the development of new microscopes, sample environments, integration of advanced computing techniques into experimental workflows, and the development of digital twins of biological systems. BNL's biomolecular characterization and imaging user facilities support BER mission research. BNL is developing computational platforms for biological science as a key contributor to KBase and by establishing the collaborative SciServer environment as part of BRaVE research. BNL's biological systems science activities are supported by: BER, the Joint Genome Institute Community Science Programs, the Environmental Molecular Sciences Laboratory's user program, Facilities Integrating Collaborations for User Science, ASCR, New York State, the National Institutes of Health (NIH), and Laboratory Discretionary Funds.

Chemical and Molecular Science

BNL's chemical and molecular sciences develop foundational knowledge to support the rational design of chemical and biological processes to enable solutions toward a net-zero carbon economy. The programs are leaders in fundamental research for sustainable carbon and hydrogen conversion in engineered and natural processes, including heterogeneous catalysis of C1 chemistry for fuels; electrocatalysis for hydrogen production and use; light capture and catalytic conversion by molecular systems for solar fuels; and carbon capture, conversion, and storage in plants. The research utilizes BNL user facilities (NSLS-II and CFN) and the divisional Accelerator Center for Energy Research (ACER).

BNL expertise in thermal heterogeneous catalysis is applied to improve understanding of catalysts for the conversion of difficult-to-activate small molecule feedstocks like carbon dioxide and methane to synthesize fuels and high value chemical intermediates. The research, including that conducted through the Synchrotron Catalysis Consortium, combines operando studies of powder catalysts, in-situ studies of model nanocatalysts at NSLS-II and CFN, and quantum chemical computation. Electrocatalysis research pursues mechanistic understanding leading to high activity and durable catalysts for electrolyzer and fuel cell applications using low or non-platinum group metals. The physical biosciences program focuses on a fundamental understanding of plant regulatory and metabolic mechanisms that can inform use-inspired modification of biological pathways to enhance bioproduction with emphasis on highly reduced (energy-dense) forms of carbon. BNL's program in solar photochemistry has expertise in the design, synthesis, and characterization of inorganic molecular catalysts and chromophores to understand and improve chemical processes for solar-to-fuels conversion in artificial photosynthesis. The radiation chemistry program develops and applies advanced pulse radiolysis capabilities at ACER for fundamental mechanistic studies of charged and radical species in condensed phase. BNL has growing capabilities in chemistry of extreme environments focused on structure, dynamics, and radiation chemistry of molten salts for future energy applications, using high temperature molten salt experimental capabilities at NSLS-II and ACER. The programs are funded by BES, EERE Hydrogen and Fuel Cell Technologies Office (HFTO), and Laboratory Discretionary Funds.

Chemical Engineering

BNL has a small, but high-impact and visible effort in applied chemistry research that translates scientific discovery into deployable technologies. Electrocatalysis research builds on expertise in synthesis and characterization of nanostructured core-shell metal, metal-oxide, and metal-nitride nanostructures for design of cost-effective, durable electrocatalysts for electrical-chemical energy conversion in fuel cells and electrolyzers. BNL developed innovative electrocatalysts with the potential to solve problems of low energy-conversion efficiency and high platinum loading in fuel cells. These catalysts contain smaller amounts of precious metal than conventional ones and improve durability, facilitating commercial applications of fuel cells in electric vehicles. The BNL program participates in the five-year program to develop high performance, high durability fuel cell systems for heavy vehicles in the Million Mile Fuel Cell Truck Consortium funded by HFTO. BNL also partners in L'Innovator with Los Alamos National Laboratory and NREL to demonstrate the incorporation of Lab expertise into new high temperature fuel cells in partnership with Advent Technologies. Scale-up of other electrocatalyst materials is also underway with additional industry partners. These programs are funded by EERE HFTO, and through Strategic Partnership Projects and Cooperative Research and Development Agreements with industrial partners.

Computational Science

Computational science, both numerical modeling and data analytics, is essential to enabling advanced scientific discovery at BNL's facilities – RHIC and EIC (NP), the BLIP (Isotope R&D and Production [IRP]); ATLAS and Belle II (HEP); the ATF (ARDAP); NSLS-II and CFN (BES); cryo-EM and ARM (BER) - and supporting science programs. Collaborations around numerical modeling applications benefit from the Computational Science Initiative's (CSI) ECP-funded research into performance portability (SOLLVE), ML-enabled surrogate modeling (ExaLearn, SciDAC RAPIDS), and LDRD-funded applied math for multiscale modeling and inverse problems. Examples are ECP LQCD, computational chemistry (NWChemEx), and the HEP Center for Computational Excellence that supports the ATLAS and DUNE experiments. CSI has also made significant advances in enhancing existing numerical modeling solutions with AI, ML driven solutions for predictive modeling. Examples include cloud-aerosol-turbulence simulations, climate modeling, solar power, and load forecasting. CSI partners with the Interdisciplinary Science Department on a new EERC to design geothermal materials with the assistance of High-Performance Computing (HPC) and ML techniques. In collaboration with the Instrumentation Division, the Scientific Data and Computing Center (SDCC), and facilities such as NSLS-II, cryo-EM, and CFN, BNL's Center for Advanced Technologies for Artificial Intelligence co-design new experimental capabilities that integrate advanced imaging technologies with high powered edge computing devices and streaming ML and AI. New efforts will focus on the development of digital twins, where advanced modeling and simulation capabilities will be employed to help design, guide, and improve experimental setups and workflows. A digital twin that simulates the physical experiments will be able to respond to environmental changes quickly and learn from past experiments. This will require the integration of HPC, AI, and advanced mathematical modeling methods. The primary sources of funding come from ASCR, HEP, NP, BES, BER, New York State, OGA, EERE, OE, and Laboratory Discretionary Funds.

Condensed Matter Physics and Materials Science

BNL conducts frontier research in Condensed Matter Physics and Materials Science, focusing on new and improved complex, nanostructured, and correlated-electron materials. The research is increasingly focused on quantum materials for quantum information science, building on strengths in high T_c superconductivity and chiral materials. Ongoing research also addresses renewable energy, energy storage, and energy efficiency. Research is pursued through interdisciplinary and tightly coupled programs in materials synthesis, advanced characterization using a range of experimental techniques, both lab and facility based, and theoretical approaches. A unique tool, known as OASIS (that integrates oxide molecular beam epitaxy, angle-resolved photoemission, and spectroscopic imaging scanning tunneling microscopy), brings together in one system the ability to fabricate thin films and examine their properties in situ using scanning tunneling microscopy and angle-resolved photoemission. OASIS capabilities have been applied to study strongly correlated cuprates and new research directions including 2D materials and heterostructures that can support topological excitations. The Condensed Matter Physics and Materials Science groups are all engaged in NSLS-II activities, including developing new capabilities that have led to proposals for new NSLS-II beamlines. A complementary ultrafast X-ray research program focuses on the unique science that can be performed at ultrafast X-ray free electron laser facilities. Ultrafast capabilities include an electron pulser device capable of “tabletop” ultrafast electron microscopy. Newer efforts focus on applications of ML and data science to materials science and understanding the many-body properties of rare earth materials and their potential applications to quantum technologies. BES and Laboratory Discretionary Funds are the primary sources of funding for these ongoing efforts.

Earth, Environmental, and Atmospheric Science

BNL’s atmospheric science efforts develop process-level insight into the role of aerosol and clouds in a changing climate through long-standing expertise in climate science and measurement science. BNL researchers are advancing the understanding of interactions along the aerosol-cloud-precipitation continuum and their impacts on climate for the Atmospheric Systems Research Program through a joint Science Focus Area program with Argonne National Laboratory. Scientific staff support the Atmospheric Radiation Measurement (ARM) User Facility and data archive as instrument mentors and as data science specialists and contribute to the design and interpretation of ARM measurements. BNL staff are serving as lead scientists for a long-term mobile ARM observatory in northern Alabama to study clouds, aerosols, and land-atmosphere interactions that will feed forward into Earth system models. Climate modeling scientists support the Energy Exascale Earth System Model (E3SM) and the Large Eddy Simulation ARM Symbiotic Simulation and Observation project. Observation techniques and strategies must evolve to support the development of DOE’S E3SM. BNL staff are developing novel measurement methodologies, instrumentation, and Laboratory facilities to support the research community. A focal point is a BNL-led, DOE and National Science Foundation-funded research consortium to inform the design of a convection cloud chamber to study the aerosol-cloud-drizzle continuum. As part of this effort, BNL has spearheaded research and development on the next generation of measurement technologies that will enable non-contact, in-situ detection of this continuum. In parallel, CSI is building capabilities for very high-resolution and data-driven simulations of the atmosphere and climate. BNL maintains a mobile remote-sensing platform to support research of atmospheric conditions in urban systems. This capability supports BER’s Integrated Field Laboratories project in Arizona and, along with BNL’s long-standing Perfluorocarbon Tracer technology, is used to support urban dispersion studies. Funding comes from BER, EERE, DHS, and Laboratory Discretionary Funds.

Isotope Science and Engineering

BNL has unique core expertise to produce isotopes for research and industrial distribution. This includes know-how in targetry and modeling, chemical separations capabilities including proficiency in nuclear and radiochemistry, isotope production, radiation shielding, nuclear data, AI/ML, robotics, chemical engineering, and automation to broaden the availability of isotopes needed for applications in industry, environmental, medical, and national security purposes. The Lab has unique accelerator facilities for irradiation such as the BLIP that can accept protons from 66-200 MeV from the Linac to bombard targets for isotope production and radiation damage studies to evaluate materials for use in reactors and accelerators. The Isotope Research and Production (IP) Department is bringing online a 13-19 MeV energy cyclotron to expand isotope production. BNL houses the Radionuclide Research and Production Laboratory that contains radioanalytical laboratories, equipment, and hot cells to study and process irradiated materials for providing isotopes for both internal and external use. The facility is fully equipped to conduct processing of isotopes, characterization, and evaluation in applications. The IP Department has expertise in the production of isotopes following current Good Manufacturing Practices and has filed two Drug master files with the Food and Drug Administration. The Lab has been deemed an acceptable supplier of isotopes. Materials irradiated at BNL's facilities can be further studied at NSLS-II at a specially outfitted beamline for evaluating the changes in structure that result from exposures. This effort is funded by IRP and Lab Discretionary Funds.

Large-Scale User Facilities/R&D Facilities/Advanced Instrumentation

BNL's large scale user facilities, R&D facilities, and advanced instrumentation are extending the frontiers of knowledge and enabling studies of important scientific challenges. In FY 2023, BNL served nearly 3600 users at its DOE designated user facilities, RHIC, NSLS-II, CFN, and the ATF and close to 900 at the NASA Space Radiation Laboratory (NSRL), the Tandems, RHIC-ATLAS Computing Facility and U.S. ATLAS Analysis Support Center. BNL continues to invest in detector and accelerator upgrades for its community of nearly 1000 **RHIC** users. **RHIC** completed Run 2023 with the upgraded STAR detector and started commissioning the newly built sPHENIX detector, which will enable precision measurements on hard probes (jets and heavy quarks). BNL will host the **EIC**, a facility that builds on **RHIC**, that will provide high-energy electron-ion collisions for studies of cold nuclear matter at extreme gluon densities and precision measurements of the structure and properties of protons and complex nuclei at the quark-gluon level. **NSLS-II** has strengths in imaging and dynamics and world-leading R&D programs in nano-focusing optics and nano-precision engineering. **NSLS-II** hosted 1885 users in FY 2023. **NSLS-II** is executing the NEXT-II beamline project and preparing for a CD-1 decision late in FY 2024 for NEXT-III. NEXT-III beamlines will complement the existing suite and provide capabilities in high throughput scattering, spectroscopy, and imaging. The **CFN** hosted 655 unique users in FY 2023. **CFN** continues to upgrade its portfolio to maintain leading-edge status, in instruments for synthesis and characterization of nanomaterials created by assembly, and tools for in-situ and operando nanoscience. A focus is in developing and installing an integrated set of four unique characterization and fabrication instruments for 2D material heterostructures assembled by the Quantum Material Press. BNL leads the Nanoscale Science Research Centers (NSRC)-Recap project for the benefit of the five NSRCs. The **ATF** supports a unique suite of advanced accelerator and laser experiments as part of the Accelerator Stewardship Program managed by ARDAP. BNL makes key contributions to international facilities – the **Large Hadron Collider (LHC)**, **SuperKEKB**, and future facilities such as a **Long Baseline Neutrino Facility (LBNF)/DUNE** and the **Rubin Observatory**. BNL plays a significant role in the globally deployed **ARM** User Facility for climate research, which serves more than 1000 users annually. BNL scientists lead the five-year **ARM** deployment to the Southeast U.S.; with partial funding from ARM, BNL has established a Center for Atmospheric Measurement Science. BNL's **cryo-EM facility,** run as a non-designated user facility with funding from BER, supports BER users and the General user community, including BES-funded researchers. BNL hosts the **Long Island Solar Farm**, a privately owned 32-megawatt solar photovoltaic power plant. BNL's **Northeast Solar Energy Research Center** enables field tests of solar technologies under actual northeastern weather conditions. From concept through construction, the **Instrumentation Division** makes major contributions to instruments and experiments at BNL and other accelerator- and reactor-based facilities worldwide. Major sources of funding are: ARDAP, BES, NP, HEP, BER, NASA, New York State, NIH, and BNL Discretionary Funds.

Mechanical Design and Engineering

At BNL, Mechanical Design and Engineering is practiced across a wide range of disciplines, programs, and projects. This ranges from conventional facilities to sophisticated and often complex systems for scientific research at the Lab or offsite, including the moon for LuSEE-Night and particle accelerator and storage ring components closer to home. BNL has advanced mechanical engineering and design capabilities including CAD software, finite element analysis, and modeling tools to realize intricate components for particle accelerators, detectors, and other scientific instruments. BNL collaborates closely with stakeholders to gather and translate research requirements into innovative engineering solutions that ensure optimal performance and reliability in challenging environments. BNL Mechanical Engineering includes: 1) Cryogenic and pressure system engineering with liquid helium used in the operation of RHIC, NSLS-II, and test facilities for superconducting magnets and cavities; 2) Magnetic design and analysis for superconducting magnets and conventional conductor magnets and permanent magnet devices; 3) Vacuum engineering with large high and ultra-high vacuum systems in the BNL accelerators; 4) Mechanical design of specialized particle beamline diagnostic instrumentation equipment including additive manufacturing; and 5) Multi-physics analysis for structural, thermal, hydraulic, stress, and electrical characteristics of a wide range of components and structures.

BNL's Mechanical Engineers fill leading roles in working with procurement, vendors, and BNL staff through the cycle of engineering, design, procurement/production, work control, installation, and coordination from concept through completion of projects and often in their subsequent operation. BNL continues to nurture its culture of safety by design while striving to standardize engineering practices, implement unified design and analysis tools, and building on the mechatronics capabilities of the staff and establishing career development paths across the Laboratory. This holistic approach should enhance efficiency, consistency, and professional growth within the organization. Sources of funding include BES, NP, HEP, ARDAP, IRP and BNL Discretionary Funds as well as BER, NASA, New York State, NIH, and other DOE laboratories.

Microelectronics

A core foundation of multidisciplinary scientific expertise and leading technical facilities positions BNL well to make significant contributions to both near-term technology issues and longer-term, microelectronics research. NSLS-II hosts world-leading, synchrotron X-ray imaging and spectroscopy instruments that are proven, unique tools for characterizing leading-edge microelectronics. The CFN complements X-ray characterization methods with state-of-the-art electron microscopy and optical probes, while also supporting synthesis of electronic materials, including 2D materials by the Quantum Material Press, and innovative self-assembly approaches using polymers and DNA. BNL expertise in circuits design, especially for unique detectors, covers device modeling, low-noise Application-specific integrated circuit (aka ASIC) design, and cryo- complementary metal-oxide-semiconductor (aka CMOS) technology. Software proficiency includes developing quantitative codesign tools, systems simulation, and design of AI algorithms. Coordinating these key strengths enables BNL to address key technology and research questions in microelectronics. These capabilities are funded by BES, NP, HEP, NNSA, DOD and Laboratory Discretionary Funds.

Nuclear & Radio Chemistry

BNL's nuclear science programs span the range from applications in medicine to national security. The BLIP uses the 200 MeV Linac and target processing facilities to produce isotopes not commercially available, mostly for nuclear medicine. BNL brought online a hot cell to routinely produce actinium 225 (Ac-225) in sufficient quantities to support clinical trials for cancer. Ac-225 is an alpha emitter that has demonstrated reduced toxicity and improved cure rates in clinical trials. A cyclotron has been refurbished and completed readiness reviews to produce needed isotopes that can't be produced at BLIP, expanding production capabilities. Ongoing work to upgrade facilities includes doubling of the beam current and installation of a second irradiation site to increase output in the future. The irradiation facilities are also used to conduct radiation damage studies. BNL hosts the Nuclear and Radiochemistry summer school that provides twelve undergraduates with hands-on experience. Next year BNL will host the annual meeting of the Horizon Broadening Isotope Production Pipeline Opportunities designed to bring together a diverse group of students from across the country - exposing them to the activities required to provide the nation with radioisotopes needed for science and applications. BNL's expertise has led to a patent for a Rapid Cycling Medical Synchrotron and for low-mass beam delivery gantries, technologies for the next generation of proton- and ion-based cancer therapy. The effects of ionizing radiation on living systems are studied at NSRL, a flagship international user facility supported by NASA. BNL is home to the NNSA Radiological Assistance Program's Region 1 team and a United States Agency for International Development (USAID)-funded international radiological/nuclear crisis operations and consequence-management events response capability. BNL supports NNSA's Defense Nuclear Nonproliferation programs by using its unique facilities, such as NSLS-II, and expertise in instrument development, chemistry, data science, safeguards, and nuclear data analysis. BNL has extensive expertise in nuclear nonproliferation and international nuclear safeguards that includes more than forty years of program management delivered by the International Safeguards Project Office, which provides technical and administrative management of the U.S. Support Program to International Atomic Energy Agency (IAEA) Safeguards. Brookhaven also develops curricula and provides safeguards implementation training for international IAEA inspectors and officials. Funding comes from sources that include NP, IPR, BES, BER, the Department of State, NASA, NNSA, USAID, and DHS.

Nuclear Engineering (Emerging)

BNL's nuclear engineering capability encompasses three major areas: Materials for Nuclear Energy Applications, Nuclear Systems and Structural Analysis, and Nuclear Data. In the area of materials for nuclear energy applications, BNL researchers are developing fundamental insights into the molecular structure of molten salts relevant to novel nuclear fuel systems as well as the interaction of these types of fuels with containment materials. To study these systems, BNL develops synchrotron characterization techniques explicitly for the investigation of materials for nuclear energy systems, including using robots for handling radioactive samples, X-ray diffraction tomography to investigate material degradation, and high temperature in-situ experiments for the annealing, corrosion, and molten salts. In the area of nuclear systems and structural analysis, BNL has experience with all phases of the design and assessment/evaluation of advanced nuclear systems, such as reactors and accelerator-driven-systems and fuel cycles, resulting from decades of support to the Nuclear Regulatory Commission (NRC) and the DOE. BNL also conducts research on next-generation reactors and alternative fuel cycles and safeguards for these systems. State-of-the-art NRC and DOE-developed computational tools are utilized for the full scope neutronics and thermal hydraulics analyses of reactor performance and safety characteristics. In the area of nuclear data, BNL hosts the National Nuclear Data Center (CC 21), which is also the lead unit of the U.S. Nuclear Data Program (USNDP) and BNL chairs the Cross Section Evaluation Working Group.

BNL's National Nuclear Data Center (NNDC) is a DOE Office of Science Public Reusable Research Data Resource. BNL's nuclear data research supports a variety of national and international efforts in reactor physics, the nuclear fuel cycle, defense, nuclear non-proliferation, and isotope production. The NNDC has decades of experience in performing high-precision gamma-ray spectroscopy experiments. The major U.S. spectrometers Gammasphere and Gamma-Ray Energy Tracking In-beam Nuclear Array and new dedicated in-house measuring capabilities are used to improve decay data relevant to isotope production, non-proliferation, and reactor applications. The programs are funded by NE, NP, NNSA, NRC, the National Institute of Standards and Technology (NIST), and Laboratory Discretionary Funds.

Nuclear Physics

BNL conducts pioneering explorations of the most fundamental aspects of matter governed by the strong nuclear force. RHIC is a unique facility allowing for a wide range of heavy ion collisions and polarized proton-proton collisions. RHIC experiments discovered that quark-gluon plasma, which existed microseconds after the Big Bang, is a nearly perfect liquid and that gluons' spins have a nonnegligible role in making up the proton spin and aligning in its direction. The success of the RHIC program benefits from BNL's strong program of advanced accelerator R&D, the support of the BNL Physics Department, the SDCC, and the Instrumentation Division. The successful completion of the RHIC science mission relies on the recently completed upgrades – STAR iTPC, STAR forward upgrade, and the completed sPHENIX detector. As a DOE user facility, RHIC has nearly 1000 users from over 21 countries. To date, the RHIC program has produced more than 370 Ph.D. nuclear physicists. Nuclear theory efforts at BNL and throughout the international theory community continue to contribute to the success of the RHIC program, including BNL's role as a lead institution in two new Topical Collaborations in Nuclear Theory. Experimental, theoretical, computational research, and nuclear science workforce development are enhanced by the presence of the RIKEN BNL Research Center. BNL develops advanced software and computing facilities for applications in nuclear physics experiments and theory, including lattice QCD simulations. Key expertise has been developed in the management and processing of near-exabyte-scale data sets generated at high rates and distributed computing for analysis, facilitated by the RHIC Computing Facility, a component of BNL's SDCC. RHIC will be transformed into the EIC through the addition of an electron accelerator and storage ring. The EIC will facilitate a rich science program based on collisions of high-energy electrons with heavy ion, polarized proton and polarized helium-3 beams to precisely image the quark-gluon structure of the proton and atomic nuclei and elucidate the origin of visible matter in the universe. BNL and the Thomas Jefferson National Accelerator Facility are the two DOE host labs for the EIC project. BNL operates the NNDC, a resource for the open dissemination of nuclear structure, decay, and reaction data that serves as the focal point for the USNDP and reactor design. The program also addresses gaps in the data, through targeted experimental studies and the use of theoretical models. Last year, there were over fifteen million data retrievals from the NNDC websites. Support is provided by NP, RIKEN, and Laboratory Discretionary Funds.

Particle Physics

BNL has key roles in developing and operating particle physics experiments that seek answers to seminal questions about the mysteries of neutrinos, secrets of the Higgs Boson, the nature of the Dark Matter and Cosmic evolution, search for new particles and interactions and quantum imprints of new physics phenomena. BNL's major capabilities are: host institution for U.S. contributions to the ATLAS detector at the LHC, consisting of managing the U.S. ATLAS Operations Program including the Tier 1 Data Center and the upgrade project and construction and testing of the high field quadrupole magnets for the LHC accelerator upgrade; leadership in neutrino oscillation experiments, including a leading role in the DUNE Technical Coordination and second DUNE module design and construction; leading roles in the short-baseline experiments at Fermi National Accelerator Laboratory (MicroBooNE, ICARUS, and the Short Baseline Near Detector); leading the U.S. Operations program of the Belle II experiment at KEK, including computing facilities, commissioning, and operations; commissioning and data analysis of the Rubin Observatory cosmological survey; and construction of the Lunar Surface Electromagnetics Experiment (LuSEE)-Night program and coordination of its operations and science programs. BNL develops advanced software and computing facilities for applications in high energy physics experiments and theory. Key expertise in high throughput computing has been developed in the management and processing of multi-petabyte-scale data sets generated at high rates and in distributed computing for data analysis. Development of new instrumentation technologies for elementary particles and data collection and storage systems provides the foundation for present and future particle physics experiments. These roles are enhanced by BNL high energy physics theory efforts and by BNL's leadership in advanced accelerator research and development, including high field magnet development, which is critical for the next generation of high energy physics experiments and accelerator facilities. Funding for this work comes from HEP and Laboratory Discretionary Funds.

Power Systems and Electrical Engineering (Emerging)

BNL focuses on research to advance the deployment and grid integration of renewable energy systems and the development of new technologies to enable the next generation smart grid. BNL has significant expertise in power system modeling and simulation, and in transmission and distribution system design, operation, and planning that can be used to analyze the systems and determine their appropriate use as solutions for grid integration of renewable generation. BNL also has capabilities in the development of control algorithms that can be applied to the operation of energy storage systems for applications to renewable integration. BNL has developed a portfolio of grid modernization research projects and will continue to build capabilities in this area. Previous and ongoing R&D projects at BNL that are related to the research areas funded by the DOE Office of Electricity include the development of a probabilistic technique for sizing energy storage systems, development of probabilistic techniques for transmission system planning, formal analysis for dynamic stability assessment, and a deep learning based online platform for critical anomaly detection and emergency control to enhance grid reliability and resiliency. BNL has invested LDRD funds for investigation of the use of energy storage systems to improve grid inertial response that are broadening these efforts. Programs funded by New York State include the evaluation of grid impacts from utility scale solar generation on sub-transmission and distribution systems and the use of Radar in real-time damage forecasting and response for restoration of electric utility systems. BNL's Interdisciplinary Science Department leads efforts that will enable simulation and validation of innovative new technologies to address the challenges for integrating renewables and energy storage systems on the grid and reduce the risk to utilities of deploying these new technologies. New York State, OE, and Laboratory Discretionary Funds are the primary sources of funding.

Systems Engineering and Integration

BNL designs, constructs, and operates large-scale facilities and advanced instrumentation to address some of the most challenging questions in fundamental science, applied science, and national security, underpinned by a highly trained, multidisciplinary, and internationally recognized workforce. The successful construction of NSLS-II and its X-ray beam lines is based on state-of-the-art technologies integrated into NSLS-II including superconducting RF systems utilizing both high powered klystron and solid-state drivers; novel RF and X-ray beam position monitors; high heat-load front-end components; and novel X-ray optics and detectors. The RHIC accelerator complex includes the only collider in the U.S. Technologies developed and employed at RHIC include high-intensity high-brightness ion sources; high-power proton targets for medical isotopes; rapid cycling synchrotrons; advanced beam cooling; and superconducting accelerators components to produce high luminosity ion and polarized proton collisions. The EIC requires strong systems engineering and integration that includes all the above and high intensity polarized electron beams, rapid cycling electron synchrotrons, and extensive superconducting RF installations at 2K temperatures. Accelerator systems engineering includes integration of modern computing, often powered by AI, and software as elements of monitoring, control, and data acquisition. BNL develops large and complex particle detectors for high energy and nuclear physics at BNL, CERN, Fermilab, and other centers around the world. Such detectors include noble liquid detectors, cold electronics, silicon-based precision trackers, particle identification, large area muon detectors, and many others. Particle detector developments include systems engineering and integration of mechanics, high voltage, cryogenics, power supplies, microelectronics, readout electronics, and computing. The major sources of funding are BES, NP, HEP, BER, NE, NIST, NRC, and BNL Discretionary Funds.

Summary: These core capabilities, along with BNL's proven expertise in large science project management, will enable the Lab to deliver its mission and customer focus, to perform a complementary role in the DOE laboratory system, and to implement its vision.

Science Strategy for the Future/Major Initiatives

Brookhaven advances fundamental science by discovering and exploring forms of matter and their interactions to gain a deeper understanding of how the universe works, by understanding and controlling electronic and materials properties down to the nanoscale, by employing its capabilities to advance emergent information science, and by addressing environmental and societal challenges. Discovered in 2005 at BNL, the Quark Gluon Plasma (QGP) – a perfect fluid where free quark charges are allowed - has revealed extraordinary properties during its exploration the last two decades including the recent discovery that it possesses a magnetic field significantly stronger than that of the Earth. BNL's light source program recently proved that toxic metals in veterans' lungs came from Iraq burn pits. This led to the Pact Act, which was signed at the White House, with the user present for the ceremony. The Lab's cryo-Electron Microscopy (cryo-EM) capabilities revealed that the COVID-19 virus protein hijacks cell-junction protein and promotes viral spread.

Much of the Laboratory's mission is enabled by its broad and distinctive accelerator complex, one of the largest and most diverse in the national lab system. BNL has constructed and operates state-of-the-art electron and ion/proton accelerators:

- Brookhaven is the only lab in the U.S. with an operating collider (Relativistic Heavy Ion Collider [RHIC]) and the only lab in the world constructing a new collider (Electron-Ion Collider [EIC]) in the next decade or more. The EIC will open a new path to discovery on the forces governing the mechanics inside the proton.
- BNL's National Synchrotron Light Source II (NSLS-II) is a state-of-the-art 3 GeV storage ring that is over-subscribed with users utilizing hard and soft x-ray scattering, imaging, and spectroscopy techniques to advance a broad range of science. Half of the beamline capacity is built out, with plans to add more according to the community's scientific plans. An upgrade is envisioned for the future, which will deliver best-in-the-world brightness in the 1-10 keV regime.
- The radioisotope actinium 225 (Ac-225), which is in high demand for cancer research and treatment, is generated at the Brookhaven Linac Isotope Producer.
- The Accelerator Test Facility provided more than 2,000 hours of beamtime to users in 2023 who performed experiments that elucidated the origin of the remnant magnetic field in our galaxy,

demonstrated new techniques using ionic liquids to generate surgically useful laser light, and is helping NASA quantify the effects of solar radiation on space-borne electronics.

To propel emergent sciences and technologies, Brookhaven uses a multi-disciplinary approach that couples its facilities and core capabilities in instrumentation and computational science to the research programs across the Lab. BNL partners with researchers across the country, particularly with leading universities in the Northeast, most of which are members of the Lab's governing body, the Brookhaven Science Associates. The progress this approach yields is exemplified by its Department of Energy (DOE) National Quantum Initiative Center – the Co-Design Center for Quantum Advantage, as well as its program in renewable energy. BNL has developed a similar plan for a center in microelectronics.

Brookhaven has a strong tradition of innovation and invention – with 7 Nobel prizes and numerous patents that changed the world and have literally saved lives. BNL carries this spirit forward, propelled by its committed staff and strong partnership with New York State ($400M commitment over the last decade) and U.S. and international institutions and an unwavering commitment to diversity, equity, inclusion, and accessibility.

Infrastructure

Overview of Site Facilities and Infrastructure

BNL is at an exciting juncture in its history. With the start of construction of the EIC and anticipated upgrade to NSLS-II, BNL will be the home for world -leading facilities in nuclear physics and energy sciences, and a destination of choice for researchers in associated fields of science.

BNL will enable their success through safe, efficient, and secure operations, a diverse, equitable, inclusive, and accessible environment, and a renewed, sustainable infrastructure. Key to the strategy for mission readiness is providing a revitalized physical plant that will enhance scientific productivity, bolster the attraction and retention of a skilled scientific workforce, which includes the significant BNL user population, and ensure the safety and reliability of scientific facilities.

BNL is in Upton, New York in central Suffolk County approximately 75 miles east of New York City. The BNL site, former Army Camp Upton, lies in the Townships of Brookhaven and Riverhead and is situated on the western rim of the shallow Peconic River watershed. Approximately 25% of BNL's 5,322-acre site is developed.

At the end of FY 2023, there were 2,862 BNL staff assigned on site, 316 in-service buildings totaling 4,790,954 square feet (sf), and 8,500 sf in 19 real property trailers. BNL does not lease any facilities and the average age of all non-excess buildings is 47 years with 60 buildings (712,241 sf) in use dating back to World War II (WW-II). Major science (or science support) facilities, including the Research Support Building, Interdisciplinary Science Building, NSLS-II, RHIC, and CFN, were constructed during the last twenty years. The remainder of the research facilities were built predominantly in the 1950s and 1960s. Repurposing and renovation of existing facilities remains a priority exemplified by the Core Facility Revitalization (CFR) Project achieving beneficial occupancy in FY 2021 and populated in FY 2022. Facility and utility condition, status and utilization statistics with analysis can be found in Appendix A.

The number of inadequate spaces will decline with the completion and occupancy of the Science and User Support Center (SUSC) building in summer of FY 2024. At the end of FY 2023, there were 29 excess buildings and trailers in the BNL 10-year Demolition Plan, comprising 195,222 sf, and 24 buildings and trailers totaling 227,939 sf in Standby status.

At the end of FY 2023, the Replacement Plant Value of all BNL buildings, trailers, and other structures/facilities was $6.9B. The total Deferred Maintenance (DM) for the site was $222M. FY 2023 Repair Needs were $611M.

The Office of Environmental Management (EM) remains responsible for the decontamination and decommissioning of legacy contaminated excess facilities at BNL, including B491 (Brookhaven Medical Research Reactor [BMRR]), B701 (Brookhaven Graphite Research Reactor [BGRR]), and B750 (High Flux Beam Reactor [HFBR]) The remaining reactor confinement buildings were placed, and are currently being maintained, in a safe and stable condition. In 2020 and 2021, EM funded the demolition of SC asset B650 (known as the "Hot Laundry"), the BMRR Stack, and B197 along with underlying mercury-contaminated soils. Demolition and restoration activities for B650 and the BMRR Stack were completed in 2021 and 2022, respectively. Demolition for B197 commenced in Q1 FY 2024; with the remainder of the building to be demolished, and mercury-contaminated soils removed, prior to the end of Q4 FY 2024. These demolition efforts contribute to the retirement of significant Environment, Safety & Health (ES&H) risks associated with contaminated excess facilities at BNL.

Campus Strategy

As BNL enters a new era with EIC construction and subsequent operation, buildout of NSLS-II beamlines, and the potential for a major upgrade of NSLS-II, the new Laboratory leadership team is focused on transforming BNL into a modern, exciting, and vibrant campus - one that will offer a world-class user experience to attract and retain the top talent needed for mission achievement, while operating efficiently and sustainably. Increased infrastructure investment fueled by the success of the Laboratory's science and technology growth strategy, coupled with increased rigor in choosing priorities for overhead investments, and external funding, will enable the transformation.

Planned infrastructure investments will be closely aligned with the Laboratory's scientific growth initiatives while also ensuring the wide range of facilities that enable BNL's ongoing core capabilities are sustained. Special emphasis is placed on projects "critical to sustainable operations" while recognizing future projects "desirable to enhance mission readiness."

The campus strategy consists of five major elements:

1. **Critical Core Buildings and Infrastructure:** Focus investment on delivering high reliability and new capabilities required to enable the scientific mission and growth objectives.

2. **Optimizing the Campus Footprint:** Consolidate and optimize space utilization in existing buildings. to reduce costs and energy use

3. **Targeted Investment in Building and Utility Infrastructure:** Ensure critical infrastructure and buildings are sustainable, energy efficient, and resilient against environmental and climate-change, and robust to endure severe weather conditions and events.

4. **Onsite Renewable Generation:** Expand on-site renewable energy generation to reduce new utility infrastructure costs for EIC, to optimize the unit cost of electric power once EIC begins operations, and to contribute to achieving carbon-free electricity goals as identified in the BNL Site Sustainability Plan.

5. **Discovery Park:** Support the Laboratory's growth objectives and expanding population of scientific users through an innovative concept called "Discovery Park."

Element 1 - Investment in Critical Core Buildings and Infrastructure

Since many core science buildings are 50+ years old and are designated as substandard facilities, they require reconfiguration and substantial sustainment and recapitalization investments in mechanical and electrical systems and architectural elements to meet the demands of modern research and sustainability goals. Many research labs need state-of-the-art upgrades, including stringent environmental and vibration controls and “clean” environments. BNL has identified those “permanent” facilities that will form the platform for current and future core capabilities. To ensure facilities are mission ready, BNL has formulated a multi-pronged strategy of consolidation and rehabilitation. Facilities will be rehabilitated using a combination of indirect funds, including Institutional General Plant Projects (IGPP), Deferred Maintenance Reduction (DMR), and DOE direct funds (Science Laboratories Infrastructure, General Plant Projects [SLI, GPP]). Additionally, supporting the Lab’s strategy are Other Infrastructure Projects (OIP), which include alterations and non-capitalized betterments.

The most significant issue facing the mission support organizations is that many are still located in Inadequate WW-II era wood buildings. To address this, the SUSC, an SLI-funded project, will not only fulfill three key mission needs by providing efficient science user and visitor processing capability, collaboration, and conference space for the research community, it will also provide modern, energy-efficient office space to relocate staff from inadequate office spaces. It will enable consolidation of staff, ultimately allowing the demolition of ~43,000 sf of WW-II-era space with a combined backlog of maintenance and modernization needs of $7M.

A significant issue is the scattered locations of BNL’s craft resource shops and maintenance, operations, and emergency management control facilities, also located mainly in WW-II era buildings, which are inadequate due to condition and configuration. There is an SLI proposal in place for a centralized facility, known as the Integrated Site Operations & Maintenance Facility (ISOMF).

In addition, significant World War II-era housing inventory remains that impedes operations, reduces efficiency, wastes energy, and impacts guest and user morale. An exciting new SLI Net-Zero Guest/User Housing Facility project is proposed for Discovery Park timed to meet the increased numbers of users associated with EIC. Details of SLI Line Items including the SUSC (which is under construction), the on-going Critical Utilities Rehabilitation Project (CURP), the proposed BNL Electrical Distribution Upgrade, ISOMF, and the New User Housing Facility are presented in Section 6.3.1.

As evidence of the effectiveness of this strategy, one of the most significant infrastructure issues facing scientific organizations is related to computing and large data management. The completion of the CFR project provides a contemporary computing facility and infrastructure that will meet current and future Laboratory needs, consolidating BNL site-wide scientific computing resources into one new, energy efficient facility. This investment made cost-effective use of existing substandard infrastructure by repurposing most of B725 (the former NSLS). The facility was also designed to accommodate BNL’s future computing needs as they are realized. Provisions for the deployment of incremental power and cooling upgrades were incorporated in the initial planning and design of the facility and are currently being implemented using IGPP funds.

Element 2 – Optimizing the Campus Footprint

An important element of the overall infrastructure strategy is elimination of excess facilities and footprint reduction to realize operational efficiencies, improved facility safety, and improved utilization and quality of space as well as reduced maintenance and operations costs. In efforts to address unutilized buildings, almost all of which are shutdown in preparation for demolition, BNL is committed to reducing the Lab’s building footprint by more than 6% over the planning period. The Lab Funded (Indirect) Table and Chart (Enclosure 4) indicate the annual overhead investments needed to eliminate existing or anticipated future non-contaminated excess facilities, albeit over an extended period. Over the planning period, the BNL

Demolition Plan estimates that ~321K sf of net excess space will be eliminated, the majority of which are WW-II-era buildings. Appropriate assignment of indirect funds is essential to meeting these goals and ultimately supports the significant reduction of Repair Needs and Deferred Maintenance across the site.

To meet these infrastructure challenges, BNL has formulated a strategy to address the mission and operational needs based on the constraints and strengths of the various funding sources. Capital projects and other requested funding are shown in the Infrastructure Investment Table and indirect expensed projects, such as DMR, are reflected in other funding plans. Capitalized betterment and alteration projects and infrastructure studies, i.e., OIP, not requested as part of Enclosure 4, round out the Lab's investment strategy. Consistent with BNL's Mission Readiness approach, funding for the various categories of indirect funds (DMR, OIP, and IGPP) can vary from year to year based on the projects selected based on mission need. The plan for improving asset condition is multi-pronged and does not solely rely on maintenance investment. Continued space consolidation efforts will be enabled by renovation and alteration of underutilized buildings and through new proposed buildings, such as the SUSC and the proposed ISOMF, allowing a major consolidation from Inadequate WW-II-era buildings.

One illustration of this strategy is BNL's new FY 2024 IGPP project to be executed upon completion of the SUSC and the planned relocation of the existing B400 occupants to the SUSC. This project will address the need to upgrade, update, and renovate select areas of B400 to provide modern/efficient administrative and other support space. The project will renovate approximately 25,000 GSF of existing office space. Support functions that are planned to be relocated to B400 include: the U.S. Post Office (Upton branch), the BNL Mailroom, the Director's Office, the Budget Office, Procurement, and the Legal Office. The relocation activities will enable the ultimate shutdown and demolition of several existing inadequate facilities, including B355 (Underutilized), B179 (Underutilized), B460, and B902M.

Element 3 - Targeted Investment in Building and Utility Infrastructure

BNL's utilities are currently reliable, but they are aging and issues impacting reliability and capacity are increasing. In FY 2011, BNL completed a baseline study, which evaluated its utilities and recommended strategies to address critical needs. The study identified significant short-term needs confirming that the aging water, electric, chilled water, and steam distribution system components need replacement. Recapitalization resources to renew and replace BNL's utility infrastructure have been limited by historically tight operating budgets. In recent years, as the Laboratory growth strategy has begun to take effect, additional overhead resources were gradually provided to operating budgets. Progress was made with the installation of new chillers to increase the Central Chilled Water Facility (CCWF) capacity and reliability to support growing science process cooling needs. The CURP SLI line-item, which is underway, addresses replacement of one of the three 1,200 Ton electric centrifugal chillers, original to the central plant and beyond its useful life. The project also includes two critical potable water projects: The construction of Potable Water Well No. 12, completed in FY 2022, and an on-going replacement of the WW-II-era 300,000-gallon elevated water storage tank with an upgraded 500,000-gallon tank, is expected to be completed in FY 2024.

The aging utility distribution systems present additional utility needs. Sections of the central steam distribution system date back to the late 1940s. Leaks, mostly in the condensate return piping, cause system inefficiencies that need localized repairs. Over the past several years, with an increasing number of water main breaks in the old "transite" (asbestos cement) piping, several sections are in critical need of replacement. Selective replacement and reinforcement of the 13.8 kV primary electrical distribution system are also needed, including an additional feeder to provide backup to the CCWF and NSLS-II. Deficiencies associated with these distribution systems will be addressed in the CURP line item and later by the Electrical Distribution and Utility System upgrade projects.

Element 4 – Onsite Renewable Generation

BNL currently has 1 MW of onsite solar generation. BNL is also host (under an easement expiring in 2031) to a privately-owned 32 MW solar powerplant (Long Island Solar Farm [LISF]) that sells all its output to the Long Island Power Authority. There are three drivers for expanding onsite renewable generation: The increase in site electrical demand from the EIC, optimizing the unit cost of electric power in the future, and achieving the site's carbon-free electricity goals.

BNL's land area can host a significant increase in solar generation. Further, given advances in technology since the original LISF and BNL's 1 MW array were constructed, repowering them with state-of-the-art panels will double their output per unit area. Also, BNL's primary electric power supplier, the New York Power Authority, has recently received legislative authority to develop solar generation. An Energy Management Working Group was chartered in Fall 2023 to explore these and other options.

Element 5 – Advancing the Innovative Public-Private Partnership Concept Called "Discovery Park"

The Discovery Park concept is a key component of BNL's infrastructure renewal plans and continues to make progress. The "keystone" of Discovery Park will be set with the completion of the SUSC. Discovery Park will repurpose approximately 60 acres of federal property at the entrance to BNL to enable joint federal and private development that replaces aging infrastructure and user housing and enables mission-enhancing technology transfer opportunities. An Alternatives Analysis conducted for Discovery Park and reviewed with the Office of Science determined the preferred development pathway is a mix of federally funded and privately funded development. Discovery Park is expected to include two distinct districts; one for federally owned facilities, referred to as Upton Square, and the other for privately financed facilities. Upton Square includes the SUSC and is ideally suited to include housing development and other user support facilities. Potential partnership opportunities exist with regional educational institutions and private investors to develop educational centers at Discovery Park, further enhancing their respective STEM programs and supporting local efforts to promote the growth of Long Island's technical workforce. Moving Discovery Park forward will require resolution of the federal enclave issue and/or other innovative approaches by BSA and DOE.

Investment Strategy

The investment strategy relies on the following direct and indirect funding sources:

DOE SLI Line-Item funds: Will be used to perform new building construction and utility infrastructure upgrades in support of state-of-the-art research facilities and a sustainable campus that can readily support current and future missions. Over the planning period, BNL has proposed projects to build new, sustainable facilities for operations and user housing and address significant utility infrastructure deficiencies in efforts to prepare the site for planned growth. BNL's projects have been prioritized to ensure they support mission critical infrastructure needs.

- **Science and User Support Center (SUSC)** (TEC $86.2M, FY 2019 start) is a 75,000 sf office and support building at the Discovery Park site to enhance the user experience, address major DOE and BNL infrastructure needs, and serve as a magnet for further development. This building (see Figure) will enhance operational efficiency by consolidating approximately 200 BNL operations staff, currently dispersed in several buildings, into a single, modern office building meeting DOE sustainability goals. It will also enable further consolidation of other staff, ultimately allowing the demolition of ~43,000 sf of WW-II-era space with a combined backlog of maintenance and modernization needs of $7M. In addition to the efficiency gained by co-located staff, the facility's location at the main entrance will enhance public access for education and commercial outreach for BNL outward facing organizations (such as Stakeholder and Community Relations, Human Resources, and the Guest, User, Visitor Center, among others), while supporting BNL core functions. A new visitor center, designed as a highly efficient one-stop user access portal, will be the front door of the SUSC structure and will enhance BNL's role as a major user facility laboratory. Scientific collaboration will also be enhanced through a new highly configurable and accessible conference center, the third major element of the SUSC facility. The project received CD-0 in 2016, CD-1 in 2018, and CD-2/3 in FY 2021. Notice to Proceed to construction mobilization was given 2/11/22 and construction 4/4/22. Although the CD-4 completion date is 2026, it is anticipated that the SUSC will be complete by the end of FY 2024, well ahead of schedule.

- **Critical Utilities Rehabilitation Project (CURP)** (TEC $92.0M, FY 2020 start) will replace and rehabilitate key utility systems required for operation of mission critical research facilities. Significant portions of the utility systems are well beyond their useful life with some in service since WW-II, including portions of the sanitary system. This project will: 1) Replace central chilled water system(s), constructed in 1990, that are beyond their useful life and no longer reliably serving critical scientific facilities; 2) Replace portions of the underground steam and condensate piping system and select manholes, some dating back to the 1940s that are failing due to extensive corrosion, leaks, and deterioration; 3) Refurbish equipment in the Central Steam Facility, first constructed in 1949, which will assure reliable steam service to the site; 4) Replace, repair, or reline the old asbestos water main first constructed in 1941, rebuild the facility housing Well 12, and replace the Elevated Water Storage Tank, constructed in 1941; 5) Repair and refurbish deteriorated sanitary lift stations and sanitary lines; and 6) Refurbish and replace electrical feeders and switchgear with modern, safe, reliable electric equipment and systems that will reduce arc-flash hazards. The project received CD-0 in 2018, CD-1/3A in 2020, and CD-2/3 in 2022.
- **BNL Integrated Site Operations & Maintenance Facility (ISOMF)** (TEC Estimated Range $70-$95M FY 2026 start) will replace approximately 100,000 sf of Substandard or Inadequate buildings, trailers, and OSF assets. The project will address BNL's site sustainability goals as well as the Administration's expectations for federal facilities with respect to carbon-free electricity (CFE), net-zero emissions buildings, and net-zero emissions from federal procurements of construction materials. The project (see Figure) will co-locate maintenance and operation resources that are spread out across 16 buildings and 19 trailers, located in five separate areas of the site, increasing operational efficiency. Most of the buildings are WW-II era wood buildings, which have an Overall Asset Condition of Inadequate. It is anticipated the project will reduce at least 20% of administrative and shops space and 30% of storage space, and a significant amount of common space, such as bath and locker rooms, breakrooms, and training space. The facility will also enable enhanced operations by centralizing the control areas for the computerized maintenance management and building management control systems. Due to co-location, the use of shared facilities will allow more effective staffing and supervision, improved communications (e.g., lessons learned and staff feedback), and greater building energy efficiency, resulting in an increase in operational efficiency. The building will include a central location for Facilities and Operations stock and material kitting, which will enable workers to receive their assignments and work kits in one location. The facility will improve workforce development by having dedicated space that will be used to develop the next generation of craft, and the co-location of Subject Matter Experts to provide technical guidance. Included will be space for training and for modern remote conferencing with external vendors to support staff development, troubleshooting, and remote instruction. The facility will also provide testing and assembly space for hands on mockups, such as for electrical protective device maintenance

and safety, fire alarm systems, and value maintenance. The building will contain a center for real-time operations performance monitoring to allow issues and improvement opportunities to be identified and implemented efficiently. The proposed ISOMF will consolidate and co-locate the new BNL Electric Vehicle (EV) fleet. The facility will also include maintenance facilities and adequate EV charging facilities for government owned vehicles.

- **BNL Electrical Distribution Upgrade** (TEC Estimated Range of $40.0 - $50.0M FY 2028 Start). This project will address BNL's science programs' expectations to double the Lab's electrical demand from approximately 55 MW to nearly 120 MW within the next six years to meet mission needs. This will create a need for dramatic expansion to the transmission system that delivers power from the local electrical utility, and onsite electrical distribution systems within BNL. Much of the equipment and components such as feeders, switchgear, circuit breakers, relays, and switches are well beyond their useful life and in need of replacement. There are many advances in technology that will allow for much safer operation of electrical equipment by lowering arc flash values and enabling remote operation and monitoring. In addition, the growth of the Laboratory and DOE O 436.1A require an increase in capacity, resiliency, and redundancy to achieve mission needs, and meet DOE requirements for sustainability. This project would also include infrastructure upgrades to the electrical transmission supply required by the local energy supplier and various systems and component upgrades related to the electrical distribution system.
- **BNL 30 MW Solar Array** (TEC Estimated Range $65 - $85M FY 2030 Start) As outlined in Executive Order 14057 Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability, BNL is working to meet the aggressive but necessary goal of 100 percent CFE on a net annual basis by 2030. DOE O 436.1a outlines a prescriptive path to CFE that maximizes consumption of CFE and/or renewable energy through on-site installation of systems and leverages DOE real property assets for onsite implementation of renewable energy. In accordance with this Order and due to BNL's projected increase in power, BNL is proposing a 30 MW capacity solar array. A solar array of this scale and type will be able to output 41,000 MWh/year, almost cutting the forecasted CFE gap in half. The array will be an open field, fixed tilt, bracket mounted system installed on-site, with its own transformers feeding into a substation. The system will tie directly into BNL's power grid, enabling distribution throughout campus. Because the power production will not exceed BNL's power needs at any given time, no on-site energy storage is required for this project.
- **BNL Utility System Upgrade** (TEC Estimated Range of $90.0 - $100.0M FY 2032 Start). Critical to BNL's success is an efficient and reliable infrastructure that includes all the major utility systems in support of research that is conducted 24/7, 365 days per year; however, portions of the utility infrastructure are still in use from the Lab's origins as a WW-II Army Base in the late 1940s. As such, there is an urgent mission need to upgrade and improve BNL's existing major utility systems including steam, water, sanitary sewer, and electrical systems. The equipment and distribution components have far exceeded their useful life. In many instances, replacement parts are no longer manufactured, creating great risk for catastrophic failures. In addition, the growth of the Laboratory and DOE O 436.1A require an increase in capacity, resiliency, and redundancy to achieve mission needs, and meet DOE requirements for sustainability. This project would also support protecting DOE assets from vulnerabilities such as impacts from climate change, cyber attack, and facility energy and water disruptions. In addition to resiliency, DOE O 436.1A requires the reduction and elimination of Scope 2 emissions through the procurement of CFE, enhanced energy efficiency of utility systems, and enhanced water efficiency practices. Scope 1 emissions resulting from the combustion of fossil fuels, wastewater treatment, and the loss of High Global Warming Potential fugitive emissions must also be

eliminated in accordance with this Order. BNL will be challenged in its ability to satisfy these requirements due to its aged utility plant and distribution network infrastructure.

- **BNL Net-Zero User Housing Facility** (TEC Estimated Range of $45.0 - $60.0M, FY 2034 start) will create a new, highly energy efficient, sustainable, resilient, and effective user housing facility at Discovery Park. This facility will create modern housing options for the users of BNL's major scientific user facilities. The project will address BNL's site sustainability goals and the Administration's expectations for federal facilities related to decarbonization and the Net-Zero policy. It will provide a publicly accessible, proof-of-concept that can inform the residential and commercial construction industry and serve as a testbed for future demonstration of cutting-edge energy saving building technologies and systems. The project will provide approximately 64 housing units, replacing an equal amount of 75+ year old housing, eliminating substantial deferred maintenance costs and significant ES&H and building code deficiencies.

Other DOE Line Items: Brookhaven's Isotope Research and Production Department receives funding from DOE IRP as one of three national laboratories and a suite of universities focused on isotope R&D and production. It prepares certain commercially unavailable radioisotopes for distribution to the nuclear medicine community and industry and performs research to develop new radioisotopes for nuclear medicine investigations. The CARP facility (TEC Approx. $74M) is proposed at BNL to meet the anticipated demand for radioisotopes for research, medical therapy and diagnosis, commercial applications, and national security. CARP will mitigate inventory constraints on the present processing facilities, enabling concurrent processing of in-demand radioisotopes for the nation. The facility will have the capability of current Good Management Practices processing and a Hazard Category level 3 designation; CD-0 was approved in December 2022.

GPP (DOE SLI): BNL continues to evaluate where DOE SLI GPP level investment will complement and accelerate BNL indirect (IGPP) investment. In many instances, project funding requirements exceed the resources available from a relatively constant indirect pool of funds. SLI and program GPPs provide the opportunity to effectively plan projects and maximize the potential return on the significantly larger management and execution efforts associated with these projects. These projects tend to go further with the realization of BNL's resiliency, sustainability, and energy efficiency goals. Several major recapitalizations and other needs to provide mission ready facilities and infrastructure were identified and prioritized. These cover several requested improvements to address the most urgent gaps. Details of cost and request year can be found in the Investment Table. The highest priority projects include the following:

- B/680 Net-Zero Entrance Portal
- B/510 Upgrade Electrical Substation - Phase I (Phase 2 already funded and in progress)
- BNL Site-wide Fire Protection Upgrades
- BNL Site-wide Electrical Upgrade

Excess Facilities Disposition (EFD): a long-range plan for low hazard, low risk, and lower cost demolitions funded from indirect operating funds has been developed and is continually coordinated with other BNL companion projects and prioritized with other indirect-funded infrastructure needs. Additional facilities will be excessed as a direct result of the completion of SUSC and the execution of the proposed ISOMF, eliminating more than $16.0M in current DMR, repair, and modernization costs. EM committed to incorporating several SC assets including B491 (BMRR) and B701 (BGRR) into its cleanup program. The demolition of the B491 Stack was EM funded and is complete. EM is also partially funding the B197 demolition by supporting the removal of the asbestos, mercury contaminated soil, and minor rad contamination, scheduled to be complete in FY 2024.

Indirect Funding (DMR, IGPP, OIP): The Laboratory anticipates increases in overall infrastructure spending over the coming ten-year period. Infrastructure funds include routine maintenance, dedicated DMR projects, IGPP, and OIP. Lab funded indirect investment levels are indicated within Enclosure 4, Table 3. OIP projects are not part of the Investment Table but fund alterations, non-capitalized betterment projects, demolition, and infrastructure studies. These OIP projects will total ~$9.2M in 2024 (36% of the overall indirect infrastructure project budget).

Collectively, this indirect funding enables the execution of the Lab's space consolidation plans, which when coupled with demolition, will help right-size the BNL footprint, and reduce operations and maintenance costs. Specifically, the projected IGPP investment over the 10-year period averages approximately $8.8M annually which is significantly higher than previous years. The plan for improving asset condition is multi-pronged and does not rely solely on maintenance investment, which was 1.1% of Replacement Plant Value for 2023. While BNL expects the Investment Index to remain consistent for FY 2024, slight improvement is expected based on planned demolition activity and targeted investment in infrastructure assets. The completion of the SUSC and proposed ISOMF will enable the demolition of close to 150,000 sf of Inadequate facilities. Continuing to consolidate out of assets not worth maintaining, followed by cold and dark, and ultimately their demolition is key to BNL's strategy. There are also proposed GPP projects that would help jumpstart recapitalization of key mission critical building systems, such as HVAC, electrical, potable water piping, and roofing, in mission critical assets and through mission-enabling renovation activity.

The strategy for use of indirect funds for non-major recapitalization and sustainment needs is as follows:

- Prioritize all proposed investments in infrastructure and ES&H and program them to support the Science & Technology programs, maximize the value of BNL's infrastructure, and reduce risk and deferred maintenance
- Defer major investments in 70+-year-old wood buildings, while performing minimum maintenance to keep these buildings safe and operational. When opportunities arise, consolidate staff from these structures and demolish them.

Non-Federal Funding: Brookhaven's plan for the EIC Project is a cost-effective, low-risk strategy based on adding an electron ring and other components to the existing RHIC complex. These modifications are critical to ensuring success for the EIC. Significant infrastructure modifications will be covered by a $100M grant from NYS and will comprise civil construction to prepare the site, provision of support buildings, and the creation of access roads for the development and operation of the new facility.

As described in 6.2.5, BNL is pursuing the development of Discovery Park. The development and operating model being pursued will allow for flexibility in the widest variety of funding sources and ownership while maintaining appropriate synergy with BNL's mission. The concept has received significant NYS and local support, including matching utility grants, and has served as the focal point to enhance regional, national, and international connectivity through NYS investment in a relocated railroad station.

Site Sustainability Plan Summary

The Laboratory is strongly committed to not only achieving, but also exceeding the targets outlined in the DOE Strategic Sustainability Performance Plan (SSPP). Through the implementation of its SSPP, BNL has been aggressively advancing its resiliency and sustainability efforts.

BNL’s leadership in sustainability is evident through its robust management practices, diligent stewardship of the BNL campus, and the integration of sustainability principles into its research and educational outreach activities.

BNL's sustainability initiatives are guided by four overarching principles:

- **Climate Neutrality:** Reduce energy consumption and implement effective energy management strategies to achieve climate neutrality.
- **Environmental Conservation:** Minimizing the environmental footprint of the campus through sustainable infrastructure development and maintenance.
- **Research Integration:** Leverage research capabilities in tandem with operational practices, and actively contribute to sustainable solutions for the northeastern region.
- **Community Engagement:** Foster a culture of sustainability among employees and engage with the broader community to promote sustainable practices.

Continuing the commitment to innovation, BNL is exploring creative solutions to overcome sustainability challenges. In the coming year, the Laboratory will evaluate a large-scale heat recovery system utilizing waste heat from the EIC, supported by recently acquired Assisting Federal Facilities with Energy Conservation Technologies funds. Collaborating with the New York Power Authority, BNL will explore sustainable energy options. Other priorities involve boosting bio-fuel usage, planning Net-Zero buildings, investigating waste-to-energy solutions, adopting low-global-warming-potential chillers, implementing efficient power management for new computing systems, integrating electric vehicles into its fleet, minimizing single-use plastics, and enhancing community and workforce investment programs.

Sustainability goals are central to proposed SLI projects, including the ISOMF facility, BNL Net Zero User Housing, a 30 MW solar installation, and a Net-Zero Entrance Portal project. Securing funding for these remains a challenge, but BNL is committed to collaboration with SLI.

FERMI NATIONAL ACCELERATOR LABORATORY

Lab-at-a-Glance

Location: Batavia, Illinois
Type: Single-program Laboratory
Contractor: Fermi Research Alliance, LLC
Site Office: Fermi Site Office
Website: www.fnal.gov

- **FY 2023 Lab Operating Costs:** $665.26 million
- **FY 2023 DOE/NNSA Costs:** $662.33 million
- **FY 2023 SPP (Non-DOE/Non-DHS) Costs:** $2.93 million
- **FY 2023 SPP as % Total Lab Operating Costs:** 0.4%

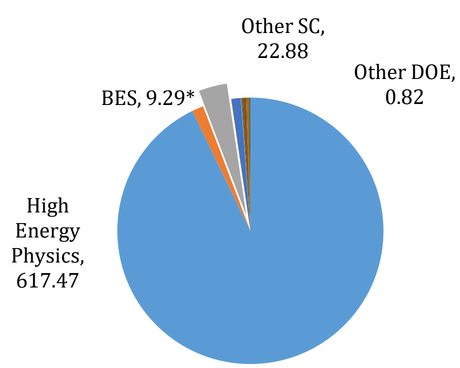
Physical Assets:

- 6,800 acres and 372 buildings
- 3.612 million GSF in buildings
- Replacement Plant Value: $3.05 B
- 28,913 GSF in 10 Excess Facilities
- 25,005 GSF in Leased Facilities

Human Capital:

- 2,137 Full Time Equivalent Employees (FTEs)
- 27 Outgoing Joint Appointees
- 9 Incoming Joint Appointees
- 123 Postdoctoral Researchers
- 62 Graduate Student
- 188 Undergraduate Students
- 2,395 Facility Users
- 1,721 Visiting Scientists

FY 2023 Costs by Funding Source ($M)



*BES number includes funds for LCLS-II and LCLS-II HE

Mission and Overview

Fermilab's core mission is to drive discovery, solving the mysteries of matter, energy, space, and time. Thousands of scientists, engineers, technicians, users, and students from around the globe contribute their expertise to advance the frontiers of knowledge and innovation. As America's particle physics and accelerator laboratory, Fermilab hosts a range of cutting-edge experiments and develops and builds technologies that support research at locations around the world, including the Large Hadron Collider (LHC) in Europe, at the South Pole Telescope, and deep underground in South Dakota. Fermilab aims to be the worldwide leader in accelerator-based discovery neutrino science, a goal endorsed by the 2023 Particle Physics Project Prioritization Panel (P5). The new Long-Baseline Neutrino Facility (LBNF) will send the world's most intense neutrino beam to massive Deep Underground Neutrino Experiment (DUNE) detectors at Fermilab in Illinois and at Sanford Underground Research Facility (SURF) in South Dakota. This is made possible by the Proton Improvement Plan II (PIP-II), the first particle accelerator on U.S. soil built with significant contributions from international partners. Through DUNE and a suite of short- and long-baseline neutrino experiments, Fermilab has brought the world together to unlock the mysteries of neutrinos.

The Fermilab Accelerator Complex produces both low- and high-energy neutrino beams for experiments such as NuMI Off-axis ν_e Appearance (NOvA) and enables muon experiments such as the Muon-to-Electron-Conversion Experiment (Mu2e). Its unique infrastructure and expertise make Fermilab a world leader in particle accelerator and detector technologies, enabling new machines for discovery science in many fields, including the Linac Coherent Light Source II High Energy (LCLS-II HE) project. Additionally, Fermilab's collider science program plays a leading role in the LHC upgrade projects and in the Compact Muon Solenoid (CMS) experiment. As endorsed in the recent P5 report, Fermilab is positioned to ramp up R&D towards an off-shore Higgs factory and a muon collider. Fermilab also hosts several world-leading cosmic science efforts exploring the mysteries of dark matter and dark energy. Fermilab leads the Superconducting Quantum Materials and Systems Center (SQMS), one of five national quantum information science (QIS) research centers, aiming to develop new and unique facilities, technologies, and capabilities for quantum computing and sensing. The laboratory's renowned theory division performs research at the confluence of these science themes. Emerging technologies, such as QIS, artificial intelligence, and microelectronics enhance the fundamental science mission and set the stage for high-impact partnerships, supported by technology transfer programs which leverage this expertise to apply particle physics technologies to problems of national importance in energy and the environment, national security, and industry.

Fermi Research Alliance, LLC (FRA), an alliance of the University of Chicago (UChicago) and the Universities Research Association, Inc. (URA), currently manages and operates Fermilab for the DOE and provides advocacy, management, and technical support, bringing considerable operational and intellectual assets to the laboratory. To achieve its ambitious goals, Fermilab is committed to instilling a culture of safety and disciplined operations, modernizing business systems and infrastructure, including moving toward net-zero operations, and remaining focused on equity, diversity, inclusion, and accessibility.

Core Capabilities

Fermilab has unique and powerful infrastructure, essential to advancing particle physics discovery, including the nation's only accelerator complex dedicated to particle physics along with a suite of particle detectors. Scientific research around the world is supported by Fermilab's facilities for design, fabrication, assembly, testing, and operation of particle accelerators and detectors; its expertise and facilities for computing; and a talented workforce with globally competitive knowledge, skills, and abilities. The laboratory is thus uniquely positioned to advance the DOE/SC mission in scientific discovery and innovation with a primary focus on high energy physics but also capabilities that address mission needs for advanced scientific computing research (ASCR), basic energy sciences (BES), nuclear physics (NP), fusion energy (FES), quantum information science (QIS), and workforce development for teachers and scientists (WDTS). Fermilab's science mission aligns with the U.S. particle physics community's goals as outlined in the 2014 and 2023 Particle Physics Project Prioritization Panel's (P5) reports. Fermilab has six core capabilities: **Particle Physics; Large-Scale User Facilities/Advanced Instrumentation; Accelerator and Detector Science and Technology**; **Advanced Computer Science, Visualization and Data; Mechanical Engineering;** and **Systems Engineering and Integration;** and two emerging core capabilities: **Plasma and Fusion Energy Sciences** and **Microelectronics**. The laboratory is requesting Microelectronics as a full core capability. Fermilab is primarily funded by the DOE Office of High Energy Physics (DOE/HEP).

Particle Physics

Particle physics is at the core of the Fermilab mission. The laboratory has a vibrant program exploring physics from the smallest scales of the quantum realm to the largest scales of the hidden universe, and the new paradigms in physics in between these - all three science themes from the 2023 P5 report. The particle physics program is enabled by unique facilities and the critical expertise built on decades of experience in the design, assembly, and operation of particle physics experiments. The Fermilab Accelerator Complex provides particle beams to a suite of experiments, as well and to a test beam facility that supports the international community.

The Fermilab Accelerator Complex is a unique facility providing intense neutrino and muon beams. The NOvA experiment studies the transformation of neutrinos over an 810 km distance to measure the parameters of neutrino oscillations, while the ICARUS and SBND experiments search for new types of neutrinos and neutrino interactions. These experiments will further strengthen the lab's core competency in the design, construction, and operation of liquid noble gas systems that will prove critical to the success of DUNE, a best-in-class experiment enabled by the PIP-II accelerator that will provide the international community with a wealth of data for studies. The Muon g-2 experiment successfully concluded data-taking in 2023, and the Mu2e project is nearing completion with first data expected in 2026.

Fermilab is the U.S. host lab for the CERN Compact Muon Solenoid (CMS) experiment collaborators, and the Fermilab-based LHC Physics Center is an intellectual hub that enhances the impact of the U.S. community on the LHC physics program, especially in studies of the Higgs Boson and searches for evidence of BSM physics. Fermilab leads U.S. CMS operations, the High-luminosity LHC (HL-LHC) Accelerator Upgrade Project and the HL-LHC CMS Detector Upgrade Project. The Fermilab scientific staff lead U.S. contributions to the CMS detector upgrade, enabled by the lab's core expertise in microelectronics and detector fabrication and using the Silicon Detector Facility (SiDet), the Rapid Prototyping and Special Materials Facility, and the Custom Detector Technology Facility.

The cosmic science program at Fermilab is based on three thrusts: cosmic surveys to understand dark energy, searches for light dark matter, and studies of the cosmic microwave background, and is derived from Fermilab's core competencies in precision assembly and testing, charge-coupled device (CCD) readout and operation, radio-frequency engineering, and design and operation of cryogenic systems. Fermilab built the Dark Energy Camera used by the Dark Energy Survey (DES) and continues to lead the scientific collaboration. Fermilab partners with other DOE laboratories to support scientific operations of new survey experiments such as the DESI and Rubin/LSST. Fermilab scientists are active in searches for light dark matter. Fermilab is the lead lab on the ADMX experiment to search for Axion Dark Matter and will host the ADMX-Extended Frequency Range (ADMX-EFR) experiment. Looking ahead, Fermilab will be poised to serve as host for Axion Dark Matter Facility with its proposed Dark Wave Laboratory. ADMX-EFR is one of two DOE/SC Dark Matter New Initiatives projects at Fermilab. The second is the OSCURA experiment, searching for dark matter using expertise in Skipper CCD technology. Fermilab is also active on the SPT-3G experiment at the South Pole and will play a leading role in the CMB-S4 project. Both the OSCURA and CMB-S4 projects are enabled by the new state-of-the-art facilities at the Integrated Engineering Research Center (IERC).

Research in the Fermilab Theory Division is shaped by its presence at the nation's primary laboratory for particle physics. It benefits from the proximity to the rich experimental program described above and also shapes the future of program. The close connection to experiments allows theorists to guide the interpretation of new experimental results and propose new analyses, while understanding the capabilities of those experiments leads to new ideas for future experiments.

Particle Physics is funded primarily by DOE/HEP with additional funding from NASA, IARPA, and the Heising Simons Foundation, (and DOE/SLI for infrastructure), and advances DOE's Scientific Discovery and Innovation mission.

Large-Scale User Facilities and Advanced Instrumentation

The Fermilab Accelerator Complex is the second-largest particle physics accelerator complex in the world. Research at this user facility has led to many significant discoveries over more than 40 years of operation, including the top quark, bottom quark, tau neutrino, determination of the properties of charm- and bottom-quark systems, and numerous precision measurements, including the discovery of new matter-antimatter asymmetries in kaon decays.

The Fermilab Accelerator Complex comprises seven particle accelerators and storage rings with particle beam capabilities found nowhere else in the world. Future upgrades of the accelerator complex enabled by the PIP-II project will provide megawatts of beam power to LBNF/DUNE. Currently, Fermilab uniquely supplies two very intense neutrino sources (the low-energy BNB and the high-energy NuMI beam) that enable the physics programs of the NOvA experiment and the SBN program, comprised of MicroBooNE in analysis mode, and SBND and ICARUS, currently taking data. The Muon g-2 experiment successfully completed its data taking in FY 2023. Fermilab will become the world center for the study of muons when high-intensity muon beams are delivered to the Mu2e experiment. The Fermilab Test Beam Facility is the only U.S. location enabling detector R&D tests with high-energy hadron beams. It is used by more than 200 international researchers annually.

Fermilab is currently managing a project portfolio of DOE O 413.3B projects with a total value of over $5.5B. These projects are fully aligned with the DOE/HEP scientific mission and will deliver a new era of scientific discovery focused on some of the most compelling questions facing science. The ACORN project modernizes a dated accelerator controls system, and SLI-UIP upgrades the site water and electrical utilities.

The next generation of projects and experiments will utilize state-of-the-art particle detector technologies conceived and developed by an experienced and talented Fermilab workforce and built-in cutting-edge facilities such as the new IERC. Achievements include the development of very-low-mass silicon detectors for particle physics collider experiments, CCD detectors for the Dark Energy Camera and other dark matter searches, scintillator detectors used for a wide variety of particle physics experiments and liquid argon time projection chambers used by current neutrino experiments and the future flagship experiment, DUNE.

Large-Scale User Facilities/Advanced Instrumentation is funded primarily by DOE/HEP (and DOE/SLI for infrastructure), and advances DOE's Scientific Discovery and Innovation mission.

Accelerator and Detector Science and Technology

Fermilab is a world leader in accelerator R&D. Fermilab's accelerator and detector science and technology competencies enable particle physics discoveries and beyond, making significant contributions to research in other scientific disciplines such as photon science, nuclear physics, QIS, industrial applications, and more. The critical areas within accelerator science and technology that are key to Fermilab's mission are: superconducting radio-frequency (SRF) acceleration technology, high-field superconducting magnets, accelerator and beam physics (ABP), AI/ML, and high-power targetry. The laboratory's competencies are enabled by unique accelerator and beam test facilities and world-leading expertise that sustain Fermilab's leadership role in high-intensity and high-energy accelerator applications.

Results from Fermilab accelerator R&D support the flagship neutrino science program and influence how U.S. and international accelerators are designed, constructed, and operated. Fermilab has achieved more than 960 kW beam power to the NOvA experiment through PIP and is running approximately $2x10^{17}$ protons per hour from the proton source to support the SBN program and the Muon g-2 experiment. Fermilab operates two high-power target stations: the 900+ kW NuMI beam (now capable of accepting 1 MW); and the BNB. A third target station is under construction for the Mu2e experiment. A fourth target station is under design for DUNE, capable of 1.2 MW and upgradeable to 2.4+ MW.

Fermilab has a long history of developing, fabricating, and delivering advanced superconducting magnets, including the world's first superconducting dipole magnets deployed in a circular collider (the Tevatron). The laboratory's core competency in high-field superconducting magnets, including novel superconducting materials and magnetic components, electromechanical magnetic designs and technologies, is essential to the luminosity upgrades of CERN's LHC accelerator. Fermilab's SRF expertise and infrastructure comprise a globally renowned core competency in the fabrication and testing of SRF technology. Laboratory staff members play an important role in the design and planning of linear and circular accelerators around the world that depend on SRF technology. This core competency enabled Fermilab to be a key partner in the construction of the superconducting linear accelerator for SLAC's LCLS-II free electron laser, the highest-priority construction project in DOE/SC. Fermilab's experienced staff and extensive infrastructure led the way in the design of SRF cryomodules and cryogenic infrastructure for LCLS-II and extended the state of the art for SRF cavity performance. By working with SLAC and TJNAF to establish LCLS-II as a world-leading facility, Fermilab is contributing its unique infrastructure and expertise to the broader scientific endeavor while simultaneously enhancing in-house capabilities for projects like PIP-II which will replace the existing linear accelerator with a high-intensity SRF linac.

The Fermilab Accelerator Science and Technology (FAST) facility hosts a unique program of advanced accelerator R&D centered around its Integrable Optics Test Accelerator (IOTA) ring and was recognized by the 2018 GARD review as the country's only "Tier-1" facility for ABP. As the world's only facility focused on intensity-frontier R&D in storage rings, the FAST research program will address key technological and scientific challenges in the realization of next-generation, high-power accelerator facilities. The FAST facility also houses a state-of-the-art, high-brightness SRF electron injector, which principally serves the IOTA program but also facilitates a range of R&D programs with outside collaborators. Furthermore, as the only operational SRF accelerator at Fermilab, the FAST injector also comprises a valuable R&D platform for SRF systems integration and operations.

Fermilab is making significant contributions to the nation's accelerator science and technology workforce training. The laboratory hosts the United States Particle Accelerator School (USPAS), which has trained over 4,500 students since its inception in 1981 and has undergone a restructuring that re-establishes the USPAS as a Fermilab-managed program. Fermilab also maintains a renowned joint university/laboratory doctoral program in accelerator physics and technology, and several undergraduate summer internship programs in collaboration with Argonne National Laboratory.

Fermilab's core capability of detector design, assembly, and operation has enabled ground-breaking experiments at Fermilab and around the world. Critical areas of detector technology that currently drive the scientific mission include low-mass silicon trackers to study the Higgs boson, CCD detectors to search for dark matter, scintillator detectors to search for rare processes, and noble liquid detectors that enable much of the neutrino program. The development of new detector technologies is further enabled by the close connection with QIS and microelectronics. The integration of quantum sensing has been critical in the development of new detectors that can search for dark matter in previously untestable mass ranges.

To enable Fermilab's world-class detector technology program, the lab operates many facilities for the development of particle detectors and their readout devices. These facilities are used for all stages of detector development: research on new technologies; development of prototype detectors; construction of small experiments; construction of major systems for international collaborations; and support of operating experiments. These facilities include: the IERC, providing state-of-the-art technical space; the Silicon Detector Facility (SiDet), supporting silicon packaging, wirebonding, and testing; the Noble Liquid Test Facility (NLTF), hosting high purity LAr test stands; the Rapid Prototyping and Special Materials Facility, for fabricating low mass detector support structures; and the Custom Detector Technologies Facility, for the development and fabrication of scintillators, fiber cutting and polishing, thin films, and large wire plane winding.

Fermilab scientists lead a Detector R&D program to drive the development of new detector technologies that will enable future experiments. The R&D focuses on the highest priorities of the field codified by P5, the grand challenges identified by the Coordinating Panel for Advanced Detectors (CPAD), and by the DOE Basic Research Needs Study on High Energy Physics Detector R&D. Fermilab has continued its mission to collaborate with university partners and other laboratories on various R&D topics. Current strategic high priorities include Picosecond Timing and Noble Liquid Detectors. This program also provides seed funding for New Initiatives through an open call each year.

Accelerator and Detector Science and Technology is funded by DOE/HEP with additional funding from DOE/BES (and DOE/SLI for infrastructure), and advances DOE's Scientific Discovery and Innovation mission.

Advanced Computer Science, Visualization, and Data

Particle physics experiments produce huge volumes of data that are second to none in basic research today. This core capability seamlessly integrates with theoretical frameworks and experimental endeavors to enhance scientific understanding through comprehensive data activities like collection, storage, reconstruction, simulation, and analysis.

Fermilab's computing facility is anchored by its robust data center. This center encompasses a mass storage system and on-site high-throughput and high-performance computing resources. Additionally, Fermilab simplifies access to external computing resources, including DOE/ASCR HPC centers, other HPC centers, and commercial cloud resources through HEPCloud. The laboratory is also committed to supporting HEP experiments through core software development and data analysis assistance, actively participating in various artificial intelligence (AI) research areas.

Fermilab's data center, recognized as the largest U.S. HEP computing center, hosts scientific computing projects and manages three major computing facilities: a CMS Tier-1 Center, Lattice QCD Computing, and FermiGrid. A highlight is Fermilab's development and operation of the HEPCloud platform, a unified portal technology facilitating streamlined access and resource sharing for data processing, storage, and analysis. This platform optimally connects Fermilab computing users to various resources, including DOE/ASCR HPC centers, international facilities, university-supported clusters, and commercial cloud resources. Notably, HEP experiments like CMS, DUNE, Mu2e, and NOvA leverage HEPCloud capabilities to expedite their scientific discoveries. Fermilab's forward-thinking approach includes adapting

HEPCloud to accommodate emerging technologies like quantum computing, recognizing its potential in enhancing scientific calculations.

Fermilab is renowned for its proficiency in designing, developing, and operating distributed computing infrastructures, exascale scientific data management, and scientific workflows. The laboratory provides access to large-scale computational and data-management facilities for a diverse range of experiments, from the CMS experiment at CERN to neutrino science and precision science experiments. Emphasizing collaboration, Fermilab actively engages with DOE/SC laboratories and international partners, including CERN, DESY in Germany, and the Korean Institute of Science and Technology Information. The laboratory collaborates on projects spanning accelerator modeling, computational cosmology, and particle physics simulations. Fermilab strategically leverages DOE/ASCR expertise to address computational challenges through partnership programs like DOE's Scientific Discovery through Advanced Computing (SciDAC) program.

Fermilab's commitment to AI research in HEP encompasses diverse topics such as particle tracking, reconstruction, advanced data analysis, and astrophysics. The laboratory focuses on AI applications in particle accelerator control systems and edge systems, notably through the ACORN project, which supports implementation of AI techniques for the next-generation accelerator control system. Edge AI systems, enabling low-latency on-chip solutions, are pivotal for seamlessly integrating AI into data acquisition systems.

Advanced Computer Science, Visualization, and Data is funded primarily by DOE/HEP with additional funding from DOE/ASCR (and DOE/SLI for infrastructure), and advances DOE's Scientific Discovery and Innovation mission.

Mechanical Design and Engineering

Custom, state-of-the-art technologies require exquisite, innovative mechanical design and engineering capabilities. Fermilab engineers provide the material, structural, thermal, fluids, and vacuum engineering that demonstrate the breadth and depth of mechanical design and engineering. Their expertise supports existing and future accelerators and detectors, and they are an integral part of quantum research. Their work is found throughout the lab, in collaborations within the DOE and in partnerships with international high-energy physics institutions. Mechanical engineers build on existing knowledge in materials, fabrication, and cooling of existing accelerator components to design, fabricate, and test components for future accelerators such as the electrostatic septa for the Mu2e beamline, conventional and SRF cavities for PIP-II, and targetry for 2.4+ MW beam for LBNF. The lab holds a unique capability in the DOE complex to design, fabricate, and test magnets for accelerator beamlines. The mechanical engineering expertise in coil materials and winding, assembling the magnetic poles, analysis of the magnet function, and testing results in providing conventional and superconducting magnets for the Fermilab Accelerator Complex, Oak Ridge National Laboratory's Proton Power Upgrade project, and CERN's HL-LHC. The next generation of beamline components, called cryomodules, use SRF technologies mechanical engineers helped to develop. They provided the expertise to fabricate and process the surface of niobium cavities, assemble the string of cavities into cryomodules, and test the cryomodule performance at the lab's Cryomodule Test Facility. This work is applied towards the cryomodules for SLAC National Accelerator Laboratory's LCLS-II and LCLS-II HE while also collaborating with international partners to deliver cryomodules for PIP-II.

Mechanical engineers have established the expertise and facilities to produce detectors and their auxiliary systems for cryogenic low background experiments for dark matter, neutrinos, and muons. Cryogenic engineering is a niche skill within mechanical engineering. Cryogenic engineers design, install, and operate the lab's large liquid helium refrigeration systems and its cryogenic distribution systems to test and operate PIP-II and LCLS-II/LCLS-II HE cryomodules and liquid argon helium systems to operate neutrino experiments like SBND and ICARUS, as well as design future systems for the PIP-II beamline and LBNF/DUNE. The research at the SQMS Center relies on mechanical engineering expertise to operate the existing dilution refrigeration system and design the future world's largest dilution refrigerator to provide the millikelvin environment for quantum computing research. Material research includes understanding material properties and fabrication techniques to optimize the performance of 2D and 3D quantum devices. As Fermilab's numerous collaborations require delivery of large and delicate assemblies, the mechanical engineering community has developed a comprehensive transportation process to ensure safe delivery of cryomodules, detectors, and magnets to their final destinations, whether across the lab's site, across the country, or overseas.

Systems Engineering and Integration

Fermilab demonstrates systems engineering and integration in the design, construction, and operations of particle accelerator systems, particle physics experiments, astrophysics systems, and QIS research. Engineers in this role integrate expertise in the fundamentals of high-energy physics, engineering, applied technology, and project management. Interdisciplinary and multi-institutional teams come together from the conceptual and design phase through commissioning and operations of technically complex systems that support the science mission while meeting safety and quality goals. The successful run of the Muon g-2 experiment, the near completion of the Mu2e beamline and experiment, and existing neutrino experiments such as SBND, ICARUS, and ANNIE are examples of systems that require large scope planning and daily interactions across organizations that involve scientists, engineers, technical staff, and project managers. These projects required building new experiments and auxiliary systems that were integrated with existing and upgraded particle accelerators. The PIP-II and LBNF/DUNE projects take this kind of collaboration a step further by scaling up the cost and scope of the new accelerators and detectors and the integration into the existing and upgraded accelerator. Both projects also involve integrating major accelerator components and detectors that are contributed by international partners. Fermilab also demonstrates its system engineering and integration capabilities with its contributions to LCLS-II/LCLS-II HE, CMS, the HL-LHC, CMB-S4, and SuperCDMS. Fermilab relies on system engineering capabilities for its projects by applying deep expertise in high-energy physics, mechanical design and engineering, power systems and electrical engineering, software applications, controls engineering, and cryogenic engineering. Emerging technologies such as AI/ML and microelectronics are being integrated into new and existing experiments to increase data flow, analysis, control, and operations to accelerate scientific discovery.

Plasma and Fusion Energy Sciences (Emerging)

For several decades, one of Fermilab's primary core capabilities has been Accelerator Science and Technology, including comprehensive expertise in design, fabrication, and testing of conventional and superconducting magnets, unique within the DOE complex.

The Magnet Technology Division (MTD) resides within the Applied Physics and Superconducting Technology Directorate (APS-TD) and is comprised of approximately 100 Scientists, engineers, technicians, and support staff. Divisions within APS-TD primarily support accelerator technology R&D and DOE/HEP projects. In addition, MTD contributes to many projects across DOE/SC, demonstrating Fermilab's potential to become the cryogenic temperature test facility/center for the national laboratories.

Fermilab's capabilities and infrastructure also align well with supporting technology development relevant to magnetic confinement fusion devices. The DOE/HEP-funded R&D program for magnets based on High Temperature Superconductors (HTS) will complement the development required for fusion magnet technology. This year, the laboratory has provided seed funds from LDRD to initiate the fusion-focused R&D program.

In recognition of Fermilab's expertise and facilities, the Offices of Fusion Energy Science (DOE/FES) and DOE/HEP have jointly funded the High Field Vertical Magnet Test Facility (HFVMTF). The HFVMTF will provide the unique capability to evaluate and test cables for fusion magnets in a high background dipole field. In addition, we have the possibility of resurrecting the solenoid test facility that was used to test large solenoid magnets. This facility would be ideal for testing model fusion magnet coils. Fermilab's goal is to become a center of excellence in the development of fusion magnet technology.

Science and Technology Strategy for the Future/Major Initiatives

Particle physics looks across the largest scales in the universe and to the behavior of the smallest building blocks of matter to describe all we see at its most fundamental level. Fermilab, with an incredible program of experiments and projects underway and an ambitious vision for the future, is poised to enter an era of scientific discovery that focuses squarely on some of the most fundamental and compelling questions facing science and particle physics in the 21st century.

The laboratory's science and technology strategy is founded on several strategic initiatives:

- Five major particle physics initiatives – in neutrinos, Higgs and the energy frontier, muons, the dark universe, and accelerator science and technology – continue Fermilab's legacy as America's premier particle physics and accelerator laboratory and push the limits of discovery into new and exciting domains. Fermilab is moving forward with experiments, international engagements, and R&D programs that support all science drivers identified by the U.S. particle physics community in the consensus 2014 and 2023 P5 reports.
- Three major emerging technology initiatives – in quantum science and technology, microelectronics, and artificial intelligence (AI) for scientific instrumentation – build upon Fermilab's core high-energy physics capabilities by applying them to emerging technologies for the benefit of particle physics, other science programs, and the nation.
- One new user and stakeholder engagement enhancement initiative to greatly enhance the on-site experience of Fermilab's national and international user, affiliate, and partner communities; and one initiative to expand and strengthen Fermilab's innovation and outreach efforts.

Infrastructure

Overview of Site Facilities and Infrastructure

Fermilab's 6,800-acre site and conventional infrastructure network is the largest within the Office of Science and provides the foundation for the laboratory's scientific research and development. The campus encompasses the Fermilab Accelerator Complex, a DOE/SC user facility. The infrastructure is evolving to support the significant requirements of the international collaborations of LBNF/DUNE and PIP-II projects and future R&D.

All Fermilab real property including the utility infrastructure in Batavia, Illinois is used and owned by DOE, and much dates from the 1960s and 1970s. In addition to the Illinois campus, DOE has 25,005 gross square footage (gsf) real-property leases in South Dakota, primarily with the South Dakota Science and Technology Authority (SDSTA) at the Sanford Underground Research Facility (SURF) in Lead, South Dakota in support of LBNF/DUNE.

The Fermilab Campus Master Plan (https://fess.fnal.gov/master-plan/), developed from 2012 and finalized in 2018, identifies the 20-year strategic plan for facilities and infrastructure. As a result of changes to underlying assumptions within the current master plan as well as post-pandemic new workplace trends, a multi-year effort to update the plan is scheduled to commence starting in FY 2025.

Real Estate Actions

In FY 2023, there were no new real estate actions, leases, renewed leases, leased disposals, gifts, or third-party financed projects. In FY 2024, the laboratory is pursuing several real estate actions including:

- Pursuing a grant from the State of Illinois to improve infrastructure at the Batavia site focusing on on-site housing facilities.
- Modifying the DOE contractor lease for the SDSD Office in South Dakota to include an additional 2,270 gsf.
- Modifying the DOE lease between DOE and SDSTA to include an additional 3,221 gsf for office use at the Ross Dry Facility.

In FY 2025 through FY 2029, the laboratory is continuing to pursue leasing additional office space in South Dakota to accommodate increased needs by the LBNF/DUNE project

Types and Conditions of Facilities

An additional tab was provided in Enclosure 4 for a detailed breakdown of condition of facilities with respect to types of facilities, overall asset condition, general square footage, and utilization. Additionally, the enclosed table provides details regarding number of each of the facilities within each category, replacement plant value (RPV), FY 2023 actual annual maintenance invested, and deferred maintenance of the various categories. A breakout of the overall asset condition by RPV and the number of facilities based on usage can be seen on the two charts in the Infrastructure-at-a-Glance section to the right.

Campus Strategy

The goal of the laboratory's campus strategy is to integrate infrastructure with the dynamic needs of its scientific mission, fostering innovation by providing robust facilities, and minimizing environmental impact in a safe and secure setting. This vision is underpinned by strategic investments in infrastructure improvements, site access and control, sustainability initiatives, and the adoption of changing work arrangements to enhance the effectiveness and efficiency of the laboratory's operations. Key objectives of the strategy include:

- Safety and Security Focus. Prioritize the safety and security of the campus and its inhabitants by implementing comprehensive measures and protocols. This includes the continuous assessment of risks, the application of security technologies, and the fostering of a culture of safety.
- Mission Infrastructure Modernization and Gap Closure. Accelerate efforts to modernize facilities and close infrastructure gaps essential for advancing mission activities.

- Facility Capability and Resilience Enhancement. Focus on enhancing the resiliency and sustainability of existing assets through strategic modernization, redundancy, and intelligent control features.
- Sustainable and Agile Work Environment. Commit to increasing maintenance and repair funding to meet or exceed DOE targets, ensuring the longevity and reliability of the laboratory's physical assets. Expand and refine flexible work arrangements and remote work capabilities to foster a more agile, mobile, and sustainable workforce, reducing the laboratory's carbon footprint and enhancing operational resilience.

Site Sustainability Plan Summary

Fermilab's vision is to be a global leader for sustainability in particle and accelerator physics and technology innovation. As a large user of energy, water, and other resources, Fermilab has the responsibility to incorporate sustainability into mission execution. And at the same time, Fermilab has world-class science and engineering expertise and facilities that can be leveraged to achieve innovations in energy and sustainability for particle physics and beyond. In FY 2023, Fermilab increased investments to improve the laboratory's ability to advance DOE sustainability goals and made significant progress around key strategic priorities, as summarized in the FY 2024 Site Sustainability Plan.

In FY 2023, Fermilab created a full-time sustainability program team with four full-time employees, providing a robust human infrastructure to identify and implement sustainability projects, and complete reporting, compliance, and accountability activities. Fermilab created a Sustainability Strategy to incorporate DOE O 436.1A requirements and Fermilab-specific sustainability goals and initiatives. The laboratory also expanded the matrixed Sustainability Management Team, chartered by the COO, to create a powerful cross-disciplinary team to implement the sustainability strategy across the laboratory. Fermilab is well positioned to support the sustainability recommendations from the P5 Report and provide U.S. leadership for advancing sustainability in the particle physics community.

Fermilab's sustainability strategy focuses on four priorities to achieve our vision and meet DOE's sustainability goals**: Make sustainability part of the laboratory culture** by incorporating sustainability into meeting the mission; **Apply best practices for sustainable operations** by embedding proven and impactful sustainability approaches into managing campus infrastructure and executing operational activities; **Drive discovery to achieve sustainability in science** by uncovering new ways to integrate sustainability into the science strategy and mission execution; and **Leverage partnerships to drive impact** by partnering and collaborating with cross-divisional teams and external partners to increase impact.

LAWRENCE BERKELEY NATIONAL LABORATORY

Lab-at-a-Glance

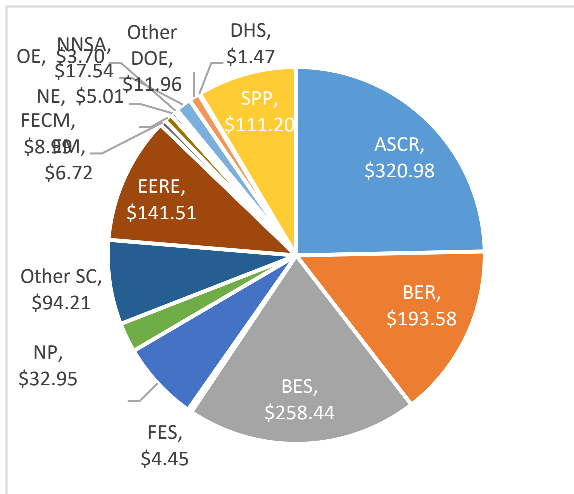
Location: Berkeley, California
Type: Multi-program Laboratory
Contractor: University of California
Site Office: Bay Area Site Office
Website: www.lbl.gov

- **FY 2023 Lab Operating Costs:** $1,160.54 million
- **FY 2023 DOE Costs:** $1,171.12 million
- **FY 2023 SPP (Non-DOE/Non-DHS) Costs:** $111.20 million
- **FY 2023 SPP as % Total Lab Operating Costs:** 8.5%
- **FY 2023 DHS Costs:** $1.47 million

Physical Assets:
- 202 acres and 97 buildings
- 1.7 million GSF in buildings
- Replacement Plant Value: $1.49 B
- 315,471 GSF in Leased Facilities

Human Capital:
- 3,804 Full Time Equivalent Employees (FTEs)
- 10 Outgoing Joint Appointees, 9 Incoming Joint Appointees (Total Joint, Regular & Shared Faculty: 224)
- 509 Postdoctoral Researchers
- 250 Graduate Student
- 177 Undergraduate Students
- 16,350 Facility Users
- 1,996 Visiting Scientists and Engineers

FY 2023 Costs by Funding Source ($M)



Mission and Overview

For over 90 years, Lawrence Berkeley National Laboratory (Berkeley Lab) has played an important and distinctive role within DOE's network of great national laboratories. Berkeley Lab delivers scientific breakthroughs over a remarkable range of science, with special focus on research addressing clean energy, climate resilience, environmental quality, health, and economic competitiveness. Our most important asset is our workforce, a diverse group of talented, creative researchers and professionals who have committed their careers to finding science solutions to the greatest human challenges of our time. Together we have forged a culture of stewardship of the Lab's people, research, and resources that keeps us at the forefront of science and technology.

Berkeley Lab specializes in integrative science and technology, taking advantage of our world-renowned expertise in materials, chemistry, physics, biology, earth and environmental science, mathematics, and computing. We advance the frontiers of science and technology through three approaches: advanced instrumentation and user facilities, large team science, and core research programs led by outstanding investigators. The close integration of these three approaches optimizes the impact of the Lab's research, to the benefit of DOE's missions.

Our five national user facilities provide over 16,000 researchers with capabilities in research computing and data sciences, chemical sciences, materials synthesis and characterization, and genomic science. Our scientific impact is built upon the foundation of strong capabilities in basic and applied science and is amplified by the world-class user facilities.

We have continuing partnerships with other national laboratories on a wide range of projects from subatomic physics to quantum information, biomanufacturing, climate science, water-energy, ecosystem science, and innovative energy technologies.

We have built strong relationships throughout California and particularly in the San Francisco Bay Area region. We partner with local industries to scale up technologies, organizations in disadvantaged communities to collaborate on energy efficient homes, and educators to provide STEM activities to students, especially those in underserved communities.

Our close relationship with the nation's leading public university, the University of California, brings the diverse intellectual capital of UC's faculty, postdocs, and students to bear on the pursuit of DOE's science and energy missions. The Lab's scientific strength is enhanced by its deep integration of basic and applied science and its emphasis on collaboration with the national scientific community. We continue to innovate with our world-class user facilities, capabilities, and expertise to solve the S&T challenges that define our time.

Core Capabilities

Each of our Core Capabilities involves a substantial combination of people, facilities, and equipment to provide a unique or world-leading scientific ability to support DOE missions and national needs. Each is executed safely, with minimal impact on the environment and surrounding community. This section summarizes Berkeley Lab's Core Capabilities, their targeted missions, and their funding sources.

The Core Capabilities lend an exceptional depth to our broad research portfolio, while enabling an integration of efforts to better support the DOE missions. To emphasize their strategic nature, the Lab has grouped these Core Capabilities into broad thematic categories: Large Scale User Facilities/Advanced Instrumentation; Chemistry, Materials Science, and Geoscience; Biological and Environmental Science and Engineering; Computational Science; Fundamental Physics; Accelerator, Detector, and Fusion Science and Technology; and Applied Science, Engineering, and Energy Technology.

Large Scale User Facilities/Advanced Instrumentation

As the first accelerator laboratory, Berkeley Lab has long had an overarching Core Capability of designing, constructing, and operating leading scientific facilities for large user communities. Among the national lab system, the Lab has the largest population of users; these researchers produce scientific breakthroughs because of their creative research at these facilities. Below are summary descriptions of our large-scale user facilities. Many of the other Core Capabilities in other areas of this report contribute greatly to the success of these user facilities, and the quality of research across the entire Lab depends on their capabilities.

The Advanced Light Source (ALS) is the world-leading facility for high-brightness soft X-ray science, with additional excellent performance ranging from the infrared through hard X-ray spectral regions.

Scientists use the data they collect to understand, predict, and ultimately control matter and energy at length scales ranging from the atomic to the macroscopic. We are building a completely new accelerator complex for the Advanced Light Source, which serves a large science community doing research in materials and chemistry, structural biology, environmental science, geosciences, and clean energy technologies. We are preparing the path toward ALS 2.0, which will feature this new accelerator complex, optimized for brighter coherent beams and has several new beamlines and improved instrumentation. In FY23 the ALS had 1,602 users (1,140 of whom were onsite). Annual budget: ~$75 million (BES).

The Molecular Foundry provides communities of users worldwide with access to expert staff and leading-edge instrumentation to enable the understanding and control of matter at the nanoscale in a multidisciplinary, collaborative, and safe environment. It encompasses facilities specializing in characterization, made up of the National Center for Electron Microscopy, along with the Imaging and Manipulation of Nanostructures facility; Nanofabrication; Theory of Nanostructured Materials; and synthesis, focusing on Inorganic Nanostructures, Biological Nanostructures; and Organic and Macromolecular Synthesis. In FY23, the Foundry had 1,090 users (792 of whom were onsite). Annual budget: ~$36.5 million (BES).

The ***DOE Joint Genome Institute (JGI)*** is a national user facility that provides advanced genomic capabilities, large-scale data, and professional expertise to support the global research community in addressing energy and environmental research grand challenges in bioenergy, nutrient cycling, and biogeochemistry. JGI is the world's largest producer of plant and microbial genomes, with programs focused on large-scale generation of DNA sequences; development of innovative DNA analysis algorithms; and functional genomics, including DNA synthesis, metabolomics and secondary metabolites. New initiatives include biomolecular materials and bio surveillance and bio preparedness. JGI recently sunsetted its 5-year Strategic Plan "Beyond Basepairs: A Vision for Integrative and Collaborative Genome Science," completing 93% of 2-year milestones and 87% of 5-year milestones. A new Strategic Plan "Innovating Genomics to Serve the Changing Planet" is being launched in 2024 that sets forth JGI's ambitious goals to meet its new vision of "Lead genomic innovation for a sustainable bioeconomy." In FY23, JGI served 2,373 primary users and over 22,000 active secondary users with an FY23 budget of $89.4 million (BER).

The National Energy Research Scientific Computing Center (NERSC) supports more than 9000 users from universities, national laboratories, and industry – the largest and most diverse research community of any DOE user facility. NERSC is the mission High Performance Computing center for the DOE Office of Science, providing resources for SC's six scientific program offices. NERSC deploys large-scale, state-of-the-art supercomputing and data storage systems, networking, and expert consulting and support services. Over the last decade NERSC's capabilities have expanded to support more robust support for AI, data analytics, and the ability to support complex workflows, so that a growing number of scientists can use NERSC to analyze data from DOE SC's experimental and observational facilities. The Perlmutter (NERSC-9) system represents a significant step forward in supporting SC user workflows and provides a boost in computing performance and capability to the user community. In 2023, the facility served 10,000 users. NERSC systems delivered 3.43 billion CPU core hours and 42.4 million GPU hours to researchers. NERSC's FY23 funding: $130M (ASCR).

The Energy Sciences Network (ESnet) is SC's high-performance network user facility, delivering highly reliable data transport capabilities optimized for the requirements of large-scale science. ESnet serves as the vital "circulatory system" for the entire DOE national laboratory system, dozens of other DOE sites, and more than 270 research and commercial networks around the world—enabling tens of thousands of scientists at DOE laboratories and academic institutions across the country to transfer vast data streams, access remote research resources in real-time, and collaborate on important scientific challenges. In essence, ESnet is a force multiplier that enhances scientific productivity and expands opportunity for discovery. In the past year, the network transported over 1.7 exabytes of data. In 2022, ESnet completed the successful launch of ESnet6, the latest iteration of its network, with the bandwidth, speed, and advanced software and services designed to meet modern science's increasing data and multi-facility collaboration needs. ESnet6 offers 46 terabits per second of aggregate capacity, 400 gigabits per second to 1 Tbps speeds on its 15,000-mile network backbone, and three 400-Gbps trans-Atlantic circuits (in addition to four such 100-Gbps circuits). In addition, ESnet staff continue to develop and deploy advanced orchestration and automation software, high-touch packet inspection tools, experimental testbed environments, and other innovative services designed to serve the DOE's Integrated Research Infrastructure (IRI) program. ESnet's FY23 funding was ~$90M (ASCR).

Chemistry, Materials Science, and Geoscience

Chemical and Molecular Science

Berkeley Lab's world-leading capabilities in fundamental research in chemical and molecular sciences support DOE's mission to achieve transformational discoveries for energy technologies, while preserving human health and minimizing environmental impact. The Lab has integrated theoretical and experimental Core Capabilities and instrumentation to enable the understanding, prediction, and ultimately the control of matter and energy flow at the electronic and atomic levels, from the natural timescale of electron motion to the intrinsic timescale of chemical transformations.

We have expertise in gas-phase, condensed-phase, and interfacial chemical physics. State-of-the-art laser systems that generate ultrashort pulses of extreme-ultraviolet light; soft X-ray sources; photon, electron and mass spectrometers; spectromicroscopy; *in situ*, *operando* and other capabilities are all used to advance the understanding of key elementary chemical reactions and excited states, reactive intermediates, and multiphase reaction networks that govern chemical transformations in realistic environments.

Berkeley Lab has deep expertise in experimentation, simulation, and theory aimed at a first-principles description of solvation and molecular reactivity confined and complex microenvironments such as interfaces and catalytic nanopores. Novel instrumentation expertise at the ALS pioneers the application of vacuum ultraviolet and soft X-ray synchrotron radiation to critical problems in chemical dynamics and interfacial chemistry.

We are a world leader in ultrafast attosecond and femtosecond probes of electron dynamics, electron momentum-imaging instrumentation, reaction microscopy, and theoretical methods that probe how photons and electrons transfer energy to molecular frameworks. These capabilities are key to understanding and ultimately controlling energy flow at the atomic scale. These laser-based ultrafast X-ray sources for chemical and atomic physics contribute to the knowledge base for current and future powerful FEL-based light sources.

Berkeley Lab's catalysis capabilities span fundamental research on homogeneous and heterogeneous chemical conversions for high efficiency and selectivity. The Catalysis Facility co-locates a suite of state-of-the-art instruments for synthesis and analysis, including high-throughput dryboxes, a micromeritics analyzer, flow UV-vis spectroscopy, liquid chromatography, pressure reactors and FTIR instrumentation. The core strengths are in three pillars of catalysis: mechanisms, transformations, and environments, to elucidate fundamental principles in catalysis and chemical transformations at the molecular level.

Research on both the catalytic center and its environment advance the field from discovery to catalyst design.

The Heavy Element Research Laboratory has unique capabilities for determining the electronic structure, bonding, and reactivity of compounds of the poorly understood actinides, including the transuranic elements. Our leading scientific personnel and instrumentation characterize, understand, and manipulate rare earth complexes for the discovery and separation of alternative elements and technology-critical materials, including those for energy storage, motors, solid-state lighting, batteries, and quantum information storage.

Our flagship geosciences group possesses the expertise and methods to discover and model the fundamental processes controlling subsurface resources, with an emphasis on molecular-scale interfacial processes that govern couplings between chemical reaction and rock mechanics. Studies are performed with advanced laboratory methods including quantum sensing, through collaborations with the Molecular Foundry and the Advanced Light Source to develop electron and X-ray probes of Earth fluids and minerals, and through multi-scale molecular modeling and machine learning. Focused on the Lab's Basic Energy Sciences mission, the geosciences group also contributes knowledge to the Lab's ***Earth and Energy Systems and Infrastructure Analysis and Engineering*** programs, described below.

Berkeley Lab has exceptional capabilities in solar photoelectrochemistry, photosynthetic systems, and the physical biosciences. These photosynthetic and photoelectrochemistry capabilities, together with spectroscopies and unique *in situ* imaging methods that use photons in the energy range from X-rays, in particular free-electron lasers, to infrared at high temporal resolution, enable elucidation of the structure and elementary mechanisms of biological and artificial photon-conversion systems. The in-depth understanding of artificial and natural photosynthesis forms a basis for efficiently engineered solar-conversion systems. We are a lead partner for the Liquid Sunlight Alliance, the DOE Energy Innovation Hub devoted to the development of new photoelectrochemical approaches to fuel production.

This Core Capability is supported primarily by BES, with important contributions from ASCR. Other DOE contractors and SPP enable this Core Capability, which supports DOE's mission to probe, understand and control the interactions of phonons, photons, electrons and ions with matter; and to direct and control energy flow in materials and chemical systems.

Chemical Engineering

At Berkeley Lab, this Core Capability links basic research in chemistry, biology and materials science to deployable technologies that support energy security, environmental stewardship and nanomanufacturing. Leading capabilities are provided in the fields of chemical kinetics; catalysis; molecular dynamics; actinide chemistry; electronic, biomolecular, polymeric, composite, and nanoscale materials; surface chemistry; ultrafast spectroscopy; crystal growth; mechanical properties of materials; metabolic and cellular engineering applied to recombinant DNA techniques that create new chemical processes within cells and vesicles; and new methodologies for genomic and proteomic analysis in high-throughput production that enable gene libraries that encode enzymes for metabolic engineering; and technologies that integrate chemistry, biology, and bio-inspired approaches into a single process or reactor design.

Other program components translate fundamental research in catalysis, chemical kinetics, combustion science, hydrodynamics and nanomaterials into solutions to technological challenges in energy storage. The Advanced Biofuels and Bioproducts Process Development Unit (ABPDU), supported by EERE and SPP, integrates biological and chemical unit operations through bioprocess engineering to understand

and optimize processes for producing biofuels, renewable chemicals and proteins relevant to the industrial biotechnology industry. Berkeley Lab also has expertise in chemical biology and radionuclide decorporation, necessary for characterizing mammalian response and developing sequestering agents for emergency chelation in humans in case of heavy-element or radioactive contamination.

The Lab is a leader in materials for advanced battery technology, and develops low-cost, rechargeable, advanced electrochemical devices for both automotive and stationary applications. This effort includes numerous applied R&D programs funded primarily by EERE VTO. The related field of fuel-cell research enables the commercialization of polymer-electrolyte and solid-oxide fuel cells for similar applications.

This Core Capability is supported by BES, ASCR, BER, EERE, and SPP, including NIH, DoD, universities, and industry. It supports DOE's missions to foster the integration of research with the work of other organizations within DOE, as well as other agencies, and applies directly to DOE's energy security and environmental protection mission, including solar and biofuels.

Condensed Matter Physics and Materials Science

Berkeley Lab researchers integrate state-of-the-art, and often world-unique capabilities in synthesis, characterization, theory, and computation to design and understand new materials and phenomena. These capabilities push the boundaries of materials research towards fundamental spatial, temporal and energy limits with the potential to directly — and significantly — impact solutions to grand challenges in energy, environment, security, and information technologies.

A key Berkeley Lab strength in this capability is in quantum materials, encompassing weakly correlated topological phases such as topological insulators and Weyl and Dirac semi-metals, and materials that exhibit novel forms of magnetic, electronic, and geometric/spatial order, including 2D materials such as graphene or van der Waals heterostructures. Through its efforts within BES programs, including specialized QIS instrumentation at the ALS and Molecular Foundry, we are targeting new paradigms for the creation, control, and understanding of coherent phenomena in materials. Novel states of matter can be explored in the ultrafast time regime, including when the system is driven far from equilibrium.

In addition, we have developed comprehensive capabilities for top-down and bottom-up synthesis and patterning of complex materials. A long track record of groundbreaking discoveries related to the synthesis of inorganic nanoparticles and nanowires has more recently been extended to highly complex and structurally dynamic ionic semiconductors. The Lab also has specific expertise in synthetic polymer synthesis, including sequence-defined polypeptoids, and organic/inorganic nanocomposite synthesis that can precisely and simultaneously control the nanoparticles and their spatial arrangements.

Berkeley Lab has deep expertise in theory and computational simulations in conjunction with novel synthesis approaches that rely on machine learning and AI concepts, which are critical to the discovery and design of new materials. Researchers develop models for understanding, predicting, and controlling complex materials with targeted properties. The Center for Computational Study of Excited-State Phenomena in Energy Materials develops new general software, theories, and methods to understand and predict excited-state phenomena in energy-related materials from first principles with exascale performance. Open access to analysis tools and computed information on known and predicted materials provided by the Materials Project helps the Lab to conduct computational work in high-throughput modalities.

Our researchers leverage the unique X-ray characterization capabilities at the ALS as well as signature electron microscopes and other instruments at the Molecular Foundry, among other facilities, to characterize properties and behavior of materials. By elucidating structure, function, and reactions, specifically at interfaces between various phases of matter, Lab researchers better understand how new materials may perform in various energy-relevant environments. Efforts rely on developing instrumentation for time-domain approaches in spectroscopy, diffraction, and quantitative microscopy. A key focus is advancing X-ray, electron beam, and scanning probe techniques, including for operation under cryogenic conditions, and *in situ* and *operando* environments with near-atomic resolution. Unique characterization tools include time-resolved angle-resolved photoemission spectroscopy for studies of materials far away from equilibrium as well as ultrafast electron diffraction.

We are addressing some of the looming challenges in microelectronics, often described as the era beyond Moore's Law, through a co-design approach, where transformative materials discoveries driven by advanced computation and property characterization are integrated with the design of device and system architectures and scale-up processing.

This Core Capability is primarily supported by BES, with important contributions by ASCR, EERE, and DoD, as well as other SPP sponsors from industry. It supports DOE's missions to discover and design new materials and molecular assemblies with novel structures and functions through deterministic atomic and molecular scale design for scientific discovery, innovative energy technology, and improved homeland security.

Earth and Energy Systems and Infrastructure Analysis and Engineering

Berkeley Lab's geosciences group develops knowledge, data, monitoring tools, and predictive models to investigate complex subsurface processes and their impacts on energy, environmental, and infrastructure systems. A unique area of expertise lies in our ability to work seamlessly across spatial, temporal, and developmental scales to move from discovery insight to deployment impact in what we term Science to Hubs. Our fundamental science investigations are supported by BES; our applied portfolio is supported by the Geothermal Technologies Office, Fossil Energy and Carbon Management, NE's Office of Spent Fuel and Waste Disposition, with other support coming from OE, EM, CESER and NNSA, and from several significant SPPs.

Experimental field research efforts benefit from the Geosciences Measurement Facility, which provides exceptional rapid prototyping and deployment of new equipment and instrumentation. Our unique BES flagship geosciences program unifies the disciplines and the expertise needed for a mechanistic understanding of how rock-fluid systems evolve in response to stress and reactive fluids and solutes, the knowledge that is required for assessing functionality and system responses of subsurface geologic resources. We develop and integrate powerful experimental methods with exceptional expertise in molecular-to-continuum scale theory and modeling. We use world-class instrumentation to quantify geologic fluids, solutes, and minerals under elevated temperature and pressure, including *in situ* X-ray imaging and spectroscopy. We also advance and integrate stable isotope measurements, including clumped isotope methods, to identify and interpret chemical signatures of rock-fluid interactions.

Our geothermal research program seeks to realize enhanced geothermal systems (EGS) and more flexible geothermal energy production. For example, we are contributing to all three of the newly awarded EGS demo projects. Our portfolio also includes discovery of conventional hydrothermal resources, direct use of geothermal energy for heating and cooling, thermal energy storage, and exploration of synergistic benefits such as the extraction of critical materials from geothermal brines, particularly in the Salton Sea region of California. With GTO support and through partnerships, our team is also addressing issues of energy justice through engagement with community-based organizations in the Salton Sea area and promoting community engaged research.

The Carbon Storage program focuses on enabling geologic carbon sequestration (GCS) at scale to support a clean energy, net-zero future. Key aspects of our program include evaluating carbon sequestration risks through DOE's NRAP program, providing leadership in DOE's SMART Initiative that involves the application of ML techniques to GCS operations for near-real time decision-making, and testing advanced subsurface monitoring solutions. Our monitoring efforts not only include research into low-cost geophysical data acquisition solutions for establishing CO_2 conformance and leak detection, but also controlled fault activation tests that provide insight into processes leading to induced seismicity. Recently, DOE has extended this type of research from 'local single GCS site' applications to address safety over entire geologic basins through funding of basin-scale modeling studies as well as a Direct Air Capture (DAC) hub feasibility study entitled CALDAC. Our future goal is to continue to refine and 'harden' these measurement technologies such that they can be applied at full-scale carbon storage sites to provide low-cost monitoring solutions. We continue developing terrestrial and geological solutions based on enhanced mineralization of rock resources for carbon removal. Our Hydrocarbon Research portfolio includes efforts to identify and mitigate leakage of methane from oil and gas infrastructure both from the identification of orphaned and abandoned wells perspective, as well as quantifying airborne emissions.

Through support from NE's Office of Spent Fuel and Waste Disposition, we are developing advanced approaches to enable safe long-term geologic disposal of nuclear waste and concomitant environmental protection. Our studies are centered on the reliable modeling of complex coupled subsurface processes triggered at different stages of waste disposal, using microscopic experiments to improve fundamental understanding, benchtop scale experiments for better parameter calibration, and large-scale in situ experiments for model validation.

Finally, our capabilities and research associated with critical infrastructure and natural hazards have realized substantial growth in the past years. Lab scientists have now established a significant program in this area with funding from DOE, the State of California, LDRD, local governments, and local stakeholders. Berkeley Lab leads the development of transformational simulation tools and a new experimental testbed for earthquake ground motion simulations.

Biological and Environmental Science and Engineering

Many of the most pressing energy and environmental challenges of our time require an ability to understand, predict, and influence environmental and biological systems. For this we need a new and deeper understanding of fundamental biology, Earth processes, and their interactions. Berkeley Lab researchers aim to decipher and map the vast networks of these interconnected systems, the scales of which range from nanometers to thousands of kilometers, and from nanoseconds to centuries. This enables predictions for how environmental changes impact biological systems and vice versa; to harness biology for sustainable energy, other valuable products, and scalable decarbonization solutions; and to develop understanding of dynamic, multi-scale Earth systems. Our growing suite of fabricated ecosystem platforms, sensors, and new simulation tools is enabling new strategies to predictably and reproducibly establish, monitor, and perturb laboratory ecosystems at multiple scales.

Biological and Bioprocess Engineering

We use integrated research teams to solve national challenges in energy, environment, and health, and to advance the engineering of biological systems for sustainable manufacturing. Biology has the potential to contribute new practical solutions to many of the major challenges confronting the U.S. and the world. Berkeley Lab's team-science approach to mission-oriented science and technology is ideally suited to address the grand biology challenges facing the nation. To do this we steward capabilities and perform research in systems biology, genomics, secure biodesign, structural biology, and imaging across length scales. Berkeley Lab is also a national leader in microbial biology, cell biology, plant biology, microbial community biology, environmental sciences, and computational biology. We have the capability to characterize complex microbial community structure and function; manage highly complex biological data; visualize biological structure; and produce large-scale gene annotation. Our research, and that of many others across the nation, is enabled by instrumentation and infrastructure available at the ALS, Joint Genome Institute (JGI), the Molecular Foundry, and NERSC, and we provide computational and data tools to the research community through the JGI, DOE Systems Biology Knowledge Base, (KBase) and the National Microbiome Data Collaborative (NMDC).

Characterizing biological systems. To fully exploit the potential of biology to solve societal problems we need to be able to characterize its fundamental components, most notably the genes that make up the blueprint for life, and the proteins those genes code for. To that end, we operate the JGI on behalf of BER. This user facility provides a diverse international scientific user base with access to state-of-the-art genomic technologies and scientific expertise to enable biological discoveries and applications in the DOE mission areas of bioenergy, nutrient cycling, and biogeochemistry. It offers a suite of capabilities that are unique in their ability and scale to advance energy and environmental science. Now well beyond a production sequencing facility, today the JGI offers users a comprehensive set of integrative genome science technologies such as state-of-the-art sequencing technologies, advanced genomics data science and informatics, epigenomics, single-cell genomics, DNA synthesis, metabolomics and organism engineering, including plants. This suite of capabilities enables users to derive deeper biological insights, and the JGI is an essential resource for many BER-funded programs and projects.

Understanding the biology of the environment. The Ecosystems and Networks Integrated with Genes and Molecular Assemblies (ENIGMA) project aims to achieve a multiscale, causal, and predictive understanding of microbial biology and the reciprocal impact of microbial communities on their ecosystems. Led by the Lab, this BER-funded Science Focus Area (SFA), is a multidisciplinary, multi-institutional consortium with a focus on the impact of environmental stresses in microbial ecology, in particular high nitrate levels. Efforts are currently focused on studying subsurface microbiomes at the Bear Creek aquifer in the Oak Ridge Reservation, a site with complex contaminant gradients, whose fate and complex dispersal flow paths are mediated by the activity of subsurface microbial communities. To understand these processes, we perform field experiments to measure the dynamics of geochemical processes and the assembly and activity of microbial communities. A unique array of culturing, genetic, physiological, computational, and imaging technologies are used in the lab to understand and model gene function and material flow. Through these studies, researchers are delivering a mechanistic understanding of complex environmental bioprocesses and ecology.

In a complementary project the Microbial Community Analysis and Functional Evaluation in Soils (m-CAFEs) SFA interrogates the function of soil microbiomes with critical implications for carbon cycling and sequestration, nutrient availability, and plant productivity in natural and managed ecosystems. m-CAFEs targets molecular mechanisms governing carbon and nutrient transformation in soil, with a focus on microbial metabolic networks, and looks at how changes persist throughout the ecosystem. A central goal is determining microbial functional roles at hot spots and hot moments during rhizosphere development and punctuated water events that account for a significant percentage of ecosystem carbon transformation and respiration. The m-CAFEs research is enabled by the application of new CRISPR-Cas and RNAi community editing technologies, and bench-scale fabricated ecosystems (EcoFABs) that recapitulate microbial networks observed in the field.

The development of fabricated ecosystems is needed to bridge the gap between highly constrained lab experiments and field-scale experiments that are challenging to control, allowing researchers to dissect microbial community dynamics and effects in relevant environments. EcoFABs are small chambers with control of liquid flows and spatially defined imagining capabilities. Also under development are meter-scale enclosed environments – EcoPODs – that allow direct and intensive monitoring and manipulation of replicated plant-soil-microbe-atmosphere interactions over the complete plant life cycle. EcoPODs are being employed to create an in-lab replica of field conditions as part of the BER-funded Twin Ecosystems project. This project is implementing laboratory and field 'twin' ecosystems that use sensors and autonomous controls. This leverages unique resources in fabricated ecosystems at Berkeley Lab, PNNL's field ecology expertise and resources, EMSL's sensor and omics expertise, JGI's lab automation and omics expertise, and CAMERA's mathematical and computational expertise.

Protecting the environment and ourselves. We leverage our historically strong biomedical research programs to develop an integrative and predictive understanding of responses to environmental challenges. We investigate the role of non-coding genomic regions in the regulation of gene expression in disease, and neurological and cellular development. We use advanced imaging techniques to understand the localized expression and accumulation of proteins, such as regional accumulation of the tau and beta amyloid proteins involved in the progression of Alzheimer's Disease, to elucidate the mechanisms underlying the progression of neurological diseases. More recently, the IARPA-funded Targeted Evaluation of Ionizing Radiation Exposure (TEI-REX) program is discovering, characterizing, and modeling molecular biomarkers associated with a variety of ionizing radiation events from minimally- and non-invasive samples that can be collected unobtrusively and painlessly.

Through these programs, and leveraging our strengths in environmental and biomanufacturing research, we are positioned to advance foundational research in the detection and mitigation of biological threats for new biosecurity and biodefense programs. Foundational research to understand the genetic networks that control susceptibility to cancer, funded through DoD's Breast Cancer Research Program, can provide the basis for understanding and mitigating health challenges resulting from aggregate or distinct environmental exposures. Reflecting the early days of Berkeley Lab and the research efforts established by John Lawrence, we advance knowledge in biomedical sciences, through NIH support, for DNA repair processes, cancer biology, radionuclide chelation, diagnostic imaging, and aging.

Data and computation supporting biological research. The JGI designs and supports several Flagship Data Portals (IMG, Mycocosm, Phycocosm. Phytozome, Secondary Metabolites Collaboratory, Genome, and Data) that provide access to JGI's unique data and integrative analysis capabilities. These resources support more than twenty thousand unique users annually. The web services infrastructure and sequencer data storage is housed in the IGB server room. JGI manages more than sixteen petabytes of data and a complementary metadata repository housed in a distributed network of data centers across DOE including NERSC, LBL IT, EMSL, and OLCF. The JGI-owned Dori computing cluster consists of 100 nodes with 512GB of memory attached to a 2 PB VAST storage system tailored to bioinformatics workloads. JGI is also able to leverage NERSC, EMSL's Tahoma system, and cloud computing through the JGI Analysis Workflow Service (JAWS) to run production data processing pipelines across a distributed computing infrastructure.

KBase is an open source, open access software and data platform designed to address the grand challenge of systems biology – predicting and designing biological function from the biomolecular (small scale) to the ecological (large scale). It enables researchers to collaboratively generate, test, compare, and share hypotheses about biological functions; perform large-scale analyses on scalable computing infrastructure; and combine experimental evidence and conclusions that lead to accurate models of plant and microbial physiology and community dynamics. The KBase platform now provides researchers with hundreds of analysis tools spanning QA/QC of sequencing reads, genome and metagenome assembly and annotation, basic comparative genomics, RNA-seq analysis, and metabolic modeling of organisms and their communities.

The NMDC provides researchers with unique capabilities for microbiome analysis aligned with the FAIR Data Principles. Led by Berkeley Lab, the NMDC supports three core infrastructure elements: (1) the Submission Portal to support collection of standardized study and biosample information; (2) NMDC EDGE, an intuitive user interface to access standardized bioinformatics workflows; and (3) the Data Portal, a resource for consistently processed and integrated multi-omics data enabling search, access, and download. Our community building includes partnerships with DOE user facilities and resources; coordinating with interagency programs like NSF's NEON; and our flagship engagement programs, the Ambassadors and Champions.

BER is the primary sponsor of the research in this Biological Systems Science Core Capability; others include EERE, NIH, IARPA, DoD, industry, and other SPP. It supports DOE's mission to obtain new molecular-level insight for a fundamental understanding of biology in relation to the environment; how biology can be exploited for cost-effective bioenergy solutions; make discoveries for DOE's needs in climate, bioenergy, and subsurface science; and coordinate bioenergy, climate, and environmental research with applied technology offices.

Biological and Bioprocess Engineering

Our strengths in biological systems science are complemented by unique capabilities for biological and bioprocess engineering to translate fundamental science discoveries to use-inspired solutions for energy and environment. We have world-renowned capabilities in synthetic biology, technology development for biology, and engineering for biological process development. By leveraging resources such as the JGI, KBase, NMDC, the ALS, the Molecular Foundry, and NERSC we develop the new technologies and processes needed to create renewable fuels and chemicals, remove environmental contaminants, and support capture and storage of carbon in soils and in durable products from point sources and the atmosphere.

The Joint BioEnergy Institute (JBEI) is one of the four DOE Bioenergy Research Centers whose mission is to advance science, engineering, and technology to support the maximum possible conversion of carbon from lignocellulosic biomass to liquid transportation fuels and bioproducts. JBEI has successfully altered biomass composition in bioenergy crops, demonstrated that new solvents can deliver near-complete dissolution of plant biomass to facilitate conversion to high yields of fermentable sugars and lignin-derived intermediates, and engineered microbes to produce energy-rich biofuels and advanced bioproducts. The production of commodity and specialty biochemicals from biomass brings environmental and economic benefits, as well as the possibility of producing diverse, novel molecules through biological conversion pathways that are challenging or currently impossible using chemical synthesis approaches. Industry realizes the economic potential of such breakthroughs, and licensed technologies and startups from JBEI's activities are steadily coming out of the strong industrial affiliate program. One of JBEI's strengths is its deep and enduring ties with industry to drive the use-inspired research that will propel the bioeconomy forward, including interactions and funded projects with companies including Protein Evolution, Erg Bio, Aemetis, Mitsubishi, Novozymes, Lygos, SAPPI, and Total. Since its inception, JBEI has launched 13 startups and engaged in multiple projects with industry to catalyze the bioeconomy.

The Advanced Biofuels and Bioproducts Process Development Unit (ABPDU), funded by DOE EERE, provides capabilities for initial scale-up of biomanufacturing processes, including biomass pretreatment, saccharification, and fermentation coupled with product recovery and purification. In collaborations with national labs and with industry, this facility develops new and optimizes existing processes for biofuels, biomaterials, and biochemicals. The ABPDU recently added gas fermentation equipment in the form of pressurized bioreactors to enable C1 biomanufacturing studies and projects with industry. To date, the ABPDU has worked with >80 companies, helping them develop technologies to the point of investor funding. The facility has been instrumental in developing and optimizing new processes for bio-based chemicals and materials. Our partners have brought eight products to market as a result of ABPDU's process improvements and optimizations. Core strategic industry partners include Bolt Threads, Impossible Foods, Huue, Checkerspot, Zymochem, Pow.Bio, Recology, BEAM Circular, Lygos, Kiverdi, and Mango Materials.

The Agile BioFoundry (ABF) supports the transformation of manufacturing practices through advanced bioconversion technologies enabling a bio-based economy. Led by Berkeley Lab and funded by EERE's Bioenergy Technologies Office, the ABF leverages capabilities across the complex; its partners include ANL, LANL, NREL, ORNL, PNNL, and SNL. The ABF integrates computer-assisted biological design, advanced metabolomics and proteomics techniques, ML, techno-economic and sustainability analysis, and process integration to optimize biological process design and develop methods for predictable scaling. The consortium engages with stakeholders through its industry engagement team and its advisory board of experts from companies in the biomanufacturing community. The ABF has had multiple collaborative projects with biomanufacturing industry leaders, including those jointly sponsored by the National Science Foundation. Examples of industry projects include those with C16 Biosciences, Lygos, Lanzatech, POET, Protein Evolution, and Pow.Bio.

While BER and EERE are the primary supporters of the Biological and Bioprocess Engineering Core Capability at Berkeley Lab, there are other key sponsors including industry and other SPPs. It supports DOE's objectives by applying understanding of complex biological systems to design systems; by creating technologies for bioenergy and bioproduct production; by increasing commercial impact through the transition of national lab-developed technologies to the private sector; utilization of national lab facilities and expertise; and demonstration and deployment for the economic, energy, and national security.

Earth, Environmental, and Atmospheric Science

Berkeley Lab's internationally recognized programs have made major advances in understanding how climate change affects atmospheric processes, climatic extremes, and ecosystem-climate interactions at local to global scales. These advances are complemented by novel observations of terrestrial ecosystem responses to climate-related disturbances and land-use change. LBNL helps DOE produce the most advanced models of the Earth system and project potential physical and biogeochemical impacts of climate change.

Supported by BER, the merged LBNL-SLAC ***Watershed Function SFA*** studies the responses of mountainous watersheds to extreme hydroclimatic events and quantifying traits across microbial to watershed scales. BioEPIC technologies (EcoSENSE, SMARTSoils testbed) enhance data-model integration, focusing initially on evapotranspiration and nitrogen cycling. LDRD investments catalyzed EcoSIM model development. Integration with ATS by the SFA this year will create the first trait-based, ecosystem hydrobiogeochemical model (ATS-EcoSIM) to predict ecosystem disturbance responses. AI surrogate models trained on these simulations and developed with ECRP support will be evaluated for applicability to new watersheds. BER investments in software design projects (IDEAS) and HPC

(ExaSheds) support these efforts. Machine Learning and AI also underpin LDRD research on coupled biological, environmental, and climatic systems.

This expertise in hydrobiogeochemical dynamics is being leveraged for challenges in agriculture, environmental remediation, harmful algal blooms, and wildfire impacts on water quality. For DOE's Environmental Management and Legacy Management, we are applying AI for long-term monitoring of contaminated DOE sites, assessing the resilience of DOE infrastructure to climate change, and exploring sustainable uranium removal from former mills.

We conduct internationally recognized research on ecosystem responses to climate change and ecosystem-climate feedbacks. The Belowground Biogeochemistry SFA advances understanding of soil organic matter dynamics using novel field experiments. Deep soil-warming experiments at Blodgett Forest and Point Reyes are combined with process–rich modeling in this SFA's multidisciplinary ModEx approach, to understand and predict biogeochemistry in soil-plant-microbe systems and the role of soils in global change.

Berkeley Lab is a major contributor to DOE's flagship E3SM, including improved representations of the soil, plant, and abiotic processes that constrain the global carbon budget. Within E3SM's land model (ELM), LBNL has developed an extensible and scalable three-dimensional hydrology and thermal module, a multiphase reactive transport solver, and the Functionally Assembled Terrestrial Ecosystem Simulator (FATES) dynamic vegetation model. To simulate interactions among human-relevant energy, food, and water resources with climate change, LBNL has included an integrated assessment model component to E3SM, to be coupled with FATES. This will enable projections of U.S.-relevant emissions pathway scenarios using state-of-the-science treatments of physical, chemical, and biogeochemical processes. LBNL co-leads the RUBISCO SFA, which evaluates biogeochemistry-climate interactions in E3SM and other ESMs. Our RUBISCO group studies permafrost carbon dynamics, land-use change, wildfire, and consequent carbon–climate feedbacks. LBNL analyzes CMIP6 models, using the SFA's ILAMB benchmarking package.

The LBNL-led flagship NGEE-Tropics project is delivering cutting-edge representations of tropical forest carbon balance and climate feedbacks in E3SM. Its pan-tropical field research and modeling explore controls on tropical forests' carbon, water, and energy fluxes, crucial for accurate climate projections. NGEE-Tropics leads development of FATES, a forest demography model, bringing a mechanistic and trait-based approach to vegetation dynamics and climate responses in E3SM. FATES is also being applied in NGEE-Arctic and in a DOE Office of Technology Transfer-supported public-private partnership on carbon sequestration.

As a key partner in NGEE-Arctic, Berkeley Lab contributes expertise in geophysics, biogeochemistry, microbial ecology, and modeling of ecosystem-climate feedbacks. We use custom sensing systems to quantify permafrost thaw controls with unparalleled resolution. In the upcoming Phase 4, we aim to reduce uncertainties in modeled hydrological and thermal processes, soil biogeochemistry, wildfire, and plant dynamics in ELM-FATES.

Three BER ECRP award projects benefit greatly from EESA-Biosciences collaborations and DOE user facilities. One project, led by Neslihan Tas, identified novel permafrost microorganisms, examined their responses to changes in soil moisture and temperature, and showed how permafrost microorganisms acclimate and take advantage of permafrost thaw. A second project, led by Nicholas Bouskill, examined the mechanisms underpinning the microbial ecosystem's response to drought in tropical forest soils, and the feedback to the carbon cycle. They found that, across multiple scales (from individual microbes to complex communities in tropical forests), anabolic traits are central to maintaining microbial activity and mitigating drought stress, and that the expression of these traits strongly affects soil carbon stability. The third project, led by Kolby Jardine, characterized the metabolism of cell wall ester modifications and volatile intermediates and their roles in plant physiology in a biofuel tree species. He found that manipulating the cell wall metabolism provided a basis for engineering plant resistance to environmental extremes. The project benefits from JBEI and EMSL collaborations to address BER's goal of developing renewable bioenergy resources.

Our research on wildfire and other disturbances leverages BER-developed capabilities and ECRP support, including investigations of forest vulnerability and surface and groundwater impacts. The Lab conducts unique watershed-based investigations of wildfire impacts on water quality and landslide risks to help inform decision-making by regional water districts and State resource agencies. Additionally, we apply ML to integrate wildfire prediction into E3SM.

Berkeley Lab's AmeriFlux Management Project (AMP) serves a network of 645 sites that measure ecosystem-atmosphere fluxes of carbon, water, and energy, as well as scientists worldwide using AMP's high-quality data products. To serve a growing network, AMP is increasing data automation and fostering engagement and career development through multi-faceted outreach across the Americas. AMP supports BER priorities, including urban integrated field laboratories with special loaner instrument packages. AMP data products (i.e., FLUXNET) are enabling Earth system model improvement and have had 75,000 site-downloads by more than 10,000 users.

ESS-DIVE hosts environmental data from ESS-sponsored research, experiencing robust growth in datasets and users, evident from its >100 participants annual workshop. It enhances data management, sharing, and large data storage for key ESS projects. Collaborating with NMDC, KBase, and EMSL, ESS-DIVE has launched multi-lab initiatives to integrate biological and environmental sciences data.

Berkeley Lab is advancing AI and sensing for comprehensive quantification and accounting of biofuel soil carbon. The PECTIN ECRP project advances plant cell wall research for bioenergy. The Lab's ROOTS and SMARTFARM teams lead new root sensing development and the integration of crop field data to generate gold-standard datasets and develop ML-based scaling approaches for biofuel carbon MRV. We contribute to other BER AI and data initiatives, including the AI4CH4 and BERAC unified data workshop reports.

Berkeley Lab leads significant projects for Atmospheric System Research (ASR) and Atmospheric Radiation Measurement (ARM) programs. The Surface Atmosphere Integrated Field Laboratory (SAIL) Campaign, concluded in 2023, deployed the second ARM Mobile Facility alongside NOAA and NSF initiatives in the Upper Gunnison River. The Lab uses these data to explore precipitation patterns in the basin and snowpack dynamics relevant for mountain regions worldwide. Our ASR probing of convection and land-atmosphere coupling is revealing discoveries about aerosols in Amazon convection and underexplored radiation processes in extreme storms. Our Clouds Optically Gridded by Stereo system provides novel data on cloud characteristics at the ARM Southern Great Plains (SGP) site, aiding the improvement of cloud models. The mentored eddy flux and trace gas systems at SGP and SEUS enable modeling of aerosol, cloud, and land-surface processes.

The Calibrated and Systematic Characterization, Attribution and Detection of Extremes (CASCADE) SFA aims to understand how and why extreme weather and climate events have changed in the observational record and how and why they might change in the future. CASCADE successfully synthesizes the team's interdisciplinary expertise in physics, statistics, and atmospheric and computer science to tackle large scientific questions that require innovative datasets, computational tools, and statistical methods.

BER is the primary sponsor of research in the Lab's Earth, Environmental and Atmospheric Science core capabilities. These capabilities support DOE's mission to advance predictive understanding of coupled biological, environmental, and climate systems.

Computing and Computational Sciences

Advanced Computer Science, Visualization and Data

The Lab is now at the forefront of the exascale computing era, with proven expertise and leading research that have significantly contributed to the realization of exascale capabilities and the successful completion of the Exascale Computing Project. We have made advancements in performance analysis and algorithms, programming languages, systems, and tools, and have explored alternative computer architectures that have revolutionized future computing potential. Many of our computer science advances in the Exascale Computing Project are poised to extend far beyond the Project and impact a broad spectrum of computational science frontiers. Our efforts in parallel I/O, machine learning (ML), scientific workflows, user experience, and data-intensive visualization and analysis have been integral to harnessing the power of exascale computing. Our scalable solutions for scientific data, including management, curation, quality-assurance, distribution, and analysis, and performance-analysis tools address the broad computational challenges faced by those who seek to understand experimental and observational data coming from environmental sensors, genomics, light sources, and cosmological observations, etc.

Our established leadership in global address space programming provides a productive, scalable, and accessible environment for data analytics and data-driven science. Global address space presents a distributed memory machine as a unified memory architecture where all memory is easily accessible via familiar language interfaces such as C++ and Python (UPC++ and PyGAS). Critical exascale era applications such as ExaBiome and ExaGraph/GraphBLAS are being extended into discrete event simulator frameworks for agent-based modeling of transportation and the power grid.

Berkeley Lab is directing expertise towards an emerging frontier of energy-efficient computing. Building on our longstanding expertise with hardware architecture and codesign, we are actively pursuing post-Moore's law supercomputing performance enhancements through forward-thinking architecture and algorithm co-design, in close collaboration with our industry partners. In Project38, our researchers are addressing critical needs of DoD and DOE in integrating heterogeneous blocks of chip designs in vendor-agnostic architectures tailored to HPC. We are also leading research in system-level approaches to resource disaggregation to more efficiently use connected data and compute center components. We have recently co-designed a custom dataflow accelerator for materials science HPC workloads on coarse-grained reconfigurable architectures, which show significant gains over the latest GPUs.

Berkeley Lab develops cutting-edge ML and AI capabilities, focusing on high-performance parallel I/O, storage, and data-intensive visualization and analysis. Our work on ML for advanced imaging automates analyses and processes such as the modeling and characterization of silicon fibers, cells, protein nanorods, and weather phenomena. Our exascale-ready topological algorithms enhance ML pipelines and provide stable feature descriptors for automatic analysis and decision-making. Our scalable infrastructure for in situ visualization enables scientific discovery. Our analytics for large simulation and experimental data exploits diverse parallel schemes and heterogeneous architectures, as well as edge computing and new technologies (e.g., FPGAs). Our work enables efficient HPC applications, delivering functionality, predictability, and high transfer rates for the evolving storage hierarchies of current and future HPC systems, through advances in parallel I/O, querying, data compression and storage management.

The Lab is a pioneer in scalable workflow solutions for scientific data, including meta-data generation, management, curation, quality-assurance, distribution, usability, and analysis. The growth in scientific data volumes has resulted in a need to scale up processing and analysis pipelines using HPC systems. Our efforts bring together core technologies based on the Jupyter Platform to create interactive, reproducible analytics at scale on HPC systems. Our work in HDF5 is expanding its impact on data across the science areas that benefit from improved organization, performance, and search. Our crosscutting user experience (UX) work helps to better understand the critical needs in individual scientific areas and translate them into requirements to focus research and development. Projects like STRUDEL advocate for and advance the inclusion of UX practices & tools in scientific software development.

Berkeley Lab is a leader in developing software to enhance, troubleshoot and debug performance of complex, distributed scientific applications. The PERFormance Service Oriented Network monitoring ARchitecture (perfSONAR) application is deployed at over 2,000 sites worldwide. Our researchers are piloting a model-based approach to allow scientific workflows to orchestrate end-to-end network paths via optimized data-transfer nodes. We are also exploring the application of ML techniques on network traffic prediction to optimize traffic engineering and routing of large scientific flows.

We are pursuing a comprehensive strategy for edge computing and in situ data processing at data sources – a crucial technology to address the increasing data volumes from new experimental facilities. We are prototyping edge-computing deployments at an ALS beamline, NCEM, and an innovative edge computing/load balancing project with JLAB.

ASCR provides the primary support for this Core Capability, with additional support from BER, EERE, IARPA, ARPA-E, LPS, NSF, and ARO, and significant benefits accrue for all SC offices and other elements of DOE, as well as strategic partners. This capability supports SC’s mission to deliver computational and networking capabilities that enable researchers to extend the frontiers of science and to develop networking and collaboration tools and facilities that enable scientists to work together and share extreme-scale scientific resources.

Applied Mathematics

Berkeley Lab has world-leading capabilities for developing mathematical models, algorithms, tools, and software for addressing important scientific challenges for the DOE. These capabilities are supported by highly recognized experts in applied mathematics, many of whom are SIAM Fellows and/or members of NAS and NAE. Berkeley Lab applied mathematicians are internationally recognized for their invention of new mathematics to tackle the challenges of transforming experimental data from DOE’s scientific user facilities into understanding, their ground-breaking research on modeling and simulation of complex physical processes, bringing the power of predictive simulation to a broad range of science areas, and for their leadership in the development of highly performant numerical linear algebra algorithms and software capable of harnessing the power of the DOE’s leading edge scientific computing platforms. Berkeley Lab’s applied mathematics research is a point of leverage for science impact during the exascale computing era. The algorithms and models are designed for parallel scalability and to reduce expensive data movement, with special attention to the hardware features emerging in next generation systems. These algorithms and models are also instantiated in open-source software libraries and frameworks that are used at NERSC and other centers across DOE.

The Center for Applied Mathematics for Energy Research Applications (CAMERA), an integrated, cross-disciplinary center, develops the fundamental new mathematics required to support DOE user facilities. CAMERA scientists have created breakthrough mathematics that are being used at DOE facilities and around the world. In recent years, this has included a focus on novel methods that will allow scientists to take advantage of current and upcoming synchrotron upgrades at several DOE facilities. CAMERA researchers also recently founded the Community for Autonomous Scientific Experimentation (CASE), which brings together hundreds of researchers accelerating the adoption of methods to enable autonomy and accelerate discovery in the experimental and computational sciences. CAMERA scientists are engaging with BER-funded projects, including the EcoTwins project, which builds, measures, and analyzes plant structures grown in a controlled environment and the RESTOR-C energy earthshot center, which is pursuing precision biology for carbon capture.

Berkeley Lab also leads the Sparsitute, one of DOE’s four Mathematical Multifaceted Integrated Capability Center (MMICCs) and a key DOE resource that provides an integrated treatment of the sparse computations that underlie many applied mathematics workflows in science and engineering. Our Sparsitute researchers are innovating combinatorial scientific computing, high-performance graph analysis, sparse matrix computations, and computational biology.

Modeling and simulation are a cornerstone of the Lab’s applied mathematics research program. Our researchers develop state-of-the-art techniques to understand and predict continuous and discrete parts of complex physical systems and their dynamic behavior. Researchers use these mathematical methods to model and simulate physical phenomena such as fluid flows, electromagnetic devices, materials, future energy, and quantum materials, and to achieve unprecedented fidelity levels at all scales, from the very large (structure formation of our universe) or very small (quantum chemistry, microelectronics design) to the very fast (particle physics) or very slow (climate change and stellar evolution).

The Lab is known for developing models and simulations that perform well at all scales, including current and next-generation massively parallel computer architectures. For example, our AMReX software framework for adaptive mesh refinement is being leveraged by a wide variety of exascale computing projects, including recent recognition with a Gordon Bell prize for the design of laser-based electron accelerators with groundbreaking mesh-refined particle-in-cell simulations. AMReX is also a core part of DOE’s energy earthshot center FLOWMAS, which develops advanced modeling and simulation for floating offshore windfarms.

Berkeley Lab has recognized leadership in developing scalable solvers for a variety of systems of equations. For example, Lab mathematicians have designed novel techniques for solving large sparse linear systems that are a key computational kernel in many multiphysics and multiscale simulations. These techniques are implemented in state-of-the-art software packages such as SuperLU and STRUMPACK, both of which have seen significant enhancements during DOE's exascale computing project to ensure performant use on current and emerging parallel supercomputers.

Berkeley Lab has a growing program in the foundations of machine learning. Researchers are innovating randomized algorithms, which allow one to compute approximate solutions to problems in linear algebra and beyond more efficiently than deterministic algorithms. A key part of our leadership is the development of standards that form the basis for the RandBLAS and RandLAPACK software libraries and facilitate broad user adoption of randomized algorithms. Lab researchers are also developing state-of-the-art algorithms for mathematical and numerical optimization, with particular capabilities in Bayesian, iterative projection-based, topological, and derivative-free optimization.

These capabilities and their applications are sponsored primarily by ASCR, with support from other DOE program offices and SPP. They support DOE missions in fusion energy science, biological and environmental research, high-energy physics, nuclear physics, accelerator technologies, basic energy sciences, environmental management, and fossil energy. They also support the development of mathematical descriptions, models, and algorithms to understand the behavior of climate, living cells, and complex systems related to energy and environment DOE mission areas.

Computational Science

Berkeley Lab is a leader in connecting applied mathematics, computer science, and data science with research in many scientific disciplines, including biological systems science, chemistry, climate science, materials science, cosmology, astrophysics, particle and nuclear physics, subsurface science, environmental management, and all Core Capability areas described in this Plan. The Lab has effectively integrated these research areas in conjunction with HPC resources to obtain significant results in science and engineering.

Within the national lab network, Berkeley Lab plays a very significant role in the Scientific Discovery Through Advanced Computation (SciDAC) Program, with the largest participation across the DOE Laboratory complex. The SciDAC program is designed to enable cutting-edge computational research into a broad range of problems where teams of applied mathematicians, computer scientists, and physical scientists are needed to make substantial progress. In addition to providing senior leadership and leveraging our Applied Math and Advanced Computer Science, Visualization and Data core capabilities in the two SciDAC Institutes, FASTMath and RAPIDS2, we are involved in many of the science partnership projects. FASTMath is focused on developing robust mathematical techniques and numerical algorithms and delivering these as capabilities via well-engineered highly performant software to run efficiently and scalably on current and next-generation supercomputers. FASTMath works closely with domain scientists to leverage our mathematical and machine learning expertise and deploy our software in large-scale modeling and simulation codes. RAPIDS2 is focused on enabling HPC as a tool for discovery across multiple domains. RAPIDS2 has major efforts in scalable data analysis; developing tools for heterogeneous computer architectures; performance modeling and application tuning; scientific data management, including performance I/O, and autonomous workflows; and machine learning/artificial intelligence methods, particularly surrogates.

Furthermore, we have played key roles in the Co-Design Centers and Application Development subprojects in the Exascale Computing Project (ECP), supporting computational science development for exascale systems across many disciplines. Our work in leading several applications has delivered several successes. The ExaStar project focused on accurately simulating coupled hydrodynamics, radiation transport, thermonuclear kinetics, and nuclear microphysics for stellar explosion simulations. Earthquake Simulation (EQSIM) advances the understanding of the physics of earthquake processes, data collection, and data exploitation to help advance earthquake hazard and risk assessments. The Subsurface project models the complex multiphysics processes occurring at multiple scales, from the micro to the kilometer scale, in high-resolution reservoir simulations to overcome the failure of a wellbore for CO2 sequestration in saline reservoirs. WarpX is developing an exascale application for plasma accelerators that enables the exploration of outstanding questions in the physics of the transport and the acceleration of particle beams in long chains of plasma channels. Addressing these fundamental research questions will lead to the design of economical plasma-based colliders and enable the characterization of the accelerator before they are built.

Berkeley Lab leads the data processing and curation aspects of the BER-sponsored AmeriFlux Management Project and NGEE-Tropics, described in the *Earth, Environmental and Atmospheric Science* core capability, which focus on distributing high quality, standardized datasets to a variety of end users. We also lead the ESS-DIVE data repository.

By leveraging all our core capabilities, we have grown multi-disciplinary teams focused on Quantum Information, Science, and Technology that are engaged in a full spectrum of activities including: developing and deploying quantum computing hardware based on superconducting qubits; developing a comprehensive quantum computing software stack; and prototyping a three-node quantum network. Our work on superconducting qubits focuses on all aspects of design, co-design, fabrication, characterization, operation fidelity optimization, and deployment of superconducting quantum computing processors. We lead AIDE-QC, building software and novel algorithms for leading edge advances such as limiting quantum operations depth and the number of qubits needed to allow for larger systems to be run on quantum computers for longer periods of time. In our explorations of quantum networking, we are building a prototype three-node quantum network featuring trapped-ion and color-center qubit modalities over a 5km-long fiber optic link. The Lab is also developing novel quantum algorithms and frameworks to realize the potential of quantum computing beyond the physical sciences.

Collaborations connected with DOE's EFRCs and JCESR continue, targeting quantum materials, materials design and synthesis, gas separation and storage, and batteries. The mathematical methods and computational tools developed have applications in many other scientific domains; we are deploying some of these to EERCs such as CIWE, to advance ionomer-based water electrolysis, and Terraforming Soil to accelerate soil-based carbon drawdown.

While ASCR is a key source of support for this Core Capability, all SC offices sponsor computational applications and software development for their respective areas of science. Others such as NASA and DoD also benefit from and contribute to the research effort. This Core Capability supports all of DOE's science, energy, environmental and security missions. For SC's discovery and innovation mission, it provides the mathematical models, methods, and algorithms to enable the accurate description of complex systems.

Cyber and Information Sciences

Berkeley Lab conducts research into a broad array of cyber and information sciences (secpriv.lbl.gov) including security for scientific and high-performance computing environments, high-throughput networks, "open science" computing workflows, and the power grid. Examples include the development of RISC-V based hardware trusted execution environments (TEEs) appropriate for HPC to isolate data and computing from cyberattacks and leveraging differential privacy to enable privacy-preserving analysis and ML model training without exposing raw data. Ongoing, current, and future work in trustworthy hardware/software co-design for "edge to HPC," scientific computing, from architecture to OS and runtime, is being performed to ensure both the integrity and the confidentiality of scientific computing in the face of accidental or malicious threats, without significant cost to either usability or performance. Gem5-based hardware architectural simulations are being constructed to enable security and performance design space exploration, and formal verification is being applied to prove correctness of protocols, APIs and key elements, and interfaces.

Novel research techniques are also leveraging the "physical" aspects of cyber-physical systems, such as the power grid, to detect cyber-attacks against equipment controlling this grid. Because these systems must act within the laws of physics, these properties can be exploited to detect malfeasance or failing sensors. In two current power grid cybersecurity projects, we are leveraging AI to automate the use of defensive control logic to maintain power grid stability in the face of solar inverters or grid-attached storage, with the development of the PyCIGAR software being integrated into the NRECA Open Modeling Framework (OMF). With LDRD funding, AI is also being examined for its vulnerabilities by developing means to detect and mitigate attacks on complex, automated, AI-driven cyber-physical systems, including power grid control elements and synthetic biology "self-driving labs."

The Lab serves in prominent leadership roles in cyber sciences, including with IEEE Security & Privacy; the NSA Science of Security Distinguished Expert committee; the DARPA Information Science and Technology (ISAT) Study Group, where it is leading a "cyber moonshot" study on accelerating security of systems with emerging technologies; and the DOE Securing Energy Infrastructure (SEI) Executive Task Force Technical Project Team (TPT) on Developing a National Cyber-Informed Engineering (CIE) Strategy.

In addition to our cybersecurity research, ESnet provides an integrated set of cyber security protections designed to efficiently protect scientific and operational data while enabling cutting edge research. ESnet's unique 100G SDN network testbed provides an international research platform for cybersecurity research at all network layers. ESnet's newly funded project from NSF, FABRIC, promotes cybersecurity research at scale. The Lab leads the world in developing technologies to optimize science data transfers across local and wide-area networks. ESnet's "Science DMZ" model champions an architecture to transfer data securely across the national and international research and education community. This model continues to be developed since many data sets have special privacy and security concerns. In particular, the "Medical Science DMZ" was designed to help address the concerns of HIPAA/HITECH while supporting the high-performance needs of big data science.

Formerly known as Bro, the Zeek network security analysis framework started at Berkeley Lab in 1995 to monitor network traffic in open scientific environments. It is now deployed at National Labs, major universities, supercomputer centers and, particularly through the Corelight commercial spinoff, *Fortune 100* companies. Starting in 2010, Zeek went through a major overhaul to support next generation networks at 100Gbs, with one of the first production 100Gbps deployments at the Lab in 2015. Currently, ESnet is exploring novel techniques to apply Zeek on a WAN environment where geographically dispersed, asymmetric traffic breaks the assumptions of most network security monitors. New technologies in ESnet6 will potentially provide the building blocks to solve this security challenge and more at scale. ESnet maintains leadership both formally on the Zeek management team, and with the many technical contributions back to the project.

Berkeley Lab also co-leads Trusted CI, the NSF Cybersecurity Center of Excellence (https://trustedci.org), where it has had leadership roles in recent years in directing the development of groundbreaking reports on profiling cybersecurity risks to open science, evaluating trustworthy data,, identifying issues in data confidentiality and privacy in scientific computing, and the state of software assurance in research computing, and the security of *operational technology* (or *cyber-physical systems*), such as sensor and control elements, used by major scientific research facilities. It has also participated in one-on-one engagements with developers of software used in research computing.

ASCR, the CEDS R&D and CEDS Threat Mitigation programs in the CESER office (including GMI/GMLC), and NSF are the primary supporters of this Core Capability, as well as recent DOE SETO, DHS S&T, CSR and LDRD support, and with additional previous support from EERE/BTO, OE, OCIO, NNSA, NSF, and NSA/LTS. Significant benefits accrue for all SC offices and other elements of DOE, as well as strategic partners such as the DoD, the IC, and NIH. This capability supports SC's mission with disciplines, technologies and practices designed to protect, analyze, and disseminate information from electronic sources, including computer systems from edge devices to HPC, computer networks, sensor networks, and network-connected scientific instruments and user facilities.

Fundamental Physics

Particle Physics

Berkeley Lab has a long record of excellence in particle physics and cosmology, with two premier programs: one in the Energy Frontier on the ATLAS experiment, with many contributions and leadership roles over three decades; and one in the Cosmic Frontier, where the Lab is leading next-generation projects in both dark energy, dark matter and a future ground-based CMB polarization experiment to study inflation. In addition, the Lab has a small but focused effort in the Intensity Frontier, where we are making key contributions to the Mu2e and DUNE Near Detector experiments at Fermilab.

Berkeley Lab's experimental program is fully aligned with the 2023 P5 roadmap. It is enabled and enhanced by our traditional strengths in instrumentation and detector R&D, expertise in QIS, microelectronics, software, and computation including AI/ML, enhanced by our proximity to NERSC and connections to the Computational Sciences Area, and a strong theory group in partnership with UC Berkeley. Strong connections with UC Berkeley bring faculty and students to collaborate in our experimental HEP programs as well, providing significant leverage and opportunities for enhanced funding support through fellowships and other non-DOE resources.

On the Energy Frontier, Berkeley Lab is playing leading roles in the pixel and silicon strip detectors for the new all-silicon ITk detector for HL-LHC ATLAS upgrade project, (including major contributions to the tracking reconstruction software). The Lab played a leading role in the international R&D program to develop the pixel readout ASIC and developed the silicon strip stave concept used in ATLAS. The Lab leads the Global Mechanics upgrade for the new ITk tracker in the U.S. ATLAS HL-LHC Upgrade project, which is soon reaching completion.

The Berkeley Lab ATLAS group has been making substantial contributions to Higgs, SM, and BSM physics analyses. We also play leading roles in the ATLAS software framework, and more recent efforts have focused on the applications of AI/ML and quantum computing techniques, as well as more efficiently harnessing NERSC's HPC capabilities. Over the years, the Lab scientists have held numerous leadership positions in the ATLAS Collaboration, from various Coordinator and Convenor roles to Deputy Spokesperson.

Berkeley Lab is a world-leading center for the search for dark matter. We are the lead DOE Lab for the LUX-ZEPLIN (LZ) experiment. The experiment began routine physics operations in December 2021. Berkeley Lab played many leading roles in the LZ construction project and continues a leadership role in the operations phase of the experiment. Our scientists served as spokesperson, physics coordinator, calibration coordinator, as well as leading many analysis working groups. Supported by a DOE ECRP Award, we are pursuing R&D on an LZ upgrade that would involve freezing the xenon to trap radioactive impurities and dissolving lighter species in the liquid xenon to enhance low-mass sensitivity. We are also pursuing advanced low-mass dark matter detection techniques supported by a QuantISed consortium grant to develop new quantum-enabled sensors and readout. We also lead the TESSERACT pre-project, supported by DMNI R&D funding, which aims to deploy TES readout on multiple targets. In addition, LBNL designs and oversees fabrication of skipper CCDs for the SENSEI and DAMIC dark matter experiments.

The Lab led the successful design and construction of the Dark Energy Spectroscopic Instrument (DESI), a Stage IV BAO experiment to create the largest 3-D map of the universe, with close to 40 million galaxies. DESI started its main survey in mid-2021 after commissioning and survey validation. The Lab has developed a detailed DESI operations plan and will continue to manage it during the five-year survey. Lab staff roles in DESI include Project Director, Project Manager, Project Scientist, co-Spokesperson and Operations Director. DESI is collecting data on schedule and will remain a unique spectroscopic capability at the end of the original survey. The Lab is working on a six-year extension of the program into a DESI-2 survey. We have expertise in designing state-of-the-art spectroscopic instruments and are leading R&D for a next-generation instrument.

Our critical contribution to the Cosmic Frontier has been the development of advanced detectors. Red-sensitive charge-coupled devices (CCDs) were invented in the MicroSystems Lab (MSL) and are the technology of choice for all Stage III and IV dark energy experiments, including BOSS, the Dark Energy Survey (DES), DESI, and Rubin. With initial LDRD support, pioneering R&D on Germanium CCDs is being pursued at MSL.

For the CMB-S4 experiment, our project roles include Lead DOE Lab, Project Director, Project Manager, Project Engineer, and we have L2 leadership roles in detectors, small aperture telescopes and data management. With our strength in project management, we established the project office to launch CMB-S4.

On the Intensity Frontier, the Lepton Flavor group is involved in two flagship experiments at Fermilab. On Mu2e, we lead the Software and Computing group that leads the simulation and reconstruction software efforts. We developed and currently maintain the track reconstruction software and lead the development and testing of the tracker's calibration and alignment software. We are also involved in exploring follow-on experiments to Mu2e.

The Lab has made significant contributions to the design of DUNE's Near Detector and the cold electronics for the readout of the Far Detector. We developed a novel low-power, cryogenic pixelated readout (LArPix) for the DUNE ND, producing and operating 300k read-out channels, which instrument a 2x2 demonstrator installed at Fermilab. Our leadership roles in the DUNE project include L2 leadership of the LAr TPC for DUNE ND, the ND integration and installation, and the vertical drift electronics for the Far Detectors.

Computation is a central aspect of our program. We have leading roles in software, simulation, and computing for numerous HEP experiments including DESI, LZ, ATLAS and DUNE, and leverage resources at NERSC and the Lab's Computing Sciences Area. We've also incorporated AI/ML as a tool in several of our simulation and analysis efforts and we have a growing and active cross-cutting AI/ML group that brings together scientists across the frontiers and even beyond HEP.

The Center for Computational Excellence has provided additional resources to take advantage of the NERSC HPC for HEP. We are poised to take advantage of the latest HPC advances and are working on cutting edge techniques that will benefit all HEP projects, including investigation of quantum computing algorithms.

Berkeley Lab's Theoretical Physics Group is closely integrated with the UC Berkeley Center for Theoretical Physics (BCTP) and plays a crucial role in our particle physics program, working with experimentalists to define future programs and develop strategies for data analysis.

We are proud to host, lead, and support the Particle Data Group, an essential resource for the field. PDG annually produces the most comprehensive and trusted compendium of measurements and averages in particle physics and cosmology, as well as curated reviews on many topics and techniques. PDG continues to evolve and is working on deploying tools for access to machine-readable data.

DOE's HEP is the primary sponsor of this Core Capability, with important contributions from ASCR, NNSA, NASA, NSF, and DHS. It supports DOE's missions to understand the properties of elementary particles and fundamental forces at the highest energy accelerators; the symmetries that govern the interactions of matter; and to obtain new insight on matter and energy from observations of the universe.

Nuclear Physics

Nuclear science has been a Core Capability since the Lab's inception. This capability supports DOE's missions to understand how quarks and gluons assemble into various forms of matter; how protons and neutrons combine to form atomic nuclei; the fundamental properties of neutrinos; to collect, evaluate, and disseminate nuclear data; and to advance user facilities and instrumentation that reveal the characteristics of nuclear matter. Current programs provide world leadership in heavy-ion physics, medium energy hadronic physics, neutrino research, nuclear structure, nuclear data, and include development of innovative equipment and instrumentation as well as commensurate handling of big data from experiments that produce multiple petabytes of data per year. The 88-Inch Cyclotron continues the long tradition of accelerator facilities in support of nuclear science.

The Lab plays a key role in training the next generation of the Nuclear Science workforce. NP recently funded a collaborative proposal led by our Nuclear Science Division and Workforce Development & Education Dept., and several minority-serving institutions, to develop and administer a traineeship program to diversify the workforce in Nuclear Science and STEM.

Leveraging our strong competency in silicon vertex tracking detectors using Monolithic Active Pixel Sensor technology, Lab scientists contributed to the discovery that the quark gluon plasma acts like a perfect fluid and the quenching of energetic "jets." In the current LHC run, ALICE will take full advantage of the new ITS2 tracker, whose middle layers we built leveraging this expertise. This technology has also been utilized in the MVTX tracker of the sPHENIX experiment at RHIC that we delivered to BNL in 2023. To develop detectors for the EIC ePIC experiment, we have initiated a consortium (seeded by the UC Multicampus Research Programs and Initiatives (MRPI) program), with UC Berkeley, UC Davis, UCLA, UC Riverside, LANL, and LLNL. Berkeley Lab is playing a leading role in the Silicon Vertex Tracker detector for ePIC.

NERSC HPC facilities are routinely used for reconstruction and simulation studies for STAR, and large-scale simulation efforts for ALICE. We are developing infrastructure to allow user analysis of large data sets from these experiments. ML/AI techniques are being applied across our NP programs, e.g., for ion source control, pattern recognition in radiation detection, nuclear data, as well as in analysis of complex multi-variable information in experiment and theory.

The Lab's strong nuclear theory group is advancing our understanding of and building the science cases for the Electron-Ion-Collider, notably elucidating the nature of gluonic matter and the structure of the nucleon. There is also a significant competency for using HPC to study nuclear physics, especially in subfields of quantum chromodynamics on the lattice (lQCD) and nucleosynthesis in supernovae and neutron star collisions.

The current focus in neutrino studies is the search for neutrinoless double-beta decay. We are playing key roles in the just-completed Majorana Demonstrator and the operating CUORE, LEGEND-200 and SNO+ experiments, and in the forthcoming CUPID and LEGEND-1000 experiments. We are the lead-Lab in the U.S. for CUPID and plan to provide key electronics for LEGEND-1000. We also have leading analysis roles in the recent sub-eV neutrino-mass limit of the direct measurement by the KATRIN experiment.

Our scientists study the structure of exotic nuclei, especially those with the largest neutron excess or the heaviest masses. The Lab has a distinguished history in developing new detector systems for gamma-ray spectroscopy, including Gammasphere and GRETINA. This tradition continues with the next-generation Gamma-Ray Energy Tracking Array (GRETA) which received CD-2/3 in 2020 and will be delivered to FRIB in 2025.

Our Nuclear Data program is a joint effort with UC Berkeley's Nuclear Engineering Dept. and has embarked on targeted measurements at the 88-Inch Cyclotron facility to address gaps in existing data for nuclear astrophysics, nuclear reactor design, nuclear safety, and national security. It also provides cross section and beam energy optimization information required by the U.S. Isotopes Program. This research represents part of Berkeley Lab's core capability in Nuclear Physics.

Isotope Science and Engineering

The primary research effort at the 88-Inch Cyclotron is focused on the physics and chemistry of superheavy nuclei. This program is unique in the U.S. and has recently achieved the discovery of a new isotope of element 105 (Db) using the FIONA mass separator coupled to the Berkeley Gas-filled Separator. The recent development of a high intensity 50Ti beam will enable the search for a new element (Z=120). The Nuclear Data program represents the second thrust for the 88-Inch. It is also a key facility for radiation hardness testing of electronics and materials destined for high altitude flights or space. We also lead the development of next generation ECR ion sources essential for current and future accelerator facilities, including FRIB at MSU.

Leveraging accelerator capabilities, the Applied Nuclear Physics (ANP) program is driving radiation detection applications for international safeguards, radiological monitoring, biomedical applications, and detectors for astrophysics. ANP leads the development and deployment of multi-sensor systems on mobile platforms and in city-wide static networks to enhance nuclear security. ANP has pioneered the use of contextual sensing and robotics while developing and integrating AI/ML for data analytics. Scene Data Fusion combines radiation detectors with auxiliary sensors such as video, Lidar, GPS, etc. to enable free moving radiation imaging and mapping in real time. ANP is also developing concepts for gamma-ray imaging in cancer therapy, e.g. for targeted alpha therapy and proton-beam therapy. The Semiconductor Detector Laboratory is currently producing advanced HPGe detectors for the next generation gamma-ray telescope, COSI, a NASA mission. The Scintillator Engineering Laboratory (SEL) is developing and characterizing luminescent radiation detector materials, and performance of scintillation detectors, to enable ultra-fast timing. Combined with laser-plasma induced 10 fs photon beams at BELLA this provides new detection opportunities such as single view 3D imaging.

Support for this Core Capability is primarily from NP, with contributions from NNSA, NASA, ASCR, DoD, and DHS.

Accelerator, Detector, and Fusion R&D

Accelerator and Detector Science and Technology

Since the founding of Berkeley Lab, we have pioneered transformative particle accelerators, photon sources, and detectors that extend the reach of science. We lead national programs in magnet development and large-scale simulation, are preeminent in development of compact laser-plasma based accelerators, and pioneer advanced controls, beam and light source methods, and detectors. These underlie the next generation of particle physics colliders, light and particle sources for broad applications, and applied nuclear physics.

The Berkeley Center for Magnet Technology (BCMT) develops state-of-the-art superconducting high-field magnets, undulators, and specialty magnets. The program offers an unparalleled set of "mesoscale to magnet” capabilities that are vertically integrated from the underlying materials science up through magnet design, fabrication, and testing. We contribute cabling and magnet assembly to the High-Luminosity-LHC-Accelerator-Upgrade-project (HL-LHC AUP) to increase collider physics integrated luminosity by an order of magnitude. We lead HEP high field accelerator magnet R&D towards future colliders to unveil new frontiers in physics under the multi-institutional U.S. Magnet Development Program (MDP). We deliver magnets for NP projects and are planning systems for the upcoming EIC collider.

The Lab is the world leader in ultrahigh-gradient laser-driven plasma acceleration (LPA) technology. Its BErkeley Lab Laser Accelerator (BELLA) Petawatt laser develops stages envisioned as modules of a future frontier electron-positron collider to and beyond 10 TeV. A new second beamline provides the unique capability of staging two multi-GeV laser plasma accelerator modules, a key next step to establish potential collider applications of plasma accelerators, and the flexibility to scale beyond its current 8 GeV single stage record using advanced laser guiding. Smaller lasers support bright beam generation for HEP and other applications including FELs (BES and Moore) and mono-energetic hard X-rays (NNSA). Integrated with experiments, theory and cross-program simulations develop accelerator designs and conduct integrated design of future 10 TeV colliders.

The Berkeley Accelerator Controls and Instrumentation (BACI) Program combines expertise in electron and ion acceleration, RF structures, and precision controls. It is a world leading center in advanced field programmable gate array (FPGA) based precision digital controls for accelerators, novel high average power fiber-laser technology, and qubit control. BACI plays a leading role in technology development and LLRF controls for projects across the DOE complex. Novel RF and cooling designs support future muon colliders. The HiRES beamline is a platform to test new photocathode materials, Ultrafast Electron Diffraction, and accelerator controls and diagnostics.

A cross-program ATAP initiative develops a new class of lasers combining high peak power – to drive plasma accelerators and other applications – with the high average power that enables accelerator repetition rate and active correction for precision and performance. A proof of principle system is being developed at the kHz, 0.2 Joule level with support from a DOE ECRP award and the Moore Foundation growing out of HEP, DARPA, and ARDAP research. The kBELLA initiative for a multi-Joule system is the key to precision LPA with active feedback to establish the stability, alignment, and performance essential to collider and other applications. Together with LPA development, this is important to the basis for a future collider.

Integrating magnet and BACI contributions, we were part of delivering the LCLS-II FEL and are a partner in construction of the LCLS-II HE system leading the design and manufacturing of new magnetic undulator components and contributing to beam-dynamics modeling and LLRF control systems to achieve FEL saturation at the higher beam energy. We develop tools for next generation light sources, including the high brightness APEX2 normal-conducting CW RF gun.

The Advanced Modeling Program (AMP) draws on deep collaboration among physicists, applied mathematicians, and computer scientists to develop cutting-edge computing techniques and codes for fast and accurate simulations. AMP trans-institutional leadership continues beyond DOE’s Exascale Computing Project WarpX with the DOE SciDAC Collaboration for Advanced Modeling of Particle Accelerators (CAMPA) and the Kinetic IFE Simulations at Multiscale with Exascale Technologies (KISMET) collaborations. We manage the Beam, pLasma & Accelerator Simulation Toolkit (BLAST), the backbone of a coherent ecosystem of advanced open-source codes including the 2022 Gordon Bell Prize winner WarpX.

ALS leadership in soft X-ray capabilities for the DOE-BES mission is enabled by an innovative program of accelerator physics driving machine improvements and upgrades. These upgrades have enabled ever better performance and reliability, maintaining support of almost 1,000 publications per year. ALS-Upgrade is implementing an ultrahigh brightness multibend achromat storage ring replacing the existing ALS ring supported by state-of-the-art accelerator design. It will provide diffraction-limited beams with orders of magnitude higher brightness.

Cross-program R&D is leveraging exascale simulations integrated with magnet, muon cooling and LPA experiments and expertise. This allows us to design and build the next generation of projects such as a Higgs factory, a 10 TeV pCM collider based on proton, muon, or wakefield technologies, the electron-ion collider (EIC), improvements to the Fermilab complex, and next generation light sources. Accelerator and related laser, QIS, fusion and plasma science and technology systems are complex and precision active control and intelligent parameter space exploration beyond the limits of conventional techniques are being developed using AI/ML. Together with algorithms that could leverage future quantum computers for accelerator science these are important to next generation accelerators.

The program is aligned with the P5 plan for High Energy Physics, the Nuclear Science Long Range Plan and related roadmaps. Staff engage actively in community planning and roadmaps including HEP and FES plan committees. This positions the Laboratory to develop accelerator capabilities that will enable that science.

The program develops accelerator talent, with over 55 students per year, strong campus engagement including two Adjunct Prof. in Nuclear Engineering, U.S. Particle Accelerator School teaching, ReNEW grants, Laboratory and American Physical Society affinity groups, planning activities, and an active IDEA committee.

Supported by HEP FES, BES and NP, with further sponsorship from ARDAP, ASCR, NNSA, DARPA, DoD, ARPA-E, DHS, other federal agencies and industry, cross-cutting accelerator Core Capability supports SC's missions to conceive, design and construct scientific user facilities; to probe the properties and dynamics of matter; to advance energy security; and to support cross-SC and Federal missions.

Berkeley Lab is a world leader in instrumentation to measure ionizing radiation, including scintillators and solid-state detectors that combine high density with excellent energy resolution and high-performance electronics for detector read-out. Complete detection and imaging systems are used for a variety of applications, including nuclear medical imaging, nonproliferation, and homeland security, as well as fundamental explorations of high-energy and nuclear physics. Unique materials-screening and crystal-growth capabilities in the Semiconductor Detector Laboratory enable optimized high-throughput development and design of scintillation and semiconductor detector materials. Capabilities include large-volume germanium and CdZnTe detector development emphasizing position-sensitive and low-noise systems, gamma-ray imaging using coded aperture masks, and Compton scattering telescopes.

Testing of critical space-based electronic components by the National Security Space Community (NSSC) uses heavy-ion beams at the 88-Inch Cyclotron. This facility's key national role was confirmed in an NAS study of U.S. chip testing needs and capabilities. "Cocktail beams," composed of a mixture of elements that mimic the composition of cosmic rays encountered by satellites, provide a unique national asset to greatly speed the testing of critical space-based electronic components. Other core facilities are the crystal growth facility, BELLA (where compact tunable monochromatic gamma sources are under development for NNSA and DoD), and the Semiconductor Detector Lab.

Berkeley Lab collects high-quality gamma-ray background data in urban and suburban environments with support from DHS. The Lab plans to fully characterize the gamma-ray background based on data collected from detectors in conjunction with visual imagery, light detection and ranging (LIDAR), weather, and other geospatial data that may affect distribution of incident gamma rays. We also obtain and evaluate background gamma-ray data from aerial environments containing complex topographical and isotopic variations. For example, areas of elevated radiation in the contaminated Fukushima region were recently mapped by the novel High-Efficiency Multimode Imager mounted on a remotely controlled helicopter. NNSA supports a feasibility study to explore an advanced system for data storage, as well as analysis and dissemination of gamma-ray background data, including detailed annotation. Standardization and analysis frameworks developed at the Lab for the HEP and cosmology communities will vastly increase the scope of the data being analyzed in the future. This Core Capability is sponsored by SC (NP, HEP, and BES), NNSA, and NE, as well as DHS, DoD, and the NRC. It contributes to DOE missions to integrate the basic research in SC programs with research in support of NNSA and DOE technology office programs.

Plasma and Fusion Energy Science

The Laboratory's strengths in magnets, lasers, diagnostics, accelerators and ion beam science together with exascale plasma simulations enable strong core capabilities for magnetic fusion, inertial fusion and high energy density science.

Capabilities in superconducting magnets are being applied to improve future fusion reactors. With public and private partners, we are investigating HTS for fusion, focusing on aspects common to FES and HEP as well as diagnostics essential for the application of HTS to fusion, and new HTS modeling capabilities. We lead the FES and HEP funded large-bore high field dipole for a HTS Cable Test Facility. These efforts leverage our leadership of the HEP U.S. MDP.

BELLA lasers are available to LaserNetUS users supporting high energy density science and inertial fusion energy (IFE), including the PW laser iP2 for very high intensities. Particle and photon sources developed under these programs offer unique opportunities in precision diagnostics for high energy density and fusion, as well as IFE fast ignition. Intense particle beams enable unique qubit synthesis very far from equilibrium, forming novel color center qubits with tailored properties.

We are developing techniques relevant to drivers and material testing including orders of magnitude advances in laser efficiency and repetition rate along with significant expertise in ion beams. Projects led by Fusion Science and Ion Beam Technology reinforce this, including multi-beam RF linacs made using low-cost MEMS techniques.

Leveraging accelerator simulations, the AMP leads the Kinetic IFE Simulations at Multiscale with Exascale Technologies (KISMET) collaboration. It supports SimNet, a new network of high-performance laser-plasma interaction simulation codes and teams in support of LaserNetUS as well as LLNL fusion users.

These capabilities enable strong support of both magnetic and inertial approaches to fusion, aligned with the 2020 FES Long Range Plan.

Accelerator, laser, QIS, fusion and plasma science and technology systems are complex and require both precision active control and intelligent parameter space exploration beyond the limits of conventional techniques to meet the goals of upcoming projects and initiatives. The Accelerator Technology & Applied Physics (ATAP) Division develops and applies the latest techniques in AI/ML to further enhance progress and enable next generation system performance.

The Division's ALS Accelerator Physics Group has embarked on a study of how modern AI/ML methods can be employed to solve long standing accelerator physics problems related to both accelerator operations and design. Using joint funding from BES (ADRP) and ASCR, an initial effort was successful in stabilizing electron beams in synchrotrons using AI/ML [*Phys. Rev. Lett.* 123, 194801 (2019)]. A follow-up study has recently launched in collaboration with ENG and ALS-U to employ AI/ML for rapid alignment corrections of magnets on measurement benches, as is typically required when field mapping hundreds of magnets before installation into a new storage ring as in the case of ALS-U. Finally, we have successfully employed AI/ML to accelerate multi-objective optimization algorithms such as those used to typically design magnetic lattices in storage rings. In this case AI/ML allows replacing computationally expensive physics evaluations with lightweight predictive models, accelerating a significant portion of the overall optimization cycle by orders of magnitude.

AMP is increasing its efforts in AI/ML activities, in particular on the development of surrogate models as an ultrafast alternative to standard beam and accelerator components modeling, and tools for efficient optimization of accelerator designs. One AMP researcher is a leading participant in the teaching team of the upcoming USPAS course on "Optimization and ML for Accelerators," and has submitted an ECRP proposal on AI/ML for accelerator simulations and is the Point of Contact on AI/ML for ATAP. AMP is also exploring venues for engaging in the development of algorithms that could enable more efficient modeling of some accelerator and beam physics problems on quantum computers than on conventional supercomputers.

Within the BELLA Center, AI/ML techniques are being applied for rapid analysis of large data sets and to optimize the performance of laser-plasma accelerators. This includes, for example, the coherent combination of laser pulses from multiple fiber lasers, where ML techniques are used to maximize the laser efficiency and optimize the pulse characteristics. This is needed to develop the next generation of high efficiency, high repetition rate lasers that will power future laser-plasma accelerators, such as those being developed with the kBELLA initiative and the Accelerator Stewardship program of HEP. These AI/ML applications are being carried out through a collaboration between the AMP, BACI and BELLA Programs within ATAP.

In the U.S. MDP, ML techniques are being applied to the development of high-field superconducting accelerator magnets. Acoustic classification of mechanical quench precursors is being investigated using Deep Learning techniques, and early detection of quenching in superconducting magnets is being explored with ML-based real-time processing of multi-domain diagnostic data. In the QIS area, BCMT scientists and engineers are supporting the development of enabling cold electronics that can drastically simplify implementations of future quantum processors.

BACI has developed an advanced AI-based design tool for RF cavity designs, supported by LDRD. The tool has been successfully applied to the RF designs of APEX2 and ALS-U RF cavities. BACI has applied its high precision timing and RF control technology, taking advantage of the program's well-developed control systems for particle accelerators, to develop ML-based advanced feedback systems for fiber laser systems and quantum computer bit control in solving the scalability problem in the control electronics.

With HEP and ASCR support, our collaboration with the UC Berkeley Quantum Nanoelectronics Laboratory (QNL) produced a prototype qubit control system (QubiC) and demonstrated single and two qubits gate operation on superconducting qubits. Associated software has been developed to streamline the qubit chip characterization, gate optimization, and execute circuits provided by users. QubiC allows for further study of the parameter space of an overall control system that interacts with the qubits. In addition, we will further develop more compact modules and interconnection among them to build up a system needed for more complex quantum computers.

Applied Science and Energy Technology

Applied Materials Science and Engineering

Our research emphasizes the design and synthesis of advanced materials for energy, information technology, structural, and other applications in a wide range of physical environments. We develop materials that improve the efficiency, economy, environmental impact, and safety for applications, including energy generation, conversion, storage, transmission, and utilization. Underlying expertise includes nanoscale phenomena, advanced microscopy, physical and mechanical behavior of materials, materials chemistry, and biomolecular materials.

Our applied materials S&E research involves advanced materials and nanotechnology for clean energy, including electrochemical energy conversion and storage, the catalytic production and storage of fuels, and nanostructured light-emitting diodes. The Lab has world-leading expertise in the tailoring of the optical properties of window materials, including the characterization of glazing and shading systems, the chromogenics of dynamic glazing materials, and low-emittance coatings for solar performance control. We led the scientific community in the development of plasma-deposition processes to enable improved window coatings.

We have a strong development program directed toward advanced sensors and sensor materials to control industrial processes to reduce the waste of raw materials on manufacturing lines, increase the energy efficiency of manufacturing processes, and minimize waste. The Lab also studies high-temperature superconductors for electrical transmission cable that could substantially reduce losses during transmission. Capabilities include analyzing the mechanical behavior of novel materials and designing novel materials with enhanced mechanical properties. We also have extensive expertise in using waste heat for electricity. In addition, we conduct next-gen lithography and support the development of tools and metrology for size reduction in future microelectronic chip manufacturing, largely sponsored by industry.

Berkeley Lab focuses software and hardware technology development on novel pathways to sense the grid at unprecedented temporal resolutions for creating a resilient and reliable grid. This includes research on automated demand response for all end use sectors including buildings, transportation (EVs), and industrial processes, which results in minimizing customer bills and supporting high levels of renewables on the electric grid.

In the area of thermal materials and advanced metrology, Berkeley Lab’s overall goal is to develop breakthrough solutions using thermal materials to address the fundamentally intermittent character of thermal energy supply and use in buildings and industry, an issue becoming ever more important in our renewable future. We have created a science-to-systems approach, building on fundamental advances in thermal storage and nonlinear thermal elements, that aims to impact large-scale applications in building and industrial sectors at low and moderate temperatures. This research will establish the Lab as a leader in thermal energy storage, non-linear thermal elements, and novel thermal topologies, all aimed at buildings and industrial impacts.

This Core Capability is sponsored by BES, EERE, DHS, ARPA-E, and SPP programs, including DoD and industry. It is underpinned by DOE-supported basic chemistry, materials, and computational research, and contributes to DOE missions in energy, the environment, and national security. This work benefits DOE technology programs such as water desalination, solar-energy conversion, electrical-energy storage and transmission, solid-state lighting, energy efficiency, and the study of materials in extreme energy environments.

Nuclear and Radio Chemistry

Here, the Lab's capabilities include fundamental nuclear measurements; actinide chemistry; the irradiation of electronic components for industry and the government, including post-irradiation and materials characterization; the design, development and deployment of advanced instrumentation; compact neutron and gamma-ray sources for active interrogation; nuclear data management; and substantial modeling and simulation expertise. Work for DOE's SC includes actinide chemistry with application to chelating agents; for NNSA, advanced detector materials, compact gamma and neutron sources, detection systems and algorithms development, and background data management and analysis. Our work for DOE NE through the Spent Fuel and Waste Disposition Campaign (SFWD) includes subsurface modeling and testing to evaluate and improve on the current technical bases for alternative prospective geologic environments for high-level nuclear waste disposal.

Systems Engineering and Integration

Our demonstrated abilities to successfully engineer, construct, and integrate complex systems underpin many of the core capabilities described in this section, and those of the major user facilities described above. Within DOE's SC, the Lab is uniquely configured with a centralized organization that makes engineering, systems and project management, and technical support available to all of the Lab's scientific endeavors.

Our internationally recognized advanced instrumentation skills (e.g., accelerating structures, detectors, data acquisition and control systems, lasers, magnets, and optics) have enabled many of the scientific breakthroughs described in this Plan; these are the direct result of the holistic coordination and deployment of engineering and technical resources. Solutions and approaches developed for one application are routinely leveraged, adapted, and applied to others. This disciplined integration and systems approach is a critical part of our contribution to the PIP-II at Fermilab, the LCLS-II upgrade, where we have completed the LCLS-II injector and undulators, and have major responsibilities in low-level RF systems. We also responsibly lead the GRETA, US-CUORE, US-CUPID, LUX, DESI, and LZ collaborative projects. The same approach has been used to assure that ALS-U is staffed with engineers that have prior experience from similar technically challenging projects. Other examples of successfully integrated systems and project management include: the ATLAS inner detector, US-CUORE, US-CUPID, LUX, the GRETINA and ALICE nuclear physics detectors, and the Transmission Electron Aberration-corrected Microscope. Further illustration of this integrating, crosscutting systems approach is Berkeley Lab's world-leading expertise in integrated silicon detectors for high-energy physics detectors that has been adapted and applied to the development of massive scientific-grade CCD detectors for astronomical applications. This expertise was further adapted and improved to provide radiation-resistant high-speed X-ray and electron detectors. These direct X-ray detecting CCD systems are deployed at national and international light sources.

In addition to Berkeley Lab's demonstrated abilities to engineer and integrate complex systems for basic science, we are the recognized leader in energy efficiency in commercial and residential buildings and industrial facilities. We develop and transfer new energy-efficient building and industrial technologies from the laboratory to the industrial and commercial world and stimulate the use of high-performance technologies through innovative deployment programs. The Lab is also a leader in developing cool surface materials for roofing, pavement, and architectural glazing.

In addition to SC, we contribute to technology research programs funded by EERE, FECM, and ARPA-E, and the DHS Chemical and Biological Security program. We leverage DOE's investment by working with state and other federal and SPP sponsors, including the Federal Energy Regulatory Commission, the California Energy Commission (CEC), the California Air Resources Board, and the California Public Utilities

Commission (CPUC). The Lab partners with national and international organizations to develop technical standards.

Decision Science and Analysis

Berkeley Lab performs integrated research on energy policies to mitigate carbon emissions and climate change while minimizing externalities such as health burdens, air quality impacts, economic disruptions, and water resources impacts. The Lab investigates the economic impact of energy-efficiency performance standards in industrial and commercial building equipment and systems, and for consumer products. We provide technical assistance to federal agencies to evaluate and deploy renewable, distributed energy, as well as demand-side options to reduce energy costs; manage electric power-grid stability; and assess the impact of electricity market restructuring, e.g., employing large-scale electric-energy storage systems. Research efforts integrate techno-economic analysis and lifecycle assessment with basic science and technology development to ensure sustainable scale-up. Another core multi-lab EERE activity that Berkeley Lab researchers participate in is the called Clean Energy to Communities program. This program connects local governments, tribes, electric utilities, and community-based organizations with national laboratory experts using customized, cutting-edge analysis to achieve clean energy systems that are reflective of local and regional priorities.

For this core capability, the Lab's role within the national lab network is to provide analysis of energy efficiency, clean energy, and electricity market policies and standards for energy efficiency requiring complex interconnected technical, economic, and environmental analyses. This capability contributes to DOE's mission by assisting government agencies to develop long-term strategies, policies, and programs that encourage energy-efficiency in all sectors and industries. It is sponsored by EERE, OE, FE, and NE, as well as the CEC and the CPUC.

Microelectronics

Berkeley Lab is addressing the future of microelectronics through a co-design approach, where the challenges of energy demand, global supply, and climate change require a new tack, going even beyond silicon chips. This Core Capability leverages strengths in device physics, next-generation patterning technology, materials science, synthesis, and materials databases, as well as the simulation, modeling and characterization of architecture, **devices,** and materials.

In BES core programs, we are advancing knowledge and achieving control of excitons and phonons in nanoscale electronic materials under real-world operating conditions, as well as developing the codesign framework of atoms-to-architectures to enable ultra-efficient microelectronics that go beyond CMOS technology. Work for the DOE includes development of next-generation microchips integrating nanomaterials and exploiting new physical phenomena to achieve higher energy efficiency in computing.

The Center for X-ray Optics has deep expertise in EUV lithography and nanostructure fabrication, supported by industry partners. Supported by BES, the Center for High Precision Patterning Science seeks to create fundamental understanding and control of patterning materials and processes for energy-efficient, large-area patterning with atomic precision, thereby enabling at-scale advanced manufacturing of future-generation microelectronics such as quantum computing and spin-based memory and logic devices.

We have extensive expertise in computational modeling and simulation of electronic materials and devices, as well as in the development of novel materials and technologies for microelectronics, such as graphene, 2D materials, and quantum computing. HPC simulation tools ARTEMIS and PARADISE++

enable device-scale microelectronic simulations and exploration of post-Moore architectures and technologies such as nano-magnetics, carbon nanotubes, and other emerging device technologies. We also have expertise in the design and implementation of integrated circuits, including ultra-low-noise analog front ends, high-performance data converters, CCD readout solutions, and CMOS active-pixel sensors for scientific imaging.

This Core Capability is supported by BES, ASCR, HEP, EERE, SPP including DoD and industry, and LDRD. It supports DOE's mission to create more energy efficient and sustainable microelectronic systems capable of meeting emerging needs in computation.

Mechanical Design and Engineering

Berkeley Lab's applied research addresses energy technology design and development, processes, models, networks, systems, and energy efficiency. The Lab leads the world in accelerating the transition of battery technology from lab to market, window technology and performance analysis, modeling of energy-saving technologies in building, whole-building, and component systems, and evaluating and tracking energy savings in industrial facilities. Battery systems research encompasses the development of new materials, theoretical modeling, and systems engineering. In addition, the Lab applies its extensive experience in subsurface science to underground energy storage options involving thermal energy storage, natural gas and hydrogen storage, as well as porous medium compressed-air energy storage. The research in long term grid scale subsurface energy storage encompasses numerical simulations of coupled processes in the porous reservoirs as well as field demonstration experiments and contributes to the DOE energy storage grand challenge.

The built environment is responsible for 40% of U.S. energy consumption and 70% of U.S. electrical usage; we are DOE's premier lab performing research on building energy efficiency, energy simulation, modeling of whole building systems and components, walls, windows, heating, cooling, ventilation, plug loads, roofing systems, and refrigeration. New research includes analysis and development of model predictive control systems, fault diagnostics, measurement and verification, agent-based IT, energy information and management systems, and using ML and advanced data science for model training and validation. The Lab is also a leader in the research of indoor environmental quality, lighting quality, ventilation, and health.

Our researchers develop and test environmental sensing technologies for both indoor and outdoor air quality. Advanced sensing and metrology systems are also being developed to evaluate the thermal performance of advanced insulating materials and windows. New approaches are being developed to evaluate window shades and glare.

As part of DOE's grid modernization effort, the Lab advances research on electric grid storage and stationary use, electricity grid modernization through technologies for smart grid, distributed generation (microgrids), energy management and demand response, and improved grid reliability. This core capability is sponsored by EERE, OE, ARPA-E, EPA, other federal agencies, the State of California, and utilities. It supports DOE's mission to develop and deliver market-driven solutions for energy-saving homes, buildings, and manufacturing, as well as sustainable transportation.

Berkeley Lab has initiated new research activities to support DOE's Grid Interactive Efficient Buildings Program that includes modeling the capability of building end-use loads to provide flexible loads, evaluation and development of control and automated communication technology, new technology development, and electric utility system modeling. Similarly, there is a growing research portfolio to develop and evaluate control of distributed energy resources that include EVs, demand response, electrical and thermal storage, PV, and other DERs.

FLEXLAB®, or the Facility for Low Energy eXperiments in buildings, consists of testbeds and simulation platforms for research, development, testing, and demonstration of low-energy building technologies, control systems and building systems integration. FLEXLAB maintains a network of industry partners for research, demonstration, and deployment. It enables development of cost-effective integrated technology solutions to meet 50% whole-building energy savings — a feat that cannot be met solely by the use of single-component or technology upgrades alone. Our major sponsors are DOE (BTO, OE), GSA, SCE, PG&E, and CEC. With the addition of solar PV and energy storage, FLEXLAB is now fully equipped to address the cutting edge problems at the confluence of renewable integration with storage and demand response as the pathway to the next generation of energy management systems. With the addition of solar PV, smart inverters, and energy storage, FLEXLAB now supports FLEXGRID which provides cutting edge technologies to test systems related to renewable integration with storage and demand response as the pathway to the next generation of energy management systems.

Power Systems and Electrical Engineering

The Lab leads the world in advanced sensing modeling and short-term control in the distribution grid and microgrids. We study customer adoption patterns of grid technologies and distributed energy resources (DER) optimization in microgrids and buildings. We developed key analytics around grid measurement and Distributed Energy Resources Customer Adoption Model (DER-CAM) for dispatch and the control of microgrids. This work also includes development of hierarchical control schemes and data analysis for large distributions of local power generation including solar, storage, electric vehicles to enable multi-level dispatch, and standards development of the interconnection of renewables and smart grid, all to enhance, modernize, and support the future distribution grid.

A related CEC and DOE-BTO funded R&D program known as CalFlexHub is exploring how to automate buildings and EVs control systems to respond to hourly price signals to support year-round demand flexibility for renewable integration and consumer energy cost savings. This program includes 5 UC campuses and includes both lab and field-based R&D activities coordinated with utility partners. Berkeley Lab's electricity markets, policy, and technology researchers also evaluate both the capabilities of customer loads to provide various grid services and the cost requirements for technology for DR automation and program incentives.

In the DOE complex, we lead and collaborate on grid modernization activities, including program management. Collaborators include LLNL, LANL, SNL, ORNL, ANL, SLAC, and PNNL. This core capability contributes to DOE's efforts to drive electric grid modernization and resiliency in the energy infrastructure, and the development of grid science for a high renewable penetration future. This work is supported by EERE-OE, ARPA-E, DoD's DARPA and ESTCP, and the CEC. The GMLC is a DOE-wide activity that is funded by EERE and OE.

Science and Technology Strategy and Major Initiatives

To sustain our ability to provide science solutions to the nation requires both a strategic vision and prudent stewardship, both of our world-class user facilities and infrastructure and of our outstanding corps of researchers. Berkeley Lab's strategy and initiatives are carefully chosen to provide for both strategic vision and stewardship, thus maximizing the opportunities for scientific breakthroughs in the future.

We have also identified seven strategic priorities that we must follow to make sure that the Lab will continue to have the research expertise, capabilities, and facilities that will be needed to address its mission as a world-leading laboratory over the next 20 years. The first five comprise the research capabilities that form the foundation of the Laboratory and provide our researchers the opportunity to make an impact on science and on the national priorities of energy and climate, resilience, the environment, health, and the economy. The other two represent our commitment to the stewardship of our people and resources, so that the Lab will remain a leading national asset in the future.

- SP1: Chemistry, Materials Science, and Geoscience
- SP2: Computational Science
- SP3: Bioscience and Environmental Science
- SP4: Fundamental Physics and Accelerator Research
- SP5: Clean Energy and Strategic Technologies
- SP6: Recruitment, Development, and Retention of Our People
- SP7: Stewardship of Our Infrastructure and Facilities

The Office of Science supports **five national user facilities** that are central to our research impact, driving advances in methods and enabling a strong base of scientific users to advance their research. A central principle of the Lab's research strategy is that we must continuously upgrade and improve these facilities to optimize the opportunities for scientific breakthroughs and to support the research mission of the Laboratory and the Office of Science.

- *The Advanced Light Source* is the nation's premier soft X-ray facility, supporting frontier research in chemistry, materials science, geoscience, structural biology, and environmental science. Its global leadership is assured by the upgrade (ALS-U) project.
- *The Molecular Foundry* provides world-class capabilities in high-resolution imaging; organic, inorganic, and biological synthesis; nanofabrication; and computational materials science and chemistry.
- *The DOE Joint Genome Institute* is an integrative and collaborative genome science user facility that makes rapidly advancing technologies in large-scale genomics and analysis available to scientists working on the full range of energy and environmental challenges.
- *The National Energy Research Scientific Computing Center (NERSC)* serves as the primary scientific computing facility for all of SC's programs, creating the computing environment that enables scientific breakthroughs across the entire portfolio.
- *The Energy Sciences Network (ESnet)* accelerates scientific discovery at DOE laboratories by delivering unparalleled network capabilities, a circulatory system for data.

The five major themes that drive the research across the entire Laboratory are described in detail in section 3. Here we list the major initiatives within each research theme, and in parentheses show which strategic priority or priorities will most benefit from the initiative (SP#, from the strategic priority list above).

Understanding the universe, from quarks and nuclei to the cosmos

- CMB-S4: a joint project supported by DOE-HEP and NSF to build the next generation facility for observing the cosmic microwave background (SP 4)
- kBELLA: a high intensity short pulse laser at high repetition rate, to advance plasma accelerators and other applications (SP 4)

Discovering materials, chemical processes, and biological systems for energy and the environment

- ALS-U: the project to build a completely upgraded x-ray facility that will deliver unprecedented capabilities for basic and applied research (SP 1)

- BioEPIC: the Biological and Environmental Program Integration Center, which will use innovative technologies to revolutionize the understanding of how microbes interact with soils and plants (SP 3)
- Predictive Biology: developing the capabilities to enable accurate predictions of biological processes and phenomena (SP 3)

Driving the future of computing and data science

- NERSC-10: a project to build a next gen HPC facility that will use revolutionary technologies to support emerging computation needs of all the SC research programs (SP 2)
- High Performance Data Facility: a project to design and building the new SC data facility, which will become part of the Integrated Research Infrastructure (IRI) (SP 1-4)
- Co-Design of Computing Devices and Systems: research at all scales on the next generation of computing systems, from atoms to devices to systems (SP 1-2)
- Quantum Information Science and Technology: quantum-based devices and systems, software and algorithms, and a prototype quantum network (SP 1-2)

Dramatically accelerating clean energy technologies

- Clean Energy Technologies: improving energy efficiency, conversion, and storage, and managing the reliable flow of energy (SP 5)
- Accelerating Decarbonization: decarbonizing and improving access to sustainable buildings, transportation systems, and energy resources (SP 5)

Revolutionizing how we do science

- Automated Experiments: automating the acquisition and management of experimental data across all fields of science (SP 1-5)
- Advanced Instrumentation: developing innovative instrumentation to advance fields of basic and applied science (SP 1-5)
- AI/ML and Data Science: accelerating discovery with AI/ML and data science in all scientific disciplines (SP 1-5)

Infrastructure

Overview of Site Facilities and Infrastructure

The Facilities and Infrastructure Strategy supports our Core Capabilities and research drivers and initiatives through campus strategy objectives that will transform the existing site into the Berkeley Lab of the future. This section summarizes and integrates approved, planned, and envisioned investments from the Lab, DOE, and alternative sources encompassing our 10-year infrastructure strategy.

The main Lab campus is adjacent to UC Berkeley, on 202 acres of (UC) land, of which 86 acres are leased to DOE. The site is located within Berkeley and Oakland, CA.; however, local land use restrictions are not applicable to Berkeley Lab. Land use planning information is in the Berkeley Lab Long-Range Development Plan, which will be completed by FY25.

The main campus building space consists of ~1.73 million gross square feet (gsf) of operating DOE-owned buildings (1.71M gsf) and trailers/storage containers (.023M gsf). For the DOE owned properties, the main campus net square footage decreased by 19.5k gsf from FY22. Two UC-owned facilities (B30 Chu Hall and B59 Shyh Wang Hall) at 202,788 gsf are used for DOE purposes under the UC occupancy agreements. There are 24,317 sq ft of UC-owned space within the Advanced Light Source building. The Guest House (B23) is UC-owned; it is not managed in the Facilities Information Management System (FIMS).

As of Sept. 9, 2023, we leased nine off-site facilities totaling 268,519 gsf. As of Q1 of FY24, we have no-fee use of 86,933 sq ft of UC-owned space at UC Berkeley. In FY23, the Lab worked with the SC Consolidated Service Center to extend a leased facility for JBEI (65k RSF) in Emeryville, CA. We anticipate no FY24 lease actions. However, in FY25, we expect to renew leased space at Potter Street (83k RSF) in West Berkeley, CA, and for the ABPDU (16k RSF) in Emeryville and terminate the leased space for our OCFO Division (31k RSF) in Emeryville.

Building and Trailer/Container Ownership Summary*		
Ownership	**Size (GSF)**	**Property Count**
DOE Owned	1,730,728	163
Contractor Leased/License	268,519	9
Contractor Owned	202,788	2
Grand Total	2,202,035	174

*Figures only include assets in Operating status

The following chart lists the operating status of DOE owned assets in FIMS for FY23. As such, the OSF asset count has increased in the standby status since the FY22 report, as these assets are prepared for removal.

Operating Status Summary - DOE-Owned Real Property Assets						
Status	**Building**		**Trailer/ Container**		**OSF**	
	GSF	Asset Count	GSF	Asset Count	GSF	Asset Count
Operating	1,707,454	86	23,274	77	N/A	66
Shutdown	16,407	3	511	1	N/A	2
Standby	4,925	3	3,696	3	N/A	33
Grand Total	1,728,786	92	27,481	81	N/A	101

Overall Condition Summary

Below is the overall condition summary of DOE-owned buildings and trailers in operational status as reported in FIMS at the close of FY23. Inadequate seismic load resisting systems and antiquated mechanical and electrical systems remain our biggest drivers for facility obsolescence.

Overall Condition – Mission Critical Assets				
Condition	**RPV**	**% of RPV**	**GSF**	**Asset Count**
Adequate	$422.9M	30.6%	389,055	19
Substandard	$432.9M	31.3%	495,272	17
Inadequate	$526.4M	38.1%	693,179	27
Grand Total	$1382.3M	100.00%	1,577,506	63

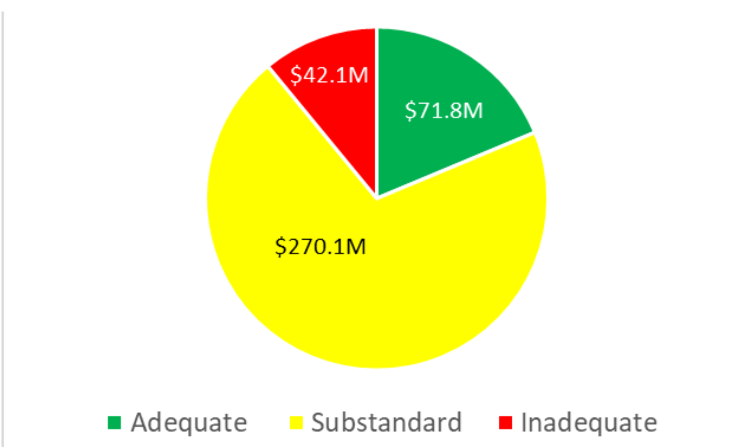
Overall Condition – Mission Dependent, Not Critical Assets				
Condition	**RPV**	**% of RPV**	**GSF**	**Asset Count**
Adequate	$52.5M	55.4%	70,211	21
Substandard	$15.4M	16.2%	12,121	7
Inadequate	$26.8M	28.4%	62,878	13
Grand Total	$94.7M	100.00%	145,210	41

Overall Condition – Not Mission Dependent Assets				
Condition	**RPV**	**% of RPV**	**GSF**	**Asset Count**
Adequate	$1.4M	100.0%	8,012	59
Substandard	0.0M	0.0%	0	0
Inadequate	0.0M	0.0%	0	0
Grand Total	$1.4M	100.0%	8,012	59

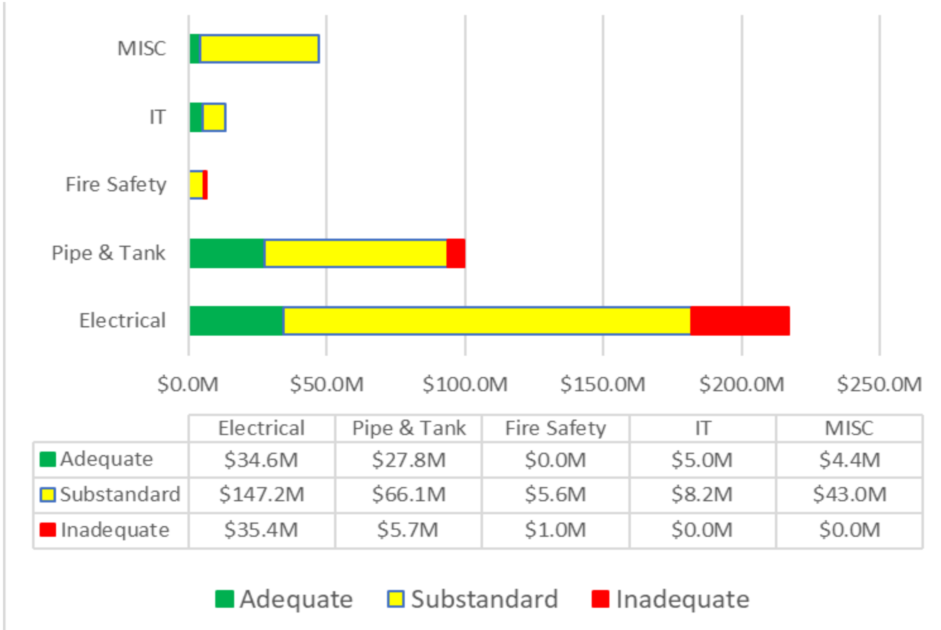
Major Site Utility Systems by Asset Condition

Below is the overall asset condition summary of the Lab's mission critical utility systems by their overall asset condition. The utilities infrastructure includes domestic and treated water, low conductivity water, sanitary sewer, storm drain, natural gas, compressed air, electrical, life safety and technology systems (e.g., telecommunications, optical fiber). These systems and their respective components vary greatly in age and condition, reflecting generations of alterations and improvements over the Lab's long history. Recent utility investments made by the Lab and SLI have addressed high risk utility deficiencies. Adequate storm drain performance during this year's heavy rains can be attributed to these investments. Examples of major site utility systems listed in the OSF classification, broken out into major utility groups.

OSF Site Utilities Mission Critical and Mission Dependent Asset Condition Per RPV



OSF Site Utilities Broken Out Mission Critical & Mission Development Asset Condition Per RPV



FIMS Status Summary

Below is the FIMS status summary of all DOE-owned buildings, trailers/containers, and structures at the close of FY23. Overall, 83.6% of all assets were in operating status. In standby status are 39 assets that are pending excess screening approval for disposition. The Lab has active projects which are replacing several retaining walls and walk ways and these make up most of the assets in standby status.

FIMS Status Summary - DOE-Owned Real Property Assets							
Status	Building		Trailer		OSF		Total Assets
	GSF	Asset Count	GSF	Asset Count	GSF	Asset Count	
Operating	1,707,454	86	23,274	77	1,806,887	66	229 (83.6%)
Shutdown	16,407	3	511	1	2,022	2	6 (2.2%)
Standby	4,925	3	3,696	3	35,246	33	39 (14.2%)
Total	1,707,454	86	23,274	77	1,806,887	66	229 (83.6%)

Asset Utilization Summary

The table below provides the asset utilization summary of DOE-owned buildings and trailers/containers. The Lab's disposition and demolition program continues to make progress removing assets that no longer support the DOE mission.

Building and Trailer/Container Utilization Summary				
Status	Utilized Count	Underutilized Count	Unutilized Count	Total Count

Operating	163	0	0	163
Standby	3	0	3	6
Shutdown	0	0	4	4
Total	166	0	7	173

Overview of 10-year Campus Strategy

Driven by mission alignment, our multiyear campus strategy has three objectives focused on:

- Modernization of enduring facilities and infrastructure,
- Replacement of non-enduring facilities and infrastructure, and
- Operations improvements to security, transportation, and chemical management programs.

Taken together, these objectives are intended to transform the Lab's aging facilities and infrastructure into a modern, integrated, interactive, sustainable, and fully mission-aligned environment for ground-breaking science.

Our daily onsite population continues to grow after the pandemic, hovering in the range of 2,500-3,000, compared to an estimated 4,500 prior to the pandemic. We remain committed to leveraging lessons learned from the pandemic by using telework and remote work to reduce pressure on available site services (e.g., parking, office space), to reduce the transportation impact on our surrounding communities, and enable increased construction activities while minimizing impacts to research. With this approach we can more easily identify opportunities to return substandard space (offices, conference rooms) to the institution for either conversion to modernized laboratory and technical space or to help reduce occupancy in substandard space while renewal activities take place. The Lab's continued use of virtual communication technology has allowed us to reconfigure open office spaces to better support collaborative work environments for both onsite and offsite staff, for example revised cubicle layouts in B33 and B91 to accommodate more researchers in newer facilities, closer to their research.

In addition to reconfiguring office space, the above efforts are also aligned with the ongoing task of identifying potentially underutilized lab spaces for modification and redeployment for current and future program needs. Facility modernization is at the core of this effort. HVAC improvements, coupled with legacy equipment disposition efforts, allow much higher and effective utilization of aging facilities. Three near-term examples of proactive improvements include renovating high-bay space in B62, modernizing lab space in B66, and converting conference rooms in B90 and B2 to dry lab and assembly space, respectively.

Funding Strategy

Our FY23 Actual Maintenance level of $47.9M was higher than the projected FY24 figure of $46M identified in the most recent annual lab plan. This level is appropriate in the context of other constraints, such as the headcount necessary to execute this level of investment, and other concurrent non-maintenance investments being made to redevelop and/or modernize the site's real property portfolio. Maintenance investment is consistent with our culture of stewardship of our facilities and colleagues. By increasing these investments, we continue to create more equitable research space for all employees. MII is planned to remain above 2% over the next several years through a combination of day-to-day maintenance activities and a growing portfolio of asset repair and major component replacement projects.

Deferred maintenance and repair needs backlog are $259M and $285M, respectively. Over the past two years, escalating costs have driven increases to the total dollar amounts, but it is worth noting that the DM Index has decreased from 15.6% in 2018 to 12.7% in 2023, with a projected 10.4% value by FY25. This trend should continue as construction market conditions stabilize from the pandemic-era economic turmoil and as our robust investment levels resolve longstanding infrastructure deficiencies. Our maintenance project portfolio includes mechanical, electrical, and building envelope corrective maintenance actions that are critical to maintaining research activities in enduring facilities constructed during the 1960s or earlier.

Our primary tool for modernizing systems in need of recapitalization and providing new or enhanced capabilities is IGPP. As shown in Enclosure 4, we are investing heavily in IGPP with $35M of actual costs and progress in FY23, about $40M planned for FY24, and investments gradually increasing to around $55M over the planning horizon. However, GPP and other forms of capital investment, though limited, are essential for updating aged and often obsolete infrastructure. We are undertaking urgent multi-program, capital improvements with the IGPP program, while essential and important non-urgent general infrastructure needs are coordinated with SLI.

As the Lab's 1960's vintage and earlier facilities continue to decline, Environmental Management (EM) funding is also critical to continue redeveloping the site by removing large facilities (e.g., B64) that no longer adequately serve the mission. EM support is critical to replacing obsolete and inefficient facilities with new, mission aligned replacements. In addition to removing several major research facilities, other core infrastructure, such as electrical distribution switch stations, are too big to be covered by Minor Construction investment. DOE Line Item Construction investment, which has been strong at the Lab in recent years, is forecast to decrease considerably following the completion of the Seismic and Safety Modernization (SSM) Project in 2026. To maintain the redevelopment momentum executed over the past decade, the Lab and DOE will need to continue to make the case that more infrastructure investment is needed across the complex. Modernization needs are likely to grow significantly over the planning horizon as stronger seismic standards and recently implemented net-zero requirements are scoped and estimated.

One particular area of concern is the recapitalization needs of the Lab's National User Facilities. Though program investment is strong for research equipment recapitalization, capital investment in legacy infrastructure has largely been lacking. For example, the ALS's (B6) most recent large-scale building renovation was in the 1980s. Unfortunately, B6 is seismically poor and the current upgrades to the accelerator machinery do not address the many building components that are reaching end-of-life. ALS support facilities like the B34 chiller plant are overdue for major equipment upgrades including replacement of end-of-life cooling towers, chillers, and associated pumps and piping. At the Molecular Foundry, many pieces of research equipment are being replaced (B67, B72 Complex), but no capital investment is being made on either building. Reliability of the tower water system that supports B72's electron microscopy activities is a specific area of concern for the Foundry, where capital dollars are necessary to improve the system. The DOE's Minor Construction Policy appears to preclude the use of IGPP to address modernization needs at these facilities, but without direct program investment, impacts to research uptime and operations will become commonplace.

The Lab does continue to pursue novel funding opportunities. Most recently we joined with UC Berkeley on a Cal-Fire grant for vegetation management that will reduce wildfire fuel on and around the Lab site. We also partnered with UCB to obtain funding to replace Centennial Bridge, a seismically deficient vehicle bridge that intersects the Lab site. Work on the bridge will finish this summer and reduce a significant seismic risk to our Lab operations. We plan to apply for Assisting Federal Facilities with Energy Conservation Technologies (AFFECT) funding in support of its net-zero journey, as described later in this section. We are also planning to request State funding to electrify the boiler plant in the UC-owned B30, Chu Hall. In short, we will pursue funding opportunities wherever it is appropriate to do so.

Objective 1: Modernization of Enduring Facilities and Infrastructure

Given the elevated cost of new construction across the Bay Area and the future-of-work trends described previously, the Lab continues to focus on improving existing enduring space and infrastructure to better align with evolving research needs. The significant number of aging facilities with substandard and inadequate spaces requires a strong investment prioritization process that considers both program research needs and the reduction of legacy safety hazards. In particular, we are aware of the implementation of new federal requirements outlined in Executive Order 14057, reduction of deferred maintenance and repair needs, accessibility improvements, and finally creation of working environments that encourage the recruitment and retention of our workforce. Successful modernization of enduring facilities requires holistically integrating these seemingly disparate aims into projects that can deliver upon them all. To that end, we have an initiative to revamp the project planning and prioritization process to better incorporate condition assessment data and research-driven infrastructure needs.

Phased Building and Fleet Electrification Strategy

The Lab is advancing efforts to meet the requirements of EO 14057 and updated DOE Orders 436.1A and 413.3B. Net-zero activities are guided by the Berkeley Lab Net-zero Vision and Roadmap. In terms of infrastructure, the ambitious goals of EO 14057 provide an opportunity to target long standing deferred maintenance and repair needs associated with building mechanical and electrical systems as part of electrifying gas-fired boiler plants that heat most buildings on the site. To coordinate efforts, subject matter experts across the Lab have developed a phased electrification strategy and deep energy retrofit approach that sequences projects in the context of boiler plant service life and natural gas consumption levels. The roadmap identifies 21 facilities to be in need of electrification. In FY25 and FY26 the Lab plans to initiate two such IGPP projects at B77 and B84 which represent our two most common building vintages. We will use lessons learned and parametric studies to create a more operationalized plan to upgrade the balance of HVAC systems. The Lab has also proposed a “Net-zero Enduring Buildings Electrification” Line Item Construction project to address a few of our largest and most complex facilities. Over the next decade, this initiative is likely to significantly increase the Lab’s modernization needs.

The second major infrastructure element for reaching the ambitious goal of achieving net-zero GHG emissions will be the transition to an all-electric fleet. Over the next decade, we will install new electric vehicle (EV) charging stations through a series of projects informed by an FY23 study that identified locations across the site. The Lab is also analyzing optimization of its broader fleet program to ensure efficient use of resources and to right-size the number of EV chargers needed over the long-term. Though these installations are primarily planned to support the future all-electric fleet, they may also support charging of privately-owned vehicles. New electrical distribution infrastructure is required for most installations.

Finally, new construction activities will continue to be guided by site-level policy that sets sustainability standards for new construction and major renovations. Updates to the policy in FY24 fully support DOE orders and Net-Zero Emission Building requirements.

Power System Stewardship Program

Our electrical power distribution system has continually adapted to meet evolving mission requirements. The current infrastructure combines recent installations with aging equipment (30-60 years old). In 2019-20, numerous system vulnerabilities were highlighted by utility outages during extreme weather and wildfire risks. Although there have not been any similar outages since 2020, power system weaknesses, and the risks they pose to research uptime and worker safety, remain an area of concern. A Power System Stewardship Program (PSSP) is being implemented to address and improve the system.

The PSSP encompasses the entire campus electrical distribution system, extending from the utility's common connection point at 115 kV to the premises wiring system within buildings. It will define guiding principles for developing work plans that prioritize, sequence, and balance efforts in enhancing reliability, redundancy, and specifying deliverables for renewal.

The PSSP has three functional areas: reliability, redundancy, and renewal. Each area's specific "workstreams" incorporate elements such as a risk-based application of a NFPA 70E compliant Maintenance Program, Power System Model, Supervisory Control and Data Acquisition (SCADA), Power System Architecture Revisions, Smart Grid, Critical Spares Inventory, Long-range Replacement/Consolidation Plan, and New Building Design Guidelines Modifications. The program activities operate as a feedback loop, where advancements in one area catalyze progress in others, gradually boosting overall power resilience. Effective implementation guarantees uninterrupted power, safeguarding the continuity of our mission. Activities underway and planned include conducting a series of engineering studies to:

- Evaluate and select the optimum approach to modify feeder configurations;
- Create distribution loops to interconnect the switching stations;
- Develop and maintain a spare parts inventory for 12.47 kV electrical distribution equipment;
- Create a modern Supervisory Control and Data Acquisition (SCADA) system;
- Replace medium voltage switch stations and building service substations that are approaching or at end of life; and
- Monitor the condition of all switch stations and aging equipment through an enhanced preventative maintenance program.

Concurrently, the Lab supports electrical modernization projects including IGPP-funded work at B50A, B70A, and switch station A3. We also seek a new SLI GPP investment to begin replacing old electrical equipment at B88. These efforts are focused on worker safety and target the highest risk gear across the site. In response to the utility power shutdowns of 2019 and 2020, the Lab is modernizing a series of critical generators including those supporting the Operations Center, Security, and the Fire Station (B45 and B48), the Bayview research cluster (B91, B91U, B92), and the Waste Handling Facility (B85), the last of which is a SLI GPP funded effort. Each of these projects contribute to improving the resiliency of the Lab.

Linear Assets Modernization Project (LAMP)

The SLI-funded, multi-year LAMP will significantly improve the Lab's utility resilience and will construct common utility corridors centered on Grizzly Substation and serving the site's East, Northwest, and Southwest areas. Where appropriate and affordable, these corridors will be connected into redundant system loops to modernize system operations and increase utility service reliability. The project prioritizes essential system improvements based on mission impacts and future programmatic needs.

LAMP's first phase will expand the Grizzly Substation and increase power capacity to 70MW to cover planned load increases, including, inter alia, building electrification, datacenter expansions and full-power operations in building 59, including NERSC, since the power upgrade will be utilized by all occupants of Building 59. The expansion will enable sitewide state-of-the-art electrical SCADA capabilities, as well as safer, segregated high voltage duct banks for improved reliability and reduced maintenance outages that impact research. A common utilities corridor will be created along Lawrence Road to provide improvements for segregated high voltage duct banks, sanitary sewer, natural gas, communications and data, compressed air, controls, and hydraugers. LAMP's second phase will focus on the common utilities corridors in the East Canyon service area and along McMillan Road.

Seismic Safety Improvements and Reduction of Landslide Risks

Located a mere quarter of a kilometer from the Hayward Fault, Berkeley Lab sits in the heart of earthquake country. After two decades of mitigation efforts, the number of buildings expected to perform poorly in a seismic event dropped from 34 to 19. However, national standards for seismic evaluations were revised in 2013 and 2017 and implemented into the California Building Code in 2019. We have since re-evaluated many buildings and, as expected, more facilities were rated less favorably than before, up from 19 to 45. However, all currently occupied facilities met the California Building Code in effect at the time of construction, thus fulfilling DOE seismic requirements.

Recognizing the hazards presented by nearby faults, the Lab utilizes a comprehensive risk-ranked prioritization process to manage and mitigate seismic risks and will continue to partner with DOE on implementing appropriate corrective measures (e.g., retrofit, demolition, etc.). Through IGPP, we are seismically retrofitting B48, which houses the Lab's onsite firefighters, and B73, with both projects planned for completion in FY24. To mitigate the potential for slide events we are also modernizing a series of retaining walls. We are mitigating further risks by reducing the number of employees working in lower seismically rated facilities, and we have reduced the occupancy of B46 and B83. As it has for several years, the Lab continues to remove obsolete seismically deficient trailers; 62A, 65A, and 65B are planned for removal this year.

Direct funded safety improvements include the removal and disposal of numerous large accelerator-contaminated shield blocks currently dispersed throughout the site and the Seismic, Safety and Modernization (SSM) Project. The SSM Project will improve the safety of Lab employees and visitors by replacing the former seismically poor cafeteria facility with a new Welcome Center building in the same location. The future Welcome Center will house the Campus Central Cafeteria, Health Services Department, Human Resource functions, the badging office, and a 250-seat Conference Center. Looking further out into the future, the Lab will seek direct funding to support the eventual removal of B46 and B70, once alternate spaces for all the tenant programs are identified over the next decade. As part of the overall strategy, we are reducing staff occupancy levels in some buildings and vacating others entirely.

Mechanical and Control Systems, Maintenance, and Improvements

Many of our enduring building stock HVAC systems are well past their useful lives. Improvements to these are closely coordinated with our net-zero efforts. Maintenance funding supports component replacements, such as chillers, air handling units, and dampers to correct building air quality issues and restore functionality at several buildings (B2, B62, B66, B77, B80, B84). As noted previously, we are transitioning away from gas-fired boiler plants, but in certain cases (e.g., B70, B88) we needed to swap out boilers on a like-for-like basis to address compliance issues or buy more time until these larger net-zero modernization efforts are ready to proceed. Sitewide HVAC Improvements, an SLI GPP funded effort, is replacing obsolete building-level automation control systems in several facilities across the site which will improve the performance of existing mechanical components. Mechanical deficiencies make up the largest portion of combined deferred maintenance and repair needs and are one of the most critical disciplines supporting research activities.

Building Envelope Maintenance

When it rains at Berkeley Lab our building occupants are immediately aware because 67% of our roofs are either "bad," "very bad," or "failed" based on a 2022 sitewide assessment performed by the National Nuclear Security Administration's Roof Asset Management Program (RAMP). We have since contracted with RAMP to begin replacing some of our worst roofs in FY24 and FY25, starting with B26, B50A, B72, and B70A. We will also perform designs for B2, B50, B50B, B62, B69, B71, B84, and B88 for replacement in FY25 and FY26. Each year we will design 5-10 roof replacements and then execute the construction the following year, catching up with roof renewal needs over the next decade. At B70A, we are performing a full-scale exterior waterproofing and painting effort to address water intrusion issues unrelated to its roof.

Objective 2: Replacement of Non-enduring Facilities

This objective includes both reclamation of acreage through the Lab's facilities D&D program and creation of new or adaptive modernization of space supporting research and operations. Much of the Objective 2 related activities are centered around the Charter Hill and Bayview Redevelopment areas, with several other projects scattered throughout the site. Redevelopment activities are central to increasing the number of buildings rated "Adequate", per the FIMS Overall Asset Condition data element.

Charter Hill Redevelopment

Berkeley Lab's multi-year strategy includes constructing a materials and chemical sciences and technology building cluster at Charter Hill, adjacent to the ALS user facility. Charter Hill is being developed on the Lab's former "Old Town" area, which is now fully cleared of buildings. Early interim uses of the newly available acreage in the Charter Hill cluster are already in place, including two new tensile structures and additional parking and laydown areas in support of projects and operations. The Linear Assets Modernization Project (LAMP) will extend utility infrastructure into the Charter Hill area.

Envisioned to enable collaboration and accelerated discovery, Charter Hill's future lab spaces would leverage advances in machine learning, artificial intelligence, and automation plus other next-gen science concepts) and proximity to the ALS beamlines, to pursue the understanding and control of materials phenomena and chemical transformations across size and time scales. The first anticipated facility would be the Cross-disciplinary Research Facility, a 3-4 story, ~68,500 gsf lab/office facility with approximately 150 occupants. This would house personnel and programs from B70, which has a poor seismic rating and is planned for demolition. The second would be the Interdisciplinary Research Building, a ~68,500 gsf lab/office facility with approximately 150 occupants. The "Chemical Observatory," is a key component of the envisioned capabilities for the site. It will be an innovative research facility designed to integrate multiple probes, such as those derived from the ALS's soft X-ray beamlines, into more traditional lab spaces. Site preparation would include grading, installation of modern utilities, and realignment of Segre Road. A Modular Utility Plant (MUP) would be constructed in stages nearby to efficiently distribute utilities between the buildings. One or more ALS beamlines may be extended into the Charter Hill cluster.

Bayview Redevelopment

Our multi-year strategy includes facilities construction to support full integration of biosciences and related programs adjacent to the Integrative Genomics Building (IGB - B91) in the Bayview cluster. With construction completion on track for early FY25, the Biological and Environmental Program Integration Center (BioEPIC – B92) will house exciting new research capabilities that will advance interdisciplinary priorities, such as fabricated ecosystems, new sensors, new simulation capabilities, new levels of lab to field connectivity, and cryo-EM for biological and environmental science. Though BioEPIC is a complete and usable facility, there was a need for another lab priority to use some of its unique space temporarily, so for the overall good of the Lab the relocation horizon for the Geosciences Measurement Facility is delayed.

Redevelopment activities will continue at the northern section of the Bayview cluster throughout the planning horizon. A planned EM-funded Bayview Cleanup Phase 2 will address the demolition of B56 and B64, including cleanup of any local site contamination. To accommodate the cleanup project, we are relocating the buildings' remaining occupants. Demolition will free up the acreage necessary to construct the third biosciences-focused facility, the Biosciences Genome Engineering and Manufacturing (BioGEM) building. A preliminary study helped scope and size this proposed building to house the Joint BioEnergy Institute (JBEI), the Advanced Biofuels and Bioproducts Process Development Unit (ABPDU), and the Agile BioFoundry (ABF). BioGEM would enable those programs to move from their leased location in Emeryville to the Lab's main site.

B71 Complex Redevelopment

We are reimagining the B71 Complex to support a new research vision that includes the installation of a future high average power laser system, kBELLA, to enable high repetition rate applications of laser plasma accelerators. For several years the lack of cooling capacity, aging electrical and mechanical system components, and seismically deficient support structures like B71A and the nearby B71 trailers have created significant constraints on what research is possible. A series of projects will reimagine the core infrastructure of these structures by removing B71A, most of the B71 trailers, and the north-western end of B71 to make room for a future program expansion to enable kBELLA and other research activities. As part of this effort, we are looking at constructing a new electrical substation and cooling plant to support the complex. We are partnering with DOE EM to plan the characterization and demolition work that will pave the way for new infrastructure in this area.

Accelerator Science and Engineering

Accelerator science and engineering are closely integrated at Berkeley Lab, which is essential for the efficient operation of our accelerator facilities, for world-class R&D in advanced accelerators and superconducting magnets, for engineering of advanced scientific instruments for key stakeholders in HEP, BES, FES and NP, and for developing new applications of accelerator technology. However, accelerator and engineering staff are currently distributed across the site. Further, many activities are housed in legacy buildings that neither encourage collaborative work nor meet current seismic standards. A new Accelerator Science and Engineering Building will bring together scientists and engineers for activities critical in programs across the Office of Science. Finally, high bay space for large structure assemblies remains in short supply when compared to the needs of numerous programs across the Lab.

Electron Microscopy (EM)

The B72 complex that has housed the National Center for Electron Microscopy (now part of the Foundry) for decades needs to be modernized. Specialized space for new types of EM will allow us to remain an international powerhouse in this area. Infrastructure that incorporates synergistic plans across the site would result in a renewed state-of-the art, world-leading electron imaging capability for diverse scientific challenges in areas such as materials synthesis, catalysis, earth and environmental science, soft matter characterization, quantum materials, energy storage and structural and cellular biology. Instruments to be developed requiring state-of-the-art space include novel in situ, time-resolved and cryo and variable temperature EM instruments, and an analytical transmission electron microscopy (TEM) with high energy resolution. A future conventional construction project would renovate and expand upon specialized laboratory space to house EMs and their supporting infrastructure and systems.

Objective 3: Modernize Traffic Circulation, Site Access, and High Hazard Risk Mitigation Systems

The Lab plans to implement security-related infrastructure improvements, modernize traffic circulation, and enhance high hazard risk mitigation systems.

Physical Protection System (PPS) Upgrades

The Lab is working on an S&S Program-funded effort to upgrade outdated and unsupported PPS components and meet expanded physical access control system requirements in support of Homeland Security Presidential Directive 12 (HSPD-12) and Design Basis Threat (DBT) requirements. Prior to the project's initiation, over 85% of Physical Access Control Systems (PACS) were no longer supported. This project targets improvements to 800 doors with PACS spread across 37 buildings. Feature upgrades include line supervision and intrusion detection. Legacy hardware is obsolete and does not support new requirements.

Vehicle Gates

The three vehicle and pedestrian entry points at the main site are an area of concern and require improvement. The Strawberry Gate Guard House (B33A) was constructed in 1965 and does not meet today's security standards, and we are leveraging the UC Berkeley-managed Centennial Bridge Replacement Project to improve the configuration of this vehicle and pedestrian entry point. Following the bridge project's completion in 2024, the new gatehouse will shift slightly to the south to align with the new Centennial Bridge Road. The new configuration will create two entry lanes with barrier gates and access readers, increased vehicular queuing space, and improve security system and lighting performance. This IGPP is planned for completion in FY25 and the Lab plans to apply lessons learned to the Blackberry Gatehouse and the Grizzly Gatehouse improvements.

Transportation

Our work modes are a mix of full-time on-site, full-time telework, and hybrid work. While most drive personal vehicles, ~30% of employees use the Lab's shuttle system during their commute. To prepare for the completion of the SSM Project and the resulting Welcome Center, we will replace the oldest of its shuttle shelters and install 1-2 new shuttle shelters with IGPP; this will improve access to the site and its facilities. We are also encouraging other commute options; for example, in partnership with several providers, we are vigorously promoting attractive leasing and purchasing options for e-bikes. A new partnership will facilitate rideshare and carpool matches through an application tailored for the Lab community.

The Lab has proposed a GPP to address a longstanding safety concern on Cyclotron Road, the main access road to Berkeley Lab for staff, visitors, and deliveries, including large trucks transporting construction and research equipment. An average of 1,200 vehicles and over 100 bicycles use this road to enter the Laboratory site each day. As the Lab continues to encourage more "Green Commutes" as part of addressing EO 14057 requirements, the mix of bicycles, shuttles, and other large vehicles entering the site is increasing the safety risks of this critical roadway. As Cyclotron Road nears the Blackberry Gatehouse vehicular entrance for the site, the road becomes steep and narrow with a 180-degree bend, colloquially referred to as the horseshoe curve. There have been a number of accidents here involving cyclists and trucks over the years. The roadway's geometry creates several safety issues, including unsafe conditions for cyclists and inadequate space to accommodate large trucks making the hairpin turn. The project scope includes:

- Increasing lane width up to 22-feet in the downhill direction, and up to 7-feet in the uphill direction;
- Add new striping and signage in accordance with the CA Manual on Uniform Traffic Control Devices;
- Add new retaining walls to accommodate road widening, and slope protection to minimize erosion;
- Perform curb, gutter and storm drain improvements;
- Add a raised sidewalk on the east side of Cyclotron Road from the uppermost crosswalk to the stairway, and
- Extend the existing Chu Road bicycle lane past Blackberry Gate to connect with the new uphill bicycle lane.

High Hazard Risk Mitigation Systems

Several high hazard risk areas are also being improved through infrastructure investments over the next several years. The most immediate is the buildout of space at B69 for a dedicated Central Chemical Receiving Facility located adjacent to the Lab's shipping and receiving area. Initiated in FY24, this IGPP investment is an important element of our "Chemical Lifecycle Management Corrective Action Plan" that has been underway since 2021. This new, dedicated space will ensure all chemicals shipped to the Lab are processed consistently, compliantly, and efficiently prior to distribution across the site.

We have begun replacing 10 fire alarm control panels serving 15 buildings across the site. Long anticipated, this project will address frequent equipment failures that, over the last decade, have led to costly building evacuations and operational interruptions. The new panels will have modern functionality such as mass notification, which will become functional as downstream devices are replaced over time through rigorous fire life safety inspection, testing, and maintenance programs. Future projects will address other major system components and fire control panels at other enduring facilities at the Lab.

In 2021, we evaluated the entire water supply system to determine whether there were weaknesses that could cause a system failure in a serious seismic and/or fire event. The study considered the level of pressurization at different areas of the site and made recommendations to improve resiliency. The Lab now has four projects in its 10-year capital plan to implement these recommendations, including installation of new pumps at water tanks 13J, 68, and 82, and the replacement of water tank 82.

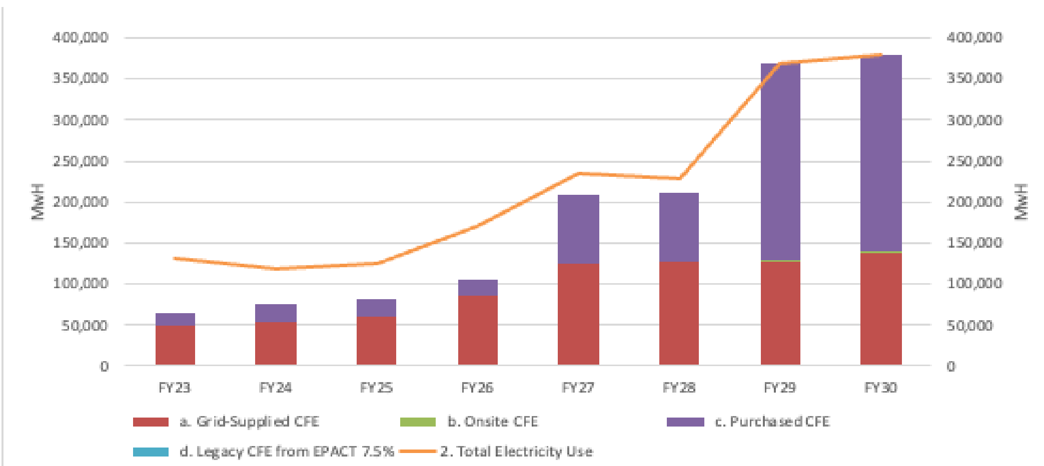
Site Sustainability Plan Summary

In FY23, carbon pollution-free electricity (CFE) accounted for 50% of total electricity consumption. Renewable electricity accounted for 34% of total electricity consumption counting a doubling bonus for renewable electricity generated on Federal land (and 23% without the bonus). The purchased renewables include.

- Specific hydropower contracts that are federally recognized as renewable;
- A direct purchase from a solar array developed with LLNL located in Livermore, CA;
- Purchases through community choice aggregators for satellite locations; and
- Purchases of unbundled renewable energy certificates (RECs)

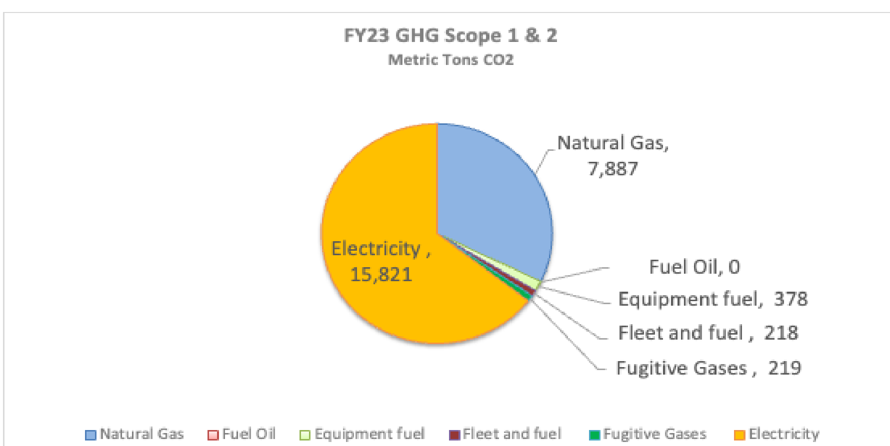
To meet our FY30 100% CFE target we will work primarily with the Western Area Power Administration to execute power purchase agreements for the development of large renewable electricity projects connected to the California grid. The Lab will purchase the output of these projects over their operating lifetimes. Renewable procurement will complement a much smaller volume of on-site renewables designed to meet resilience or research objectives, or to maximize the use of newly constructed rooftops. We are working closely with LLNL and SLAC to coordinate projections of CFE needs to develop a common CFE procurement strategy. The plan to meet the CFE requirements is shown in the figure below:

Figure 1- CFE Plan



In 2023, the Lab released the [Berkeley Lab Net-Zero Vision and Roadmap]() to guide efforts to meet the requirements of EO 14057 and updated DOE Orders 436.1A and 413.3B. Overall, the Lab's FY23 greenhouse gas emissions were 41% lower than in FY15. The distribution of Scope 1 and 2 emissions sources for FY23 is shown below.

Figure 2 – FY23 GHG



Efficiency and Conservation

Energy management activities are foundational for our net-zero strategy. Key efforts include:

- Sustainable and electrified new construction, following the recently updated Lab policy on Sustainability Standards for New Construction and Major Renovations;
- Improving building operations, driven by an Ongoing Commissioning Team that continually identifies, selects, and fixes energy- and water-wasting operational deficiencies in buildings;
- Expanding use of data analytics to guide efficiency and operational improvements;
- ISO 50001 certification of the Lab's energy and water management system to ensure that activities are strategic, effective, and persistent.

From FY15 to the end of FY23:

- Building energy consumption per square foot has decreased 29% (weather corrected) excluding major computing process loads at NERSC and B50A/50B as well as major accelerator process loads at the Advanced Light Source (ALS) and the 88-inch cyclotron
- Natural gas consumption has decreased 30% (weather corrected)

Adaptation and Resilience

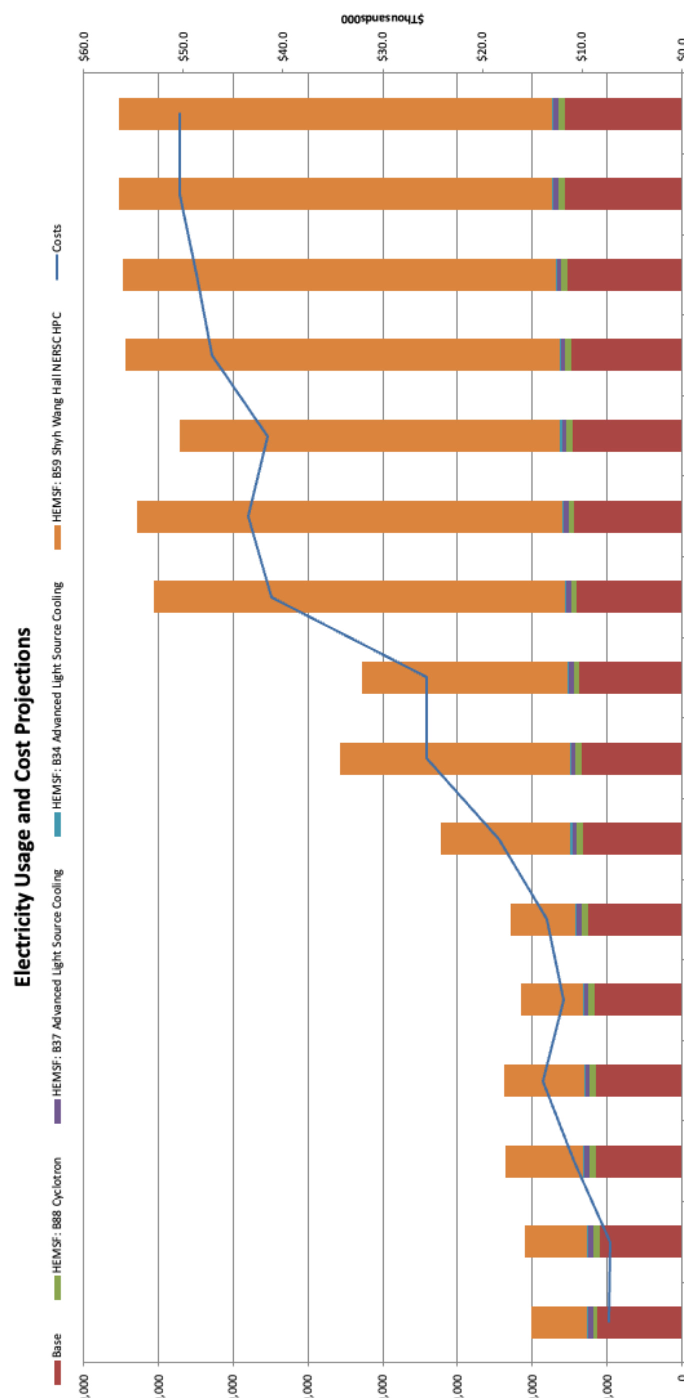
The Lab continues to track projects identified in its climate Vulnerability Assessment and Resilience Plan submitted to DOE at the end of FY22. Projects with a cost totaling ~$10M are proceeding in FY24. A key focus of resilience efforts includes advancing a Power System Stewardship program to improve electrical system reliability.

Electricity Usage and Cost

The following chart provides projections for electricity consumption and costs through FY35. Key changes include:

- Advanced Light Source (ALS): Decreases in electricity in FY24-25 in preparation for ALS-U, a 9-month full shutdown in FY26-27, followed by a commissioning period extending into FY28, with full operation beginning in FY28; and
- Shyh Wang Hall: Increased electricity in FY26 associated with NERSC-10 and further planned expansion of computing in FY29.

Figure 3 - Electricity Usage & Cost Projections



	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32	FY33	FY34	FY35
HEMSF: B59 Shyh Wang Hall NERSC HPC	37,323	42,001	51,805	53,415	41,291	43,149	86,458	153,740	137,442	275,110	283,976	254,059	290,484	289,693	289,693	289,693
HEMSF: B34 Advanced Light Source Cooling	1,055	986	1,021	934	998	990	990	990	990	990	990	990	990	990	990	990
HEMSF: B37 Advanced Light Source Cooling	3,108	3,080	3,092	2,952	3,031	3,030	3,030	3,030	3,030	3,030	3,030	3,030	3,030	3,030	3,030	3,030
HEMSF: B88 Cyclotron	2,803	4,087	4,262	4,510	4,078	4,171	4,171	4,171	4,171	4,171	4,171	4,171	4,171	4,171	4,171	4,171
Base	56,754	55,063	57,508	57,156	58,220	62,915	66,134	66,877	68,324	70,033	71,801	73,112	73,723	76,227	78,543	78,543
Costs	$7.3	$7.2	$10.8	$13.9	$11.8	$13.5	$18.4	$25.6	$25.6	$41.2	$43.5	$41.6	$47.1	$48.7	$50.4	$50.4

OAK RIDGE NATIONAL LABORATORY

Lab-at-a-Glance

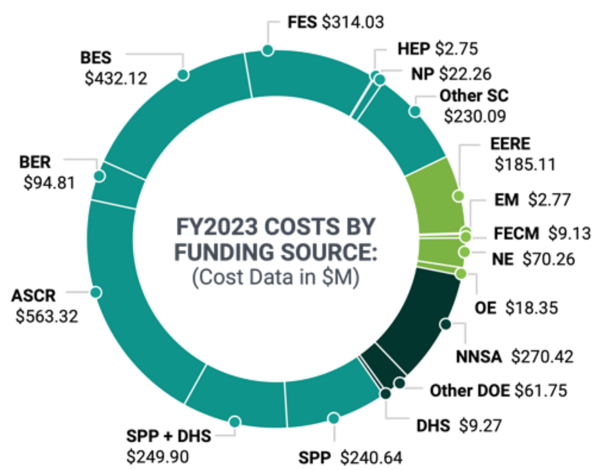
Location: Oak Ridge, TN
Type: Multi-program Laboratory
Contractor: UT-Battelle, LLC
Site Office: ORNL Site Office
Website: www.ornl.gov

- **FY 2023 Lab Operating Costs:** $2,584.7 million
- **FY 2023 DOE/NNSA Costs:** $2,276.9 million
- **FY 2023 SPP (Non-DOE/Non-DHS) Costs:** $240.7 million
- **FY 2023 DHS Costs:** $9.3 million

Physical Assets:
- 4,421 acres and 285 buildings
- 4.77 million GSF in buildings
- Replacement Plant Value: $9.1B
- 1.15M GSF in 52 Excess Facilities
- 0.84M GSF in Leased Facilities

Human Capital:
- 6,467 Full Time Equivalent Employees (FTEs)
- 51 Outgoing Joint Appointees, 50 Incoming Joint Appointees
- 264 Postdoctoral Researchers
- 230 Graduate Students
- 136 Undergraduate Students
- 3,672 Facility Users
- 1,648 Visiting Scientists

FY 2023 Costs by Funding Source ($M)



Mission and Overview

For over 80 years, Oak Ridge National Laboratory (ORNL) has advanced scientific discoveries and powerful research facilities and translated capabilities into solutions that address some of the most pressing national challenges. Many of the laboratory's signature strengths have their roots in the Manhattan Project—ORNL's isotopes, neutron scattering, nuclear energy, biological sciences, material sciences, and computing were used to address the national priority of the time to win the war and subsequently advance *Atoms for Peace* program strategies. As national needs have evolved, so too have ORNL's strengths, which now also include energy science and technologies, environmental sciences, and national security.

As a US Department of Energy (DOE) Office of Science multipurpose laboratory, ORNL advances and integrates across 24 core capabilities to accelerate scientific breakthroughs, build and host world-class facilities, and develop solutions critical for the clean energy transition and national security. Convergent basic science and translational research are engrained in the laboratory's ethos and strategy, yielding outcomes with international scale and impact. ORNL stewards an extraordinary ecosystem of world-leading facilities that enable thousands of investigators each year to propel breakthroughs in science and technology. The ecosystem includes four DOE Office of Science user facilities that enable scientists worldwide to, for example, use the world's only known exascale computer to numerically tackle challenges that cannot be addressed using any other approach and to utilize neutron scattering facilities to probe the structure and function of materials in unique ways that are critical for advancing the energy transition, human health, and the nation's quantum future. One of the facilities at ORNL is a research reactor that can produce dozens of isotopes that are critical for medical, energy, security, industrial, and research purposes—an institutional strength not found anywhere else in the Western Hemisphere. ORNL also leads the Manufacturing Demonstration Facility and four other applied energy research facilities. Through these energy facilities, ORNL staff engage thousands of additional investigators each year, including many from industry, to propel new technologies and solutions critical for US manufacturing competitiveness and a resilient, clean, and integrated energy system.

ORNL's impact is amplified in many ways by its extensive partnerships. Located in Oak Ridge, Tennessee, ORNL is managed by UT-Battelle LLC, a partnership between the University of Tennessee System and Battelle Memorial Institute, through a contract that includes eight southeastern partners: Vanderbilt University, Duke University, Georgia Tech, North Carolina State University, Virginia Tech, The University of Virginia, Florida State University, and Oak Ridge Associated Universities. ORNL engages with these and other university, industry, and community partners to extend the impact of the laboratory—regionally, nationally and globally.

With ORNL's creative, dedicated, and mission-ready workforce; breadth of core competencies; unique ecosystem of facilities; diverse partnerships; and extensive portfolio, ORNL is a powerhouse that is propelling scientific discoveries and impactful solutions to address DOE's missions in clean energy, environment, and security.

Core Capabilities

The 24 core capabilities assigned to Oak Ridge National Laboratory (ORNL) by the US Department of Energy (DOE) provide a broad science and technology base that catalyzes fundamental scientific advances and technology breakthroughs to support DOE's mission of addressing the nation's energy, environmental, and nuclear challenges. The capabilities, each of which has world-class or world-leading components, reflect a combination of exceptional people, equipment, and facilities. Synergies among these core capabilities accelerate the delivery of scientific discovery and technology solutions and allow ORNL to respond to changing priorities and the critical needs of the nation.

Accelerator and Detector Science and Technology

ORNL stands as a global leader in high-intensity hadron beams, driven by advanced technologies across beam production, acceleration, accumulation, and utilization. The Spallation Neutron Source (SNS) leads the forefront, operating at 1.7 MW power on target, distinguishing it as the world's most potent pulsed proton accelerator and the highest-power superconducting linac for hadrons. This capability positions ORNL at the forefront of high-intensity hadron beam dynamics research and the development of high-power proton targets. ORNL's expertise also spans negative hydrogen ion (H^-) sources, superconducting radiofrequency technology, and high-power target systems. Employing computational science, ORNL excels in beam dynamics modeling and data management, using artificial intelligence and machine learning to forecast and mitigate system failures, thereby enhancing operational reliability.

The ongoing Proton Power Upgrade project, slated for completion in FY 2025, is positioned to enhance SNS's power by up to 40%, enabling novel neutron scattering experiments with thermal neutrons at a high resolution of energy.

Recent advances to this core capability include the following:

- In July 2023, SNS set a world record when the particle accelerator beam operating power reached 1.7 MW, an essential component in enabling new science, including insights into advanced materials for clean energy applications.
- A Radio Frequency Quadrupole was delivered in FY 2022. The medium-beta cryomodule is complete, along with a spare module. The spare high-beta and medium-beta cryomodules that have been plasma processed will ensure constant beam energy, which will be critical to support SNS operations after the Proton Power Upgrade is completed. The cryogenic moderator system was demonstrated to have the capacity to operate at 1.9 MW.

These core capabilities are supported by the DOE Office of Science, Basic Energy Sciences, and grants and early-career awards from High Energy Physics.

Advanced Computer Science, Visualization, and Data

ORNL staff are deeply engaged in research and development to enable the deployment of scalable computing infrastructure to support the DOE mission with an emphasis on the programs, facilities, and operations at ORNL. The laboratory participates in numerous Scientific Discovery through Advanced Computing application teams and leads several components of RAPIDS (a Scientific Discovery through Advanced Computing Institute for Resource and Application Productivity through Computation, Information, and Data Science).

Three interconnected areas of emphasis distinguish the ORNL computer science research program: (1) exploring and evaluating emerging accelerated computing technologies; (2) developing the tools and methods needed for the analysis and management of data from the computational, experimental, and observational facilities across DOE; and (3) developing the tools and methods needed to federate facilities in support of the DOE mission.

The ORNL computer science program stewards two service-oriented capabilities: the engineering of research software and the engineering, curation, and visual analysis of datasets. These software and data engineering capabilities focus on ensuring quality in the software and data-related artifacts being developed across the laboratory. The overarching purpose of the computer science program is to ensure that the programs, facilities, and operations at ORNL and throughout DOE use the best technologies available. The computer science program is focused on long-term impact, and the service-oriented capabilities provide a critical linkage between the research program and the programs that rely on the results of the research program. ORNL has established research programs in workflow systems (including ADIOS, BEAM, and ICE), system science (including networking), and data and information visualization.

Recent advances to this core capability include the following:

- Scalable training of graph convolutional neural networks was developed for fast and accurate predictions of the highest occupied molecular orbital–lowest unoccupied molecular orbital gap in molecules. ORNL led important advances in the development of Discontinuous Galerkin methods for multiscale kinetic equations with diffusive limits.

- DFT-FE 1.0, which is a massively parallel hybrid CPU–GPU density functional theory code, was developed using finite-element discretization. Notably, owing to the parallel-scaling of the GPU implementation, researchers obtained wall clock times of 80−140 s for full ground-state calculations, with stringent accuracy, on benchmark systems containing approximately 6,000−15,000 electrons.
- The Virtual Infrastructure Twin for Computing-Instrument Ecosystems: Software and Measurements was implemented. A Virtual Infrastructure Twin is implemented using virtual hosts connected over emulated local-area networks at sites, which are in turn connected over an emulated wide-area network.
- Graph-based machine learning was developed to improve just-in-time defect prediction. In this work, researchers built contribution graphs consisting of developers and source files to capture the nuanced complexity of the changes required to build software.
- Work contributed to Visualization ToolKit for Massively Threaded Architectures (VTK-m): Visualization for the exascale era and beyond. VTK-m is a toolkit of scientific visualization algorithms for these emerging processor architectures. VTK-m supports the fine-grained concurrency for data analysis and visualization algorithms required to drive extreme-scale computing by providing abstract models for data and execution that can be applied to a variety of algorithms across many different processor architectures.

These capabilities are supported by the DOE Office of Science and Office of Electricity, the US Department of Homeland Security, and Strategic Partnership Project sponsors, including the US Department of Defense and the US Department of Health and Human Services.

Applied Material Science and Engineering

ORNL operates comprehensive suites of Applied Materials Science and Engineering capabilities encompassing (1) materials development—designing novel and improved materials through discovery and computational (artificial intelligence/machine learning) materials science, syntheses of innovative materials, and processing of advanced alloys, ceramics, polymeric materials, and composites; (2) materials manufacturing—developing and applying advanced manufacturing technologies and new feedstock materials to provide access to novel, innovative design spaces for engineering materials and components; (3) materials characterization—characterization of materials from atomistic to engineering scales and evaluation of material performances/behaviors in various extreme environments; and (4) applied materials modeling—multiscale and multiphysics performance modeling for materials' behaviors and interactions in complex operating environments.

This capability is underpinned by basic materials and chemical sciences, computational tools, and user facilities, including the High Flux Isotope Reactor, Spallation Neutron Source, Center for Nanophase Materials Sciences, and Oak Ridge Leadership Computing Facility, and is enabled by applied materials facilities such as the Manufacturing Demonstration Facility, Carbon Fiber Technology Facility, and Low Activation Materials Development and Analysis laboratory. Research performed by world-leading staff translates into signature capabilities in designing and developing structural alloys, carbon fiber composites, fusion and fission materials, lightweight materials, welding and joining processes, advanced manufacturing, and modeling. ORNL's ability to deliver against national priorities has been demonstrated by the development of solutions for various energy/power plant materials (e.g., nickel alloys, ferritic/martensitic steels, oxide dispersion–strengthened steels, ceramic matrix composites), and vehicle technology materials (e.g., printable aluminum alloys, printable steels, ultraconductive copper, superlubricity materials).

Recent advances to this core capability include the following:

- Researchers developed a technique that enables the design of compositionally graded composite parts, including the joining of superalloys and refractory alloys that typically cannot be welded or joined.
- Researchers designed a closed-loop path for synthesizing an exceptionally tough carbon fiber–reinforced polymer and later recovered all its starting materials.

Funding comes primarily from the DOE Office of Science Basic Energy Sciences and Fusion Energy Sciences, Office of Nuclear Energy, Office of Energy Efficiency and Renewable Energy, Office of Fossil Energy and Carbon Management, National Nuclear Security Administration, US Department of Defense, and National Aeronautics and Space Administration.

Applied Mathematics

ORNL's applied mathematics program spans four highly visible and externally recognized areas of research: (1) multiscale modeling and simulation; (2) mathematical tools for the analysis of scientific data, including artificial intelligence and machine learning; (3) discrete mathematics, including graph theoretic methods and matrix factorizations; and (4) systems analysis and decision-making, including statistics and the analysis of complex networks. Strategic foci include (1) scalable, architecture-aware, and resilient mathematical and computational capabilities for modeling and simulation; (2) robust algorithms for machine learning and data analysis, including uncertainty quantification, accelerated learning, and physics-informed learning; (3) the analysis of complex multiphysics and multiscale systems and algorithms; and (4) demonstrated impact on applications in science and engineering.

Algorithms developed within the applied mathematics program continue to be a critical component of ORNL's modeling and simulation capabilities and are widely recognized and used beyond ORNL. Applied mathematicians and theoretical computer scientists have developed key results for efficient and robust learning algorithms focused on dimension reduction and stochastic optimal control using reversible networks, upper quartile, and image classification, with a strong focus on scalable implementation targeting Frontier. Several application domains, such as medical imaging, neutron science, and materials design, have benefited from these algorithmic advancements. For example, in neutron sciences, ORNL's applied mathematics capabilities are being used for advanced data analysis, such as using graph neural networks to study dynamic systems, as a step toward developing science foundation models. This effort has shown promise with the creation of a machine learning model to predict thin-film structures in the context of electrochemical ammonia synthesis. If successful, this type of modeling would significantly improve overall experiment workflow. Additionally, the Center for Nanophase Materials Sciences, Manufacturing Demonstration Facility, and the National Transportation Research Center are among the experimental facilities where the applied mathematics program enables supervised and unsupervised learning methods to be implemented for their specific user communities. This work builds on top quartile strengths such as optimum reconstruction from sparse and large amounts of noisy data; optimization, control, and design of high-dimensional physical and engineering systems; and linear and nonlinear solvers.

Recent advances to this core capability include the following:

- Implementing uncertainty quantification of machine learning models to improve streamflow prediction under changing climate and environmental conditions:[2] In this work, researchers integrated a novel uncertainty quantification method, called PI3NN, with long short-term memory networks for streamflow prediction. PI3NN is computationally efficient, robust in performance, and generalizable to various network structures and data with no distributional assumptions.
- The future of neuromorphic computing for scientific applications:[3] In this work, researchers identified several science areas in which neuromorphic computing can either make an immediate impact (within 1 to 3 years) or where the societal impact would be extremely high if the technological barriers can be addressed.
- SuperNeuro—A fast and scalable simulator for neuromorphic computing:[4] In many neuromorphic workflows, simulators play a vital role for important tasks such as training spiking neural networks; running neuroscience simulations; and designing, implementing, and testing neuromorphic algorithms. SuperNeuro is a toolkit that can be approximately 10–300 times faster than some of the other simulators for small sparse networks. On large sparse and large dense networks, SuperNeuro can be approximately 2.2 and 3.4 times faster than the other simulators, respectively.
- Advancing Interconnected Science Ecosystem (Interconnected Science Ecosystem [INTERSECT]): The INTERSECT Laboratory Directed Research and Development (see Section 3) architecture team completed a software framework design that includes a common protocol abstraction layer, a microservice software layer composed of autonomous capabilities, and a software development and operations layer to streamline deployment. The software team built the protocol abstraction layer required for command and control. These teams are coordinating with the science domain teams to integrate these common software tools into the autonomous laboratories. These project road maps are being integrated into an INTERSECT Initiative road map to guide future development.

Funding comes primarily from the DOE Office of Science, US Department of Defense, the National Science Foundation, US Department of Health and Human Services, and other Strategic Partnership Project sponsors.

Biological and Bioprocess Engineering

ORNL brings substantial strength in fundamental biology to bioprocessing and bioengineering to address DOE mission needs in bioenergy production, carbon capture and long-term storage, and environmental contaminants processing. ORNL is (1) leading the Center for Bioenergy Innovation, a nexus for research on biomass utilization for biofuels and bioproducts (e.g., higher alcohols, esters, jet/marine fuel, and lignin coproducts); (2) characterizing the largest population of *Populus* genotypes for biomass deconstruction gene discovery and expanding that analysis to switchgrass; (3) developing new microbial

[2] S. Liu, et al., "Uncertainty quantification of machine learning models to improve streamflow prediction under changing climate and environmental conditions," *Front. Water, Water and Artificial Intelligence Section* 5 (2023). DOI: 10.3389/frwa.2023.1150126.

[3] R. Patton, et al., "Neuromorphic Computing for Scientific Applications," IEEE/ACM Redefining Scalability for Diversely Heterogeneous Architectures Workshop, Dallas, Texas, 2022, 22–28. DOI: 10.1109/RSDHA56811.2022.00008.

[4] P. Date, et al., "SuperNeuro: A Fast and Scalable Simulator for Neuromorphic Computing," *Proceedings of the 2023 International Conference on Neuromorphic Systems*, 2023 International Conference on Neuromorphic Systems, Santa Fe, New Mexico, 2023, 1–4. DOI: 10.1145/3589737.3606000.

platforms for the conversion of biomass to products; (4) coupling fundamental and applied research in biomass production and conversion (both thermochemical and biochemical conversion) for high-value materials and chemicals, fuels, and power; and (5) making sustained contributions to assess biomass feedstock supplies at regional and national scales.

ORNL leverages its next-generation capabilities in chemical engineering, chemistry, materials science, artificial intelligence, high-performance computing, and systems engineering to accelerate the translation of research outcomes into demonstrable improvements in bioproducts and biofuels and to move research from the laboratory to the field or pilot level. ORNL uses integrated expertise in plant sciences, microbiology, molecular biology, molecular modeling, and bioinformatics—in combination with facilities such as the common gardens, high-throughput phenotyping equipment, neutron sources (Spallation Neutron Source and High Flux Isotope Reactor), and computing resources (Compute and Data Environment for Science and Oak Ridge Leadership Computing Facility)—to address the needs of the bioeconomy. ORNL continues to innovate in analytical technologies from chemical imaging to multimodal small-angle neutron scattering.

ORNL is a recognized leader in multiple aspects and scales of bioenergy production, including biofeedstock sources and sustainability analyses, with emphasis on an integrated systems approach (e.g., landscape design) at multiple landscape scales (from hectares to nations) for applied impacts. This leadership has been leveraged to assess the potential for carbon management through bioenergy for carbon capture and long-term capture in soils. ORNL also leads in the use of a suite of biomass conversion processes: novel microbes and applied systems biology, computational chemistry and biophysics modeling for biomass conversion, and biofuels and bioproduct upgrading to advance bioenergy production.

Recent advances to this core capability include the following:

- The engineering of auxotrophic bacteria to help control overgrowth during plant transformation[5]
- A split selectable marker system for simultaneous transformation of multiple plant genes6
- The Serial Analysis of Gene Expression system for rapid insertion of DNA into nonmodel organisms[7]

The DOE Office of Science and Office of Energy Efficiency and Renewable Energy are the primary sponsors of this work. ORNL also performs impact analyses for the US Environmental Protection Agency and bioremediation design projects for the US Department of Defense. Other current sponsors include the US Department of Health and Human Services National Institutes of Health, the US Department of Agriculture, and the Advanced Research Projects Agency–Energy.

---

[5] M. Prías-Blanco, et al., "An *Agrobacterium* strain auxotrophic for methionine is useful for switchgrass transformation," *Transgenic Research* 31 (2022): 661–676. DOI: 10.1007/s11248-022-00328-4.

[6] G. Yuan, et al., "Split selectable marker systems utilizing inteins facilitate gene stacking in plants," *Communications Biology* 6 (2023): 567. DOI: 10.1038/s42003-023-04950-8.

[7] J. R. Elmore, et al., 2023. "High-throughput genetic engineering of nonmodel and undomesticated bacteria via iterative site-specific genome integration," *Science Advances* 9, no. 10 (2023). DOI: 10.1126/sciadv.ade1285.

Biological Systems Science

ORNL's core capability in biological systems science directly improves the understanding of complex biological systems through (1) integration of plant sciences with synthetic biology, ecology, computational biology, and microbiology; (2) discovery of gene function; (3) foundational research in plant science that enables the development of sustainable plant feedstocks for bioenergy and bio-derived materials; (4) the use of neutron science and exascale computing to characterize protein structure and interaction; (5) development of imaging and chemical measurement analytics at multiple spatial and temporal scales; and (6) development and application of data analytics, artificial intelligence, and simulation for biology. The fundamental understanding delivered through application of this core capability is essential to solving challenging societal problems in bioenergy, nutrient cycling, climate change, carbon management, and environmental remediation.

ORNL has strategic strengths in plant biology that have largely focused on more than 1,000 genome sequenced *Populus* lines, and the lab is the host institution for the Center for Bioenergy Innovation. ORNL has developed the state-of-the-art Advanced Plant Phenotyping Laboratory, a multispectral imaging system that enables a new level of high-throughput phenotyping of plant systems. The Center for Bioenergy Innovation continues to lead improvements in the economics and sustainable production of biomass and its conversion to bioproducts and biomaterials. ORNL leads the shift toward a more diverse set of sustainable bioderived materials and fuels obtained through lignin valorization and biomass processing. ORNL's strengths in plant biology and microbiology support additional fundamental research in Science Focus Areas, such as Plant–Microbe Interfaces, Secure Ecosystem Engineering and Design, and Biofuels. Plant–Microbe Interfaces studies the fundamental mechanism underlying plant–microbe systems, and Secure Ecosystem Engineering and Design uses CRISPR and anti-CRISPR technologies for secure biodesign. ORNL is also part of collaborative projects with other national laboratories (e.g., Ecosystems and Networks Integrated with Genes and Molecular Assemblies, National Microbiome Data Collaborative, and KBase).

ORNL has launched an effort to connect gene function with higher-order biological and ecosystem effects as well as to create gold-standard datasets compatible with DOE Biological and Environmental Research resources such as the National Microbiome Data Collaborative. Integrated capabilities in biochemical sciences, neutrons, and computing benefit the Biofuels Science Focus Area and the Critical Interfaces Science Focus Area. ORNL research within the Plant–Microbe Interfaces Science Focus Area characterizes the soil and plant microbiome and elucidates fundamental aspects of plant–microbe signaling and symbiosis, leading to chemical cycling in the terrestrial biosphere. These data-rich experimental efforts interface with bioinformatics expertise in microbial annotation and computational investigation, including artificial intelligence approaches for modeling and design using complex systems biology and protein structure data.

The new Advanced Plant Phenotyping Laboratory Biological Systems Science capability described in Section 3 will benefit significantly from partnerships with BES-supported capabilities—particularly neutron sciences and the future Spallation Neutron Source Second Target Station. Incorporating neutron scattering into its research toolkit will enhance the lab's ability to achieve bioenergy and environmental missions by providing a deeper molecular understanding of complex biological systems and processes. This insight will lead to innovative solutions for challenges in bioenergy, environmental sustainability, and climate change. Neutron scattering will offer unparalleled insights into molecular and structural dynamics, uncovering mechanisms underlying biofuel production, greenhouse gas regulation, nutrient cycling, and microbial interactions. This understanding is critical for designing targeted science cases, enhancing research efficacy, and informing future DOE initiatives. ORNL's neutron scattering resources can currently be leveraged through the Center for Structural Molecular Biology, including the Biological Small-Angle Neutron Scattering (Bio-SANS) instrument at the High Flux Isotope Reactor. A new Biological and Environmental Research–funded effort is prototyping a multimodal small-angle neutron scattering instrument for the Second Target Station. Additionally, ORNL has capabilities in both solid and solution nuclear magnetic resonance spectroscopy, optical spectroscopy, and multiple modalities of imaging.

Recent advances to this core capability are described in the following list:

- Advanced Plant Phenotyping Laboratory, a world-class and unique facility, was invested in, built, and operationalized, which enables a new level of high-throughput phenotyping of plant systems and their response to environmental change and represents a major enhancement to this core capability
- Explicit atom deuteration contrast matching algorithm for neutron scattering data[8]
- Genetic tools for CRISPR-Cas9 gene editing in fungi[9]
- Advanced systems for CRISPR-Cas9 gene editing in poplar[10]

The DOE Office of Science and Office of Energy Efficiency and Renewable Energy are the primary sponsors of the work within this capability. Additional work is sponsored by the US Department of Homeland Security, National Institutes of Health, Advanced Research Projects Agency–Energy, US Department of Defense, and US Environmental Protection Agency.

Chemical Engineering

ORNL's leadership in chemical separations, catalysis, isotope production, combustion, and biofuel production has enabled it to advance new chemical processes to improve efficiency, economy, and industrial competitiveness. For example, advancements in environmentally friendly and economical separations methods have been made at ORNL as part of the Critical Materials Innovation Hub for recovering rare earth elements from scrap magnets and recycling batteries. Likewise, ORNL possesses robust capabilities in chemical processing to convert and upgrade biomass into useful chemicals and fuels, which span from bench-scale catalyst formulation, characterization, and testing up to computational modeling and conversion expertise at the reactor scale.

Stable isotope research and production depend on specialized or potentially novel feedstock chemicals not available commercially, including the reformulation of enriched stockpiles for use in processes to further increase enrichment of the desired isotope. ORNL is pursuing the development of synthetic processes, enrichment processes, and physical property measurements including process design for the first centrifuge production system for enriched stable isotopes. ORNL applies expertise in chemical engineering to advance the understanding of the nuclear fuel cycle associated with processing, purifying, and enriching uranium. ORNL separations expertise in both electromagnetic and gas centrifuge techniques is enabling the design and construction of the Stable Isotope Production Facility and the Stable Isotope Production and Research Center. Plutonium-238 produced at ORNL is vital for

---

[8] A. Hicks, et al., "SCOMAP-XD: atomistic deuterium contrast matching for small-angle neutron scattering in biology," *Acta Crystallographica* D79 (2023): 420–434. DOI: 10.1107/S2059798323002899.

[9] J. Tannous, et al., "Establishment of a genome editing tool using CRISPR-Cas9 ribonucleoprotein complexes in the non-model plant pathogen *Sphaerulina musiva*," *Frontiers in Genome Editing: Section—Genome Editing Tools and Mechanisms* 5 (2023): 1110279. DOI: 10.3389/fgeed.2023.1110279.

[10] T. Yao, et al., 2023. "CRISPR/Cas9-based gene activation and base editing in *Populus*," *Horticulture Research* 10 (2023): uhad085. DOI: 10.1093/hr/uhad085.

radioisotope power systems. Innovative chemical processes being developed for the recovery and recycling of nonnuclear materials from used nuclear fuel assemblies have great potential for simplifying secure used nuclear fuel disposition pathways and for reducing the mass and volume of waste streams.

Renewed interest in nuclear power technologies prompted ORNL to develop capabilities, laboratories, and systems for producing and characterizing molten fuel and coolant salts for fast and thermal molten salt reactor concepts. For example, a chemistry laboratory was equipped to measure molten salt properties, improved models were developed to accurately predict the behavior of candidate fuel and coolant salts, and sensors were used to detect off-gas from molten salt processing. These new capabilities allow researchers to produce and characterize beryllium- and chloride-based salts in high-temperature environments to understand thermophysical and chemical properties.

Recent advances to this core capability include the following:

- Researchers developed a novel technique to visualize molten salt intrusion in graphite.[11]
- Caldera Holding licensed ORNL's membrane solvent extraction technique to separate rare earth elements in mined ore.
- Neutron scattering experiments uncovered molecular mechanics behind accelerated processing of cellulose for biofuels.[12]

Funding originates from several sources, including DOE Basic Energy Sciences, Office of Isotope R&D and Production, Office of Energy Efficiency and Renewable Energy, Office of Nuclear Energy, Office of Environmental Management, US Department of Homeland Security, National Nuclear Security Administration, and Strategic Partnership Project sponsors.

Chemical and Molecular Science

The chemical and molecular sciences portfolio includes research in catalysis, separations, geochemistry, isotopes, and biosciences. Additionally, ORNL has extensive expertise in heavy-element chemistry. Researchers provide fundamental knowledge for the development of new chemical processes: carbon capture, removal, and conversion; isotopic separations and radiochemistry; energy storage and conversion; mitigation of environmental impacts of energy use; and national security.

ORNL scientists are world leaders in neutron science for chemistry. In geoscience, neutron and x-ray small- and ultrasmall-angle scattering enables the determination of how pore structures influence coupled dissolution and precipitation replacement reactions. In catalysis, neutron reflectivity provides insights into the state of surfaces, including electrocatalysts, under operating conditions. Combining advanced atomistic simulations of reaction free-energy landscapes with neutron diffraction and isotopic substitutions is enabling an unprecedented understanding of reactions that underlie separations of critical elements, as well as nucleation and growth of mineral phases.

ISO 17025 accreditation of multiple nuclear analytical chemistry techniques combined with a suite of state-of-the-art mass spectrometers enables ORNL's Nuclear Analytical Chemistry Lab to quantitatively answer questions in nuclear, forensics, biological, and radiochemistry. A new capability was developed that enables elemental maps of articles, biological tissues, and nondigestible materials that were previously out of reach for inorganic mass spectrometry.

[11] Jisue Moon, et al., "A Neutron Tomography Study to Visualize Fluoride Salt (FLiNaK) Intrusion in Nuclear-grad Graphite," *Carbon* 213 (September 2023): 118258. DOI: 10.1016/j.carbon.2023.118258.
[12] Gabriela Schröder, et al., "Capture of Activated Dioxygen Intermediates at the Copper-active Site of a Lytic Polysaccharide," *Chemical Science* 13 (November 2022): 13303–13320. http://doi.org/10.1039/D2SC05031E.

This capability is strengthened though the coupling between characterization tools available at the Center for Nanophase Materials Sciences and elsewhere at ORNL with data analysis methods and artificial intelligence/machine learning–based computational chemistry approaches to study reactive and dynamic interfaces over a range of time and length scales. Machine learning algorithms for data analysis of many spectrum-imaging techniques as well as electron microscopy are leading to improved sample analysis and detection of trace signals in complex local nano environments and reactive interfaces. To overcome bottlenecks in the synthesis of new materials, the Laboratory Directed Research and Development Interconnected Science Ecosystem (INTERSECT) Initiative is establishing an autonomous chemistry lab, wherein a robotic chemist, guided by artificial intelligence, is used to discover new catalysts and separations media.

Recent advances to this core capability include the following:

- Researchers compared magnesium oxide exposed to the atmosphere for decades with others exposed for days to months to gauge the reaction rates. ORNL found that carbon dioxide is taken up more slowly over longer time periods because of a reacted layer that forms on the surface of the magnesium oxide crystals. This result has direct implications for carbon dioxide capture approaches.
- The lab licensed fundamental discoveries using aqueous glycine for direct air capture and polymer upcycling to local companies.
- Researchers developed capabilities to investigate continuous flow chemistries and polymerization reactions under controlled temperature, pressure, volume, and multiphase conditions that can be guided by simulation and optimization algorithms and made this capability available to users at the Center for Nanophase Materials Sciences.

Funding comes primarily from DOE Basic Energy Sciences, Biological and Environmental Research, and the Office of Isotope R&D and Production. Applied programs sponsored by the Office of Environmental Management, Office of Nuclear Energy, National Nuclear Security Administration, Office of Fossil Energy and Carbon Management, and Office of Energy Efficiency and Renewable Energy benefit from this research.

Computational Science

ORNL's core capability in computational science focuses on developing and delivering scalable solutions that integrate theory, experimentation, data analysis, and modeling and simulation to address complex scientific and engineering problems of national interest. ORNL expertise provides foundations and advances in quantum information science to enable quantum computers, devices, sensors, and networked systems. This core capability resides within a capable complex comprising world-class staff, infrastructure, and supercomputers dedicated to a diverse research portfolio spanning many interests.

Integrated teams of domain scientists, computational scientists, computer scientists, and mathematicians provide foundational expertise in mathematics and computer science, advanced computational capabilities, high-performance computing, artificial intelligence (AI), and quantum information science to advance science insights and engineering solutions. These advances include modeling new quantum and nanomaterials with favorable and predictable properties; characterizing and closing the carbon cycle; predictive understanding of microbial, molecular, cellular, and whole-organism systems; simulation of existing and advanced light-water reactors; characterization of fusion systems; real-time capture, prediction, and optimization of energy infrastructure and use; reliable predictions, with uncertainties, of regional and community-scale climate change, including extreme events and biogeochemical feedbacks; data-driven and simulation campaigns to tackle molecular, cellular, and human-scale health challenges; and advanced software and algorithmic environments for enrichment of rare isotopes. A synergistic, interdisciplinary computational capability also supports early-stage research for companies of all sizes.

Recent advances to this core capability include the following.

- Enabling Exascale Science on Frontier:[13] ORNL's signature core capabilities were critical to the deployment of Frontier, the world's first supercomputer to break the exascale speed barrier and the world's fastest supercomputer dedicated to open science. Frontier, still ranked number one on the TOP500 list, offers a new level of capability for supporting increasingly diversified computational campaigns.
- Building an ecosystem: ORNL is working to propel a hyperconnected, energy-efficient exascale ecosystem by making significant Laboratory Directed Research and Development investments in AI, the Interconnected Science Ecosystem (INTERSECT), and quantum information science, which are described in Section 3.
- Focusing on AI: The AI Initiative at ORNL underwent a crucial reprioritization toward the development of scalable AI systems for scientific discovery, engineering (including self-driving laboratories), and national security. The AI Initiative has three crosscutting technical objectives: *Secure AI* (emphasizing alignment, security, and robustness), *Trustworthy AI* (focusing on validation and verification, uncertainty quantification, and causal reasoning), and *Energy-Efficient AI* (concentrating on scalability, edge computing, and codesign). The projects funded in FY 2024 are scoped to achieve these objectives.
- Studying large language models: Large language models have demonstrated remarkable success as foundational models, benefiting various downstream applications through fine-tuning. Recent studies on loss scaling have demonstrated the superior performance of very large language models compared with their smaller counterparts. ORNL has conducted research exploring efficient distributed training strategies to extract this computation from Frontier, the world's first exascale supercomputer dedicated to open science. Researchers have identified efficient strategies for training exceptionally large language models of varying sizes through empirical analysis and hyperparameter tuning. For the training of models with 175 billion parameters and 1 trillion parameters, researchers achieved 100% weak scaling efficiency on 1,024 and 3,072 MI250X GPUs, respectively.[14]
- Modeling integrated quantum frequency processors toward robust quantum networks:[15] The quantum frequency processor paradigm promises scalable construction of quantum gates. A model was introduced for designing quantum frequency processors comprising microring resonator–based pulse shapers and integrated phase modulators. This model can be extended to other material platforms, providing a design tool for future frequency processors in integrated photonics.

---

[13] R. D. Budiardja, et al., "Ready for the Frontier: Preparing Applications for the World's First Exascale System," *Proceedings of the High Performance Computing: 38th International Conference*, Hamburg, Germany, May 21–25, 2023. DOI: 10.1007/978-3-031-32041-5_10.

[14] S. Dash, et al., "Optimizing Distributed Training on Frontier for Large Language Models," preprint on arXiv (December 2023). DOI: 10.48550/arXiv.2312.12705.

[15] B. E. Nussbaum, et al., "Modeling integrated quantum frequency processors towards robust quantum networks," *Proceedings Volume 12446, Quantum Computing, Communication, and Simulation III* 1244601 (2023), SPIE Quantum West, San Francisco, California, 2023. DOI: 10.1117/12.2649212.

- Two-mode squeezing over deployed fiber coexisting with conventional communications:[16] Squeezed light is a crucial resource for continuous-variable quantum information science. Distributed multimode squeezing is critical for enabling continuous-variable quantum networks and distributed quantum sensing. The demonstration of two-mode squeezing enables future applications in quantum networks and quantum sensing that rely on distributed multimode squeezing.

Funding for this work comes from the DOE Office of Science, Office of Nuclear Energy, Fusion Energy Sciences, Office of Energy Efficiency and Renewable Energy, and Office of Electricity. Other offices and agencies, including the US Department of Defense, US Department of Veterans Affairs, US Department of Health and Human Services, and National Science Foundation, also sponsor or collaborate on activities that leverage DOE investments in computational science

Condensed Matter Physics and Materials Science

The scientific themes of ORNL's condensed matter physics and materials science portfolio include (1) emergent phenomena in correlated and topological materials, (2) quantum information science, and (3) clean energy and sustainable manufacturing. These theme areas arise from ORNL's world-leading capabilities for predicting, synthesizing, characterizing, and controlling materials systems across temporal and spatial scales, welding, and expertise in materials for extreme environments, including fusion materials and corrosion inhibition. The focus in condensed matter physics lies at the forefront and intersection of two fields—electron correlation and topology. The aim is to discover emergent physical principles to stabilize correlated topological states that exhibit exotic physical properties, emergent collective behaviors, and macroscopic quantum effects realized in a broad spectrum of materials systems. In quantum information science efforts, ORNL has focused on quantum sensors to advance the study of dark matter, for example, as well as quantum transduction. For clean energy and manufacturing, the focus includes understanding how functionalities emerge at interfaces, tailoring microstructures, and studying materials under nonequilibrium conditions. Understanding the multiple competing degrees of freedom, interactions, and energy scales at the root of these challenges requires a concerted effort that deeply integrates experiments with theory, computation, modeling, and simulation. ORNL's world-leading neutron scattering capabilities, Low Activation Materials Development and Analysis laboratory, Center for Nanophase Materials Sciences, and leadership computing facilities, along with extensive expertise in using these capabilities, underpin ORNL's strength in this area. The development and application of scalable computational approaches take advantage of ORNL's exascale computing facility to push the frontier in materials modeling and discovery. Neutron irradiation and advanced neutron scattering provide key information on the spatial and temporal correlations in materials and give unique insight into microscopic interactions, including those that give rise to collective quantum phenomena. Along with ORNL signature strengths in precision synthesis and nano- and atomic-scale imaging and spectroscopy, these capabilities provide the foundation for accelerating the discovery of entangled and correlated quantum states for microelectronics and quantum information applications, as well as fusion materials and other new, clean, and sustainable materials for future energy technologies.

Recent advances to this core capability include the following:

[16] J. C. Chapman, et al., "Two-mode squeezing over deployed fiber coexisting with conventional communications," *Opt. Express* 31, no. 16 (2023): 26254–26275. DOI: 10.1364/OE.492539.

- A new class of cleavable Kagome metal compounds was discovered in which topological electronic structures are intertwined with magnetism.[17]
- Guided by machine learning, ORNL designed a record-setting carbonaceous supercapacitor material that stores four times more energy than the best commercial material.[18]
- A technique was developed that enables the visualization of charge motion at the nanometer level and at speeds thousands of times faster than conventional methods.[19]

This work is primarily supported by DOE Basic Energy Sciences and Fusion Energy Sciences. Expertise in this area supports other programs, including the DOE Office of Energy Efficiency and Renewable Energy, Office of Nuclear Energy, Advanced Research Projects Agency–Energy, US Department of Defense, Nuclear Regulatory Commission, National Aeronautics and Space Administration, and Strategic Partnership Project.

Cyber and Information Sciences

ORNL's cyber and information science core capability includes expertise and resources in cybersecurity, cyber-physical security, identity sciences and biometrics, visual analytics, data analytics, artificial intelligence (AI)/machine learning, database architectures, secure communications, signals analysis, quantum information science, data privacy, and information security. ORNL works with DOE, the US Department of Homeland Security, and other partners to (1) securely and resiliently collect and share and intelligently store or retrieve, transmit, analyze, and classify enormous and heterogeneous collections of data; (2) create knowledge from disparate and heterogeneous data sources; and (3) understand, assess, defend against, and defeat known or unknown adversaries to protect the nation's critical infrastructure.

ORNL is among the national leaders in big data management with the ability to solve cybersecurity and information challenges at scale and in near real time. The lab leverages the Oak Ridge Leadership Computing Facility, Knowledge Discovery Infrastructure, and Compute and Data Environment for Science to organize and structure complex and voluminous data, so they are useful for research. For example, ORNL provides data management and analysis support to the DOE Office of Cybersecurity, Energy Security, and Emergency Response's Energy Threat Analysis Center and the Southeast Region Cybersecurity Collaboration Center to provide insights to private grid operators nationwide on potential adversary activities.

ORNL is also establishing itself as a leader in the new field of AI security research, and AI for national security is now a core, integrated component of the laboratory's AI Initiative. The lab recently launched the Center for Artificial Intelligence Security Research to provide objective scientific analysis of the vulnerabilities, threats, and risks related to emerging and advanced AI.

In the information science domain, quantum information science research and development is providing game-changing capabilities for secure communications and control systems, especially in the protection of the electric grid. For example, ORNL is participating in a project to develop photonic integrated

---

[17] B. R. Ortiz, et al., "Evolution of Highly Anisotropic Magnetism in the Titanium-Based Kagome Metals $LnTi_3Bi_4$ (Ln: La⋯Gd^{3+}, Eu^{2+}, Yb^{2+})," *Chem. Mater.* 35, no. 22 (2023): 9756–9773. https://doi.org/10.1021/acs.chemmater.3c02289.

[18] T. Wang, et al., "Machine-learning-assisted material discovery of oxygen-rich highly porous carbon active materials for aqueous supercapacitors," *Nat. Commun.* 14 (2023): 4607. https://doi.org/10.1038/s41467-023-40282-1.

[19] M. Checa, et al., "High-speed mapping of surface charge dynamics using sparse scanning Kelvin probe force microscopy," *Nat. Commun.* 14 (2023): 7196. https://doi.org/10.1038/s41467-023-42583-x.

circuits of larger optical systems, such as quantum random number generators, to dramatically reduce technology costs and ultimately support manufacturing readiness. The combination of information science and quantum communication capabilities spans areas such as sensitive data analytics or distribution, cyber-physical systems protection, trusted and secure communication architectures, and persistent threat detection and mitigation in networks.

ORNL infrastructure supporting this core capability includes the Distributed Energy Communications and Control Laboratory, Grid Research Integration and Deployment Center, classified high-performance computing systems, Center for Trustworthy Embedded Systems, Manufacturing Demonstration Facility, Vehicle Security Laboratory, Cyber Science Research Facility, Cyber Operations Research Range, and Center for Artificial Intelligence Security Research. This infrastructure enables the laboratory to tackle cyber and cyber-physical security challenges for multiple critical infrastructure systems and compute platforms.

Recent advances to this core capability include the following:

- Launched the Center for Artificial Intelligence Security Research in collaboration with the US Department of Homeland Security and the Air Force Research Laboratory
- Reorganized and created three new research groups to showcase capabilities in cyber, computational imaging, and AI/machine learning for national security—Radar and Computational Imaging, Emerging Cyber Systems Research, and Emerging Cyber Technologies Research
- Licensed two advanced cybersecurity monitoring technologies, Situ and Heartbeat, to U2opia Technology, earning a Federal Laboratory Consortium Excellence in Technology Transfer Award
- Announced the Collaborative for Energy Resilience and Quantum Science, a joint research effort with EPB of Chattanooga focused on enhancing the resilience and security of the national power grid
- Completed the first demonstration of continuous variable quantum key distribution over a deployed optical network with a true local oscillator
- Created a demonstration facility for reliable, resilient distribution of precision timing protocol using an alternative timing source to mitigate vulnerabilities and risks associated with GPS interruption.

Funding for this work comes from the DOE Office of Science; Office of Electricity; Office of Cybersecurity, Energy Security, and Emergency Response; Office of Energy Efficiency and Renewable Energy; National Nuclear Security Administration; intelligence community; US Department of Homeland Security; US Department of Veterans Affairs; Centers for Medicare and Medicaid Services; and US Department of Defense.

Decision Science and Analysis

ORNL's decision science and analysis core capability assists a variety of decision-makers who grapple with local, regional, national, and global issues. Quantitative and qualitative social, institutional, and behavioral research is conducted on topics as diverse as technology acceptability, market transformation, societal implications of emerging technologies, and decision-making itself. ORNL's data-driven methods, models, analyses, and tools create insights useful in anticipating, planning for, managing, and quantifying the risks and impacts of current and emerging technologies on infrastructural, environmental, and human systems.

ORNL scientists have established critical capabilities and expertise in the practice of data-driven decision science, risk analysis, and uncertainty quantification and propagation. These scientists draw on diverse disciplinary expertise that includes engineering, environmental science, geographic information science, computer science, economics, political science, psychology, and sociology. ORNL's interdisciplinary expertise can (1) assess the impact of market dynamics; human behavior; and regulations, policies, and practices on the development and uptake of emerging technologies and (2) further the understanding of and trade-offs among resource and technology options. Verification and validation tools are being developed within a comprehensive uncertainty quantification framework and applied across a variety of modeling and simulation applications, including Earth systems, critical infrastructure, extreme events, and advanced energy technologies, allowing for improved analysis with reduced model uncertainties. ORNL's capabilities and expertise enable an unprecedented level of spatial and temporal resolution, providing opportunities for scenario-driven analyses and evaluation of the consequences of current and future technologies, policies, geographic changes, population dynamics, and more.

The new ORNL Systems and Decision Sciences Group builds advanced software capabilities for the study of complex engineered and natural systems. The group combines research in high-performance computing and data-driven artificial intelligence/machine learning methods with state-of-the-art simulation sciences to build key decision-making and operations control tools. Examples include at-scale what-if scenario capabilities for high-fidelity analysis of critical infrastructure systems such as the electric grid and healthcare systems with an emphasis on their behavior under disruptions. These tools help policymakers and operations managers prepare for contingencies and make informed real-time interventions in response to disruptions.

ORNL's new Spatial Statistics Group advances statistical learning strategies that explicitly link geospatial theory, data, and modeling with critical domain-specific decision processes. Key among these strategies are frameworks for Bayesian reasoning under uncertainty that meet national security decision challenges with inherently explainable artificial intelligence and transparent propagation of uncertainty. Bayesian reasoning allows artificial intelligence to extend its reach into complex problem sets in which quantifiable domain expertise and relevant engineering principles reinforce understanding and decision-making, particularly in data-poor environments.

ORNL also recently established DecisionScience@ORNL, a subeffort of the Laboratory Directed Research and Development Transformational Decarbonization Initiative. This effort focuses on projects such as process-level techno-economic and life cycle analyses, systems-level infrastructure siting, and environmental and socioeconomic analyses. These projects pair experimentalists and technology developers with analysts and modelers to explore how novel solutions might figure into the broader suite of decarbonization activities at scale and to assess where the opportunities and barriers may lie.

Recent advances in this core capability include the following:

- Developed Peregrine, a software tool leveraging artificial intelligence and material science fundamentals to evaluate in real time the quality and performance of components created with modern advanced manufacturing systems and to certify them for critical applications
- Spearheaded the multi-institutional, flagship 2023 Billion Ton project, an effort that combines agriculture, forestry, environmental systems, and techno-economic analyses to understand the potential for biomass feedstocks, residues, and other land-based resources to contribute the US energy supply mix over the coming decades
- Developed a first-of-its-kind, multicriteria analysis framework to explore candidate locations for distributed direct air capture systems colocated with existing buildings' heating, ventilation, and air-conditioning equipment in urban areas (named *UrbanDAC*)

Funding for this work comes from the DOE Office of Science, Office of Nuclear Energy, Office of Electricity, Office of Energy Efficiency and Renewable Energy, Office of Clean Energy Demonstrations, US Department of Homeland Security, US Department of Defense, US Department of Transportation, US Department of State, Nuclear Regulatory Commission, National Cancer Institute, private companies, philanthropic foundations, and the US Food and Drug Administration, among others.

Earth and Energy Systems and Infrastructure Analysis and Engineering

ORNL performs translational research and development in collaboration with industry partners to support clean and renewable energy production, transmission, and utilization across numerous energy-use sectors. Additionally, ORNL researchers analyze the ecological interactions of and develop quantitative indicators for the impacts of human activities, natural disturbances, and varying climatic conditions on spatial patterns and processes on the Earth's natural environment as well as built energy and water infrastructure systems. Activities enabled by this core capability include (1) linking a fundamental understanding of mercury biogeochemistry to engineering applications to address DOE's legacy mercury contamination issues;[20] (2) identifying and modeling ecological functions of rivers and streams within the site selection, design, and operational decision-support systems for hydropower; (3) developing and assessing sustainability indicators and ecosystem services for bioenergy feedstock production and hydropower development through integration of landscape and aquatic ecological science and socioeconomic analyses; and (4) producing downscaled future weather, hydrology, water availability, extreme events, and hydropower projections to support the evaluation of climate change–induced impacts, vulnerability, adaptation strategies, and infrastructure safety.[21]

This capability supports DOE's energy and environmental missions and contributes to the technical basis for policy decisions. ORNL takes advantage of laboratory- to field-scale resources and expertise in geochemistry, hydrology, microbial ecology, aquatic ecology, environmental informatics, data science, economics, and engineering to evaluate the impacts of energy production, transmission, distribution, and use on the environment.

Relevant leadership areas for ORNL include (1) novel integrated sensor and monitoring networks for long-term assessment of environmental change in response to energy production and use; (2) understanding contaminant cycling and fate in ecosystems to inform the development of innovative remediation technologies and improve risk-based decision-making; (3) assessing impacts of energy production and distribution systems, including hydropower (existing and in development), on aquatic ecosystem integrity through sensor systems, novel geospatial analyses, and modeling to identify thresholds and promote adaptability of monitoring and management regimes; (4) modeling and assessing biomass feedstock resources and the logistical and environmental effects of supplying biomass to facilities producing biomass-based fuels, power, heat, or bioproducts;[22] and (5) technologies, systems analysis, and decision support for sustainable hydropower and other energy production and water use.

---

[20] H. Du, et al., "Sonochemical oxidation and stabilization of liquid elemental mercury in water and soil," *Journal of Hazardous Materials* 455 (2023): 130589. DOI: 10.1016/j.hazmat.2022.130589.

[21] S.-C. Kao, et al., *Third Assessment of the Effects of Climate Change on Federal Hydropower*, ORNL/TM-2021/2278 (Oak Ridge, Tennessee: Oak Ridge National Laboratory, 2022). DOI: 10.2172/1887712.

[22] DOE Bioenergy Technologies Office, *2016 Billion-Ton Report* (Washington, DC: US Department of Energy, 2016).

ORNL's Earth, energy, and infrastructure system analysis and engineering projects take advantage of world-class experimental and computational infrastructure, including neutrons at the Spallation Neutron Source and High Flux Isotope Reactor, the Compute and Data Environment for Science data infrastructure, high-performance computing at the Oak Ridge Leadership Computing Facility, state-of-the-art greenhouses, field and laboratory facilities (including the Environmental Science Laboratory, Aquatic Ecology Laboratory, Watershed Dynamics and Evolution Science Focus Area field sites, and the Y-12 National Security Complex Integrated Field Research Challenge site), and the Center for Nanophase Materials Sciences.

Recent advances to this core capability include the following:

- Extended ORNL's comprehensive HydroSource water energy platform by incorporating new datasets such as national hydropower market assessments and fish passage information to support sustainable hydropower development and management
- Leveraged the Frontier supercomputer to accelerate the development of the lab's high-resolution 2D Runoff Inundation Toolkit for Operational Needs inundation model to support Innovative and Novel Computational Impact on Theory and Experiment–scale ensemble flood simulations in projected future climate conditions for critical US infrastructures
- Compiled and released the most comprehensive biomass resources database (biokdf.ornl.gov), which includes details on the geographic distribution, logistical availability, and economic accessibility of biomass resources across the US. This information is essential to inform research, development, and deployment strategies for a sustainable US bioeconomy.

Funding comes from the DOE Office of Science, Office of Environmental Management, Office of Energy Efficiency and Renewable Energy, Office of Nuclear Energy, Office of Fossil Energy and Carbon Management, National Nuclear Security Administration, US Department of Defense, and Nuclear Regulatory Commission.

Earth, Environmental, and Atmospheric Science

ORNL's core capability in Earth, environmental, and atmospheric science is focused on improving understanding of the causes, impacts, and predictability of climate change by (1) conducting large-scale, long-term, ecosystem experiments and observations to improve Earth system models (ESMs); (2) performing watershed investigations to understand how gradients in land cover and changing precipitation patterns affect the export of water and material at regional scales; (3) leading DOE's ESM development in biogeochemistry for the Energy Exascale Earth System Model (E3SM) project; (4) integrating multidisciplinary research connecting data, terrestrial and atmospheric sciences, and large-scale computing; (5) developing novel software to improve the credibility and scalability of next-generation ESMs; (6) developing model–data integration tools, machine learning methods, and synthesized data for model evaluation, diagnostics, and benchmarking; (7) performing data management for observations and large model output, as well as building tools for data discovery, distribution, and archiving; and (8) coupling ESMs to components of human systems, such as land use and land cover change, that incorporate significant feedback to the climate system.

ORNL advances next-generation ESMs and regional-scale models by improving the characterization of processes that control the exchange and transport of carbon, nitrogen, nutrients, water, and energy through different compartments of the terrestrial and aquatic ecosystems. ORNL is at the forefront in the use of knowledge derived from these long-term experiments and observational networks to improve the representation of key plant and microbial traits in terrestrial biosphere models (e.g., spanning scales from genes to ecosystems) and their contributions to global carbon and other biogeochemical cycles. For example, the Spruce and Peatland Responses Under Changing Environments team recently developed a new conceptual framework, referred to as the *ecosystem wilting point*, as a tool to understand and predict how forest ecosystems respond to extreme drought. Similarly, the Next-Generation Ecosystem Experiments Arctic team demonstrated that drying tundra landscapes will limit subsidence-induced accelerated permafrost thaw, thereby addressing the largest uncertainty about how carbon-rich regions of the Arctic will respond to warming temperatures. ORNL advances a transformative watershed predictive capability through the Watershed Dynamics and Evolution Science Focus Area and Interoperable Design of Extreme-scale Application Software-Watershed projects, both of which leverage machine learning to integrate diverse data with river basin–scale simulations of unprecedented spatial resolution and mechanistic detail. This information is required not only to inform model inputs but also to assist in model–data integration and to create surrogate models to support scaling of observations to river basin scales.

ORNL is the premier data resource for DOE's Atmospheric Radiation Measurement (ARM) Facility. With over 5 PB of data from more than 11,000 routine data products, the ORNL-led ARM Data Center distributes key atmospheric radiation measurement data to researchers around the world to improve the understanding of atmospheric dynamics and cloud processes. For example, the ARM Data Center deployed a new satellite-based network at the North Slope of the Alaska Site, added a new hybrid storage cluster to replace the aging high-performance storage systems, released a user data workbench with Jupyter notebook capabilities, and designed and implemented a new Large-Eddy Simulation ARM Symbiotic Simulation and Observation discovery interface for the Cloud, Aerosol, and Complex Terrain Interactions Large-Eddy Simulation ARM Symbiotic Simulation and Observation data.

ORNL infrastructure supporting climate change science and atmospheric science includes a growing data storage facility and *private cloud* capacity for computing using nearby data through the National Center for Computational Sciences; leadership-class computing through the Oak Ridge Leadership Computing Facility, which supports process-based and machine learning modeling and simulation and big data applications; state-of-the-art greenhouses; field and laboratory facilities; and the Spallation Neutron Source and High Flux Isotope Reactor, which enable characterization of soil organic matter and multimodal imaging of whole plant and soil systems and plant–water interactions.

Recent advances to this core capability include the following:

- Developed a new model structure in the E3SM Land Model for representing shorter- and longer-lived fine-roots with differing functions and their Mycorrhizal fungal partners—This new approach approximates the hierarchical branching structure of fine-root systems and allows for improved representation of belowground processes in ESMs.
- Incorporated the newly developed ultrahigh-resolution E3SM Land Model into the DOE's fully coupled E3SM—The new E3SM Land Model is designed to run efficiently on DOE's leadership-class computing (e.g., Frontier).
- Extended ORNL's unique multiscale capabilities in the Advanced Terrestrial Simulator tool by adding new capabilities to represent subsidence and time-varying conditions in stream corridors—The addition of subsidence enables more accurate representation of large- and small-scale topography changes caused by thawing permafrost in Arctic landscapes, whereas the extension of Advanced Terrestrial Simulator's stream-corridor model to unsteady conditions allows the effects of small-scale hyporheic zone processes to be represented in regional-scale watershed models.

Funding for this work primarily comes from the DOE Office of Science. The National Nuclear Security Administration, National Aeronautics and Space Administration, US Department of Defense, US Department of Homeland Security, US Geological Survey, National Oceanic and Atmospheric

Administration, and US Department of Agriculture's Forest Service also sponsor or collaborate on activities that leverage and enhance DOE investments in climate change and atmospheric science to generate solutions for the nation.

Isotope Science and Engineering

ORNL has been producing and supplying isotopes since 1945, and the lab's current isotope mission continues to address critical needs for the nation and global community. ORNL has world-leading expertise in and facilities that support the application and production of critical isotopes for scientific discovery, medical treatments, industrial use, and national security applications. ORNL also maintains and distributes the US inventory of enriched stable isotopes and radioisotopes for DOE's National Isotope Development Center.

The specialized hot cells in the Radiochemical Engineering Development Center, which are near the High Flux Isotope Reactor, allow ORNL to handle postirradiation testing and isotope processing that cannot be done at other isotope production sites, and the transuranic processing capabilities are unique in the Western world. ORNL is capable of elemental and radiochemical analytical measurements for all radiological samples, including from environmental to highly radioactive sample types, as detailed in Section A.19. ORNL's expertise also includes environmental radiochemistry and nuclear measurements using inductively coupled plasma mass spectrometry and high-pressure ion chromatography–inductively coupled plasma mass spectrometry for characterizations of nuclear materials and medical isotopes. Advances in stable isotope enrichment science are made possible with expertise in electromagnetic and gas centrifuge separations and enabled by investments in the Stable Isotope Production Facility and the Stable Isotope Production and Research Center.

Advanced target design and separation techniques for a broad range of applications, including cancer treatment, commercial uses, and research, are being demonstrated through emerging capabilities such as inkjet printing of thin-film targets and the use of artificial intelligence/machine learning to predict and optimize radiochemical separations, which will modernize isotope manufacturing at ORNL.

As the national steward of uranium science and processing technology, ORNL applies expertise in isotope science and engineering to advance the understanding of fuel cycle operations associated with processing, purifying, and enriching uranium. Established uranium chemical processes, operated at a range of scales, support ORNL's nonproliferation mission while providing learning opportunities for the next generation of radiochemical engineers and scientists. High-speed analytical capabilities usable in two-phase systems have been developed to elucidate separations and reaction mechanisms toward the control of residence time to improve separation efficiency and reaction yields.

Recent enhancements to this core capability include the following:

- Invested in new research to study the use of artificial intelligence/machine learning to develop autonomous systems for radioisotope production
- Established or are reestablishing domestic production of in-demand stable and radioisotopes as a result of the Russian invasion of Ukraine (ytterbium-176, radium-226, iridium-192, krypton-85, promethium-147)
- Developing new actinide separation methods that improve processes and increase yield (einsteinium-254, actinium-225)
- Established current Good Manufacturing Practice for actinium-225 and investigating other medical isotopes produced at ORNL (thorium-228, radium-224) capable of current Good Manufacturing Practice production
- Developed new plasma diagnostics to help advance ORNL's electromagnetic isotope separation technology

Major funding sources for this work include the DOE Office of Isotope R&D and Production, Office of 1Nuclear Energy, National Nuclear Security Administration, National Aeronautics and Space Administration, and other government agencies.

Large Scale User Facilities, R&D Facilities, and Advanced Instrumentation

ORNL is recognized for its capability to conceive, design, construct, and operate leading-edge specialty research facilities. ORNL operates four cutting-edge DOE Office of Science user facilities (Spallation Neutron Source [SNS], High Flux Isotope Reactor [HFIR], Center for Nanophase Materials Sciences [CNMS], and Oak Ridge Leadership Computing Facility [OLCF]), each of which are at the forefront of scientific discovery and innovation, as well as five Office of Energy Efficiency and Renewable Energy research and development facilities. Several additional major DOE Office of Science facilities are planned for upgrades or refurbishment or are under development.

HFIR and SNS collectively host over 30 neutron scattering instruments and offer unparalleled opportunities for studying materials, biological systems, and neutron physics. SNS, the world's most potent pulsed spallation neutron source, complements HFIR's steady-state neutron beams, thus providing an extensive spectrum for scientific exploration. Maintaining global leadership in neutron scattering requires significant upgrades, including the Proton Power Upgrade, Second Target Station, HFIR Beryllium Reflector Replacement, and HFIR Pressure Vessel Replacement.

The Proton Power Upgrade project will elevate neutron production by amplifying the power into the First Target Station from its current 1.7 MW to a goal of 2 MW. Coupled with ongoing instrument upgrades, the Proton Power Upgrade will generate orders of magnitude more data than currently achievable. An ongoing Laboratory Directed Research and Development project is investigating the potential of using extra available power for radioisotope production. Moreover, initiatives such as the HFIR Pressure Vessel Replacement project and the HFIR Beryllium Reflector Replacement project ensure the sustained operation and enhancement of HFIR's capabilities. These projects underscore ORNL's commitment to ensuring the nation remains at the forefront of neutron scattering research and innovation.

OLCF is home to two of the world's fastest supercomputers. Frontier, which debuted in May 2022 as the first exascale supercomputer, achieved 1.194 exaflops by May 2023, topping the TOP500 list and surpassing the combined speed of the next four supercomputers. In 2024, Summit is being offered as a key DOE resource supporting the National Artificial Intelligence Research Resource program. OLCF continues advancing quantum information science through the Quantum Computing User Program for researchers to assess combined quantum–classical algorithms. ORNL also operates high-performance computers such as Gaea for the National Oceanic and Atmospheric Administration, Fawbush and Miller for the US Air Force, and Cumulus for DOE's Atmospheric Radiation Measurement program, fostering multiagency cooperation and research and development partnerships.

CNMS serves as a cornerstone for advancing nanoscience research, providing unparalleled access to cutting-edge facilities, expert guidance, and collaborative opportunities. Through its diverse programs, thematic research areas, and strategic initiatives, CNMS continues to push the boundaries of nanoscience on a global scale, contributing to scientific advancements and fostering innovation.

CNMS offers a range of facilities and programs for nanoscience research, including synthesis, fabrication, imaging, and theory. Researchers become part of a vibrant community alongside staff and collaborators. CNMS also facilitates access to ORNL's neutron sources and computing resources. Thematic areas of focus include polymers, quantum science, and multiscale dynamics. Recent initiatives aim to enhance capabilities and outreach, such as expanding chemical deuteration and increasing university engagement. Investments are being made to improve instrumentation, including an extension of the Advanced Microscopy Laboratory expected to be completed by December 2025.

ORNL is also leading the development of several other large-scale projects and facilities, including the Material Plasma Exposure eXperiment, US ITER, and ton-scale Large Enriched Germanium Experiment for Neutrinoless ββ Decay.

Recent advancements to this core capability include the following:

SNS and HFIR

- Over the past 3 years, remote control of all instruments has been enabled at SNS and HFIR, allowing users to fully control instruments remotely for entire or portions of experiments.
- The Versatile Neutron Imaging Instrument (VENUS) project is on schedule, entering its commissioning phase in July 2024. It will provide a major upgrade to the ORNL neutron scattering capability and will provide users with world-leading neutron imaging capabilities to support automated artificial intelligence (AI)-informed studies on broad areas of science, including additive manufacturing, battery materials research, and life science applications.
- ORNL is investing heavily in and advancing data systems for neutron scattering applications, including scientific software development, high-performance computing, storage, and networks. These major improvements not only accelerate the time to scientific discovery by reducing the time between experiment and publication, but they also improve overall accessibility to neutron scattering from new or inexperienced user communities and place ORNL in a key position to engage with and leverage the Interconnected Science Ecosystem (INTERSECT) Initiative, Integrated Research Infrastructure, and the DOE High Performance Data Facility.
- The upgraded Beam Test Facility, featuring an improved Radio Frequency Quadrupole and new topology, began operations in December 2023 and is enhancing exploration of the beam's 6D phase space and understanding of beam halo. It also enables the development of a future moderator test facility, promising significant progress in neutron scattering efficiency.
- ORNL developed and continues to develop world-leading scientific software for the following:
    - Neutron imaging, including AI-enabled automated acquisition and reconstruction and software for Brage edge analysis
    - Pair distribution function analysis of diffraction data
    - Data treatment and visualization for 4D datasets from inelastic neutron scattering experiments, including workflows to execute simulation and modeling workflows on high-performance computing infrastructures
    - Standardized data processing workflows for all technique areas and automated data processing workflows
    - Frameworks for smart automation agent control of neutron scattering experiments

OLCF

- Frontier, the first exascale machine, came online in May 2022. It was designed to address critical problems beyond the capability of existing supercomputers, including nuclear reactor safety and efficiency, genetics of diseases, and precision medicine.
- Frontier applications were extended to merging AI with data analytics, modeling, and simulation for advanced research and analysis, as was described in Section 3. For example, SummitPLUS is a new program for the final year of Summit operations (2024) supporting large-scale high-performance computing campaigns including AI, integrated research infrastructure, and National Artificial Intelligence Research Resource allocations.

CNMS

- CNMS has extended the impact of its unique chemical deuteration capabilities through expanded awareness on both the neutron scattering website and the CNMS website to enhance user access to deuteration and foster greater collaborations between CNMS, SNS, and HFIR.
- CNMS developed new engagements from universities underrepresented in the DOE portfolio (e.g., increase accessibility by historically Black colleges and universities and minority-serving institutions) to expand its user base and further the impact of its science.
- Laboratory investments are expanding capabilities for ORNL's most sensitive instrumentation, including CNMS equipment. New semiconductor fabrication and characterization equipment critical for ORNL's microelectronic initiative is being incorporated into CNMS. An extension of the CNMS Advanced Microscopy Laboratory, which houses the most-sensitive electron microscopes, will be completed by December 2025.

Major funding sources for this work include the DOE Office of Science Basic Energy Sciences, Advanced Scientific Computing Research, Biological and Environmental Research, Fusion Energy Sciences, Office of Nuclear Physics, Office of Nuclear Energy, Office of Isotope R&D and Production, National Nuclear Security Administration, National Aeronautics and Space Administration, and other government agencies.

Mechanical Design and Engineering

ORNL's unique combination of expertise, large facilities, and innovative tools in mechanical design and engineering support critical missions as diverse as fission and fusion energy, accelerators, enrichment, manufacturing, buildings, and transportation. The lab deploys these capabilities for core priorities and evolving research while developing new resources for projects such as US ITER, the Proton Power Upgrade and Second Target Station at the Spallation Neutron Source, the Majorana Demonstrator, and the Material Plasma Exposure Experiment.

Examples include developing remote systems for the Spallation Neutron Source and nonreactor nuclear and radiological facilities as well as creating production-level separation processes based on electromagnetic and gas centrifuge separation for radioisotopes and stable isotopes. The Centrifuge Manufacturing Capability, completed in FY 2021, supports fabrication of gaseous centrifuge isotope separation machines for the Stable Isotope Production Facility and the Stable Isotope Production and Research Center. Another example is combining mechanical design and engineering expertise with other disciplines to support a range of nuclear capabilities, including thermal/hydraulic design of Spallation Neutron Source mercury target systems, High Flux Isotope Reactor irradiation experiments, the High Flux Isotope Reactor closed-loop supercritical-hydrogen cold neutron source, a molten salt experimental loop facility, and Wendelstein 7-X superconducting stellarator components.

ORNL's applied research facilities (Manufacturing Demonstration Facility, Carbon Fiber Technology Facility, Building Technologies Research and Integration Center, National Transportation Research Center, and the remote systems development high-bay facility) support work by staff with expertise in robotics and remote systems design, thermal hydraulics, energy-efficient manufacturing, transportation, and residential and commercial buildings.

Recent advances to this core capability include the following:

- Developed rail and marine laboratories to support low- and net-zero carbon fuels and combustion research for the decarbonization of these sectors
- Developed, designed, and 3D printed a new tool for the removal of process lines as a full assembly when completing a rebuild of the Stable Isotope Processing Facility project
- Developed designs for modular hot cell concepts for the Radioisotope Processing Facility
- Developed a new shipping vial gasket to reduce radon-222 escape risk during radium-226 shipment

Funding in this area originates from several sources, including the DOE Office of Science, Office of Nuclear Energy, Office of Energy Efficiency and Renewable Energy, National Nuclear Security Administration, and Strategic Partnership Project sponsors.

Microelectronics

ORNL is advancing energy-efficient microelectronics in the post-Moore computing era, strategically addressing computational and material challenges in the face of diminishing scaling laws. By leveraging interdisciplinary expertise in computer architecture and materials science, ORNL is positioning itself at the forefront of creating more sustainable and efficient computing technologies underscored by significant investments in synthesis and lithography tools and other instrumentation located in the class 100/1,000 cleanroom at the Center for Nanophase Materials Sciences, as well as in electronic design automation tools such as the Siemens EDA toolchain. Additionally, ORNL has equipment and experience to support advanced electronics research and development prototyping and testing, including a new wire bonding capability and a new aerosol jet printer capable of supporting 2.5D and 3D electronics packaging.

This effort aligns with the strategic goal of advancing scientific breakthroughs and contributes to reducing the environmental impact of digital technologies. Through developing a cross-laboratory strategy, fostering collaborations, and establishing a pathway for microelectronics innovation, ORNL ensures a holistic approach to advancing microelectronics, underpinning future computing systems such as OLCF-7 and beyond with groundbreaking energy efficiency and performance. ORNL is addressing the Office of Science’s focus on accelerating the advancement of microelectronic technologies in a codesign innovation ecosystem in which materials, chemistries, devices, systems, architectures, algorithms, and software are developed in a closely integrated fashion through a cross-directorate working group that brings all these aspects together. Through such a multidisciplinary effort, integration is assured, and advances will be achieved more rapidly.

ORNL leads the microelectronics codesign project named Abisko, which aims to develop an energy-efficient spiking neural network computing chiplet using novel neuromorphic devices, such as memristors and electrochemical RAM. The Center for Nanophase Materials Sciences supports this initiative, providing capabilities for synthesizing new materials and leveraging high-performance computing for microelectronics research. Additional research areas include a focus on the discovery of materials systems for next-generation microelectronics and realizing autonomous approaches for efficient materials discovery. Lastly, ORNL researchers provide expertise in custom mixed-signal integrated circuits applicable to analog computing/analog signal processing, neuromorphic computing, and edge processing toward advancing ORNL/DOE mission goals in energy, computing, and national security. Specifically, staff have experience in harsh-environment electronics (high radiation and elevated temperature) and systems based on silicon and wide-bandgap materials gallium nitride and silicon carbide. Radiation-tolerant junction gate field-effect transistor devices in silicon and high–electron mobility transistor devices in gallium nitride have demonstrated exceptional gamma and neutron radiation hardness, respectively.

Lastly, efforts in physics include a focus on the irradiation of microelectronics and using microelectronics to meet the needs of the long-range plans for the Office of Nuclear Physics and High Energy Physics. The lab is advancing its capabilities to be a key partner for the development of novel integrated circuits and advanced detector technology, including the development of highly segmented large-area neutron and photon detector systems and the advancement of artificial intelligence and machine learning algorithms directly in the readout stream, creating autonomous and intelligent detector systems.

ORNL's commitment to innovation and security in microelectronics positions it as a key player in shaping the future of computing technologies, with a focus on sustainability, efficiency, and cutting-edge research methodologies and advancing the state of the art in electronics for nuclear-based clean energy generation (both fission and fusion).

Recent advances toward this core capabilities include the following:

- The lab developed microelectronics-based partnerships with Georgia Institute of Technology, North Carolina State University, Purdue University, Arizona State University, Sandia National Laboratories, and Columbia University
- ORNL provided an investment of approximately $6.5M into microelectronics equipment and software. Funds are directed toward semiconductor fabrication and characterization equipment to be deployed at the Center for Nanophase Materials Sciences and electronic design automation software to be deployed ORNL-wide.

Funding in this area originates from several sources, including internal Laboratory Directed Research and Development investments and external sponsorship from DOE Office of Science offices in Advanced Scientific Computing Research and Basic Energy Sciences, as well as US Department of Defense agencies and other Strategic Partnership Project sponsors.

Nuclear and Radio Chemistry

ORNL's nuclear and radiochemistry research focuses on the nuclear engineering design of advanced targets for the efficient production of isotopes and the development of highly selective separation techniques for harvesting isotopes after target irradiation for a broad range of applications, including cancer treatment, commercial uses, and research. This is a key capability that enables the isotope production detailed in A.15.

ORNL's unique facilities enable innovative isotope research, development, and production. The High Flux Isotope Reactor, which provides the world's highest neutron flux, is used to irradiate target materials for the production of various radioisotopes through the DOE Isotope Program and other sponsors, and separations are conducted in the Radiochemical Engineering Development Center and other hot cell facilities and radiological laboratories. ORNL is addressing long-term needs for satisfying the increasing demand for isotopes used in medical, industrial, research, and national security applications through investments in the Radioisotope Processing Facility, Stable Isotope Production Facility, and Stable Isotope Production and Research Center. Additionally, ORNL offers a full suite of elemental and radiochemical analytical measurements for all radiological samples, from environmental to highly radioactive sample types. Emphasis also includes environmental radiochemistry and nuclear measurements using inductively coupled plasma mass spectrometry and high-pressure ion chromatography–inductively coupled plasma mass spectrometry for characterizations of nuclear materials and medical isotopes.

Recent enhancements to this core capability include the following:

- Investments in nuclear battery research are enabling new capabilities in advanced thermoelectric devices.
- Current research is bridging the knowledge gap in promethium's solid-state chemistry and developing pathways for performing advanced measurements in the solid state on radioactive materials.
- Recently developed methods of purifying berkelium-249 have resulted in higher purity and could be applied to other actinides in the future.

Funding in this area comes from the DOE Office of Nuclear Energy, Office of Isotope R&D and Production, National Nuclear Security Administration, National Aeronautics and Space Administration, and other government agencies.

Nuclear Engineering

At the height of the Manhattan Project, ORNL helped to invent the field of nuclear engineering, not only building the world's first continuously operating nuclear reactor and fuel cycle facility but also applying the capabilities of that machinery to support broader discovery and science and technology advancement. ORNL's staff, facilities, and equipment provide a comprehensive research and development capability portfolio supporting fuel technology innovation, advanced reactor development, siting and licensing decision-making, and an integrated fuel cycle strategy that spans from preparing fuel material to final disposal. The capability enables reactor developers to meet worldwide energy demand, radioisotope availability needs, and climate goals by translating discovery science breakthroughs into market-ready nuclear technologies.

ORNL has core capabilities and facilities in material science, neutron science, advanced manufacturing, computing, and other areas. These fundamental capabilities enable the laboratory to address important multidisciplinary problems ranging from the reduction of predictive model uncertainties through improved fundamental nuclear interaction data to the development of novel materials and sensors for fission, fusion, and accelerator systems. ORNL is a leader in modeling and simulation for reactor physics and radiation transport, computational thermal hydraulics, reactor systems, nuclear criticality safety, and reactor safety; radiation detection and imaging; system engineering, control, and data analytics; advanced fuel form development and qualification; and radioisotope production. ORNL has a wide range of specialized facilities for nuclear materials development and characterization. Capabilities include a complete cradle-to-grave suite spanning nonradiological material characterization and material compatibility testing capabilities, materials irradiation capabilities at the High Flux Isotope Reactor, and postirradiation characterization facilities at the Low Activation Materials Development and Analysis laboratory, as well as hot cells facilities for examination and testing of irradiated fuels. The Spallation Neutron Source is used to understand material structures, augment nuclear interaction data, and provide insight into relevant fundamental physical phenomena. The planning of work in these facilities and the data they generate serve as a proving ground for ORNL's modeling, simulation, and validation capabilities.

Recent advances to this core capability include the following:

- A structural model has been developed that simulates the long-term degradation of the concrete biological shield of light-water reactors when exposed to a high-neutron radiation dose. This understanding is critical in predicting the long-term performance of concrete in nuclear systems. ORNL developed a mechanical model accounting for radiation-induced expansion, creep, and damage in concrete using the Grizzly finite element code, informed by ex-core neutron flux calculations using the VERA tool.[23]

- Molten salt reactors, particularly the fluid-fueled types, pose unique considerations with regards to the compatibility of materials with molten salt coolants during operations. A sound understanding of materials compatibility is crucial to monitor and manage the lifetime performance of nuclear structural components. In a previous report, several technical gaps were identified, including the lack of systematic data collection using static corrosion methodologies and testing standards. Though the present report did not attempt to develop a standard for molten salt corrosion static experiments, it provides insights on key experimental parameters used to assess the molten salt compatibility of structural materials in static halide salts that could aid the development of test standards. Additionally, the report advances the understanding of materials compatibility in molten salt reactors to prepare the Nuclear Regulatory Commission staff for future licensing reviews.[24]

Funding in this area comes from the DOE Office of Nuclear Energy, National Nuclear Security Administration, National Aeronautics and Space Administration, Advanced Research Projects Agency–Energy, and other government agencies.

Nuclear Physics

ORNL's nuclear physics research addresses the matter–antimatter asymmetry in the universe with the planned ton-scale Large Enriched Germanium Experiment for Neutrinoless ββ Decay project to search for the hypothesized neutrinoless ββ decay of nuclei. It also operates the Fundamental Nuclear Physics beamline at the Spallation Neutron Source, which is home to the Nab experiment that will make a precision measurement of the beta decay of the neutron. At the Large Hadron Collider at the European Organization for Nuclear Research (CERN), ORNL is a member of the ALICE (A Large Ion Collider Experiment) Collaboration, studying the properties of the quark–gluon plasma.

The Oak Ridge Leadership Computing Facility is used to investigate nuclear structure and reactions and nuclear astrophysical processes. ORNL develops the highest-fidelity core-collapse supernova and neutron-star merger simulations and develops the framework for charged particle transport to provide detailed simulations of detector responses for collider experiments in particle and nuclear physics.

ORNL hosts the COHERENT Collaboration at the Spallation Neutron Source to measure the coherent elastic neutrino nucleus interaction of low-energy neutrinos on different nuclei and the PROSPECT Collaboration at the High Flux Isotope Reactor, the only reactor-based neutrino experiment in the country, to study fundamental neutrino interactions.

ORNL has a strong instrumentation capability, enabling physics experiments at the Facility for Rare Isotope Beams and constructing the Electron-Proton/Ion Collider detector for the future Electron Ion Collider at Brookhaven National Laboratory. ORNL performs research and development for understanding and exploiting combined signatures from radiation decay, radiography, and tomography;

---

[23] A. Cheniour, et al., "A structural model of the long-term degradation of the concrete biological shield," *Nucl. Eng. Des.* 405 (2023): 112217. DOI: 10.1016/j.nucengdes.2023.112217.

[24] B. Pint, et al, *Evaluating Static Isothermal Molten Salt Compatibility with Structural Alloys*, TLR-RES/DE/REB-2023-04, ORNL/SPR-2023/2856 (Oak Ridge, Tennessee: US Nuclear Regulatory Commission, Oak Ridge National Laboratory, 2023).

system modeling and detection networks for use over a range of fundamental physics; and next-generation advanced conceptual systems. ORNL's world-leading neutron and gamma ray imaging capability supports nonproliferation activities. This nuclear data program includes cross section measurements, the development of evaluation and data analysis methods, and data processing, which is a critical component for national security and the development of next-generation nuclear energy sources.

Recent advances to this core capability include the following:

- Researchers used radioactive beams of excited sodium-32 nuclei to test nuclear shapes far from stability and found an unexpected result—a long-lived state of sodium-32—that raises questions about how nuclear shapes evolve.[25]
- The Majorana Collaboration published its final results proving that the techniques used by the collaboration could be deployed on a much larger scale to search for the rare, never-before-seen neutrinoless ββ decay that could help explain the existence of matter.[26]

This work is primarily supported by the DOE Office of Nuclear Physics. Expertise in this area supports other programs including the Office of Nuclear Energy, National Nuclear Security Administration, and US Department of Defense.

Plasma and Fusion Energy Sciences

ORNL has a long history as a key player in the development of the knowledge base for plasma and fusion energy sciences essential for fusion energy deployment. With activities ranging from developing and testing innovative confinement concepts to delivering large-scale fusion components, ORNL is the US leader—and in many cases, the world leader—in several key areas of fusion development.

ORNL is home to core DOE programs in fusion materials and fusion nuclear science and technology. Materials scientists at ORNL conduct experiments to support the development of alloys and silicon carbide composites that have been leveraged to develop a suite of economical, high-strength, radiation-resistant steels. Recent experiments have leveraged the capabilities of the High Flux Isotope Reactor to expose candidate materials to high-energy neutrons to better characterize the response of these materials to fusion-like conditions. This capability is unparalleled in the world, and numerous international labs are partnering with ORNL to develop data of interest for specific materials they are contemplating using in future fusion systems. ORNL is developing the technical expertise and capabilities to be a world leader in tritium breeding blanket technology. The lab possesses a comprehensive blanket design and analysis team with expertise in nuclear and activation analysis, computational fluid dynamics, computational magnetohydrodynamics, thermomechanics, and tritium transport. Combined with experiments to advance the state of the art in helium cooling via additively manufactured heat transfer enhancements, develop material compatibility solutions for liquid metal and molten salt blankets, and investigate hydrogen retention in advanced materials, ORNL is well-positioned to deliver the foundational blanket research and development to establish the basis for a future Fusion Pilot Plant.

ORNL is the world leader in pellet fueling and blanket systems for fusion applications. This designation is evidenced by the recent development and initial testing of a steady-state pellet injector to be deployed

---

[25] T. J. Gray, et al., "Microsecond Isomer at the *N* = 20 Island of Shape Inversion Observed at FRIB," *Phys. Rev. Lett.* 130, no. 24 (2023): 242501. DOI: https://doi.org/10.1103/PhysRevLett.130.242501.

[26] I. J. Arnquist, et al., MAJORANA Collaboration, "Final Result of the MAJORANA DEMONSTRATOR's Search for Neutrinoless Double-β Decay in ^{76}Ge," *Phys. Rev. Lett.* 130, no. 6 (2023): 062501. DOI: https://doi.org/10.1103/PhysRevLett.130.062501.

on the Wendelstein 7-X stellarator in Germany. These capabilities have positioned ORNL to play a key role in long-pulse particle transport and control experiments on the Wendelstein 7-X. Additionally, ORNL has delivered multiple shattered pellet injection systems to devices around the world to support the development of the technical basis of using shattered pellet injection for disruption mitigation in ITER and future fusion devices. ORNL also has facilities to support radio frequency heating of plasmas and remote handling.

As directed by DOE, ORNL leads the US ITER project and executes the program in conjunction with its partner laboratories, Princeton Plasma Physics Laboratory and Savannah River National Laboratory. The project draws on ORNL’s breadth of experience in fusion technology, radiation transport, high-power plasma heating systems, and advanced electronics for extreme environments. US hardware contributions include the world’s highest–stored energy pulsed superconducting magnet; a superconductor for ITER toroidal field coils; a 1 GW cooling water system; high-power, long-pulse plasma heating systems; plasma diagnostics; parts of the tritium exhaust system; plasma instrumentation; and plasma disruption mitigation systems. The US ITER Project Office also works with the ITER Organization and other ITER domestic agencies to achieve the required integration of management, design, and procurement activities. Much of the research and development is also executed at ORNL.

ORNL scientists and engineers are building the Material Plasma Exposure Experiment to address the challenges associated with exposing materials to high-energy, high-density plasmas. The project is under construction; Critical Decision (CD)-1 and CD-3a were completed in 2020, and CD-2/3 was completed in 2022. The design, construction, and commissioning activities have further strengthened the team in the skills required to deliver high-power, high–heat flux facilities required to advance the country toward fusion energy. Once operating, the Material Plasma Exposure Experiment will provide world-leading capability for experiments in which power plant–level fluxes and fluences of particles will be incident on neutron-irradiated materials in prototypic geometries.

Finally, ORNL is developing and integrating simulation capabilities for both core and edge plasma physics, plasma-facing and structural materials, and blanket and fuel cycle systems. Bringing together both physics and engineering is essential for optimization of the full fusion system. ORNL leads new simulation projects aimed at fusion system design and optimization, liquid metal dynamics, and the application of artificial intelligence and machine learning to efficient fusion simulation.

Recent enhancements to this core capability include the following:

- Integrated capability to simulate and optimize the full fusion system, including core and edge plasma, plasma-facing components, blanket, magnets, and structural materials
- Steady-state pellet injection technology
- Comprehensive capability to simulate liquid metal blankets and plasma-facing materials

DOE Office of Science Fusion Energy Sciences is the primary sponsor of this work. The Advanced Research Projects Agency–Energy also benefits from ORNL expertise in this area.

Power Systems and Electrical Engineering

ORNL capabilities in power systems and electrical engineering drive innovations in power flow, electric grid modernization, energy-efficient buildings and transportation, and smart manufacturing, all enabled by a unique combination of expertise, facilities, and capabilities. This crosscutting research is illustrated by projects such as bidirectional wireless charging for electric vehicles. This technology holds the promise to not only reduce driver range anxiety but also increase electric vehicle adoption, which is a critical national goal.

These core capabilities deliver advances in high-temperature, high–power density applications; enable high-efficiency transportation and electrification systems to reduce US reliance on foreign oil; develop technologies for power flow control, grid monitoring (e.g., FNET/GridEye), and grid protection for a secure, reliable electricity delivery system;[27] and create advanced building sensors, communications, and controls to maximize energy efficiency.[28] An advanced grid also requires new materials for power electronics and energy storage devices;[29] ORNL is a leader in power electronics research and development and is leveraging resources at the National Transportation Research Center and Grid Research Integration and Deployment Center to develop high-power devices to improve reliability and reduce costs.[30]

Work in this area is conducted at the National Transportation Research Center Power Electronics and Electrical Machinery Laboratory, Grid Research Integration and Deployment Center, Distributed Energy Communications and Control Laboratory microgrid, and Powerline Conductor Accelerated Testing Facility.

Recent enhancements to this core capability include the following:

- Established the Power Electronics Accelerator Consortium for Electrification to enable a partnership with industry for component-to-systems development for grid applications
- Licensed Peregrine to five industrial partners. Peregrine is an artificial intelligence–based quality control platform for powder bed additive manufacturing that assesses the quality of parts in real time. ORNL had never previously licensed a single product that many times in a single year.

DOE Office of Energy Efficiency and Renewable Energy, Office of Electricity, and Office of Policy are the primary sponsors of this work. DOE Office of Science also benefits from ORNL expertise in this area.

Systems Engineering and Integration

Solutions to pressing scientific and technical challenges are developed by integrating fundamental science, technology, and project management with cross-laboratory multidisciplinary teams as well as through partnerships with universities, other national labs, and industry. Recent accomplishments include a transformational manufacturing capability for making large energy components, understanding and designing materials properties for advanced manufacturing, improving technology to advance fusion energy systems, and modeling energy use of buildings at the community scale.

ORNL supports national and international projects, such as the Spallation Neutron Source, Oak Ridge Leadership Computing Facility, Material Plasma Exposure Experiment, ITER, the plutonium-238 process development project, the Nab and Neutron Electric Dipole Moment, ton-scale Large Enriched

---

[27] L. Kong, et al., "Enhanced Synchronization Stability of Grid-Forming Inverters With Passivity-Based Virtual Oscillator Control," *IEEE Trans. Power Electron.* 37, no. 12 (2022): 14141–14156. DOI: 10.1109/TPEL.2022.3187402.

[28] J. Joe, et al., "Model-based predictive control of multi-zone commercial building with a lumped building modelling approach," *Energy* 263, no. 1 (2023): 125494. DOI: 10.1016/j.energy.2022.125494.

[29] A. R. Ekti, et al., "A Simple and Accurate Energy-Detector-Based Transient Waveform Detection for Smart Grids: Real-World Field Data Performance," *MDPI Energies* 15, no. 22 (2022): 8367. DOI: 10.3390/en15228367.

[30] J. Landon Tyler, et al., "Nafion Inhibits Polysulfide Crossover in Hybrid Nonaqueous Redox Flow Batteries," *J. Phys. Chem. C* 126, no. 50 (2022): 21188–21195. DOI: 10.1021/acs.jpcc.2c06735.

Germanium Experiment for Neutrinoless ββ Decay experiments, ALICE (A Large Ion Collider Experiment) at the European Organization for Nuclear Research (CERN), and the Electron-Ion Collider Comprehensive Chromodynamics Experiment detector at the Electron-Ion Collider. ORNL's systems engineering capabilities deliver solutions in manufacturing, transportation, and buildings, often leading to licensing technologies as a lead and partner on the Critical Materials Innovation Hub, the Institute for Advanced Composite Materials Innovation, and other collaborations.

The lab's nuclear research focuses on high-temperature reactors and supporting systems. Researchers study surface degradation, tribology, and welding and leverage discoveries to improve a system's durability in industrial machinery and renewable energy systems. ORNL is also delivering methods for existing building systems to perform direct air capture of carbon dioxide, leveraging Basic Energy Sciences–funded discoveries.

ORNL's Office of Energy Efficiency and Renewable Energy research and development facilities (National Transportation Research Center; Building Technologies Research and Integration Center, including Maximum Building Energy Efficiency Research Laboratory and Distributed Energy Communications and Control Laboratory; Manufacturing Demonstration Facility; Grid Research Integration and Deployment Center; and Carbon Fiber Technology Facility) build on the lab's scientific systems infrastructure to develop and deliver market-driven solutions.

Recent advances to this core capability include the following:

- Established a transformational manufacturing capability for making large energy components (e.g., composite blades for wind turbines, buildings, battery boxes for lightweight electric vehicles) for cost-effective domestic manufacturing and supply chain for clean energy
- Integrated high-performance computing modeling of manufacturing processes, in situ data collection, and advanced characterization to gain greater scientific insight, increase efficiency, decrease emissions, and decrease time to develop and deploy new materials and processes for energy applications
- Established a thermal energy storage group by integrating expertise in chemical and material science with heating, ventilation, and air-conditioning and envelope engineering for cost-effective, market-ready solutions

Primary sponsors for these efforts include the DOE Office of Science, Office of Energy Efficiency and Renewable Energy, Office of Electricity, Fusion Energy Sciences, Office of Nuclear Energy, and National Nuclear Security Administration, with additional support from the US Department of Homeland Security, Nuclear Regulatory Commission, US Department of Defense, and other Strategic Partnership Project sponsors

Science and Technology Strategy for the Future

With the same sense of urgency and purpose that drove the laboratory's original mission, Oak Ridge National Laboratory (ORNL) is currently tackling some of the most pressing and complex challenges facing humankind—including the clean energy transition, national security, and environmental change—and is now embarking on an ambitious lab-wide strategic vision and plan for the next decade. The time is opportune for ORNL to initiate this planning effort given the inflection point in many of its core scientific areas (such as leadership computing, fusion, isotopes, and emerging technologies including artificial intelligence [AI] and quantum information science), the recent growth of the laboratory, and an almost entirely new leadership team that is energized to define a future that best positions ORNL to have the greatest possible impact. The strategy is also being developed through recognition of the broader science and technology (S&T) landscape, including international research competitiveness, collaboration, and security; an urgency to accelerate basic science and its translation into solutions critical for a clean energy transition and national security; the need for adaptation to the environment and climate change; and recognition of the opportunity and threats of emerging platform technologies (such as AI and quantum information science).

ORNL's 10-year strategy will embody the goal of simultaneous excellence in S&T, community, and operations, including key operational strategic objectives described in Section 6 (predictive operations, net-zero campus, and simple and agile customer-centric services). The lab-wide strategy will build upon the following foundational ORNL S&T strengths.

Table 4.1. ORNL S&T Objectives

4.1	Deliver world-leading neutron scattering capabilities to enable scientific discoveries for the nation
4.2	Pioneer energy-efficient exascale computing from system to ecosystem
4.3	Discover and design next-generation materials and chemical processes that enable clean energy and emerging technologies
4.4	Enhance understanding and harness coupled biological, environmental, and built systems in a changing world
4.5	Accelerate fusion and advanced fission energy for clean energy
4.6	Provide strategic capabilities in isotope research and development, enrichment technology, and production
4.7	Accelerate transformational clean, sustainable, and resilient energy solutions
4.8	Advance science-based national security solutions to outpace the nation's adversaries and mitigate evolving threats

- The most valuable resource for ORNL's future is its extremely dedicated workforce of more than 6,400 researchers and professional staff. To support the growth over the last few years and to position staff for success, ORNL has developed several new programs that are described in Section 7, including a new early career development program, a mentorship program, and Management Bootcamp. Because an inclusive culture is imperative for impactful science, ORNL has taken many measures to strengthen its culture. Examples include activating ORNL values (i.e., impact, integrity, teamwork, safety, and service), developing a new childcare facility, formalizing new hybrid and remote work policies, optimizing how decisions are made, and enhancing a focus on frontline supervisor training and engagements. Over 100 ORNL research staff have been recognized over the past year, including 60 fellows and named professional society awards, as well as invited memberships in prestigious organizations, including the National Academy of Engineering.
- ORNL has the honor and responsibility of stewarding a unique ecosystem of world-leading facilities. The four US Department of Energy (DOE) Office of Science facilities at ORNL enable scientific breakthroughs in neutron scattering (Spallation Neutron Source and High Flux Isotope Reactor [HFIR]), material discovery (Center for Nanophase Materials Sciences), isotope production (HFIR), and leadership computing (OLCF-4 and OLCF-5 at the Oak Ridge Leadership Computing Facility). ORNL is also leading the development of several major new projects and facilities, which will deliver world-class DOE Office of Science capabilities needed to enable future breakthroughs. Select examples include the Second Target Station, OLCF-6, the Stable Isotope Production and Research Center, the Material Plasma Exposure Experiment, and the Ton-Scale Large Enriched Germanium Experiment for Neutrinoless ββ Decay (LEGEND-1000). ORNL also operates several unique applied energy facilities. An example is the Manufacturing Demonstration Facility (MDF), which is the nation's foremost R&D facility for catalyzing advanced manufacturing technology development. Over just the last year, MDF has engaged over 4,800 partners. ORNL's Grid Research Integration and Deployment Center (GRID-C) was developed to help

enable a resilient, secure, and smart future grid through offering advanced power electronics system prototyping capabilities, physical test beds, and advanced simulation platforms to enable integration and testing of key grid elements under one roof. The Carbon Fiber Technology Center is an export-controlled facility enabling the production of carbon fiber and new materials for clean-energy applications and defense programs. The National Transportation Research Center focuses on key technologies such as energy storage, intelligent mobility systems, and vehicle cybersecurity, and the Building Technologies Research and Integration Center (BTRIC) performs early-stage R&D in building technologies.

- A distinguishing characteristic of ORNL is its strength in advancing *and* translating scientific discoveries into solutions having national scale and impact. This characteristic is enabled through the extraordinary breadth of ORNL's 24 core capabilities embodied by ORNL's staff, facilities, and other elements, as well as by the diverse funding support from the DOE Office of Science, the DOE Applied Energy offices, and the National Nuclear Security Administration.
- Another key element critical for ORNL's strategy is partnerships, including with other laboratories, over 200 universities (including 60 minority-serving institutions and historically Black colleges and universities), multiple industry partners, and various regional partners. For example, ORNL has been strengthening its partnership with core universities, and the University of Tennessee–Oak Ridge Innovation Institute (described in Section 3) will be home to 100 joint research faculty and hundreds of graduate students who will work together at ORNL on priority S&T challenges that meld select strengths of both organizations. ORNL's Innovation Crossroads and the Techstars accelerator are key elements for regional innovation, as are many other partners who collaborate to advance innovation on topics important for the region such as manufacturing, advanced mobility, radiotherapeutics, quantum information science, and nuclear energy.

The lab's 10-year strategy aims to position ORNL to make the greatest possible S&T contribution to the DOE mission and the nation, as well as to foster a scientifically stimulating and inclusive culture that not only attracts new talent but that also inspires and engages staff to bring their best to the mission. To realize this vision, ORNL will chart an S&T strategy that harnesses the diverse expertise, facilities, core capabilities, programs, and partnerships. The S&T strategy will be developed in the context of many of the elements described in the first paragraph of this section, including inflections in many current ORNL S&T areas, as well as the urgency to accelerate scientific discoveries and their translation into solutions needed for energy, the environment, and national security. To initiate the ORNL planning effort, strategic plans associated with individual ORNL S&T objectives are well underway.

As part of the lab's strategy, ORNL is also considering emerging objectives. An example of an emerging objective is neutrinoless ββ decay, supporting DOE Office of Nuclear Physics' efforts to determine whether neutrinos are their own antiparticle. ORNL leads the ton-scale LEGEND-1000 project. ORNL has assembled an outstanding team consisting of 51 national and international partners with complementary capabilities and resources to deliver on the goals of LEGEND-1000. ORNL is also committed to training the next generation of nuclear physicists in this important area and supporting efforts to understanding the underlying physics. The Critical Decision-1 review for the LEGEND-1000 project will occur in 2024.

As a first step in developing a lab-wide plan that builds upon the individual ORNL S&T Objective plans, the lab has identified several guiding principles. A key principle is that ORNL aims to focus on S&T impact rather than growth. Through planning, investments, extreme cross-laboratory collaboration across ORNL S&T, and operational objectives as well as through purposeful alignment, ORNL aims to enhance its role as a *laboratory integrator* by accelerating science-to-solution pathways that will lead to greater overall impact. Figure 4.1 notionally indicates the current significant connectivity between ORNL S&T objectives (and associated expertise, facilities, and programs). As indicated by the number of arrow tips pointing primarily to the application areas, the figure illustrates that the ORNL S&T objectives that are primarily supported by the DOE Office of Science currently significantly nourish the ORNL S&T objectives that are primarily supported by the Applied Energy and Security offices.

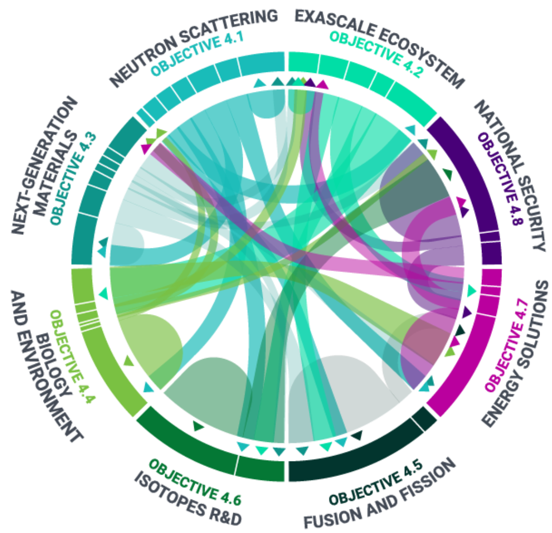


Figure 4.1. Connectivity between ORNL S&T objectives

As part of the lab-wide strategy, road maps will be developed for prioritized S&T challenges that require integration across ORNL objectives, core capabilities, and facilities. In addition to focusing on identified S&T topics, the lab will also focus on developing plans for *how* ORNL investigators perform research in the future. Building on advances developed through ORNL's Interconnected Science Ecosystem (INTERSECT) and AI Initiatives (in the near term) and multilab Integrated Research Infrastructure contributions (in the longer term), capabilities will be developed that allow staff to autonomously and simultaneously drive experiments across ORNL's extraordinary, diverse research infrastructure with feedback from large-scale, AI–enabled analytics (run on Oak Ridge Leadership Computing Facility machines). Development of this *scientific laboratory of the future* concept is expected to transform how staff will perform research, leading to greatly accelerated scientific discoveries and the translation of those discoveries into solutions.

The following sections describe the developing plans for the eight ORNL S&T objectives listed in Table 4.1. The order of the objectives is intentional, starting with objectives that are primarily supported by the DOE Office of Science and ending with those that are aligned with the DOE Applied Energy offices and the National Nuclear Security Administration.

Infrastructure

Overview of Site Facilities and Infrastructure

Located 10 miles southwest of the city of Oak Ridge, Tennessee, ORNL occupies about 4,421 acres of the federal Oak Ridge Reservation (ORR; 34,000 acres). Typically, ORNL hosts approximately 35,000 people annually, comprising ORNL's roughly 6,500 employees, other prime contractors' staff, subcontractors, and guests. To support its R&D missions, ORNL provides a wide variety of on-site services, including operation and maintenance of all supporting utilities and infrastructure, 24/7 security, dedicated fire and emergency response, medical facilities, fabrication and assembly services, a guest house, and other support functions. It incorporates sustainability through improved designs and is reducing its carbon footprint by developing and implementing sustainable technologies. On ORNL's main campus, work is performed in 197 operational buildings (3.8 million gross sq. ft. [GSF]) owned by the DOE Office of Science (SC) and 77 operational buildings (0.45 million GSF) owned by DOE's Office of Environmental Management (EM). Fifty-one buildings owned by SC and EM are in shutdown/decommissioning/stabilization status and represent 1.15 million GSF of ORNL's building inventory. A total of 23 buildings owned by SC (0.75 million GSF) are awaiting disposition, having been excessed to DOE. Eight buildings owned by SC, one owned by DOE Office of Nuclear Energy (NE), and two owned by EM (0.06 million GSF) are in standby status, awaiting repurpose or reuse. All SC mission-unique facilities (1.0 million GSF) have a condition rating of *adequate*.

Of SC's facilities that are not mission-unique, 94% are rated *adequate*; the rest are rated *substandard*. Building 4500N (363,758 ft^2), the largest substandard building on campus, has $2.7 million in operating costs and $17 million in repair needs. That facility and aging plantwide utility systems (i.e., substandard Other Structures and Facilities) are important focus areas for modernization. The cost for total repair needs at ORNL is $608M, and deferred maintenance totals $297M. All the ORNL assets make up a replacement plant value of $9.1B. No new leases were added during FY 2023; however, four leased buildings supporting carbon fiber, ITER, the Grid Research Integration and Deployment Center (GRID-C) and logistical support, totaling 137K GSF, will be renewed during FY 2024 and FY 2025. Maintenance and repair investments are between DOE's acceptable range of 2% and 4% of the replacement plant value, with a Maintenance Investment Index of 2.41%. ORNL continues to proactively invest in the aging utility infrastructure and aging mission-critical facilities; in FY 2023 maintenance expenditures totaled $102.5M. Thirty-five percent of ORNL's operational non-mission-unique facilities, representing approximately 30% of the total gross square footage, are more than 50 years old and carry nearly 31% of deferred maintenance. ORNL's most impactful deferred maintenance reduction strategy will be to continue demolition of shutdown assets that carry a high deferred maintenance. ORNL continues to evaluate the ability of the facilities and infrastructure to adequately support its science mission, with the goal of upgrading inadequate and substandard facilities when feasible and demolishing them if necessary. ORNL must employ a multitude of funding sources to continually invest in modernization. Much of its infrastructure is 70+ years old, and considerable investment is required to address these needs. As such, the lab invokes a combination of Science Laboratories Infrastructure (SLI) and institutional investments.

Research requiring ready access for industrial partners is conducted in 10 off-site leased facilities totaling 0.31 million GSF. ORNL's Hardin Valley Campus, about 7 miles from the main campus, hosts the Manufacturing Demonstration Facility (MDF), GRID-C, and the National Transportation Research Center. The Carbon Fiber Technology Facility, a separate site in Oak Ridge, is located about 5 miles from the main campus. In pursuit of optimal support for mission needs, ORNL's leased space portfolio is evaluated frequently to identify opportunities for consolidation. The 2023 evaluation indicated there were no opportunities to consolidate. Therefore, no change was made to the leased space portfolio. ORR land use is governed by the current ORR land use plan[31] and ORNL's *Site Wide Master Plan*.[32]

---

[31] *Oak Ridge Reservation Planning: Integrating Multiple Land Use Needs. FY 2012 Update*, DOE/ORO/2411, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[32] *Site Wide Master Plan*, PDGEN020000A001, Oak Ridge National Laboratory, Oak Ridge, Tennessee. https://services.ornl.gov/ronweb/Media/ORNLswmp.pdf

Campus Strategy

ORNL's campus strategy is to create sustainable infrastructure, through development of new assets, revitalization of existing assets, sustainment of facilities, and enhancement of infrastructure to advance scientific missions. The success of this strategy relies on achieving four primary objectives:

1. Support science missions, initiatives, and critical programs.
2. Establish a modern, adaptable, and sustainable support infrastructure to reduce single-point failure risk.
3. Evaluate and implement technologies to ensure carbon footprint reduction.
4. Reduce excess facilities and environmental liabilities and optimize footprint.

These objectives will be accomplished, in part, by successfully addressing critical infrastructure needs identified through ORNL's Mission Readiness process. At ORNL, space is managed as a strategic asset and an institutional resource. Clear understanding of design, limitations, and utilization is leveraged to provide efficient solutions. Space utilization in support of scientific initiatives is maximized by co-locating and consolidating scientific disciplines, thus creating synergies in support of ORNL's science missions. ORNL holds an annual Space Summit to inform space and resource allocation needs by reviewing supply and demand and renovation needs for office and lab space. The figure below illustrates ORNL's vision, which combines DOE and institutional investments needed to advance the laboratory's scientific and technical capabilities and to continue transforming the ORNL campus into modern research space. Over the last two decades, ORNL has implemented sustainable designs and has built buildings certified by Leadership in Energy and Environmental Design as integral components of campus modernization.

ORNL's planned programmatic line items and General Plan Projects (GPPs) for the ORNL campus are shown in the table below. The table shows the importance of utility systems (Science Laboratories Infrastructure line item [SLI-LI] Critical Infrastructure Improvement Project, which will address the single-point failure risk for potable water) and institutional capital investment projects to the delivery of major science and technology projects. No new programmatic line item starts are planned for West Campus.

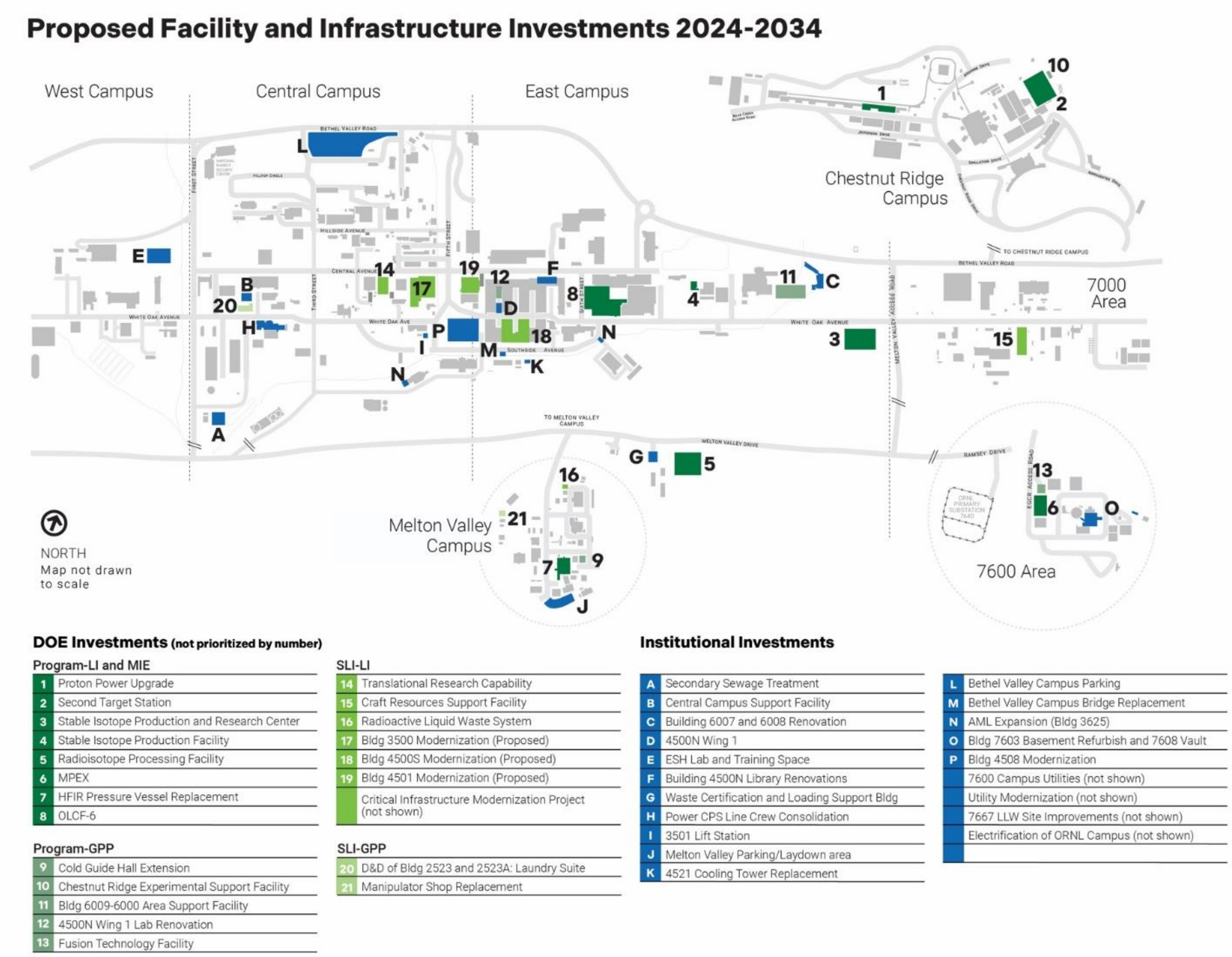


Figure: Proposed facility and infrastructure investments

		West campus	Central campus	East campus	EGCR campus	Melton Valley campus	Chestnut Ridge campus
	Programmatic (single) Line Items and GPP ongoing and proposed by location			OLCF-6, SIPRC, SIPF	MPEX, Fusion energy facility	HFIR guide hall, RPF, Manipulator shop facility, PVR	PPU, STS, Exp. Support facility, He recovery
Signature strengths	Neutrons					✓ (HFIR)	✓ (PPU, STS, Exp. Facility, He recovery)
	Exascale computing		✓	✓ (OLCF-6)			
	Nuclear science and technologies				✓ (Fusion)	✓	
	Isotope R&D			✓ (SIPF, SIPRC)		✓ (RPF, Manip. Shop)	
	Materials and manufacturing		✓		✓ (MPEX)		✓
SLI- CIMP	Potable water		✓	✓	✓	✓	✓
	Electrical		✓	✓	✓	✓	
	Chilled water		✓	✓			
	Steam		✓	✓		✓	
	Condensate		✓	✓		✓	
	Natural gas	✓	✓	✓	✓	✓	
	Sanitary/storm sewer		✓	✓	✓	✓	
	Telecom	✓	✓	✓	✓	✓	
SLI-LI	TRC		✓				
	Radioactive liquid waste		✓	✓		✓	
	Craft resources support facility	✓	✓	✓	✓	✓	✓
Institution	New construction	✓	✓	✓			
	Existing renovation	✓		✓	✓		
	Utility systems	✓	✓	✓	✓	✓	✓
	Parking, roads & grounds	✓	✓	✓		✓	✓

[a] CIMP = Critical Infrastructure Modernization Project, GPP = General Plant Project, HFIR = High Flux Isotope Reactor, MPEX = Material Plasma Exposure Experiment, OLCF = Oak Ridge Leadership Computing Facility, PPU = Proton Power Upgrade, PVR = Pressure Vessel Replacement, RPF = Radioisotope Processing Facility, SIPF = Stable Isotope Production Facility, SIPRC = Stable Isotope Production and Research Center, STS = Spallation Neutron Source Second Target Station, TRC = Translational Research Capability

Table: Science Strategy and Infrastructure Connectivity

Key facility and infrastructure investments are crucial for successful delivery of ORNL's science strategies.

These programmatic investments are shown in the figure above and summarized in the following list:

- Spallation Neutron Source (SNS) Proton Power Upgrade (PPU) project (described in Section 4.1), supported by DOE SC Basic Energy Sciences (BES) (CD-2/3 approved, CD-4 planned for FY 2025)
- SNS Second Target Station (STS), supported by BES (CD-1 approved)
- High Flux Isotope Reactor (HFIR) Pressure Vessel Upgrades, supported by BES (CD-0 approved)
- Stable Isotope Production and Research Center (SIPRC), supported by the Office of Isotope R&D and Production (IP) (CD-2/3 approved)
- Radioisotope Processing Facility, supported by the IP (CD-0 approved, CD-1 in process)
- Fusion Technology Development Facility, supported by DOE SC Fusion Energy Sciences (FES) (proposed)

Three Major Item of Equipment (MIE) projects:

- Stable Isotope Production Facility (SIPF), supported by IP (PD-2/3 approved, PD-4 in 2024)
- Material Plasma Exposure Experiment (MPEX), supported by FES (CD-2/3 approved)
- Oak Ridge Leadership Computing Facility-6 (OLCF-6), supported by the Advanced Scientific Computing Research (ASCR) program (CD-1 approved)

Seven SLI-LI construction projects:

- Translational Research Capability (TRC) (CD-2/3 approved, construction in process, CD-4 by CY 2024)
- Craft Resources Support Facility (CRSF), (key decision [KD]-3 approved)
- Radioactive Liquid Waste System (CD-0 approved))
- Critical Infrastructure Modernization Project (CIMP) (CD-0 approved, CD-1in process)
- Building 3500 modernization (proposed)
- Building 4500S modernization (proposed)
- Building 4501/4505 modernization (proposed)

Three programmatic General Plant Projects (GPPs):

- HFIR Cold Guide Hall, supported by BES (proposed)
- Chestnut Ridge Experimental Support Facility, supported by BES (proposed)
- Building 6009 support facility for isotopes, supported by IP (ongoing)

Five SLI GPPs:

- Manipulator shop replacement (proposed for FY 2026)
- Demolition of Laundry and annex (ongoing)
- Upgrade 4000 Area 2.4 kv to 13.8 kv (proposed for FY 2025)
- Upgrade 2000/3000 Area 2.4 kv to 13.8 kv (proposed for FY 2026)
- Upgrade 7000 Area 2.4 kv to 13.8k v (proposed for FY 2027)

These projects, as well as numerous smaller projects supported through Institutional GPP (IGPP) funding, are discussed in the following sections.

Objective 1: Support Science Missions, Initiatives and Critical Programs

Our campus strategy focuses on five areas of infrastructure investment outlined below to advance ORNL's science and energy leadership and enable accomplishment of major initiatives.

Maintain and strengthen global leadership in neutron sciences. Continued operation of SNS and HFIR as world-leading neutron scattering user facilities requires two major programmatic investments. The PPU project at SNS will increase power delivered to the First Target Station to 2 MW, increase neutron flux on available beamlines, and provide additional proton pulses to support operation of the STS. The addition of the STS will provide ORNL with three complementary neutron sources, ensuring US leadership in neutron sciences into the foreseeable future. HFIR has operated for 57 years and is a key scientific asset. In response to the September 2020 Basic Energy Sciences Advisory Committee report,[33] DOE-SC has approved the mission need statement for the replacement of the reactor pressure vessel and other major components for long-term sustainment of HFIR capabilities. The HFIR Pressure Vessel Replacement project, which is the first replacement of a pressure vessel for a DOE-operated reactor, introduces unique complexities. Efforts are currently focused on standing up a team of laboratory and industry experts to handle regulatory requirements for replacing the 60-year-old reactor and identifying qualified nuclear suppliers to successfully deliver a conforming vessel.

[33] *The Scientific Justification for a U.S. Domestic High-Performance Reactor-Based Research Facility*, Report of the Basic Energy Sciences Advisory Committee, July 2020.

Growth in the use of ORNL's neutron scattering facilities will increase demands on research support functions, requiring an infrastructure investment for the GPP-funded HFIR Cold Guide Hall Extension. The extension will allow ORNL to optimize neutron instrumentation, expand capabilities, and properly store samples. GPP funding is also requested for an experimental support facility at Chestnut Ridge to accommodate increasing demand for interdisciplinary research.

Computing to enable convergence of experiment, theory, simulation, and data for science and engineering. Leadership-class computing underpins nearly all scientific disciplines. Thus, continued development of ORNL's high-performance computing (HPC) infrastructure as part of the OLCF is a high priority. DOE's well-defined path to maintain leadership in HPC includes continued operation of the initial exascale system, Frontier (OLCF-5), located in E102 in Building 5600. In addition to operating Frontier, the OLCF worked to secure another year of operations for the Summit supercomputer system, as it remains a powerful and reliable instrument for scientific discoveries. Summit's focus in 2024 will be on projects with emerging paradigms for computational campaigns, including data-intensive science, artificial intelligence (AI), and Integrated Research Infrastructure (IRI) projects. In addition, the OLCF is continuing work to deliver the next powerful supercomputer through the OLCF-6 project, which received CD-1 approval in March 2024. The OLCF will execute a CD-3A in the fall of 2024 for approval to do the necessary infrastructure upgrades to support the OLCF-6 system. In addition, the SLI-funded TRC facility will provide additional resources for housing novel capabilities in quantum and neuromorphic computing. Institutionally funded replacement of older router and core fiber technology is ongoing. Phase 1 completion is expected in FY 2024. The ESNET 400G project will address campus-redundant border routers for business continuity, fiber-optic cables, and border firewalls. Investments are also planned for high-bandwidth network capability.

Discover and design next-generation materials and chemical processes for clean energy. Accelerating design, discovery, and deployment of new materials and manufacturing processes requires specialized instrumentation and facilities. Over the past 3 years, ORNL has made discretionary investments to secure new, world-class tools for materials science, including a near-atmospheric-pressure x-ray photoelectron spectrometer, nuclear magnetic resonance capabilities (for radiological materials), a gas atomizer, multiplasma focused ion beam systems as well as a new atomic layer deposition system, and a direct-write lithography system. To support increasingly sensitive imaging equipment, institutional funds have been allocated to provide a low-vibration, low-electromagnetic-field space as an extension to the Advanced Microscopy Lab. Additionally, the characterization space in Building 4508 is being renovated to deliver on the science mission. ORNL has successfully completed CD-3 approval for the TRC (an SLI-funded facility), and construction is in process. CD-4 is anticipated in December 2024.

Advanced manufacturing is an important component of the lab's materials portfolio. The MDF houses integrated capabilities to assist industry in adopting new manufacturing technologies, including a focus on decarbonizing the industrial sector, and provides a gateway to expertise in materials synthesis and characterization and process technology.

Advance the fundamental science, engineering, and integrated technologies to accelerate the deployment of fusion and advanced fission energy. ORNL's nuclear capabilities support a broad range of efforts: several SC programs (IP, FES, and BES), other DOE programs (NE and the National Nuclear Security Administration), and other sponsors in areas that span fission energy technologies, fusion R&D for plasma-facing materials, fuel cycle and burning plasma, radioisotope production and R&D, and nuclear security. These capabilities are dependent on the following:

- *HFIR operation as a high-flux irradiation source.* Continued success in this area depends on sustained programmatic operations support, new fuel fabrication, spent fuel shipment, and annual funding to perform necessary planned maintenance and life extension projects. Investments above fixed operating costs will be required to address fuel fabrication and inspection process improvements implemented at BWX Technologies. In addition, a new permanent beryllium reflector, four new beam tubes, and other core components are being fabricated in preparation for the beryllium reflector replacement outage. A mission need has been approved for replacement of the HFIR pressure vessel, which will extend the reactor life for at least another half-century.

- *Operation for radioisotope production and for processing and handling of irradiated and nuclear materials.* ORNL's isotope complex comprises five nonreactor nuclear facilities, including the Radiochemical Engineering Development Center (REDC), four primary radiological facilities, and various research and support facilities in Bethel and Melton Valleys. Significant program growth, particularly in isotope production, is challenging the capacity of these facilities. Consistent funding of ORNL's nuclear facilities is needed to ensure long-term sustainability and compliance with DOE's nuclear safety standards. Investments are needed to establish a radioactive waste infrastructure to ensure nuclear facility footprints and radioactive isotope production.
- *Material Plasma Exposure Experiment (MPEX) project.* MPEX received CD-2/3 approval in August 2022. MPEX will be a key tool in understanding plasma-surface interactions, and ultimately, the performance of divertor and plasma-facing materials. ORNL continues to place high priority on the execution of the MPEX project; construction completion is scheduled for August 2024, and commissioning completion is expected by August 2026. Resources are being prioritized to assist project execution as needed. Institutional investments, including replacement of the cooling water tower are ongoing, and 7600 campus utility system upgrades are also planned to support growth. Aligned with ORNL's Interconnected Science Ecosystem (INTERSECT) initiative and ASCR's IRI framework, it will also be important to ensure that necessary infrastructure is in place for real-time diagnostic analysis and feedback response.
- *Fusion prototypic neutron source.* A fusion prototypic neutron source has been identified by the American Physical Society's Division of Plasma Physics Community Planning Process as a high-priority facility for fusion energy and has been endorsed by the Fusion Energy Sciences Advisory Committee (FESAC) Long-Range Plan in a recent report (2020). As stated previously, ORNL is interested in hosting this facility, although the project and siting process have not yet begun. Options to repurpose existing ORNL facilities are being evaluated, but utilities would be required. ORNL is ready to support a mission need statement and identification of potential approaches when the sponsor is ready to move forward.
- *Fusion Technology Development Facility.* ORNL is developing a plan for the Fusion Technology Development Facility, which will enable advancement in several key fusion technology areas. The plan was developed with the assumption that the project would require investment in a facility with multiple flexible laboratories, high-bay space, and sufficient utilities to support a diverse R&D program. A DOE-funded preconceptual design study of a small, multipurpose building is ongoing. This building would provide much-needed near-term lab space for fusion technology activities and would serve as the first step in the buildout of the Fusion Technology Development Facility.

Provide strategic capabilities in isotope R&D and production. The DOE Isotope Program (IP) makes extensive use of ORNL's research and production facilities: HFIR, the Enriched Stable Isotope Facility, the Radiochemical Engineering Development Center (REDC), and other radiological facilities.

- *Stable isotope portfolio.* To meet demand for critical isotope production and reduce national dependence on foreign suppliers, ORNL proposes to complete the SIPF MIE by 2025 and to continue to expand stable isotope research and production capabilities through several major initiatives. SIPRC, which has received CD-3b approval, will greatly expand research and production capabilities for stable isotopes using several different enrichment technologies. In close association with SIPRC, ORNL plans to optimize all aspects of the stable isotope portfolio, including electromagnetic, gas centrifuge, and other isotope enrichment technologies; R&D and other supporting laboratories; stable isotope storage and dispensing operations; and technical services for preparing special isotope forms through physical and chemical conversions.

- *Radioisotopes.* Continued growth in demand for ORNL radioisotope production is anticipated to meet multiple needs in areas such as basic science, applied R&D, and medical applications. CD-0 was approved on April 29, 2021, for the proposed Radioisotope Processing Facility (RPF). RPF will eliminate the capacity gap introduced with increased demand and will provide wider availability and improved quality assurance for multiple emerging reactor-produced radioisotopes. Eliminating this capacity gap allows for increased radioisotope production in support of the entire DOE complex and other needs.

ORNL is conducting a gap analysis to identify chemical processing needs for stable isotopes and is also developing a more detailed risk registry for enrichment and isotope production, both of which will help identify, refine, and prioritize other future space needs. Expanded manipulator capabilities will be required with the addition of RPF and will also eliminate safety risks. The existing manipulator shop will be fully utilized by REDC, necessitating the need for a new manipulator shop. ORNL will utilize creative and cost-effective solutions for ongoing construction projects.

Objective 2: Establish a Sustainable, Modern, and Adaptable Infrastructure to Support Research

The cornerstone of this objective consists of strategic investments that optimize, modernize, and sustain facilities and utility systems to best accomplish current and future ORNL missions. ORNL fosters safe, efficient, reliable, and environmentally responsible operations through targeted investments.

Modernization of ORNL's utility systems. Efficient, reliable (reducing single-point-failure risk), and maintainable utility infrastructure provides the foundation for successful scientific achievement. Uninterrupted reliable operation of ORNL utilities underpins modern scientific tools used to support the cutting-edge research that drives technological breakthroughs. ORNL consistently provides a high level of service through routine preventive maintenance and continued institutional investments. However, this achievement is becoming increasingly difficult with aging infrastructure. (Many of ORNL's core utilities were installed as part of the Manhattan Project.) Aged infrastructure requires more frequent emergency repairs, which are complicated by the need to secure obsolete parts. These factors ultimately culminate in decreasing reliability, increasing inefficiency, and escalating costs. To meet the SLI funding capacity and to correct the highest-risk utility system deficiencies identified by utility system stewards through condition assessments and inspection, a new critical infrastructure modernization project strategy with a minimum required scope has been proposed, and various implementation strategies have been developed to accommodate available funding. The IGPP-funded secondary sewage system, slated for completion in FY 2025, will provide much-needed increased capacity and will improve operational efficiency by reducing costs associated with outdated and deteriorated equipment. Additional institutional investments are being made in the 7600 area and Central Campus to support research activities and improve utility distribution systems, thus providing interconnections for redundancy.

Campus revitalization. ORNL's 7000 area is a centralized craft asset supporting research and laboratory operations. This campus area hosts multiple craft shops and services, centralized and co-located security and fire response personnel, and 600 craft personnel. Institutional investments have funded the Mission Support Facility, an environmentally controlled, conditioned workspace, and infrastructure modernization to address roads, parking, and sidewalks. The CRSF, which received KD-3 approval, will provide modern facilities to include vehicle garages and shops for sheet metal workers, carpenters, mechanics, and electricians. This new facility will be used to maintain high-value equipment and materials by eliminating current infrastructure capability gaps such as inadequately designed, aging infrastructure; insufficient storage capacity; and poor environmental controls. A detailed ventilation study has also been completed for seven major facilities, and risk evaluation is underway to guide targeted investments for modernization. The SLI program also provides investment of $46M in annual funding for nuclear operations, which is absolutely essential to enabling continued operations for programs relying on nuclear facilities.

Repurposing space to maximize utilization. ORNL continues to maximize utilization of space by repurposing and modernizing existing facilities. Repurposing Building 2719A, the old biomass facility, will consolidate power operations from Buildings 2500 and 2621 while freeing up 5,000 ft^2 of space within Building 2621 for research. Repurposing of Buildings 6007and 6008 is also underway to consolidate craft personnel to support the computational complex. Additional institutional investments planned to modernize and maximize space utilization in Building 4500N include renovations to the library and Wings 1 and 2.

Management of radioactive waste. Historically, ORNL has relied on EM infrastructure for management of gaseous, liquid, and transuranic (TRU) waste from nuclear and radiological facilities. Although EM has invested to extend the life of facilities on and serving the ORR, EM infrastructure is 30 to 60 years old, oversized, and not designed for the waste generated by today's isotope production and nuclear R&D missions. EM plans to shut down portions of existing infrastructure once legacy waste missions are completed. With this in mind, ORNL is developing independent waste management capabilities to achieve self-sufficiency. IGPP investments have created a remote-handled waste loading station at REDC. Investments to construct a local high-efficiency particulate air filtration system and exhaust ventilation stack in Building 3525 enabled independence from the EM-operated central stack 2023. However, Buildings 3047 and 3025E continue to be reliant on the EM-operated central stack. An initial plan has been developed to address operation of these facilities following elimination of the 3039 stack by EM. Several options that are being evaluated are guided by other infrastructure projects, such as the RPF.

SC needs to acquire facilities from EM for the storage of TRU waste. One of the most important issues is to address to ORNL's newly generated TRU waste. Investments will be needed to construct TRU waste certification and shipment loading support infrastructure adjacent to the storage facilities to support future certification and shipment of TRU waste to the Waste Isolation Pilot Plant. ORNL will continue to collaborate with EM while ORNL develops its own waste management capabilities to support the enduring R&D mission of the laboratory.

Infrastructure investments will also be needed for an enduring mission treatment capability for high-activity radioactive liquids generated by the ORNL nuclear mission. The need for SLI-LI funding is driven by the EM schedule to shut down portions of the existing liquid waste system at ORNL. A mission need (CD-0) for this capability was approved in 2015. Efforts over the past few years have been devoted to radioactive liquid waste minimization activities to reduce the TRU concentrations in newly generated liquid wastes and to lower the life-cycle costs for treatment and disposal. Additionally, institutional investments are also planned for site improvements at the 7650 Waste Services Area for a low-level waste (LLW) auxiliary staging area to consolidate waste-handling operations and improve efficiencies

Objective 3: Evaluate and Implement Technologies to Ensure Carbon Footprint Reduction

The ORR (inclusive of ORNL and Y-12 National Security Complex [Y-12]) constitutes a small city, ideal for demonstration and deployment of a carbon-neutral test bed. ORNL's Net-Zero Carbon Campus efforts will include approaches that demonstrate a variety of technologies, such as electrical storage, carbon capture, integration of renewables, transition to an all-electric vehicle fleet, and efficiencies gained through infrastructure modernization that reduce or eliminate carbon emissions. Carbon capture research will be conducted in a phased manner. Prototype technologies will be developed that will have the potential for implementation across campus. Disposition of captured carbon will also be evaluated for potential reuse, conversion to fuel, or disposal. In addition to these efforts, deployment of new nuclear generation will help ORNL to reach net-zero carbon emissions. TVA has approved up to $200 million to prepare for the proposed construction of a small modular reactor (SMR) at its Nuclear Regulatory Commission (NRC)–licensed site, which could provide carbon-free electricity for the reservation and the region. ORNL's success in reducing electricity consumption and greenhouse gas emissions are directly related to successful completion of an SMR. If the plan to construct an SMR is not realized, ORNL's ability to meet the DOE executive order requirement for a NetZero goal will be severely curtailed.

To further ORNL's progress toward net-zero carbon emissions, UT-Battelle has established an MOU with TVA focused on the following decarbonization technologies:

- Point source and direct air carbon capture
- Carbon utilization
- Hydrogen generation and utilization
- Electric vehicle charging and vehicle-to-grid interaction applications
- Light water SMRs and fourth-generation advanced nuclear reactors
- Long-duration energy storage
- Electrification of parts of economy that are currently dependent on fossil fuels
- Grid resiliency and security

In addition to these efforts, deployment of new nuclear generation will help ORNL to reach net-zero.

ORNL's goal is to develop a dynamic inventory of research and operational projects that represent opportunities to advance the ORNL campus toward net-zero strategies. Projects are evaluated on several sustainability priorities, including energy and water savings from energy conservation measures (ECMs), net-zero initiatives, and operational resilience. Each year, Sustainable ORNL makes a call for Showcase Projects to help identify and initiate research projects that can be integrated into sustainable operations. The following three Showcase Projects were selected in FY 2024

- 5600-5700-5800 complex sustainability and decarbonization using waste heat recovery from OLCF
- Monitoring and replacement of an oversized (250 gal) natural gas water heater with heat pump water heater for a demonstration of CO2 reduction and energy savings
- Building 3147 pilot living laboratory demonstration of personalized heating and cooling management for grid-interactive efficient buildings

Institutional investments were made to develop a design to replace the 7601 fuel-oil-fired boiler with an electrified one, purchase hardware and software necessary to implement a vehicle pooling program for fleet vehicles rather than assigning vehicles to directorates, and accelerate transition of lighting to energy-efficient LEDs. In FY 2024, ORNL will submit requests to secure funding for two projects from Assisting Federal Facilities with Conservation Technology. These projects include (1) an investigation to convert a fuel oil boiler to an electric boiler, thus creating a small all-electric mini-campus, and (2) a study to eliminate Scope 1 emissions, specifically focused on natural gas.

Objective 4: Reduce Excess Facility Liabilities and Footprint

ORNL currently expends approximately $2.5 million annually to address environmental and safety risks associated with excess SC facilities. ORNL's rationale in prioritizing facilities for demolition is based on removing significant risks and liabilities, enabling future development by clearing aging facilities from prime locations, and eliminating assets that are unlikely candidates for renovation due to age, condition, and deferred maintenance.

SC and NE facilities at Y-12. Due to their deteriorated condition and size, ORNL facilities at Y-12 represent the highest cost risk to ORNL. EM has demolished 9207, 9207A, 9210, 9743-02, 9767-06, 9767-07, and 9770-02. At present, EM is preparing to demolish Buildings 9201-2, 9204-1, 9401-1, 9422, and 9732-2.

SC facilities in ORNL's Central Campus. A prime location for future development, the Central Campus houses several excess facilities awaiting demolition. The presence of these aging facilities hinders mission delivery and modernization while increasing liabilities and risks. Modernization of this campus area will be most quickly enabled when facility demolition is accompanied by the removal of associated contaminated soil, allowing for immediate redevelopment. Continuation of a strong EM funding profile is key to ensuring ORNL's ability to deliver on its mission. EM actions to complete the cleanup of the Central Campus, in parallel with investments in modernization by SC and ORNL, are enabling future mission assignments. ORNL has transferred operational responsibility of several SC-owned buildings to EM in preparation for demolition (Buildings 3003, 3010A, and 3080 in 2019; Buildings 3034 and 3036 in 2020). EM is currently removing the 3026 C and D hot cells and is working toward the removal of Isotope Row facilities and the research reactors (Buildings 3005, 3010, and 3042) in the Central Campus.

ORNL actively coordinates with EM contractors to enable the decontamination and decommissioning activities. ORNL's long-term plan for this campus is the construction of a series of modern facilities built upon a revitalized utility infrastructure. Planned actions include (1) construct TRC, (2) renovate or replace aging facilities, and (3) vacate and demolish 1940s-era facilities. ORNL is currently in the process of demolishing the old laundry facility and annex funded by SLI-GPP. Operations at the laundry facility ceased in the mid-2000. Most of the equipment except for the contaminated equipment was removed. The final demolition with the removal of contaminated equipment will be completed in 2024 as Hazardous Waste Operations and Emergency Response (HAZWOPER) work under Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA).

Infrastructure Investment Data (outlined in Enclosure 4). The laboratory aligns all investments with science missions through the mission readiness process.

Computing Infrastructure

ORNL's enterprise computing capability is delivered based on four core priorities: advance research excellence, improve agility and efficiency, enhance core services and infrastructure, and ensure cybersecurity and compliance. These priorities underpin operational strategies that enhance predictive delivery of core services, proactive maintenance of digital services, more streamlined digital solutions, and material enhancements to user experience.

Computing Infrastructure Strategy

Following best practice to optimize support of business service delivery, ORNL has adopted a number of strategic platforms that provide a strong foundation to build business capabilities. With the adoption of these standard platforms, ORNL is executing a strategy to merge legacy capabilities, rationalize and reduce application footprint, and migrate services into one of the core platforms, all of which reduce total cost, increase agility, homogenize user experience, and insulate ORNL from long-term technology antiquation. Strategic platforms include SAP (ERP, Ariba, and SuccessFactors); Hexagon Enterprise Asset Management; Documentum; RESolution; and Microsoft M365. The framework allows more expeditious implementation of needed capability at a more cost-effective and future-proofed approach. This capability is owned and managed by the ORNL Digital Services Infrastructure and Operations Division (DSIO); solution development on those platforms is managed by the Application Development Division (AppDev).

In conjunction with establishing platforms, ORNL leverages the “Software Quality Assurance and Other Software Requirements” subject area in the Standards Based Management System to drive consistent quality by supporting much of the strategy for managing and delivering ORNL’s application ecosystem. Currently, approximately 800 applications are registered at ORNL. ORNL is executing and maturing a strategic plan to determine the appropriate disposition of ORNL’s application landscape. Disposition options include additional investment, maintenance, consolidation with other apps/platforms, and retirement. This strategy will be driven by the operational strategic objectives of predictive operations, net-zero campus with energy security, and simple, monitored, reliable transparent services. These objectives are underpinned by a commitment to continuously enhancing user experience.

ORNL is implementing a broad governance model to support standards, prioritize initiatives, and ensure that delivery aligns with the information technology (IT) strategy. Governance will include prioritizing strategic IT investments, maintaining existing capabilities, and considering unique needs and initiatives as they arise from DOE and lab priorities. Governance is managed through a board structure consisting of a broad cross section of lab leadership representing mission and operations organizations. In conjunction with the Information Technology Services Division (ITSD), this governance structure will support enhanced visibility into risk management and reduction realized from execution of the technology project portfolio.

Research Computing, Data, and Networking Infrastructure

Management Model for IT Resources. ORNL extends embedded IT staff to research organizations to support researcher needs and apply common administration models and hardware standards. This model promotes compliance with existing system requirements with respect to National Institute of Standards and Technology (NIST) guidelines and Cyber Security plans. Compliance is measured through the Device Monitor tool and scanning done by Cyber Security. Additionally, ORNL supports research computing, data, and networking infrastructure to elevate scientific impact across diverse research domains, projects, and organizations via cutting-edge computing solutions. By considering and evaluating resource requests, ORNL builds creative, secure, and adaptive resource solutions that provide secure environments and that allow for an economy of infrastructure in costs, equipment, and space.

The Computing and Computational Sciences Directorate (CCSD) and ITSD provide the Compute and Data Environment for Science (CADES) as an essential construct for supporting research computing at the lab as a joint venture. CADES exists as a resource to deliver scientific discoveries and consists of HPC, cloud, and edge computing combined with human expertise to incubate and mature research as it moves from conception to self-sufficient funding models. This intentional architecture design is repeatable and keeps pace with emerging technological advancements by leveraging ORNL best practices. The CADES architecture is flexible and can be adapted for use based on data sensitivity and strategic alignment. Current CADES installations include HPC as a pathway to the OLCF and HPC/cloud resources in low, moderate, and classified ORNL environments. COVE, the classified installation of CADES cloud capability, is currently running approximately 25 research projects.

Data Centers. The ORNL Enterprise Data Center, located in the Computational Sciences Building (5600), is a 14,700 ft^2 data center built upon a 250 lb/ft^{2,} 18 in. plenum raised-floor environment. It hosts a mixture of operations and mission computational capability. The data center is equipped with 8 MW of power, up to 8 MW of chilled water, and 4 MW of medium-temperature water. The data center employs six cool-aisle containment pods, six rows of cabinets equipped with rear-door heat exchangers, and two rows of direct liquid cooling. The enterprise data center surpasses DOE Power Usage Effectiveness (PUE) standards and is a leader in the computing industry with a PUE score of 1.06.

Additional power, space, and cooling are needed to expand support of ORNL cloud computing and its research and development computing space; this has been identified in the *FY 2023 Strategic Plan for ORNL Unclassified Computing Facilities*. ORNL is decommissioning the National Oceanic and Atmospheric Administration (NOAA) C4 supercomputer along with the F4 storage system in CY 2024. A timeline is being planned to decommission or relocate the infrastructure for various programs. The lab plans to expand its operation as systems are decommissioned and/or relocated to data centers.

Sharing Infrastructure Opportunities. Current data center space and facility infrastructure are shared across programs; costs are charged back to the respective programs. In addition to accruing valuable economies-of-scale benefits, shared staff expertise enables best-practice operations. Continued sharing opportunities of deployed infrastructure are possible in the form of federal and nonfederal entities partnering with DOE on deployments that help DOE realize greater benefits to its mission. These deployments may be tightly coupled in new emerging supercomputing platforms or take the form of new, loosely coupled partnering agreements for power, space, and cooling (similar to existing models).

Intracampus Networking Infrastructure. Investments in internal campus infrastructure upgrades will support the IRI objectives of DOE. Campus network upgrades have taken place to improve the connectivity of the Advanced Plant Phenotyping Laboratory to OLCF—the upgrades will continue to be required to connect major observational science facilities (SNS, CNMS, etc.) to computing capabilities (OLCF) at higher bandwidths. In addition, the 400G upgrade of connectivity of ESnet to ORNL will drive the upgrade of the network from the ESnet point-of-presence to OLCF and the other SC facilities on the ORNL campus.

Cloud use and access. ORNL uses three cloud providers, Amazon Web Services (AWS), Microsoft Azure, and Google Cloud Platform. Each platform has services enabling research at ORNL. Users choose the platform based on their needs, and the ORNL cloud team helps to get the accounts provisioned for use.

AWS. The AWS infrastructure at ORNL consists of over 90 AWS accounts, which provide account owners isolated and dedicated compute, storage, and networking accessible to authorized users. The infrastructure is managed by a cloud orchestration platform that supports day-to-day configuration management, monitoring, and security administration. AWS services leverage ORNL Single Sign On/Multifactor Authentication credentials, and authorization via standardized cloud access roles. This solution provides self-service capabilities that allow researchers to agilely and securely provision, scale, and decommission compute and storage as needed. As network connectivity evolves, communications between AWS and ORNL will evolve from an internet-based connection to being directly connected, allowing an additional level of security.

Azure. ORNL manages two Azure commercial environments to support mission and mission-support activities up to moderate security demands. The Microsoft for Azure Government environment encompasses more than 50 subscriptions utilized for essential operational functions and critical research efforts. In the Azure commercial environment, essential services like Outlook, Teams, and SharePoint Online for ornl.gov account users are secured through authentication, policy enforcement based on conditional access, and identity protection. The broad service offerings are designed to securely support local mission demands as well as broad collaborations with other research labs, the private sector, and academic institutions.

ORNL Google Cloud. ORNL manages two Google services, Google Cloud console and the Google Admin Workspace Console. Google Cloud Console supports more than 50 projects and allows users to manage department-based structures to deliver project/initiative services; Google Admin Workspace offers traditional Google productivity services and applications largely supporting intraorganization collaboration and specific project demands. Both offerings integrate Google and ORNL security precautions and capabilities to appropriately protect the data and collateral.

Enterprise Cyber and IT Risk Management

ORNL has created a cybersecurity strategy to drive the implementation of best practices, enhance cyber capabilities for defense and remediation, modernize platforms with automation to combat rising threats, and advance compliance with stakeholder requirements. ORNL created capabilities that did not previously exist, focusing on machine learning algorithms for anomalous activity (in-place and operational) and future projects that focus on effectively combatting adversarial AI as well as user behavioral analytics. The cybersecurity strategy focuses on collaborations, automation, and integration where possible, and on increased awareness and training.

ORNL's cybersecurity strategy is grouped into four goals:

- protect DOE and ORNL information and assets and reduce risk while enabling research,
- modernize technology, tactics, and capabilities; enhance defensive measures; comply with contractual, statutory, regulatory, and other requirements; and integrate best security practices,
- advance internal and external collaborations and partnerships to maximize data sharing and minimize threats to ORNL, and
- create a more robust and resilient cybersecurity architecture through the integration and automation of processes and platforms.

To combat current and future threats, ORNL focuses on enhanced threat detection tools and practices, including user behavior analytics to identify insider threats and workstation scanning for data that requires controls at or beyond a predetermined minimum level.

ORNL's cloud strategy embraces cloud technology when it is in the best interest of the mission owing to cost, capability, risk, or mission needs. With this approach, modernization of the lab's local Unclassified Cyber Security Program Plan (CSPP) and enclave model similarly reflects the need to protect the information posture as ORNL reaps cloud benefits.

ORNL's current execution strategy and planned initiatives will greatly reduce the lab's risk while enhancing the security posture. The strategy reduces risk by adding automation and AI, hiring and retaining strategically to ensure staff retention, and expanding collaboration across government and industry to optimize data and intelligence sharing, promote collaborative learning, and build a community of trust to support its members. ORNL expects allocation of FS10 funding, along with potential increases, to be primarily used in the following areas:

- Adopt and integrate zero-trust architecture to effectively achieve design objectives and improve cybersecurity posture by applying an approach that balances risk, research, and operations support.
- Enhance data management and security:
    - implement data-cataloging and data-tagging capabilities to minimize data loss and to protect ORNL's research, records, and reputation;
    - implement and enhance cybersecurity attack surface reduction measures, including the reduction of externally facing services; and
    - review cloud solutions and unmanaged software.

- Mature the ORNL Penetration Testing program through the implementation of an attack, detect, and respond solution that includes the ability to emulate adversarial capabilities.
- Hunt, detect, and respond to threats.
- Integrate government and industry threat intelligence to provide insight from collaborators into the mechanisms and implications of threats, allowing ORNL to strengthen defense strategies.

ORNL employs a layered approach to assessment and mitigation of cyber risks:

- the DOE Cyber Threat Statement and the SC Cyber Security Threat Statement, which include the threats applicable to the various information categories at ORNL;
- the site-wide ORNL Cyber Threat Statement and Security Risk Assessment, where increases to the specified consequence-of-loss concerns and associated minimum security controls are considered in addition to site-wide threats;
- the ORNL Threat Statement and Cyber Security Risk Assessment, which also serves as the Risk Register for cyber; and
- the ORNL enclave ecosystem, consisting of various systems segregated by information security categorization.

Each enclave requires specific security controls and mitigations based upon the information and system types within it. All enclaves physically exist within the ORNL network boundaries; however, they are separated by firewall and/or router-based access control lists as well as administrative, technical, and operational controls. Each enclave can inherit threats from the sitewide Cyber Security Risk Assessment, in which case, a security assessment report is developed that contains threats unique to the respective enclave.

ORNL's risk management approach to assessing and mitigating risk involves (1) identifying, (2) assessing, and (3) taking steps to reduce the risks to an acceptable residual level. For unique individual information systems and software applications, specific risk assessments document unique threats, mitigation, containment or acceptance, and residual risk. For information systems and software applications adhering to ORNL cybersecurity policies for which no additional unique threats are applicable, the residual level of risk is determined to be low and acceptable.

ORNL's Cybersecurity Division is in alignment with the SC CSPP. ORNL Cyber has performed a gap analysis and provided resolution plans with budget requests to SC. Progress toward alignment with the SC CSPP is reported quarterly to the SC chief information officer and chief information security officer. Feedback indicates that ORNL Cyber is in alignment with the SC CSPP.

A critical aspect of closing the gaps with the SC CSPP has been the modernization of ORNL CyberSecurity's legacy capabilities. These efforts have included

- consolidating device logging agents into a single agent and enabling centralized management for deployment while providing for more rapid logging policy configuration changes;
- re-coding of a custom real-time black hole routing capability, to include IPV6, to more efficiently block malicious IP addresses and domains;
- re-architecting vulnerability scanning to simplify architecture and integrate automated discovery of subnets to improve and maximize scanning coverage across the ORNL enterprise;
- upgrading the log streaming platform to make sure data are both encrypted in transit and at rest; and

- replacing existing email protection with enhanced capabilities that allow for more real-time analysis of threats and integration of user experiences with existing cyber training programs.

Site Sustainability Plan Summary

The Sustainable ORNL program promotes the legacy of system-wide best practices, management commitment, and employee engagement that will lead ORNL into a future of efficient, sustainable operations.[34] Many DOE sustainability goals build on prior successes and strive for additional annual improvements. The Sustainable ORNL program contains over 15 sustainability subject areas and subject matter experts who contribute their respective sustainability reporting toward federal sustainability goals.

The figure below summarizes the ORNL Site Sustainability Plan (SSP) progress toward federal sustainability goals, specifically for the Energy Management, Clean and Renewable Energy, Efficiency and Conservation Measures, and Adaptation and Resilience categories. These goals were taken directly from the FY 2024 SSP with FY 2023 data submitted to the DOE Sustainability Performance Office in December 2023. The figure depicts an executive summary of SSP DOE goals. The status was acquired from the table in the SSP the executive summary.

[34] https://www.ornl.gov/sustainable-ornl

DOE goal	Current performance status	Planned actions and contribution	Overall risk of non-attainment
Energy management			
Reduce energy intensity (British thermal units per gross square foot [GSF]) in goal-subject buildings by 50% by the end of FY 2030.	ORNL's FY 2023 calculated energy use intensity (EUI) is 237,514 Btu/GSF. This is a cumulative reduction of 34.7% since FY 2003, a reduction of 1.43% from the FY 2021 baseline, but an increase of 1.41% from FY 2022. ORNL continues to improve identification of energy-consuming facilities as the mission expands.	Continued EUI reduction for goal-subject facilities is seen as attainable by concentrating on the best mix of ECM projects for energy savings and by incorporating net-zero strategies into all levels of lab planning efforts.	High
Achieve a net-zero emissions building portfolio by 2045 through building electrification and other efforts,	ORNL is currently evaluating buildings with dedicated boilers (not associated with the ORNL steam plant) to remove from fuel oil. An ORNL mini-campus can be made all electric by pursuing a project to remove the fuel oil–powered boiler to electric-power boiler.	ORNL is also planning the possibility to conduct an electrification study for the entire campus in the future	**High**
Clean and renewable energy			
Achieve 100 percent carbon pollution-free electricity on a net annual basis by 2030, including 50 percent 24/7 carbon pollution-free electricity.	ORNL purchased 48,400 MWh renewable energy credits (RECs) to supplement on-site renewable energy generation. These RECs represent 8.6% of the lab's electrical energy consumption, exceeding the 7.5% statutory requirement. Tennessee Valley Authority's (TVA's) specific percentage CFE with the 7.5% REC equivalent results in 58.5% CFE. ORNL will continue to consider TVA's specific percentage CFE to better reflect grid-provided CFE.	ORNL will remain compliant with the Energy Policy Act (EPAct) of 2005 7.5% renewable electric energy requirement via REC purchases. ORNL will continue to explore innovative renewable energy projects. REC purchases will reflect significant mission growth in the near future but will transition to energy attribute certificates (EACs) as ORNL works toward CFE requirements.	**Medium** The numbers of RECs/EACs to purchase will increase with mission growth. REC/EAC pricing may become volatile and create budgetary issues as the market attempts to meet increasing demand for EACs.
Investments: improvement measures, workforce, and community			
Implement life-cycle cost effective efficiency and conservation measures with appropriated funds and/or performance contracts.	The ORNL Energy Efficiency and Sustainability (EE&S) program on average funds over $500,000/year toward ECMs. DOE has a current contract with Johnson Controls Inc. (JCI) for an ORNL energy savings performance contract (ESPC) project. The delivery order was July 31, 2008, with a term of 24 years and 7 months. It includes ECMs consisting of steam system decentralization, building management system improvements, advanced meter installations, energy-efficient lighting upgrades, and domestic water conservation.	ORNL's ECMs need to be evaluated to determine which are life cycle cost-effective, and if found to be so, fund and begin installation to the maximum level of funding available. ORNL plans on expanding the auditing process and integrating this process with the facility condition assessments (FCAs). ORNL will then continue to investigate the best potential funding pathway strategies as the life cycle cost-effective ECM list grows moving forward.	**Medium**
Adaptation and resilience			
Implement climate adaptation and resilience measures.	In response to EO 14008 and DOE directives, ORNL submitted the VARP in September 2022 along with a portfolio of actionable resiliency solutions. For FY 2023, ORNL has updated the resiliency project status. One project was funded and completed in FY 2023.	Implementation status updates to ORNL's solutions will be reported annually to SPO.	**Low**

Figure: Goals and performance status taken from the executive summary of SSP DOE Goals and Statuses in the ORNL Site Sustainability Plan

Carbon Pollution–Free Electricity

In FY 2023, ORNL had 42.1% carbon pollution–free electricity (CFE), based on grid-supplied CFE data from ORNL's supplied electricity region as defined by EPA as the eGRID Subregion SRTV (SERC Tennessee Valley). The SRTV region includes TVA, which is ORNL's direct electricity provider. The DOE Sustainability Performance Office (SPO) utilizes the eGRID CFE as the default but permits electricity providers to self-attest their CFE. TVA provided its specific generation resource mix for CY 2022 (the most recent data provided), resulting in a TVA-dedicated 50.81% CFE for FY 2023 CFE reporting. TVA is reporting 56% CFE for FY 2024, pending final certification. DOE is still refining the mechanics and methods of calculating and reporting meaningful CFE values at the site level, and ORNL will work with the new reporting to incorporate TVA's self-attested CFE data. ORNL's annual projections or targets for percentage of CFE through FY 2030 are listed in the figure below. Utilizing the 7.5% renewable energy requirement for the Energy Policy Act of 2005 (EPAct),35 and its reconciliation with CFE, the FY 2023 Legacy CFE is 2.57%, and is projected to grow to 7.5% in FY 2024 and beyond.

Combining with ORNL's on-site generation, the FY 2023 Total CFE is considered 53.39%. FY 2024 Total CFE is projected at 63.51%, reaching 100% Total CFE by FY 2030.

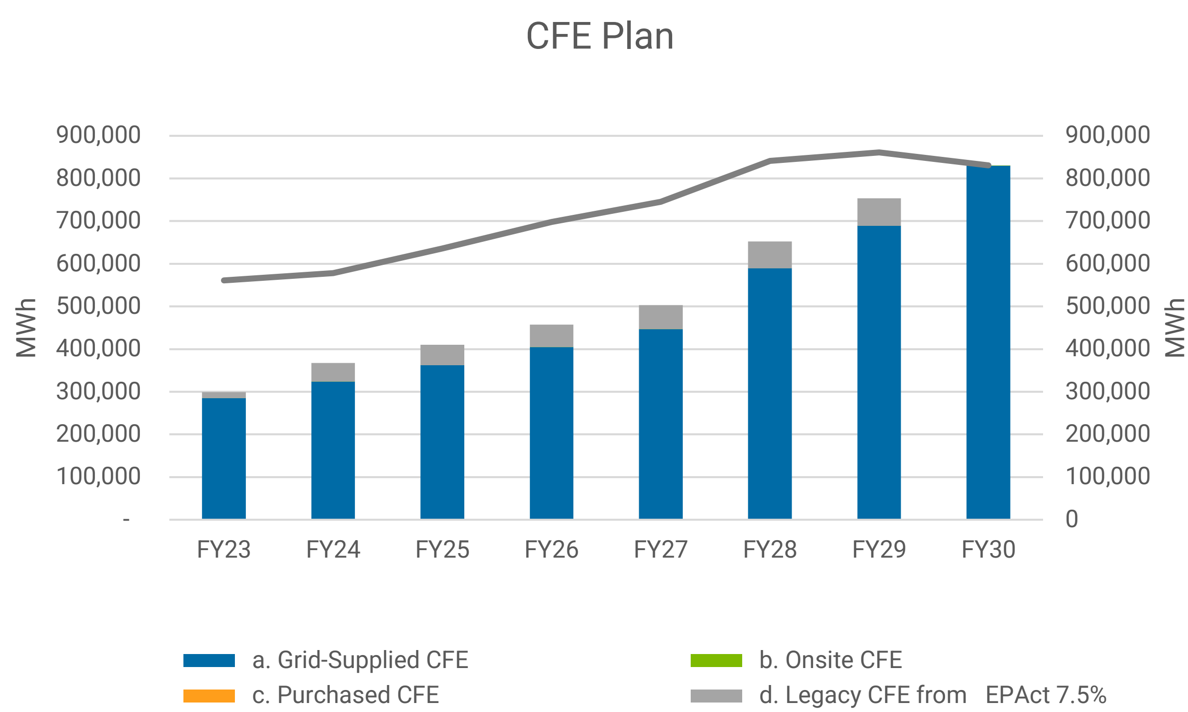


Figure: Annual carbon pollution-free electricity projections

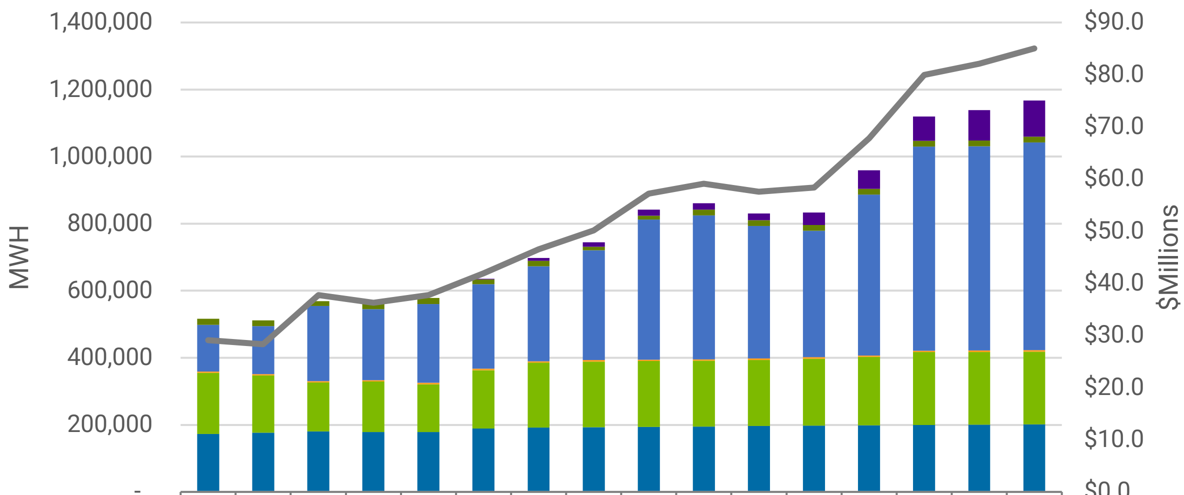
Most of ORNL's annual CFE target increase relies upon TVA's commitment to CFE increases through FY 2030. According to a DOE press release, on December 7, 2023, DOE and TVA announced they have signed an MOU to provide ORNL, the Y-12 National Security Complex, and potentially other federal facilities in TVA's service territory, with 100% locally supplied CFE by 2030. [36]

Electricity Usage for High-Energy Mission-Specific Facilities

[35] Energy Policy Act of 2005. www.congress.gov/109/plaws/publ58/PLAW-109publ58.pdf

[36] Press release: https://www.energy.gov/articles/doe-partners-tennessee-valley-authority-power-oak-ridge-facilities-100-carbon-pollution

The figure below, an electrical energy use and projection bar graph for high-energy mission-specific facilities (HEMSFs), demonstrates the importance of electrical energy at ORNL. Electricity consumption is the largest component of HEMSF energy. About 68% of all ORNL electricity is consumed at the HEMSFs. Electrical consumption is expected to increase slightly because HFIR operations are projected to return to a normal number of cycles in FY 2024. Likewise, SNS operations are expected to be limited in FY 2024 because of the implementation of the PPU and to return in FY 2025. As the mission continues, HEMSF electrical consumption is projected to grow from 68% to nearly 74% by FY 2030 based on projections for data center expansion, infrastructure improvements for SNS's STS, and the projected increase in isotope production and fusion support facilities (identified as *Future* in the figure below). Base energy is expected to increase with additional facilities to support the expansion of mission-critical systems and processes. The bar graph in Figure 6.9 shows the electricity use and projections for each of the four ORNL HEMSFs. All other electricity consumption is also shown on the bar graph as *Base Site Usage*.



	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32	FY33	FY34	FY35
Future					-	2,27	8,84	13,3	17,7	19,1	20,1	37,6	55,1	72,6	90,2	107,
HFIR	18,2	17,4	14,7	16,0	18,2	13,7	16,5	11,0	11,0	17,5	17,5	17,5	17,5	17,5	17,5	17,5
DataCenters	139,	142,	223,	211,	234,	252,	282,	327,	418,	428,	394,	376,	479,	608,	608,	619,
CNMS	3,85	3,99	4,13	4,15	4,14	4,16	4,18	4,20	4,22	4,24	4,26	4,28	4,31	4,33	4,35	4,37
SNS	181,	171,	145,	150,	142,	173,	194,	196,	196,	196,	196,	199,	204,	217,	217,	217,
Base	173,	176,	180,	178,	178,	189,	191,	192,	193,	194,	196,	197,	198,	199,	200,	201,
Costs	$29.1	$28.3	$37.7	$36.3	$37.8	$41.9	$46.5	$50.1	$57.2	$59.1	$57.5	$58.3	$67.8	$80.0	$82.1	$85.0

Base SNS CNMS
DataCenters HFIR Future

Figure: Electricity use and cost projections

PACIFIC NORTHWEST NATIONAL LABORATORY

Lab-at-a-Glance

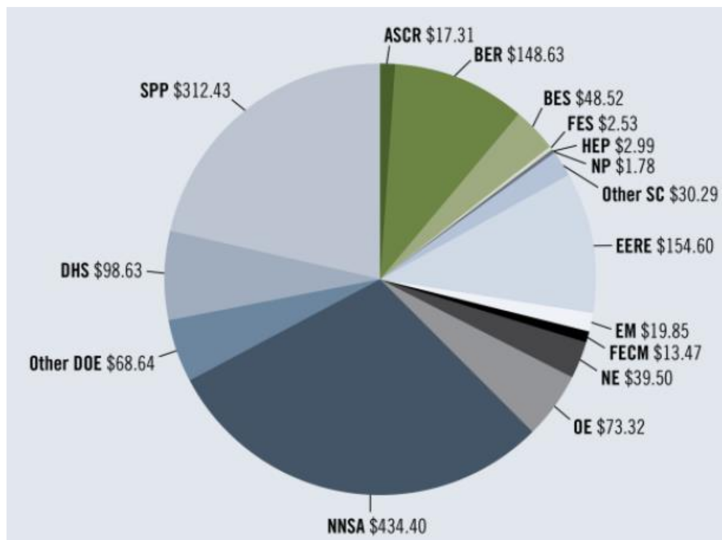
Location: Richland, Washington
Type: Multi-program Laboratory
Contractor: Battelle Memorial Institute
Site Office: Pacific Northwest Site Office
Website: www.pnnl.gov

- **FY 2023 Lab Operating Costs:** $1,466.9 million
- **FY 2023 DOE/NNSA Costs:** $1,055.8 million
- **FY 2023 SPP (Non-DOE/Non-DHS) Costs:** $312.4 million
- **FY 2023 SPP as % Total Lab Operating Costs:** 28%
- **FY 2023 DHS Costs:** $98.6 million

Physical Assets:
- 594 acres and 88 buildings (DOE & Battelle Facilities)
- 1,441,103 GSF in buildings
- Replacement Plant Value: $1.997B
- 1,050,659 GSF in 29 Leased Facilities
- 44,399 GSF in 8 Battelle Buildings
- 2,536,045 GSF total buildings and trailers

Human Capital:
- 5,105 Full Time Equivalent Employees (FTEs)
- 120 Outgoing Joint Appointees, 95 Incoming Joint Appointees
- 303 Postdoctoral Researchers
- 539 Graduate Students
- 564 Undergraduate Students
- 312 Facility Users
- 227 Visiting Scientists

FY 2023 Costs by Funding Source ($M)



Mission and Overview

Pacific Northwest National Laboratory (PNNL) draws on signature capabilities in chemistry, Earth sciences, biology, and data science to advance scientific discovery and address some of the nation's toughest challenges in energy sustainability and national security.

A Department of Energy (DOE) Office of Science (SC) laboratory, PNNL focuses on discovery science. In chemistry, we design catalysts and chemical pathways for new fuels and feedstocks, and we discover new materials for energy storage to transform energy systems. Our Earth science research strengthens the predictive power of DOE's Earth system models, emphasizing Earth systems in transition, clouds and aerosols, and coastal zones. PNNL's biology research strives to understand, predict, and control biological phenotypes to augment ecosystem resilience and develop bioproducts. In data science, we combine machine learning (ML), artificial intelligence (AI), visualization, and modeling to develop machine reasoning capabilities and integrate them with domain research. PNNL manages two DOE user facilities—the Environmental Molecular Sciences Laboratory (EMSL) and the Atmospheric Radiation Measurement (ARM) user facility.

PNNL plays a key role in efforts to heighten the resilience of U.S. energy systems through development of energy storage and grid control technologies. We apply deep knowledge of the North American grid to design, test, and evaluate technologies for security, optimization, and energy storage, drawing on strong chemistry and materials science capabilities to develop advanced energy storage media. In 2024, PNNL will open the Grid Storage Launchpad (GSL) to spur innovation in grid-scale energy storage.

PNNL is a key partner to a number of U.S. national security agencies, providing technologies for the detection of weapons of mass effect and expanding capabilities for nuclear materials characterization and nuclear forensics. Federal agencies turn to PNNL for innovations that expand the nation's nonproliferation tool set, automate threat analyses, secure our borders, and harden critical infrastructures against cyberattacks.

Core Capabilities

PNNL's ability to meet changing DOE needs relies on the strength of each of its 22 core S&T capabilities, described below. Twenty-one of these core capabilities are discipline-based and are grouped into four categories—Biological and Earth Sciences, Chemical and Materials Sciences, Engineering, and Computational and Mathematical Sciences. The twenty-second capability, User Facilities and Advanced Instrumentation, supports two BER user facilities managed by PNNL—EMSL and ARM.

One of the most important functions served by a DOE national laboratory within the U.S research ecosystem is that of integrating a diverse set of scientific disciplines, aligning them with sponsor needs and resources, and bringing them to bear on societal problems requiring S&T solutions. The dynamic interplay of these factors is the engine of innovation, often leading to the discovery of new knowledge, and the invention of high-impact, breakthrough technologies.

Chemical and Materials Sciences

Chemical and Molecular Sciences

Chemical and Molecular Sciences advance the understanding, prediction, and control of chemical and physical processes down to the atomic scale in complex, multiphase environments. PNNL has significant expertise in molecular science, chemical physics, catalysis, chemical separations, geochemistry, physical biosciences, heavy element chemistry, and theoretical and computational chemistry. The Chemical and Molecular Sciences core capability has important connections to the Condensed Matter Physics and Materials Science and Plasma and Fusion Energy Science core capabilities.

World-class experimental capabilities in areas such as nuclear magnetic resonance spectroscopy, tip enhanced Raman spectroscopy, atom probe tomography, and scanning electron microscopy enable unique and impactful experiments that allow applications of theory to achieve in-depth understanding of novel processes.

PNNL has the largest BES-funded research efforts in catalysis science and condensed phase and interfacial molecular science. These outstanding programs are the foundations of PNNL's Institute for Integrated Catalysis.

The Center for Understanding Subsurface Signals and Permeability (CUSSP) Energy Earthshot Research Center highlights PNNL's strengths in geosciences. CUSSP aims to predict and control water flows through hot rock formations in the subsurface through simulations and field measurements. The

Interfacial Dynamics in Radioactive Environments and Materials (iDREAM) Energy Frontier Research Center (EFRC), funded since 2016, is also grounded in PNNL's geochemistry expertise.

EMSL's computational chemistry software suite (NWChem/NWChemEx) is used internationally to address large molecular science problems on computing architectures ranging from workstation clusters to high-performance leadership class computer architectures. Further computational capabilities targeting excited states are being designed in the Scalable Predictive Methods for Excitations and Correlated Phenomena project, recently renewed by BES, to deliver scalable, open-source, electronic structure software libraries.

This capability receives support from DOE programs (BES, BER, ASCR, DHS, EERE, Office of Fossil Energy and Carbon Management [FECM], and OE, and the Office of Environmental Management [EM]) and other federal agencies, including NNSA, Department of Health and Human Services (DHHS), and DoD. Several applied programs also rely on PNNL's Chemical and Molecular Sciences capability for improvements in sustainable energy technologies, catalysis and reaction engineering, hydrogen storage, biomass conversions, environmental remediation, and carbon capture/sequestration.

Condensed Matter Physics and Materials Science

PNNL's Condensed Matter Physics and Materials Science expertise is the basis for the development of new materials for energy generation, storage, and conversion. It enables experiments on the manipulation of electronic and quantum effects as well as on mitigation of materials degradation and replacement of low-abundance elements with high abundance materials without loss of functionality.

PNNL has distinctive strengths in materials synthesis, focusing on atomically precise materials, hierarchical materials, energy materials and metallic alloys, catalytic surfaces, quantum materials, nanostructured materials, and heterointerfaces. PNNL develops tools for materials characterization, advanced imaging, tomography, and spectroscopy. Computational approaches draw on PNNL's expertise in computational chemical physics and drive development of new capabilities in condensed matter theory and computation. Drawing on these strengths, PNNL is participating in the Energy Storage Research Alliance proposal, an Energy Innovation Hub that is the successor to the Joint Center for Energy Storage Research led by Argonne National Laboratory. The successful renewals of the Fundamental Understanding of Transport Under Reactor Extremes (FUTURE) EFRC led by Los Alamos National Laboratory and the Center for the Science of Synthesis Across Scales (CSSAS) EFRC led by UW were enabled by PNNL's strength in this core capability. Most recently, this core capability which also includes synthesizing and characterizing quantum materials has enabled PNNL to play a significant role in the Co-Design Center for Quantum Advantage, a new QIS research center led by Brookhaven National Laboratory.

This core capability also contributes to applied work, including the study of radiation effects in materials and multiscale behavior of structural materials, energy storage materials, lightweight vehicle technology, nuclear reactor safety assessment, regulatory criteria and life extension, legacy waste forms, accelerator technology, development of extremely radio-pure materials for detection of dark matter and neutrino experiments, and nuclear nonproliferation research. This capability receives support from programs in BES, BER, OE, Office of Nuclear Energy (NE), EERE, and from NIH.

Plasma and Fusion Energy Sciences

The Plasma and Fusion Energy Sciences core capability focuses on the understanding, control, maintenance, and use of plasmas in applications ranging from microelectronics fabrication and nanomaterial synthesis of low temperature plasmas to high temperature/high pressure plasmas, laying the scientific foundations for fusion energy. PNNL is recognized for its fusion science expertise in fuel cycles for magnetic confined fusion, materials in extreme environments, and advanced simulations.

Nuclear and Radio Chemistry

PNNL has deep expertise in interfacial chemistry, radiochemical and chemical separations, analytical measurement techniques, actinides, irradiated materials characterization, spectroscopy, and microscopy. The Laboratory processes and measures plutonium and its fission products across a wide range of highly radioactive samples that require the use of hot cells and tiny samples that undergo ultratrace measurements in clean rooms. PNNL has a unique combination of sample analysis expertise and advanced nuclear facility instrumentation, including two focused ion beams and state-of-the-art measurement systems such as the aberration-corrected nuclear scanning transmission electron microscope and atom probe tomography. Mission-ready instrumentation includes suites of microscopy, mass spectroscopy detection, magnetic resonance, and specialized ultra-low-background radiation detectors; numerous specialized wet chemistry laboratories; and ultratrace radioanalytical and radiometric facilities, including a shallow underground lab, providing one of the largest collections of instrumentation and expertise at any single institution in the world.

PNNL is a leader in plutonium production and waste processing knowledge, forensic signatures of plutonium production, post-irradiation examination of materials, and tritium target fabrication. Through DOE-EM's Hanford Tank Waste R&D program, PNNL researchers are developing new real-time sensors and radiochemical insights, equipping DOE-EM to expand waste processing operational windows, enable new treatment alternatives, and accelerate the waste processing timelines at Hanford waste treatment facilities. PNNL leads international teams, focusing on the corrosion of multiphase wasteforms and glass corrosion using ancient analogs, to predict the long-term performance of waste forms.

PNNL stewards a set of facilities unique to the DOE complex, including a Hazard Category II non-reactor nuclear facility (RPL). RPL can perform an extraordinary range of research quickly and flexibly, process materials adjacent to world-class assay technology, and perform broad testbed-scale operations. At RPL, PNNL can work with micrograms to kilograms of fissionable materials and megacurie activities of other radionuclides. Programmatic support for Nuclear and Radiochemistry includes scientific discovery in the search for dark matter and neutrino mass (High Energy Physics program [HEP], Nuclear Physics program [NP], and BES). EM sponsors PNNL's work to understand legacy waste behaviors, for pilot-scale testing and validation, and development of new processing options. The NNSA Office of Defense Nuclear Nonproliferation R&D and the Defense Threat Reduction Agency rely on these capabilities for next-generation nuclear detection systems.

Isotope Science and Engineering

PNNL applies its expertise in chemistry, radiochemical and chemical separations, and analytical measurement techniques to create novel and more efficient isotope production and processing techniques for medical, industrial, and strategic national needs. The Laboratory has a unique combination of in-depth knowledge of process development with instrumentation in nuclear facilities and non-nuclear facilities supporting the development and scale-up of industrially viable processes. This work includes leveraging unique micro-fluids, real-time online monitoring, and radiological characterization integrated into complex processes.

PNNL stewards a set of facilities unique to the DOE complex, including a Hazard Category II non-reactor nuclear facility (RPL). RPL can perform an extraordinary range of research quickly and flexibly, process materials adjacent to world-class assay technology, and develop first-of-a-kind separations techniques. RPL facilitates work with micrograms to kilograms of fissionable materials and megacurie activities of other radionuclides as source material to support DOE's isotope mission. PNNL's isotope science and engineering expertise supports the DOE Isotope Program to produce and distribute critically important isotopes. Currently, the DOE Isotope Program relies on the RPL capability for radioisotope production and dispensing of life-saving isotopes, such as Sr-90 and Pb-212, which are used in cancer treatment.

Applied Materials Science and Engineering

PNNL's capability in Applied Materials Science and Engineering emphasizes the development and validation of materials synthesis, manufacturing, and component fabrication concepts relevant to DOE mission needs and readily scalable for industry adoption. PNNL has made significant contributions to the commercialization of automobile catalysts, organic light-emitting diodes, new battery technologies, tailor-welded blanks, and many other zero-carbon emission energy technologies. PNNL has deep expertise in materials characterization, particularly in in situ characterization; solid phase processing approaches for the production of alloys and composites as well as fabrication of semi-finished products; development of scalable materials synthesis approaches; design and fabrication of electrodes and electrolytes for emerging battery systems; materials theory and simulation, including data management and machine learning approaches to accelerate materials discovery, development, and scale-up; solid oxide reactors for fuel cells and/or electrolyzers; durable polymers and composites for hydrogen infrastructure; and materials performance in hostile environments, including radiation effects. PNNL can engineer nanostructured and self-assembled materials, tailored thin films, ceramics, glasses, cements, polymers, metal alloys, and composites.

The Laboratory leverages its Applied Materials Science and Engineering capability to develop new materials and strategies in many areas, including grid- and transportation-scale energy storage, renewable hydrogen production, solid-state lighting, absorption cooling, lighter-weight vehicles, ultraconductors, next-generation reactors, tritium production, separations, and nuclear waste management. PNNL develops advanced waste forms, process control models, and tactical processing strategies for safe and successful immobilization and processing of nuclear wastes. PNNL maintains unique laboratory facilities, including high- and low-dose radiological facilities, laboratories for materials synthesis and deposition, the Solid Phase Processing Demonstration Facility, the Advanced Battery Facility, Battery Reliability Laboratory, Redox Flow Battery Prototyping Laboratory, and the Solid-State Lighting Test and Analysis Facility. In 2024, PNNL will inaugurate a new OE funded battery development facility, the GSL.

This core capability forms the basis of PNNL's sponsor-funded research programs in metals manufacturing; electrochemical energy storage; radiation effects in materials; multiscale behavior of structural materials; integrated computational materials engineering; gas and liquid separations; electric and lightweight vehicle technology; nuclear reactor safety assessment, regulatory criteria, and life extension; and legacy waste forms. These efforts are sponsored by basic and applied DOE programs, including BES, Fusion Energy Sciences, EERE, OE, NE, FECM, EM, Advanced Research Projects Agency – Energy (ARPA-E), NNSA, and the Nuclear Regulatory Commission (NRC). It supports research programs for DoD and for the private sector through SPPs.

Biological and Earth Sciences

Earth, Environmental, and Atmospheric Science

PNNL has extensive experience and strengths in measuring, modeling, and understanding atmospheric, environmental, and climate system processes from molecular to global scales, as well as the interactions between human activities and Earth system processes. Activities include laboratory and field measurements as well as multiscale numerical simulations for integrated analyses of climate impacts and response, environmental remediation, and carbon sequestration. PNNL has expertise in atmospheric aerosol chemistry, cloud physics, boundary-layer meteorology, land-atmosphere interactions, extreme weather, climate analysis, hydrology, hydrogeology, geophysics, biogeochemistry, ecosystem science, coastal system science, energy-water-land interactions, multisector dynamics, and adaptation and resilience. We leverage expertise from related core capabilities, including Chemical and Molecular Science; Biological Systems Science; Earth and Energy Systems and Infrastructure Analysis and Engineering; Decision Science and Analysis; Power Systems and Electrical Engineering; Advanced Computer Science, Visualization, and Data; and User Facilities and Advanced Instrumentation.

PNNL's climate change and atmospheric science research focuses on improving our basic understanding of and ability to project changes in the Earth system and related human systems, and on developing the measurements and data-driven modeling frameworks needed to do so. PNNL manages two BER user facilities—the ARM user facility, which is operated by a consortium of nine national laboratories, and EMSL. Key biological and Earth sciences facilities at PNNL include the ARM Aerial Facility (AAF), Atmospheric Measurements Laboratory, EMSL, the PNNL-Sequim campus, and JGCRI (a partnership between PNNL and the University of Maryland focused on understanding the interactions among climate, natural resources, energy production and use, economic activity, and the environment). These facilities house a wide range of world-class equipment, such as a flow-through environmental chamber, cutting-edge radar systems, and crewed and uncrewed aerial observational systems. PNNL is also a leading developer of atmospheric, climate, land surface, coastal, and integrated human-Earth system models, including the Global Change Analysis Model, the Weather Research and Forecasting model, and the E3SM.

PNNL's Environmental Subsurface Science capability focuses on developing and applying knowledge of fundamental biogeochemical reactions, thermodynamics, and mass transfer processes to the prediction and assessment of natural processes and engineered systems. PNNL provides DOE with domain expertise in molecular-to-field-scale biogeochemistry, reactive transport modeling, lab-to-field-scale geohydrology, biogeochemistry, multiphase flow and transport analyses, computational geochemistry, subsurface technology development and deployment, advanced geophysical and geomechanical modeling and monitoring, isotopic analyses, and high temperature and pressure geochemistry. Potential applications include enhanced oil recovery, design and operation of carbon sequestration reservoirs and enhanced geothermal systems, technology development for nuclear waste repositories, and remediation of contaminant plumes.

PNNL's capability includes programs in atmospheric process research, regional and global Earth system modeling, subsurface science research, multisector dynamics, coastal and Arctic systems research, coastal system science, and wind energy, along with advanced computation and data management techniques. Our observational and modeling capabilities are deployed to develop a more robust understanding of how extreme events and long-term stresses influence the Earth system and human systems, especially the energy sector and national security. This core capability is funded by programs in BER, ASCR, EERE, EM, FECM, NNSA, National Aeronautics and Space Administration (NASA), EPA, NOAA, and other sponsors.

Earth and Energy Systems and Infrastructure Analysis and Engineering

PNNL's Earth and Energy Systems and Infrastructure Analysis and Engineering capability comprises research on the impacts of energy production, storage, and use on environmental resources and functions; develops and deploys technologies to mitigate the environmental impacts of energy production and to improve the performance of energy generation and minerals extraction. This capability spans terrestrial, aquatic, and coastal ocean systems, both biological and abiotic. Technologies developed in this capability area have diverse applications, including Arctic and deep-ocean energy production from oil and gas, hydropower, wind power, marine and hydrokinetic generation, algal biomass production, nuclear energy, and legacy waste.

This capability includes PNNL scientists and engineers across many disciplines, including aquatic and terrestrial ecosystems science, oceanography, biogeochemistry, hydrology, environmental engineering, and microbiology. Its domain expertise encompasses molecular-to-field-scale biogeochemistry, laboratory-to-field-scale hydrology, multiphase flow modeling, integrated (e.g., biogeochemical, physical, and ecological) aquatic modeling, aquatic acoustics and tracking technologies, ecosystem-level adaptive management, biofouling/bio-corrosion, climate-simulating culturing of algae and higher plants, minerals extraction, ecosystems modeling and restoration, human health and environmental risk assessment, and environmental systems technology development and deployment.

PNNL's marine research laboratory in Sequim, Washington, provides coastal locations and facilities that enable studies of anthropogenic impacts on marine species and systems; a controlled study area for development and testing of marine energy systems; biogeochemical, ecotoxicological, and biotechnology investigations with ambient seawater; and a platform for development and testing of autonomous and in situ marine technologies. PNNL's distinctive Aquatics Research Laboratory supports fisheries research focused on sustainable hydropower operations and development. Advanced environmental monitors and ecological sensors for conventional hydropower, wind, marine, and hydrokinetic renewable energy systems are developed and tested at PNNL's nationally accredited Bio-Acoustics and Flow Laboratory. The advanced experimental and instrument capabilities of EMSL are also used to advance research in this area, with a focus in molecular-scale biogeochemistry and proteomics.

PNNL is leading key coastal research programs, including ICoM and COMPASS. ICoM focuses on an integrated and multiscale approach to develop robust predictive understanding of coastal evolution that accounts for the complex, multiscale interactions among physical, environmental, and human systems. COMPASS is advancing scalable, predictive understanding of the fundamental biogeochemical processes, ecological structure, and ecosystem dynamics that distinguish coastal terrestrial-aquatic interfaces (TAIs) from the purely terrestrial or aquatic systems to which they are coupled. The Earth Systems Science and Engineering capability is funded through DOE programs in BER, BES, EM, NE, and EERE, and by other agencies including NRC, EPA, DHS, BPA, Department of Interior, NOAA, and the U.S. Army Corps of Engineers.

Biological Systems Science

Through PNNL's Biological Systems Science core capability, the Laboratory is developing capabilities to understand complex multicellular systems and their responses to perturbations. It aims to enable improved predictions of the impacts of environmental change, energy production, and emerging technologies and biothreats on ecosystem sustainability and human health.

PNNL has made significant contributions in deciphering mechanisms of microbial community metabolic interactions and dynamics, understanding multiscale terrestrial biogeochemistry, predicting contaminant behavior and microbial ecology of the subsurface, quantifying the effects of renewable energy devices on aquatic ecosystems, and applying a systems biology approach to plant, microbial, and algal systems relevant to DOE's missions in science, energy, and environment. PNNL's Soil Microbiome SFA aims to achieve a systems-level and predictive understanding of the soil microbiome's phenotypic response to changing environmental conditions through spatially explicit examination of the molecular and ecological interactions occurring within and between members of microbial consortia. Capabilities in microbiome science, multi-omics measurement, and computational biology are used to understand functional interactions across biological kingdoms, as well as how metagenomic information is translated to the function of microbial communities to influence the resilience and sustainability of ecosystems, bioenergy crops, and human health. Investments in synthetic biology have expanded into capabilities to identify novel functions of gene products in soil microbe and plant rhizosphere environments and to develop strategies for the secure biodesign of engineered functions in these systems to advance BER bioenergy missions. PNNL's expertise in fungal biology has yielded a deeper understanding of biological processes underlying efficient fungal bioprocesses for fuel chemical production. In addition, PNNL is providing insight into the development of medical countermeasures and early diagnostics, characterizing emerging pathogens, and advancing human exposure assessment to improve health and biodefense. This is particularly true for toxins with a growing capability to assess the threat from bacterial and viral pathogens.

PNNL's integrative omics capabilities, widely used by the BER programs, leverage this broad suite of expertise to provide unprecedented molecular to mesoscale resolution of the function of biological systems. BER investments in advanced bioimaging capabilities at PNNL (e.g., cryo-EM, nanospectroscopy), including a program to develop a first-of-kind quantum bioimaging capability, further strengthen PNNL's effort to elucidate the structure and functions of proteins and other gene products needed to advance predictive modeling of biological systems. This capability is funded through programs in BER, ASCR, BES, EERE, EM, DHS's Science and Technology, DoD, NIH, and NASA.

Biological and Bioprocess Engineering

PNNL is developing technologies and processes that create opportunities from ecological and economic liabilities by leveraging the capabilities in Biological and Bioprocess Engineering. These capabilities are critical to realizing energy and industrial decarbonization by sustainably converting biomass and carbon-containing waste materials into fuels and chemicals. Potential carbon feedstocks include food wastes, sewage sludge, municipal solid wastes, polymers, industrial wastes, lignocellulosic materials (e.g., agricultural residues and wood wastes), and algae. This capability is strengthened through collaboration with Laboratory expertise in our Earth and Biological Sciences Directorate for biological processes and PNNL's unique approach to integrating biological processing with catalysis and reaction engineering from the Institute for Integrated Catalysis; separations, process engineering, and process flow and system analysis; materials science; and techno-economic modeling. The capability also benefits from strong collaboration with external partners through the WSU-PNNL Bioproducts Institute and several Bioenergy Technologies Office and BER consortia, including the Chemical Catalysis for Bioenergy Consortium, Feedstock-Conversion Interface Consortium, Bioprocessing Separations Consortium, Agile BioFoundry, and the Joint Bioenergy Institute.

PNNL successfully leverages cross-directorate capabilities in multi-omics and computational biology combined with fungal genetic engineering and bioprocess engineering to enable dramatic improvements in organisms and process conditions to achieve industry-relevant rates for the production of renewable bioproducts and chemical precursors. In addition, we have advanced hydrothermal liquefaction for conversion of wet feedstocks to products, catalytic hydrotreating of bio-oils to fuels, conversion of renewable carbon-derived alcohols to jet fuels, and conversion of intermediates to chemical products. PNNL houses unique indoor, climate-controlled raceway ponds and photobioreactors that can cultivate microalgae strains under conditions that simulate outdoor ponds at any geographic location in the world. The capability also includes a unique Biomass Assessment tool that can quantify potential resource supplies, infrastructure connectivity, and biomass production from microalgae and waste feedstocks.

Current applied research focuses on fungal genetic and bioprocess engineering to produce commercial bioproducts from lignocellulosic or organic wastes. A recent example of the Lab's success in technology commercialization leveraging this capability is the PNNL-developed alcohol-to-jet process that has been licensed to LanzaTech to enable the production of jet fuel from alcohol derived from industry flue gases using fermentation followed by thermochemical processing. Through the PNNL-LanzaTech partnership, the jet fuel has been certified by the American Society for Testing and Materials for commercial use, and the first transatlantic flight utilizing a waste-gas derived jet fuel was flown by Virgin Atlantic.

Computational and Mathematical Sciences

Advanced Computer Science, Visualization, and Data

PNNL applies deep expertise and decades of experience in computing, AI, and visual analytics to advance scientific discovery, strengthen energy resiliency, and enhance national security. We leverage this capability along with strengths in energy efficient computing; performance, power, and reliability modeling; and novel computing architecture design to research data/model convergence to integrate the historically distinct computing platforms for HPC. Our work is recognized internationally by scientific peers in areas of performance, power, and reliability modeling for codesign of systems and applications, design space exploration and optimization, human-centered computing, visual analytics, and AI. Other domain areas of excellence include AI assurance, predictive modeling and simulation of complex architectures, programming models, advanced workflow orchestration, resiliency, architectural testbeds, fault tolerance, image processing, data analytics, and data management and engineering.

PNNL has advanced the state of the art in machine learning algorithms and their application to DOE missions such as biology, chemistry, the power grid, and cybersecurity. In addition, the Lab has developed new approaches for domain-aware machine learning to accelerate training and interpretability of models and few-shot learning to accelerate discovery in scientific domains characterized by limited data. PNNL is integrating theory and experiments with HPC and AI to discover new chemical transformations that are fast and selective, understand separations processes, investigate materials for QISs, and realize new chemistries and materials for advanced energy storage. In collaboration with SLAC National Accelerator Laboratory, Brookhaven National Laboratory, and university partners, PNNL leverages cloud resources to develop machine learning models to predict long-term catalyst activity. PNNL drives novel research in scientific machine learning to better understand coupled, dynamic systems like the power grid and extreme weather prediction. PNNL is investing in AI to increase scalability and interpretability, including advances in the mathematical foundations of AI for automated reasoning, large-scale multimodal machine learning models, and data analytics. Our expertise in programming models for extreme-scale computing is demonstrated through toolkits such as Global Arrays, which powers NWChem and other important scientific applications, including subsurface flow modeling code Subsurface Transport Over Multiple Phases (STOMP) and power grid modeling code.

PNNL integrates interactive visualizations with advanced automated data analysis techniques, enabling users to gain deeper insights from their data. PNNL has developed new techniques to improve human interfaces to AI systems to increase trust and interpretability, enhance situational awareness and discovery in high-throughput streaming data analytics, and interactively train and evaluate machine learning algorithms. We are making significant advances in graph analytics, including hybrid architectures for exploiting large graph datasets and algorithms for scalable graph query on multithreaded systems. Finally, PNNL has deep expertise in scientific data management, including workflow, system architecture, and database architecture.

Special facilities in support of this core capability include the Center for Advanced Technology Evaluation, an advanced architecture for evaluation of early technologies for incorporation into post-exascale systems; institutional computing resources providing general purpose HPC, including hybrid CPU/GPU nodes and specialized large memory systems; on-ramp systems for the new exascale platforms deployed at DOE Leadership Computing Facilities; GPU-based platforms for AI/ML workloads, including state-of-the-art NVIDIA accelerators; specialized systems and testbeds for AI (Sambanova, Graphcore); heterogeneous CPU/GPU/field programmable gate array (FPGA) computing platforms; new FPGA and ARM processor-based hybrid architectures; laboratory-scale scientific data management platforms and services; and human-computer interaction research laboratories. This capability receives support through programs from DOE-SC (ASCR, BES, BER, HEP, FECM), EERE, NNSA, DHS, and other federal sponsors, including DHHS and DoD.

Computational Science

Computing underlies all research domains at PNNL. The Laboratory computing capabilities span all scales of the continuum computing, from edge to HPC and cloud. PNNL actively employs physics-based simulations, scientific machine learning, and AI to solve compelling, extreme-scale scientific problems, and has a long history of developing computational tools and application codes built collaboratively by multidisciplinary teams composed of domain scientists, computer scientists, data scientists, and applied mathematicians. PNNL maintains strong capabilities across many computational science domains, including computational chemistry, computational materials science, high energy physics, computational engineering, computational biology, computational geochemistry with subsurface flow, and computational fluid dynamics, as well as climate science. This capability leverages the state-of-the-art computing infrastructure and services provided by PNNL's Research Computing division, which includes CPU/GPU mid-range HPC systems for computational sciences and AI, and on-ramp systems to optimize computational codes for DOE Leadership Computing Facilities (LCFs). PNNL also has cloud access to advanced quantum systems with various qubit configurations through DOE's Quantum Centers. The Laboratory also provides access to private and public cloud infrastructure to accelerate scientific computing and AI training.

In computational chemistry, PNNL developed and maintains NWChem, a unique molecular modeling capability that dramatically advances the state of the art through the development of scalable predictive methods for excitation and correlated phenomena and directly ties to experiments at DOE light sources. During the Exascale Computing Project, the software was extended to incorporate new theoretical approaches and to adapt to the new exascale architectures creating the new NWChemEX. The exceptional scalability of PNNL's chemistry codes has resulted in DOE grants providing significant computing time and resources on Leadership Computing Facility systems and at the National Energy Research Scientific Computing Center. This computational science capability is a key component of the Computational and Theoretical Chemistry Institute, a multidisciplinary effort aimed at positioning PNNL as a world-leader in scalable computational chemistry. The Northwest Quantum Nexus partnership and PNNL's participation in three of the DOE QIS centers also provide leadership opportunities at the intersection of quantum computing and quantum chemistry with the goal of applying quantum computing in computational chemistry and materials science. PNNL's partnership with Microsoft and the Azure Quantum Elements platform provides a scalable framework to demonstrate the potential cloud computing for science.

The same integrative, codesign-based approach is also being employed to develop advanced multiscale and multifidelity models for the power grid, high energy physics, materials science, health, and climate, to name only a few. Internal LDRD investments have focused on bringing together interdisciplinary teams of data scientists, computer scientists, applied mathematicians, applied statisticians, and domain scientists to work on a wide range of DOE-relevant problems in microbiology, soil science, climate sciences, materials, renewable energy, and nonproliferation. Recently, these investments have focused on the development of novel software and hardware architectures for scalable and AI-accelerated scientific machine learning methods.

This capability leverages PNNL's Applied Mathematics and Advanced Computer Science, Visualization, and Data core capabilities. It supports research sponsored by DOE-SC, including BES, BER, ASCR, HEP, FECM, and NP. Internal LDRD support across multiple initiatives and Agile investments contribute to the continual growth of this core capability.

Applied Mathematics

PNNL is a leader in applied mathematics and statistics, using mathematical models to predict the behavior of dynamic, complex systems and quantify associated uncertainty to accelerate scientific discovery. Our researchers develop mathematical methods for predictive modeling, uncertainty quantification, risk and decision analysis, physics-informed AI/ML, complex information modeling, data analytics, and control of complex systems. A strength at PNNL is the seamless integration of applied mathematics with computer science, data science, and domain expertise to advance scientific discovery and address national problems, such as the reliability and security of critical infrastructures.

PNNL has broad expertise in multiscale mathematics, including dimension reduction, mesoscale Lagrangian particle methods, and hybrid methods for coupling multi-physics models operating at different scales. The Lab develops capabilities in domain-aware AI/ML as well as physics-informed methods for scalable parameter estimation and uncertainty quantification. These techniques focus on solutions for nonlinear and high-dimensional systems and include surrogate and multifidelity modeling for both forward prediction and inverse models. PNNL also develops novel approaches to generate scientifically interpretable mathematical models capable of reasoning over numerous complex scenarios defined by partial information and partial model understanding. The integrated use of mathematical or statistical techniques—such as uncertainty quantification, machine learning, signature discovery, causal reasoning, and game theory—enables domain scientists to generate and validate novel hypotheses in both static and streaming applications.

PNNL also develops operational models focused on resource utilization and risk assessment via simulation, optimization, and mathematical programming. In addition, PNNL is growing capabilities in distributed and hierarchical decision systems, reinforcement learning, verifiable machine learning based control, and concurrent system and control design for safety-critical systems.

PNNL pursues innovative research in the analysis and integration of complex, high-dimensional data, advancing computational methods rooted in topology, algebra, geometry, hypergraph theory, and applied category theory. We use these methods to build novel representations of tabular, relational, and time-series data aimed at synthesizing quantitative and qualitative information with complex, multi-way dependencies. Other applications include sensor fusion, anomaly detection, and visualization of complex data for critical problems in cybersecurity, geolocation, and open-source data analysis. PNNL has strong capabilities in discrete mathematics, used across DOE missions to solve crosscutting problems. PNNL is heavily invested in solving issues related to large-scale graph analysis, time evolution of discrete structures, and the development of network invariants and their applications. PNNL researchers leverage emerging capabilities in QISs to develop algorithms for combinatorial optimization and quantum machine learning.

This core capability supports sponsor-funded research by DOE-SC, including ASCR and BER, and government-funded innovation and technology transfer programs such as Small Business Innovation Research/Small Business Technology Transfer. Our applied mathematics research related to AI/ML is funded by diverse sponsors, including ASCR, DoD, and NNSA.

Cyber and Information Sciences

The Laboratory conducts research and develops technology that brings scientific approaches to cyber operations and defense, giving the United States a strategic advantage in the cyber domain. PNNL's work enables cyber resilience and security for today's most vulnerable systems, including U.S. critical infrastructures, global communications networks, and ubiquitous technology networks. Research, engineering, and analysis staff are nationally and internationally recognized in cybersecurity resiliency theory, secure design principles for control systems, fundamental research in complex cyber-physical systems, creation of advanced cyber analytics, the development of methodology for cyber and physical security risk evaluation and testing of secure communications, invention and deployment of advanced sensing techniques, laboratory-based cyber supply chain risk assessment, and the ability to turn scientifically driven insights into actionable techniques for decision-makers.

PNNL's cybersecurity expertise spans IT, industrial control systems, operational technology, AI assurance, and the Internet of Things. The power of the Laboratory's cybersecurity portfolio lies in the ability of these cybersecurity researchers to effectively collaborate with mission partners, industrial sectors, and additional core capability areas of the Lab to provide rapid and effective solutions in an evolving domain. By leveraging our fundamental capabilities in sensing and analytics to meet the challenges identified by our threat intelligence capabilities, PNNL has grown a strong capability in the deployment and operation of cybersecurity sensors for wide-scale network intrusion monitoring and situational awareness. This portfolio of work spans multiple critical infrastructures from the DOE complex under the Cooperative Protection Program and the U.S. energy sector under the Cybersecurity Risk Information Sharing Program (CRISP) and the Energy Threat Analysis Center (ETAC), and is now moving to determine other markets and infrastructure sectors. Within this framework, we have developed several tools and methods that have transitioned from early concept research to deployed operations within large portfolios, like the Office of Radiological Security Global Security Program. An emerging area of focus, SCRM, will identify, assess, and mitigate potential risks and disruptions within the software and hardware supply chain. Specifically, PNNL has supported DOE's efforts to prioritize operational technology components for testing, develop standard approaches to vulnerability testing, develop standards for reporting and storing SCRM data, and work with operational technology manufacturers and users to frame mutual cooperation.

PNNL's information science expertise is in areas of data acquisition and management (e.g., experimental design, analytic pipelines, provenance, and quality assurance), analytics and algorithms (e.g., streaming and graph analytics and scalable machine learning), and decision support (e.g., novel visual interfaces, real-time analysis, and model/algorithm steering in response to user input). PNNL's cybersecurity portfolio has leveraged these fundamental competencies within our domain through the study of fundamental scientific and mathematical foundations of cybersecurity, multiscale graph methods for active cyber defense, critical infrastructure resiliency analysis and modeling, supply chain security, vulnerability assessment, and integrated cyber and physical security. An emerging area of focus is within the field of assured AI, where we leverage our systematic interrogation of software and hardware systems to improve integrity. In partnership with PNNL's Center of Excellence in Artificial Intelligence, we participate in national and international conversations on data integrity, trust, and explainability.

Cyber research requires an evolving combination of physical and logical resources in both computing and sensing/emitting. To meet that demand and support sponsor missions, we utilize traditional HPC, industrial grade cloud systems, and purpose-built testbeds, such as the PNNL-developed CyberNET and PowerNET virtual enterprise testbeds, to simulate real-world cyber activity and improve cybersecurity for industrial control systems. In addition, facilities such as the Cyber Security Operations Center, the EIOC, the Internet of Things Common Operating Environment, the Advanced Wireless Communications

Laboratory, and the Electricity Infrastructure Cyber Security/Resilience Center support this capability by providing researchers the ability to put theories into practice. Given the operational parameters of cyber networks in today's world, the ability to rapidly instantiate a fully functional environment is vital to the understanding of cybersecurity. External collaborations include industry, academic, and governmental partners from across the nation and around the world. Primary sponsors for PNNL's Cyber and Information Sciences research include Office of Cybersecurity, Energy Security, and Emergency Response; ASCR; OE; DoD; DHS; and Strategic Intelligence Partnership Program sponsors.

Demand for this core capability remains very strong. Aggressive hiring among early career cyber researchers and engineers has improved the staffing situation; however, additional attention is still required for mid- to senior-level hires. The demand, coupled with a maintained level of strong competition for talent with relevant hot skills and the associated high compensation levels, makes this core capability one of several being addressed through intensive recruiting and cross-training. Increased emphasis on modernizing PNNL's equipment and infrastructure through focused investment in the Lab's digital research infrastructure and cloud computing efforts are essential.

Decision Science and Analysis

PNNL maintains strong capabilities in modeling, analyzing, communicating, and mitigating crosscutting impacts at the interface between science, technology, policy, and society. Working collaboratively with scientists and engineers across the Laboratory and with external partner organizations, our experts remain committed to developing and implementing innovative, resilient, and holistic solutions to complex decision problems on the front lines of the nation's energy, environment, and national security challenges.

PNNL's staff expertise is focused on the areas of decision science, risk analysis, economics, systems engineering, decision support systems, operations research, policy analysis, social and behavioral science, statistics, and safety analysis. This capability enables the development and application of cutting-edge decision and risk analysis; safety, impact, and risk assessments; resilient decision-making under uncertainty; alternatives analysis; strategic process/systems improvements; and operational decision support. Additional modeling and analysis capabilities include socioeconomic modeling, market and policy analysis, techno-economic modeling and analysis, regional and national energy simulation, and cost-benefit analysis and uncertainty analytics. The team's breadth and depth of decision and risk analysis expertise fosters flexibility in assembling dynamic, multidisciplinary teams to develop science-based strategies for minimizing risks to individuals or the public, program life cycles, facility designs and operations, and the environment at the local, state, regional, national, and global levels.

Staff supporting this capability are recognized in the areas of nuclear and alternative energy; operational safety review and risk assessment; technology testing, evaluation, and performance assessment; technical and programmatic risk assessment; geospatial decision analytics and visualization; geointelligence; nuclear proliferation risk modeling; knowledge management and data reuse; multi-organizational collaboration decision support; distributed decision-making for power grid reliability; energy policy and regulatory development/deployment; appliance and commercial equipment energy efficiency codes and standards; and feasibility analyses of technology, siting, policy, and tax structures for energy technology deployment. Leadership in safety assessment, probabilistic risk assessment methodology development and application, environmental impact assessment, and analyses and feasibility assessments for nuclear, geothermal, hydropower, and other sustainable energy technologies, such as hydrogen-powered vehicles, are specific strengths. Current stakeholders that primarily use our capabilities include DOE (EERE, OE, EM, FECM, and NE), NNSA, DHS, DoD, EPA, BPA, and NRC.

Engineering

Nuclear Engineering

PNNL has expertise in complex irradiation systems that support materials science, tritium production, advanced fuel modeling, and reactor production analysis. Research staff members have broad and deep technical skills across the full spectrum of nuclear engineering disciplines, including reactor physics, mechanical design, thermal-mechanical analysis, fluid dynamics, heat transfer criticality safety, nondestructive evaluation, and robotics, as well as materials science and microscopy. PNNL applies these skills in radiological facilities (e.g., RPL) to characterize and understand irradiation effects on materials through post-irradiation examination, and to make precise measurements and analyses that enable nuclear archaeological assessments. In addition, PNNL has modeling and experimental testing capabilities that enable the design, development, and fabrication of advanced, accident-tolerant fuel for the current fleet of commercial reactors, advanced non-light water commercial reactors, and low-enrichment fuel for research reactors, as well as the design, modeling, fabrication, and deployment of complex irradiation tests to evaluate nuclear materials.

PNNL is known for its development of the Graphite Isotope Ratio Method—the world's most accurate estimation tool for graphite reactor operational history. The Laboratory has deep expertise in proliferate plutonium production, from reactor irradiation to plutonium metal. Over the past several years, PNNL has expanded our support for NNSA's Office of Defense Programs for the modernization of critical materials. PNNL is the design authority for tritium production targets, and this year the Lab embarked on design analysis that will enable higher production capacity for the tritium targets. The combination of thermal, nuclear, and structural skills is also used to evaluate spent nuclear fuel storage, transportation, and disposal options. PNNL is currently testing high burn up spent nuclear fuel to assure safe dry storage at nuclear power plants across the nation is maintained, as well as its subsequent transportation.

A wide range of sponsors rely on PNNL's Nuclear Engineering capability, including BES, which relies on PNNL to understand the benefits of modeling interfacial dynamics in radioactive environments and materials. DOE-NE uses our expertise to develop new nuclear materials and manufacturing processes, improve upon molten-salt and sodium-cooled reactor technologies, and advance the state of the art of spent fuel recycling. The NRC relies on PNNL to evaluate reactor safety and risk, confirm the thermal performance of nuclear systems, and develop new techniques for nondestructive evaluation to extend the life of existing reactors. This strong knowledge base and expertise in the commercial nuclear industry enables the design of targets for isotope production and fuel performance modeling to develop or evaluate fuels for use in NRC-regulated commercial or research reactors. NNSA's Office of Defense Programs relies on nuclear engineering to understand the production of materials for the nuclear deterrent, most notably tritium. NNSA's Office of Defense Nuclear Nonproliferation supports the understanding of future reactors and their impact on nuclear proliferation.

The infrastructure upgrade investments by NNSA at RPL (e.g., ventilation and electrical system upgrades, laboratory remodels, and recapitalizing glove boxes and fume hoods) are in progress and will sustain this unique national capability for the future to support a wide variety of DOE radiochemistry and nuclear engineering missions.

Chemical Engineering

PNNL's chemical engineering capabilities translate scientific discovery into innovative, first-of-a-kind processes to solve tough energy and environmental challenges for DOE and other stakeholders. PNNL develops materials, catalysts, unit operations, and integrated chemical processes at scales ranging from molecular interactions to engineering-scale experiments to full-scale demonstrations that can be transferred to the sponsor or to industry for commercialization. The processes are designed for industry-relevant geometries and scales with typical operations over extended periods of time. PNNL's competency in this area includes chemical engineers and related disciplines specializing in catalysis and reaction engineering, gas and liquid phase separations, heat exchange, process intensification, fluid dynamics and mixing, thermal-mechanical modeling, electrochemistry, flowsheet development and modeling, and techno-economic analyses. Nuclear waste treatment (from milligram- to ton-scale) is another area of expertise, encompassing slurry transport and mixing, glass melting, advanced rheology, and fluid dynamics for complex multiphase systems.

Examples of how PNNL successfully applies its chemical engineering capabilities include the invention and development of affordable, scalable processes for CO2 capture and utilization, biomass and waste carbon conversion to fuels and products, hydrogen production and liquefaction, liquid organic hydrogen storage and release, catalytic automobile emissions control, and novel heat pumps to increase energy efficiency. Other examples include magnetocaloric liquefaction of hydrogen and other industrial gases, micro-channel-based reactors and separations systems for high efficiency chemical conversions and solar-aided natural gas reforming, solid oxide electrolyzers and fuel cells, and the development and application of software to predict the thermal and structural performance of spent nuclear fuel storage and transportation systems. Working in collaboration with academia, industry, and other national laboratories, PNNL has a leadership role in high-impact national programs, such as H2@Scale, Hydrogen from Next-generation Electrolyzers of Water (H2NEW), and HyMARC.

This core capability supports sponsor-funded research by DOE-SC (BES), as well as many of DOE's Applied Energy Offices (EM, EERE, FECM, and NE), NNSA, and ARPA-E. PNNL's Chemical Engineering core capability is also leveraged in support of research funded by DHS and DoD.

Mechanical Design and Engineering

PNNL is a recognized leader in the application of mechanical engineering and design to improve performance of residential and commercial buildings. Our buildings research has yielded significant energy savings and has enabled groundbreaking approaches to coordinating building energy use with the power grid through advanced controls, diagnostics, and data analytics. Primary supporting disciplines are mechanical, architectural, software and systems engineering, data analytics, control design and optimization methods, and cybersecurity economic analysis and valuation.

Key research areas include advanced lighting, residential and commercial buildings, thermal and electrical energy storage, building controls for energy efficiency and building to grid applications, building energy modeling and simulation, mechanical system design, performance evaluation, and indoor environmental quality.

The research is made possible with the use of several unique world-class facilities. PNNL's "Lab Homes" use two identical 1,500 sq. ft. homes—one baseline and one experimental—for experiments focused on reducing energy use and peak demand. The Lab Homes serve as a project testbed for PNNL and its research partners who aim to achieve high-performance homes. The Connected Lighting Test Bed, a research facility in Portland, Oregon, is a large warehouse filled with lights, cables, controllers, and computers where researchers study connected lighting. The Connected Lighting Test Bed infrastructure enables the efficient installation of indoor and outdoor lighting devices. The test bed includes a software interoperability platform that allows installed lighting devices and systems, which are not natively capable of exchanging data with each other, to communicate through a defined middleware interface. PNNL's Environmental Chambers provide a simulation and testing capability to measure the performance of HVAC systems and other building equipment. The two side-by-side units, also referred to as psychrometric chambers, can precisely control temperature and humidity. The chambers are the largest of their kind in the DOE laboratory system and can accommodate HVAC units of up to 20 tons (240,000 Btu/hour). The capabilities are supported by DOE (SCEP, FEMP, and EERE), DoD, and GSA.

Systems Engineering and Integration

PNNL is internationally recognized for systems engineering and integration through the implementation of technology in real-world complex systems focusing on smart and robust nuclear and radiological security and energy systems optimization and integration. This core capability has solved some of the most challenging national problems by defining and interpreting complex technical requirements and translating them into fieldable solutions that address economic, social, policy, and engineering considerations. Using a structured approach to understand complex systems throughout their life cycle, PNNL applies its domain knowledge and experience in engineered systems simulation and modeling; system architecture and design; testing, evaluation, and optimization; technology assessment, integration, and deployment; policy assessment and economic evaluation; and regulatory analysis, risk assessment, and decision support. This allows our staff to effectively take early-stage research through the development and technology maturation processes and to deploy technical solutions that address our sponsor's most critical challenges.

PNNL proactively engages with other national laboratories and industry to define best practices for applying systems engineering in early-stage R&D and applies a graded approach to our systems engineering discipline that enables us to deliver solutions in a highly efficient, effective way. PNNL is known worldwide for effectively field-deploying international nuclear materials safeguards, nuclear and radiological security, and complex radiation detection systems. PNNL is also known for leadership in integrated building energy technologies, including advancing solid-state lighting, advanced building control, and building-grid integration technology. PNNL is also recognized nationally for the rigorous analyses that support building energy code development and enable DOE to fulfill statutory requirements related to appliance standards. Finally, PNNL is widely known for advancing national power grid reliability and smart grid technologies.

Staff members are housed in facilities that include the Systems Engineering Building (SEB), EIOC, System Engineering Facility, 2400 Stevens, Engineering Development Laboratory, APEL, Radiation Detection Laboratory, and the Large Detector Test Facilities. The Systems Engineering and Integration capability is funded through programs in BES (design and operation facilities), BER, HEP, NP, EERE (buildings and transportation), EM (waste processing and nuclear materials disposition), OE (infrastructure security and energy restoration), FECM (carbon and co-sequestration), NNSA (nonproliferation and safeguards), DHS (radiation portal monitoring and critical infrastructure and analysis), NRC, EPA, and DoD.

Power Systems and Electrical Engineering

has internationally recognized capabilities spanning the entire electric power grid. Staff at PNNL have deep expertise in transmission and distribution modeling, networks, reliability and resilience, smart grid and intelligent systems, distributed energy resources, market systems, and energy demand across sectors. PNNL addresses emerging challenges facing the power industry through better planning, operating, and controlling of modern power grids for enhanced resilience and reliability as well as decarbonization. Primary supporting disciplines include power system, electrical, and control engineering; computational science and software engineering; cybersecurity; data analysis; and policy analysis. PNNL is the national leader in defining a decarbonized, resilient power grid, delivering innovative tools to enable unparalleled grid performance (resilience, reliability, security, transparency, efficiency, affordability, and sustainability) and new control and architectures that anticipate future demand and supply for unprecedented consumer engagement.

Key research areas include grid architecture, transmission and distribution system reliability and control analysis, power system protection, advanced grid data applications, computing and visual analytics, renewable resource integration, energy storage, system modeling, power system economic analysis, and grid cybersecurity. PNNL's expertise in grid simulation and analytics enables high-performance grid monitoring and control at an unprecedented speed, from minutes to sub-seconds. For over a decade, PNNL has led the world in the development and application of transactive systems that combine economics and controls to enable distributed optimization and integration of distributed energy resources, including controllable loads, batteries, and renewable generation. PNNL's expertise in advanced control theory, application, and testbeds supports advancements in the development of new, distributed controls for the electric power system. PNNL's leadership in phasor measurement technologies supports broader national deployment, enabling unprecedented grid visibility and enhanced situational awareness. PNNL's one-of-a-kind, utility-grade control center infrastructure supports research in grid visibility, control, and resiliency, with the largest national repository of grid data and models to inform research.

This research is made possible with the use of the EIOC, the Interoperability Laboratory, and the Power Electronics Laboratory. These laboratories and facilities support world-class commercial tools, as well as PNNL-developed tools, including the GridLAB-D™ open-source simulation and analysis tool for power distribution system design and operation, the GridAPPS-D open-source platform for advanced distribution system planning and operations application development, the GridPACK open-source package for parallelizing power grid simulations, the VOLTTRON™ open-source software platform enabling grid-interactive efficient buildings, the R&D 100 award-winning Dynamic Contingency Analysis Tool for enabling power grid cascading failure analysis, and tools for assessing power grid ramping capabilities with increased variable generation. These capabilities are supported by sponsors in OE, the Grid Deployment Office, EERE (transportation, water power, solar energy, wind energy, hydrogen storage, building technologies, and fuel cell technology); Office of Cybersecurity, Energy Security, and Emergency Response; ARPA-E; DHS; ASCR; DoD; the U.S. Department of State; and private industry.

Microelectronics

PNNL's in-house fabrication capabilities can design and fabricate devices with features down to 5 microns on substrates varying from 100 mm wafers to 10x10 mm*2* chips. This capability is supported by several deposition systems, which include DC/RF sputtering, PLD, and chemical vapor deposition, and photolithography is supported by both wet and dry etching to match materials per project needs. This capability is currently dispersed across several PNNL buildings, making fabrication difficult. Therefore, PNNL will be commissioning a new centralized cleanroom dedicated to device fabrication R&D to support projects. Additionally, PNNL is improving the photolithograph capability by the acquisition of a maskless aligner capable of direct writing to integrate irregular samples into devices and fabricate devices with features down to 1 µm. Furthermore, PNNL is acquiring an electron beam deposition system to enhance our QIS programs and enable the fabrication of qubits at PNNL; this system can be used to support other programs as well.

User Facilities and Advanced Instrumentation

Environmental Molecular Sciences Laboratory

As one of BER's national scientific user facilities, EMSL leads molecular-level discoveries for BER and DOE that translate to predictive understanding and accelerated solutions for national energy and environmental challenges. Our vision is to provide a predictive understanding of dynamic molecular transformations underpinning biological and ecosystem functions. Research in EMSL focuses on three science areas: Functional and Systems Biology; Environmental Transformations and Interactions; and Computing, Analytics, and Modeling. Within each of these thematic areas, EMSL scientists partner with users from around the world to explore critical questions in BER-relevant science.

The *Functional and Systems Biology* area focuses on understanding and harnessing enzymes and biochemical pathways that connect genotypes to complex phenotypic responses through a deep understanding of interactions within cells, among cells in communities, and between cellular membrane surfaces and their environment for microbes, fungi, and plants. This understanding encompasses experimental observations, metabolic reconstruction, and biosystems modeling leading to improved strategies for designing plants, fungi, and microbes for biofuels and bio-based products, as well as unraveling the complexities of carbon, nutrient, and elemental cycles within cells and their immediate environment.

The *Environmental Transformations and Interactions* area focuses on the mechanistic and predictive understanding of environmental (physiochemical, hydrological, biogeochemical), microbial, plant, and ecological processes in above- and below-ground ecosystems, the atmosphere, and their interfaces.

EMSL provides the experimental, data analytics, modeling, and simulation expertise to investigate and model the cycling, transformation, and transport of critical biogeochemical elements, contaminants, and atmospheric aerosols. Coupled experimental and modeling approaches will accelerate understanding of the mechanisms and dynamics of processes, their interdependencies, and feedbacks at molecular to ecosystem scale.

The *Computing, Analytics, and Modeling* area focuses on combining advanced data analytics and visualization and computational modeling and simulation with state-of-the-art experimental data integration to develop a predictive understanding of biological and environmental systems. Our approach to integrating experimental and computational methods advances predictive biodesign for biofuel/bioproduct production and accelerates research to understand the molecular mechanisms underlying biological and hydro-biogeochemical processes controlling the flux of materials (e.g., carbon, nutrients, and contaminants) in the environment.

PNNL is recognized for its ability to conceive, design, build, operate, and manage world-class scientific user facilities, and is known internationally for its advanced instrumentation designed to accelerate scientific discovery and innovation. As new capabilities are developed, special calls for first science applications promote rapid and effective use of these new tools. EMSL is active in leveraging its capabilities with other DOE user facilities to maximize the scientific community's ability to address critical challenges in biology, environment, and energy. For example, EMSL jointly sponsors user calls with JGI and ARM through BER's FICUS initiative. The EMSL-JGI FICUS calls optimize DOE's genomic/transcriptomic and other omics capabilities, as well as EMSL's chemical and physical measurements for breakthroughs in systems biology. The EMSL-ARM FICUS call enables investigation of aerosol processes or aerosol-cloud interactions by studying the physical, chemical, optical, and microphysical properties of aerosols, including biological particles to develop a process-level understanding of the formation, transport, and evolution of aerosols and their impact on warm and cold cloud formation, and ultimately improve Earth system models. EMSL also partners with other user facilities via the FICUS initiative, such as the BES-funded Bio-SANS beamline at the High Flux Isotope Reactor and the National Ecological Observatory Network. In addition, EMSL collaborates with other user facilities through the new Society for Science at User Research Facilities.

ARM User Facility

ARM is a DOE user facility, managed and operated by a consortium of nine national laboratories, that provides a global network of instrumented fixed-location, mobile, and aerial observatories for obtaining cloud and aerosol measurements, as well as precipitation, solar and thermal radiation, surface heat and moisture, and meteorological conditions. ARM observatories are deployed to diverse meteorological regimes around the world where there are critical science questions and deficiencies in global-scale models. Fixed-location observatories are in the U.S. Southern Great Plains (SGP), the North Slope of Alaska, and Graciosa Island in the Eastern North Atlantic. These observatories are operated by Argonne National Laboratory, Sandia National Laboratories, and Los Alamos National Laboratory, respectively, in collaboration with instrument scientists located across the ARM consortium of laboratories, including PNNL. Diverse ARM datasets are being incorporated into high-resolution atmospheric process models and large-scale Earth system models, such as the DOE E3SM Model.

ARM has developed a high-resolution modeling framework that combines ARM observations with a Large Eddy Simulation model to bridge the scale gap between ARM observations and global Earth system models. This modeling system is led by PNNL in collaboration with Brookhaven National Laboratory. ARM observations provide 3-D constraints and a test of model output. The combination of the ARM observations with high-resolution model output and associated diagnostics provides a more complete representation of the ARM site domain, enabling broader use of the data by the scientific community and direct application to large-scale models. The first test of this approach was at the SGP observatory. ARM next applied the framework to study deep convection. This second application made use of measurements from the Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign, held in Argentina from October 2018–April 2019. The CACTI simulations have been released and ARM is now working on a set of cases aligned with its Eastern North Atlantic observatory with a focus on marine stratocumulus clouds. These clouds represent a significant challenge to global models because of their complexity and significant impact on the Earth's energy balance.

ARM continues to deploy mobile facilities as approved through the user proposal process. Mobile facility deployments are led by Los Alamos National Laboratory. As with the fixed-location observatories, operations are in collaboration with instrument scientists across ARM. In FY 2024, the first ARM mobile facility is completing a deployment to coastal Southern California, where it is supporting a study of aerosol interactions with marine stratocumulus. The second mobile facility will begin a deployment in Tasmania, Australia, at the Kennaook research station, where it will support studies of aerosol-cloud-precipitation interactions in this pristine southern ocean environment.

The AAF, which is managed and operated at PNNL, is working on the development of its new research aircraft, a Bombardier Challenger 850. The Challenger 850 is undergoing a modification project that includes the addition of mounting points for scientific instruments and an extensive reworking of the aircraft interior to provide power, communications, mounting systems for research equipment, and workspace for researchers. Final physical modifications are being made this year in preparation for flight testing and certification by the Federal Aviation Administration.

PNNL leads the development of UAS capabilities within ARM, managing and operating a mid-size UAS, the ArcticShark, that can carry payloads of up to 100 pounds as high as 18,000 feet for up to eight hours. The ArcticShark flies over ARM ground-based observatories to augment the measurements from those observatories. The ArcticShark flew three science missions at the ARM SGP observatory in FY 2023. These flights required coordination with Argonne National Laboratory, which operates the SGP observatory. In FY 2024, the science community will have an opportunity to engage with the ArcticShark through a call for proposals associated with additional flights at the SGP this year.

PNNL is responsible for the overall technical direction of ARM's scientific infrastructure through leadership of a collaboration among nine DOE laboratories. PNNL has lead responsibility for a variety of facility components, including the management and operation of the AAF and related operations, technical leadership for various instruments and data product development processes, and communications. This capability is stewarded by BER.

Science and Technology Strategy for the Future/Major Initiatives

Scientific Vision

FPNNL advances the frontiers of knowledge, taking on some of the world's toughest S&T challenges. Distinctive strengths in chemistry, Earth sciences, biology, and data science are central to our scientific discovery mission (Figure 2). PNNL's research drives innovation that advances sustainable energy through decarbonization and energy storage and enhances national security through nuclear materials production S&T and threat analysis. We achieve our vision via the six Major Initiatives presented in this section of the Laboratory Plan. Each of these Major Initiatives describes our intent to address a major science or technology challenge of importance for the missions we serve.

While these Major Initiatives are separately stewarded and executed by the Laboratory, two themes tie them together. First, there is a strong alignment of this overall S&T strategy with national decarbonization objectives. The first five Major Initiatives provide direct support to this critical national and global challenge. The second theme that connects all of the Major Initiatives is contemporary AI. The first four Major Initiatives leverage AI as a tool that will accelerate discovery science through making sense of voluminous data, advancing simulation power, and providing experimental autonomy. AI has a role to play in grid control within the fifth Major Initiative. And finally, the sixth Major Initiative centers on advancing the power and utility of AI itself for scientific discovery.

The sidebar boxes in this section contain several notable examples of activities at PNNL. These activities, while not strictly part of our S&T strategy, are important and strategic for our mission stakeholders and receive considerable attention from the Laboratory as a whole.

Major Initiative 1. PNNL's first initiative, *Catalysis for Renewable Carbon and Hydrogen* (Carbon Catalysis), builds on PNNL's long-standing strengths in chemistry. Through this initiative, we intend to demonstrate the ability to store and release energy in chemical bonds reversibly and efficiently, design systems and processes that enable the repeated reuse of carbon atoms, and enable the energy efficient separation and reuse of carbon from a variety of feedstocks, including wastes. These achievements will be necessary if we are to decarbonize the "hard-to-electrify" aspects of our energy systems (e.g., heavy industries such as chemical, steel, and cement production) and meet U.S. net-zero carbon intensity and climate change goals.

Major Initiative 2. In a related effort, PNNL is debuting a new initiative this year focused on *Precision Synthesis and Processing to Accelerate Materials Discovery* (Precision Materials Synthesis). The ability to precisely synthesize the mechanical, electronic, and chemical properties of materials to meet performance demands is a central challenge in materials science today. PNNL's focus is on elucidating the design principles that will enable greater precision with respect to mass, charge, information, and energy transport characteristics during the synthesis and processing of materials at various scales. While both our Carbon Catalysis and Precision Materials Synthesis initiatives emphasize expanding our understanding of fundamental science, we are inspired in each by specific applications, including sustainable transportation fuels, clean hydrogen production, quantum information systems, energy storage technologies, and microelectronics.

Major Initiative 3. Our *Understanding and Predicting Multiscale Earth System Dynamics* (Earth System Dynamics) initiative will deliver the science necessary to improve the range and confidence of future Earth system models, and thus enhance our ability to plan for, and respond to, climate-driven impacts on U.S. infrastructure, ecosystems, national security, and economic growth. PNNL's effort will concentrate on areas in which insufficient data, incomplete understanding of key processes and interactions, and/or inadequate modeling tools that do not (yet) fully capture the relevant processes and feedback loops across scales are limiting progress. We are currently focused on atmospheric, land, coastal, and integrated human-Earth systems.

Major Initiative 4. The observable traits of an organism depend on both genomic expression and that organism's interaction with its environment. These relationships are the subject of our initiative entitled *Understanding, Predicting, and Controlling the Microbial Phenome* (Predictive Phenomics). To date, the scientific community has relied heavily on inferences from gene sequences and abundance analyses that are often found to be misleading, inaccurate, or incomplete. By contrast, PNNL's approach is to derive functional information from examination of the relationships between proteins, metabolites, their associated genes, and their environment, specifically with respect to microbes and microbial communities. Our success will allow us to design biological systems that provide new avenues to decarbonization and contribute to the bioeconomy, biosecurity, and human health.

Major Initiative 5. PNNL's *Grid Control and Energy Storage for a Reliable and Resilient U.S. Electric Grid* (Grid Control and Energy Storage) initiative encompasses linked goals that will allow for the decarbonization, resilience, and security of the U.S. energy system. Our efforts are focused in two areas: 1) grid sensing and control technology that will improve reliability while incorporating dramatically higher levels of electrification and carbon-free generation, and 2) grid-scale, low-cost, long-duration, energy storage materials that will add flexibility and resilience to our existing infrastructure.

Major Initiative 6. PNNL's *Advancing Artificial Intelligence through Algorithmic and Architectural Diversity* (AI Algorithms and Architectures) initiative is grounded in PNNL's expertise in data science. Our initiative will advance DOE's ability to apply AI to scientific discovery by developing new architectures and reasoning methods using distributed, edge, and cloud computing across large-scale AI ecosystems; collaborating with industrial AI leaders (e.g., Microsoft and Micron) to codesign specialized computing solutions for important problems in chemistry, materials science, and biology; and expanding our use of AI to drive the automation of experimentation and simulation.

Infrastructure

Overview of Site Facilities and Infrastructure

PNNL is committed to providing DOE with access to facilities that are safe, secure, sustainable, and equipped with state-of-the-art features. Our commitment is underscored by the institutional goal of planning future campus investments and optimizing the functionality, reliability, utilization, and operating costs of F&I capabilities for world-class research. In pursuit of this goal, PNNL's 10-year campus strategy aims to have our F&I not only meet the current needs of our research community but also remain adaptable to future challenges and opportunities related to sustainability and resiliency.

Located in southeastern Washington State, PNNL's primary campus is in Richland, with additional buildings in the 300 Area of the Hanford Site. PNNL also operates a secondary campus in Sequim, Washington, home to its marine and coastal research laboratories, along with additional sites in Seattle, Washington; Portland, Oregon; and College Park, Maryland. PNNL's strategy for delivering mission-ready F&I planning is detailed in our PNNL-Richland Campus Master Plan and PNNL-Sequim Campus Master Plan.

In alignment with PNNL's mission objectives, maintenance and operations benchmarks have been established to optimize facility conditions and asset management. These benchmarks include achieving and maintaining a laboratory condition index of 95 or above, reflecting a state of excellence in facility upkeep. PNNL is also committed to an appropriate level of maintenance investment—targeting 2 percent of the replacement plant value or greater—signifying a sizable investment in the maintenance and longevity of its infrastructure.

Each real property asset is assessed annually to identify deferred maintenance items that are then calibrated across the campuses to establish a deferred maintenance priority list. The calibration is a risk-based decision process prioritizing deferred maintenance items with the highest mission impact regardless of ownership (DOE-EM or DOE-SC). Factors considered include safety, security, significance of a building or system, likelihood of failure, cost of repair, and the ability to operate in an impaired or failed state. Those deferred maintenance items with the highest priority are funded sooner in PNNL's planned major maintenance (PMM) strategy. The existing PMM strategy has a portfolio of projects that resolve all existing deferred maintenance of $57.8M by 2034 and plans for high-risk repair needs (total $114,688,000) and efficiencies before they progress into a deferred maintenance item. The table summarizes PNNL's FY 2023 inventory of assets.

PNNL CAMPUS SUMMARY As of 09/30/2023	COUNT	GSF
BUILDINGS		
OPERATING		
DOE-Owned	50	1,441,103
DOE-SC	35	1,097,153
DOE-EM	15	343,950
Contractor-Owned	8	44,399
Contractor-Leased	24	914,075
Contractor-Licensed	1	240
STANDBY		
DOE-Owned	2	37,713
Contractor-Leased	1	29,108
SHUTDOWN		
Contractor-Leased	2	62,837
OTHER STRUCTURES & FACILITIES (OSFs)		
DOE-OWNED	**33**	-
CONTRACTOR-OWNED	**17**	-
OVERALL ASSET CONDITION		
DOE-OWNED BUILDINGS		
Adequate	51	1,477,416
Substandard	1	1,400
DOE-OWNED TRAILERS		
Adequate	4	6,570
DOE-OWNED OSFs		
Adequate	31	-
Substandard	2	-
CONTRACTOR-OWNED BUILDINGS		
Adequate	8	44,399
CONTRACTOR-OWNED OSFs		
Adequate	16	
Substandard	1	
CONTRACTOR-LEASED BUILDINGS		
Adequate	27	1,006,020
CONTRACTOR-LICENSED BUILDINGS		
Adequate	1	240
ASSET UTILIZATION LEVEL		
DOE-OWNED BUILDINGS		
Utilized	50	1,441,103
Unutilized	1	17,621
Underutilized	1	20,092
DOE-OWNED TRAILERS		
Utilized	4	6,570
CONTRACTOR-OWNED BUILDINGS		
Utilized	8	44,399
CONTRACTOR-LEASED BUILDINGS		
Utilized	25	966,772
Unutilized	1	29,108
Underutilized	1	10,140
CONTRACTOR-LICENSED BUILDINGS		
Utilized	1	240

Our thoughtful approach to maintenance, operations, and sustainable infrastructure development demonstrates PNNL's dedication to advancing DOE's mission through our state-of-the-art facilities. We have established benchmarks that position our facilities at the forefront of operational efficiency and environmental stewardship. These efforts are complemented by our strategic priorities of PMM activities, aiming to keep our infrastructure robust and adaptable to future S&T advances.

PNNL's campus plan includes a significant recapitalization for F&I that totals $1.2B by 2033. This plan reflects our commitment to fostering a thriving environment for discovery and innovation. It is rooted in five underpinning F&I goals (figure to the right) designed to enhance our capacity for groundbreaking research while minimizing our environmental impact.

F&I PLANNING GOALS

To maximize mission impact for DOE, PNNL's F&I planning is underpinned by five goals:

1. Maintain a ready-to-serve, mission-ready campus
2. Increase federal ownership of the campuses and facilities and reduce dependence on third-party leasing
3. Leverage local support for utility infrastructure and services, fire, police, and emergency response
4. Invest in F&I to maintain or improve our current low level of deferred maintenance
5. Prioritize resiliency and sustainability to reduce energy use, water use, waste, and other natural resources

Campus Strategy

The mission-related elements of PNNL's campus strategy are driven by a need to sustain the health of the Lab's core capabilities and support key programs and sponsors. Campus planning consists of understanding the mission need, assessing the state of readiness, determining the space or infrastructure gap consistent with our ICM review, assessing alternatives (including cost-benefit impacts), and developing and implementing the resulting strategy.

PNNL, in collaboration with DOE, actively engages in strategic partnerships with various federal entities and the state of Washington to orchestrate a comprehensive investment strategy for the Lab. This strategy has integrated federal line-item construction projects, overhead funding, state funding, and sponsor investments.

PNNL's 10-year campus strategy is driven by alignment with its emerging S&T mission and F&I needs. In support of this, PNNL has committed to an increased level of overhead funding starting in FY 2023. Figure 4 illustrates PNNL's 10-year campus strategy to sequence institutionally and sponsor-funded projects to maintain, replace, and modernize F&I. This rolling 10-year campus strategy is evaluated and updated annually through a disciplined process as the campus strategy evolves. Successful implementation of the complex and interdependent components of our 10-year campus strategy will require a large-scale project integration effort that includes internal stakeholders, project staff, and DOE.

The strategy is broken down into six primary objectives:

1. Line-Item Projects
2. Carbon-Free Energy
3. National Security Missions
4. Extend the Life of Nuclear Mission Capabilities of the 325RPL Facility
5. Align the PNNL-Sequim Campus Strategy with Current and Future Research Needs
6. Delivery Mission-Ready F&I.

PNNL anticipates bringing approximately 24 new facilities online across these objectives to meet the current and future mission demand. The actual number of new facilities realized will depend on several factors, including the accuracy of mission and growth projections and the facility designs that will be developed. This strategy is coupled with major campus infrastructure investments to drive down the current deferred maintenance backlog and funding allocations to address new maintenance and repair investments that will emerge over time. Table 5 shows the five-year planned PNNL institutional investment levels.

	FY 2023	FY 2024	FY 2025	FY 2026	FY 2027
Total ($K)	**63,865**	**69,038**	**75,272**	**77,523**	**79,140**
Institutional	**55,620**	**52,600**	**57,700**	**59,620**	**61,960**
PNNL G&A[1]/MCE[2]	34,945	30,075	34,800	36,720	38,560
PMM[3]/MC[4] (FSSC[5])	7,675	8,525	8,400	8,400	8,400
PM/CM[6] (FSSC)	13,000	14,000	14,500	14,500	15,000
Overhead Adder	**8,245**	**16,438**	**17,572**	**17,903**	**17,180**
RPL Adder[7]	2,000	2,000	2,000	2,000	2,000
NSM Adder[8]	6,245	14,438	15,572	15,903	15,180

[1] General & Administrative
[2] Minor Construction & Equipment
[3] Planned Major Maintenance
[4] Minor Construction
[5] Facilities Space Service Center
[6] Preventative Maintenance/Corrective Maintenance
[7] Radiochemical Processing Laboratory Adder
[8] National Security Mission Adder

Table: FY 2023 – FY 2027 PNNL planned institutional investments

Projects beyond five years will be conceptual in nature, support anticipated mission alignment and maintenance, and be discussed within ICM for prioritization. The annual planning cycle inputs, data analysis, and validations with Laboratory leadership inform PNNL's out-year investment strategy. This process provides the output for annual investment, as summarized in the figure below, which shows the timeline for PNNL's 10-year capital investment plan.

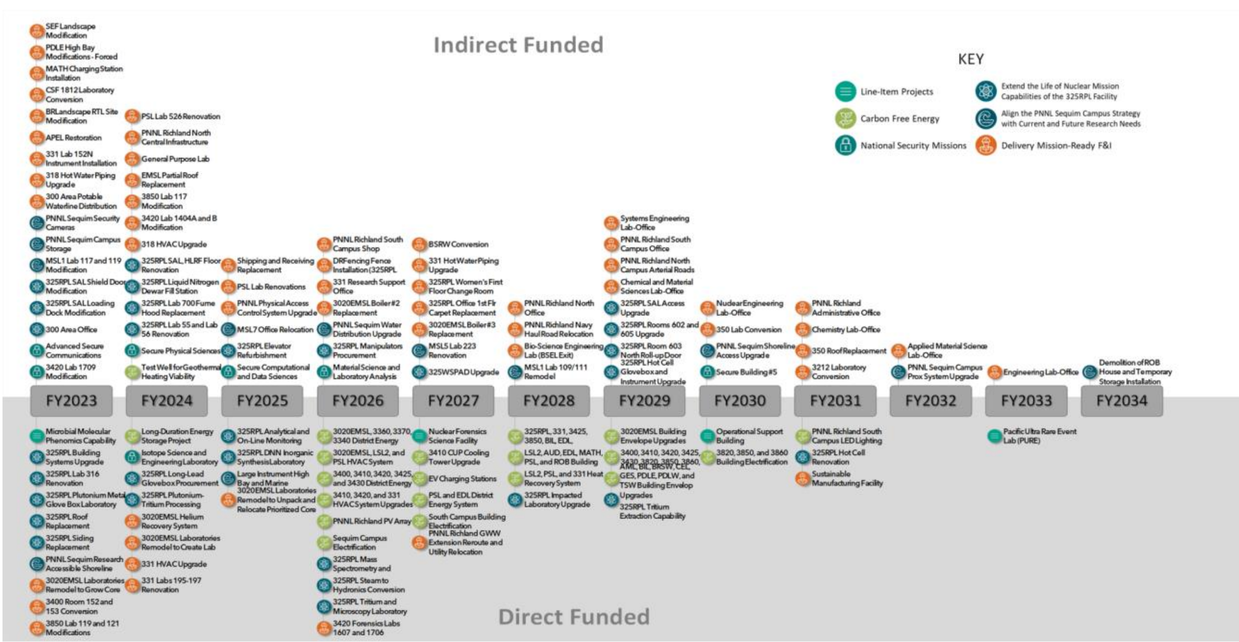


Figure: PNNL's 10-year campus strategy

Outlined below are five key near-term focus areas relative to our campus strategy. These focus areas are in addition to the critical and prolonged focus on providing mission-ready F&I to meet the needs of our researchers.

Leverage a Diverse Set of DOE Sponsor Investments

PNNL benefits from a diverse set of DOE sponsors, some of which have extensive and long-standing portfolios of investment at the Laboratory. The projects listed below are a testament to the value of PNNL's contribution to these sponsors and serve to illustrate one of the many benefits of a diverse sponsor base. Not only does PNNL strengthen its core capabilities from exposure to new R&D challenges and the general overhead recovered from these sponsors' project work, but it also now benefits directly from their F&I investments at PNNL, which further defray the overhead burden on all sponsors.

Grid Storage Launchpad

In August 2019, OE selected PNNL as the site for the new GSL, with the mission to accelerate the development of next-generation, low-cost, long-duration grid-scale storage technologies; provide independent validation of new technologies under grid operating conditions; and foster greater collaboration across DOE and the entire R&D community. PNNL has achieved beneficial occupancy of the $77M project, enabling independent testing and validation of next-generation grid-scale energy storage technologies under realistic grid operating conditions. The GSL provides ~93,000 gsf of laboratory, workstation, and collaboration space to address the capability gap.

Extend the Life of Nuclear Mission Capabilities of the RPL Facility

RPL is crucial for research in nuclear material production, radioactive waste management, and nuclear forensics. Since it was built in 1953, RPL has undergone several upgrades to extend the life of the facility. Most recently, DOE-SC reached an agreement with the National Nuclear Security Administration (NNSA) to invest $150M (with an additional investment of $19M from PNNL) over ten years for the RPL Extended Life Plan. The process started in FY 2022 to modernize and enhance the capabilities of RPL; it is anticipated that a total of ~$71M will be received by the end of FY 2024, which is nearing half the total NNSA funding level in the first three years. The first two completed projects were to replace the roof and the siding of the facility; there are several other projects that are in the design and construction phases. These projects include modernizing laboratory space, replacing gloveboxes, and upgrading ventilation. Institutional investments include a new 300 Area Office building to be constructed in FY 2024 and a $2M annual investment in hot cell and other improvements to support RPL nuclear mission capabilities.

Microbial Molecular Phenotyping Capability

The M^2PC project received Critical Decision-1 (CD-1)—approved alternative selection and cost range—in early FY 2024 to be funded by DOE-SC Biological and Environmental Research (BER). This proposed project scope will include an approximately 25,000 net sq. ft. expansion of EMSL as well as an integrated high-throughput automation equipment solution for culture development, screening, and phenotyping workflows. The project has identified a $100–167M cost range.

EMSL Capability Enhancement

Four projects totaling $20M funded by BER to upgrade existing space in EMSL and integrate EMSL's HPC cooling system with the Heat Transfer Building (HTB) are planned to be executed between FY 2022 and FY 2027. Approximately 13,000 sq. ft. will be repurposed to grow science areas of strategic importance, incorporate new capabilities, reorganize laboratories for safety and efficiency, and create core lab spaces for crosscutting EMSL Integrated Research Platforms. These projects, in support of the User Facilities and Advanced Instrumentation capability, are crafted with flexible scopes to adapt to evolving mission needs, aiming for minimal research disruption. There is also a current project to enhance HPC infrastructure, which will provide waste heat to be used to temper single-pass air needed at the Energy Sciences Center (ESC) and GSL. These projects (current and future) are listed below.

- 3020EMSL Laboratories Remodel to Grow Core Capabilities of Strategic Importance to EMSL.
- 3020EMSL Laboratories Remodel to Create Lab Space to Co-Locate Capabilities that Cross-Cut EMSL's Integrated Research Platforms.
- 3020EMSL Laboratories Remodel to Unpack and Relocate Prioritized Core Capabilities.
- 3020EMSL HPC Infrastructure Upgrade

Additionally, PNNL has commenced efforts to evaluate the existing capabilities for future pursuit and possible redeployment in aerosol sciences capabilities and biology research related to predictive phenomics. The evaluation consists of reviewing the current space for utilization and mission alignment, as well as the longevity of the F&I and any needed maintenance and repair for operating the user facility. Staying ahead of maintenance activities, such as replacing the roof by leveraging programs like NNSA's Roof Asset Management Program to perform design at a reduced cost and replacing the variable air volume units, can increase efficiency and contribute to the continuity of operations.

Isotopes Program

The DOE Isotope Program mission is to produce and distribute isotopes of critical need to the nation and the world that are in short supply. PNNL has supported the DOE Isotope Program for decades through the use of PNNL-developed technology for isotope production and expertise gained from supporting Hanford Site production and cleanup missions. PNNL is currently undertaking a project to expand its existing capabilities as the only domestic entity that can produce certain stable isotopes to meet the critical national need. Additionally, PNNL is preparing to design and construct a new $29M direct-funded facility for critical isotope production starting in FY 2024.

Enhanced Marine Science Capabilities

Accelerating marine energy development necessitates specialized facilities for testing new materials in marine settings, integrating marine power systems, and providing accessible field-testing sites to expedite testing and environmental assessments. These efforts require a blend of onshore lab testing and offshore test beds with advanced data capabilities. The PNNL-Sequim campus, DOE's only marine and coastal research laboratory, plays a crucial role in supporting coastal and ocean-based technology R&D but needs facility upgrades and additional laboratory space. Funding from the Water Power Technologies Office has initiated improvements to the campus's shoreline, enhancing its capability to load and deploy large research equipment, thereby bolstering marine energy development efforts. Additionally, an FY 2024 investment of $21.3M from the Water Power Technologies Office will provide a multi-story shoreline bench-to-bay marine research facility to support large instrument handling and testing, mechanical and electronics development and testing, environmental control capabilities, and biological research.

National Security Research Complex

PNNL plans to break ground in FY 2024 on the NSRC, which will enhance capabilities in advanced secure communications with design underway on capabilities to improve upon the protection of critical energy infrastructure against adversaries. This complex will comprise up to eight secure research facilities focused on advanced fields, such as AI/ML, data analytics, and radiofrequency technologies. The most critical capabilities encompass areas like secure communications, physical sciences, and computational data sciences. Additional facilities will support growing mission needs as well as facilitate the exit of another third-party lease, the Systems Engineering Facility. The individual projects are independently funded through PNNL’s National Security Mission Adder Pool, which includes activities unique to PNNL’s national security customer base.

Nuclear Forensics Capability

NNSA is evaluating a potential nuclear forensics facility to meet new interagency requirements for forensics, particularly the post-detonation mission, with the interest in driving down analysis timelines via increased operational lab capacity. Given PNNL's historical and current roles in nuclear forensics, we anticipate investments to expand nuclear forensics technical and physical capabilities. With support from NNSA, we are renovating space in the existing building and expanding the nuclear forensics footprint. Depending on NNSA decisions and priorities, this expansion is likely to continue and could lead to a new facility that is ~100,000 gsf within the next five years.

The next two projects are notional.

Pacific Ultra Rare Event (PURE) Lab

QIS is an area of growth worldwide, encompassing a broad spectrum of technologies that use features of quantum mechanics for practical benefit and moving PNNL beyond the possibilities of classical technologies. PNNL has demonstrated that interactions of ionizing radiation with QIS devices degrades their performance. The Shallow Underground Laboratory (SUL) at PNNL—a world-class capability in low-level ionizing radiation measurements—is now being leveraged to investigate the effects of radiation on QIS devices. We anticipate a generic community desire for expanded underground device testing capabilities, especially in dilution refrigerators. The vision for underground QIS is to host a noisy intermediate-scale quantum computing user capability for the United States in expanded SUL facilities in the 2030s, which would allow for solving quantum chemistry problems on quantum computers.

Sustainable Manufacturing Facility (formerly Manufacturing Acceleration Center)

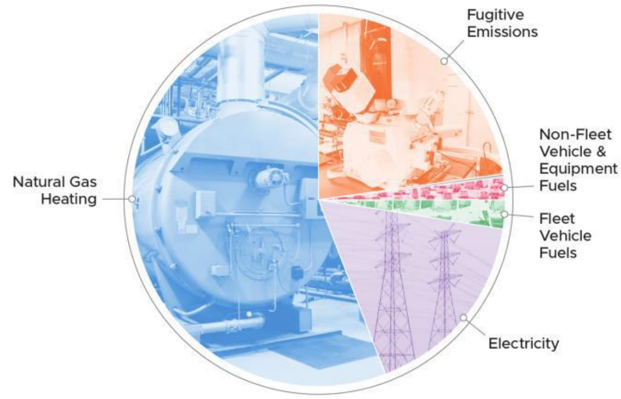
The Sustainable Manufacturing Facility will enable decarbonization of the U.S. transportation and industrial sectors. This facility will house state-of-the-art equipment unique within the DOE complex and bring together PNNL capabilities for the development and deployment of sustainable metals manufacturing technologies and products. The Sustainable Manufacturing Facility will serve as a focal point to connect industry partners with national laboratory and university researchers to develop process technologies to rapidly address technology barriers, de-risk production scale-up, and accelerate adoption. The Sustainable Manufacturing Facility will integrate scientific discoveries with novel metals manufacturing processes to demonstrate scale-up of processes at commercially relevant levels and to accelerate adoption. It will also validate the performance of processes and resulting products through real-world testing. Finally, it will enable coordination of research development and demonstration across disciplines and capabilities to maximize leadership and impact for multiple DOE mission areas. This notional project has a rough-order-of-magnitude cost range of $27–29M and the funding source is to be determined.

Sustainable and Resilient Infrastructure and Operations

Advancing Sustainability to Reduce or Eliminate Carbon Emissions

In partnership with DOE, PNNL has begun a Laboratory-wide transformation of standards to achieve carbon-free emissions and resiliency at our campuses. PNNL has launched a Net-Zero Emissions and Energy-Resilient Operations (NZERO) objective to reduce energy consumption, replace carbon-based fuels and eliminate other greenhouse gas emissions, enhance the resiliency of operations, and establish PNNL as a NZERO research testbed.

PNNL's objective to achieve net zero includes a variety of infrastructure investments and the integration of innovative technologies into existing infrastructure and operations. Initial planning efforts have identified net-zero strategies, each with a list of projects aimed to reduce PNNL's greenhouse gas emissions (shown in the figure to the right) and increase resiliency by reducing the amount of energy required to operate PNNL:



- Improve operating efficiencies of heating and cooling systems through district energy systems.
- Electrify building heating sources and on-campus transportation to eliminate carbon-based fuel.
- Capture or eliminate fugitive emissions from our research instruments.
- Provide more efficient heating, ventilation, and air-conditioning (HVAC), heat recovery, and lighting systems.
- Leverage the use of district energy systems and microgrids with energy generation and energy storage to add resiliency.

The main elements of PNNL's plan to reduce greenhouse gas emissions are illustrated in the figure above.

PNNL has received funding from the Science Laboratories Infrastructure program toward PNNL's net-zero goals for several projects to replace gas-fired heating systems with electric or geothermal systems and upgrade end-of-life HVAC system with newer, more efficient systems, including the following:

- Testing & Analysis Laboratory Boilers Replacement (complete)
- LSL2 Steam to Hydronics Conversion (in design)
- AUD/PSL Steam to Hydronics Conversion (in design)
- 331 HVAC Upgrade (in design).

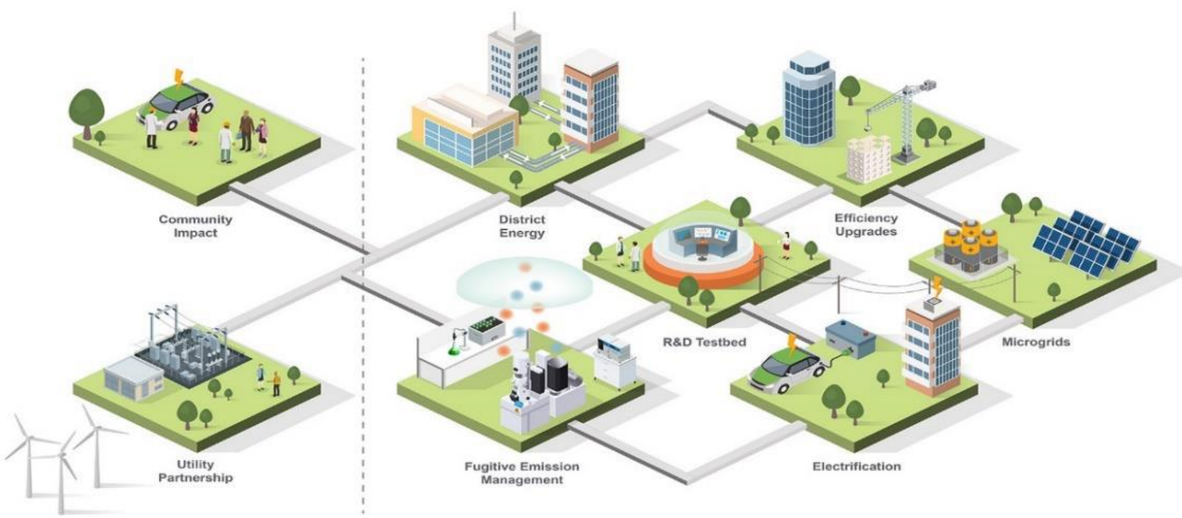


Figure: PNNL's strategy to reduce carbon emission

With the recent award of the direct-funded Office of Clean Energy Demonstrations research project, the LDES project, PNNL has accelerated plans to evaluate the feasibility of a microgrid, harnessing solar energy by constructing the PNNL-Richland Photovoltaic Array (proposed Science Laboratories Infrastructure funded project) complemented by an internal investment in the EMSL Photovoltaic Array Repurpose.

PNNL Power Strategy

Electrical utilities for the PNNL-Richland campus are provided by the city of Richland, which receives its power directly from the Bonneville Power Administration (BPA). The power for the PNNL-Richland campus is supplied through a primary substation (Sandhill Crane Substation) located just west of the PNNL-Richland campus. To date, the city of Richland has provided sufficient power to PNNL; however, with the expected mission growth and F&I electrification projects to advance our net-zero objective, the availability of additional power is now a significant concern. The city of Richland has limited power availability to the PNNL-Richland campus until a major BPA infrastructure project is completed in FY 2027–2028, bringing more power into the fast-growing region. To address this limitation, PNNL and the city of Richland are leveraging their long-standing partnership to develop shared solutions to expand power availability and reduce peak usage. PNNL will internally prioritize projects based on funding and power priority should sufficient power not be secured for all development plans.

Robust Campus Planning Process

PNNL has achieved substantial advancements in realizing its ambitious vision for campus transformation, supported by a strategic plan calling for an investment of $1.2B extending through 2033. As we execute against this plan, we have identified several areas for continuous improvement, enhancing an already rigorous annual planning process by capturing lessons learned or gaps and building frameworks, processes, or even formal documentation to capture the opportunities. In remaining committed to improving our strategic processes, we provide better outcomes for the Laboratory and our sponsors.

Enhancing Our Integrated Approach to Campus Planning and PNNL's Institutional Investments

The campus strategy is developed through an integrated planning approach between the research organizations and M&O. PNNL's rigorous annual planning process includes engaging with research organizations on F&I mission needs, performing a gap analysis on office and laboratory space, and validating the health of PNNL's core capabilities through the ICM process. Two examples of how PNNL has continued to enhance the integrated planning process include the development of an approach that involves taking a broader look at institutional investments—not just F&I—and the incorporation of a project high-hazard siting rubric. The new approach to looking at institutional investments across the Laboratory includes considerations from significant areas of the operating model improvement portfolio, the F&I portfolio, and the minor construction and equipment portfolio and integrating them into a five-year financial planning horizon. By looking across several portfolios over a multiyear horizon, PNNL can better anticipate shortfalls or overplanning, allowing for early mitigations or financial risk avoidance. Second, the siting rubric is a collaborative effort between research organizations and Campus Planning to perform an early qualitative review to identify the types of operation and associated hazards to better understand potential impacts on people or the environment. This new siting rubric informs the project's alternative analysis by driving higher-hazard work to the north end of the PNNL-Richland campus or the Hanford Site 300 Area (further away from the public).

Strategic Space Optimization for Current and Future Growth at PNNL

PNNL is advancing a lab-centric operational strategy to enhance space utilization, incorporating annual gap analyses to anticipate future laboratory space needs against projected headcount growth and alignment with our core capabilities. Additionally, we are revitalizing a centralized space management model for office and laboratory spaces designed to seamlessly integrate with PNNL's Hybrid Workplace policy. This model aims to address the measurement of laboratory space utilization and foster optimization principles and practices while underpinning our commitment to mission fulfillment, fostering a sense of community, and offering the flexibility needed to improve work-life integration. In response to PNNL's growth and our staff's new hybrid work arrangements, we refined our use of individual and collaborative spaces to maintain our status as a leading research institution. This strategy creates an environment that supports innovation, collaboration, and the well-being of our staff, emphasizing the importance of in-person and virtual interactions. We have upgraded our facilities and systems to support these goals, including developing over 90 hybrid-ready conference rooms and introducing several resources to enhance hybrid work collaboration and inclusivity. Through educational programs and resources, we aim to enable effective collaboration and task management for our staff, with the goal of maintaining PNNL as a vibrant, innovative, and inclusive workplace.

- *Lab Space*. PNNL is advancing a laboratory-focused operational approach to enhance lab space usage efficiency. This strategy involves collaboration with diverse business units, integrating human resources hiring forecasts to establish precise growth metrics tailored to PNNL's principal areas of expertise. Present forecasts identify notable deficiencies in laboratory space across several key capabilities, necessitating the development of numerous laboratory and office structures specifically designed to support these distinct areas of specialization.
- *Office Space*. PNNL is continuously monitoring existing office space usage to meet current and future demands while remaining ready to meet today's and tomorrow's mission objectives. In pursuit of this objective, we are expanding our current office space inventory through a series of strategic actions. This expansion involves constructing new office buildings, converting the Guesthouse into office space, and establishing the NSRC. These actions are intended to accommodate the anticipated demand for additional workstations, keeping us mission ready.

Mission-Ready F&I

PNNL remains committed to advancing our strategy for institutionally funded general purpose F&I needs required to meet current and future mission demand as identified in the gap analysis process. PNNL's institutional general plant projects for the next 10 years include the construction of 14 new facilities, totaling ~260,000 gsf, and four infrastructure projects.

- Facilities (next 5-years):
  - General Purpose Lab (in design)
  - Shipping and Receiving Replacement (in planning)
  - PNNL-Richland South Campus Shop (in planning)
  - 331 Research Support Office (planning approved, pending Section 106 review)
  - PNNL-Richland North Office (planning complete)
  - Bio-Science Engineering Lab (pre-conceptual)
  - Systems Engineering Lab (pre-conceptual)
  - PNNL-Richland South Campus Office (pre-conceptual)
  - Chemical and Material Sciences Lab (pre-conceptual).
- Infrastructure:
  - PNNL-Richland North Infrastructure (in construction)

- PNNL-Richland North Central Infrastructure (in planning)
  - PNNL-Richland Navy Haul Road Relocation (pre-conceptual)
  - PNNL-Richland North Arterial Roads (pre-conceptual)

PNNL is continuously evaluating the mission drivers to construct additional facilities or renovate and modernize existing facilities or infrastructure to support a variety of core capabilities. Projects to renovate, modernize, or upgrade existing F&I in the next three years include the following:

- 318 HVAC Upgrade (in design)
- 325RPL SAL, HLRF Floor Renovation (in design)
- 3420 Lab 1404A and B Modification (in planning)
- 325RPL Lab 55 and 56 Renovation (in planning)
- PSL Lab 526 Renovation (in planning)
- 325RPL Lab 700 Fume Hood Replacement (In planning)
- 325RPL Liquid Nitrogen Dewar Fill Station Installation (in design)
- PSL Lab Renovations (in planning)
- PNNL-Sequim Water Distribution Upgrade (planning complete)
- DR Fencing Fence Installation (325RPL Boundary) (pre-conceptual).

Additionally, PNNL is focusing on space used to store and manage critical spare parts and equipment that is essential to operations. PNNL recently developed a long-term storage strategy to provide general campus storage facilities and associated outdoor laydown space that will accommodate proper storage and maintenance of large equipment when not in use and facilitate the exit of existing leased storage space. In the near term, the leasing of warehouse-type space is being pursued as a temporary solution to provide space for institutional storage needs until warehouse space is available on campus. The strategy encompasses several projects:

- South Campus Warehouse (complete): Strategically sited to the south in the low hazard area of the campus, the new warehouse freed up space in the higher-hazard northern portion of the campus to convert to high-ceiling research space.
- South Conex Yard (complete): Consolidation of conex boxes to a safer, more secure area that is fenced with proximity card access and security camera coverage.
- Shipping and Receiving Replacement (in planning): Facilitate more efficient flow of goods in and out of the facility for faster delivery to their destination.
- Bulk Receiving and Shipping Warehouse Conversion (pre-conceptual): Repurpose as a dedicated Excess Materials and Redeployment Services facility.

The figure below describes PNNL's plan for campus transformation, showing an investment trajectory of $1.2B through 2035. This figure encapsulates a range of direct and indirect funded F&I activities tailored to support the lab's mission over the next decade and beyond. It illustrates our dynamic approach to enhancement and innovation, emphasizing how insights gained are systematically integrated into an improved strategy to assure mission readiness.

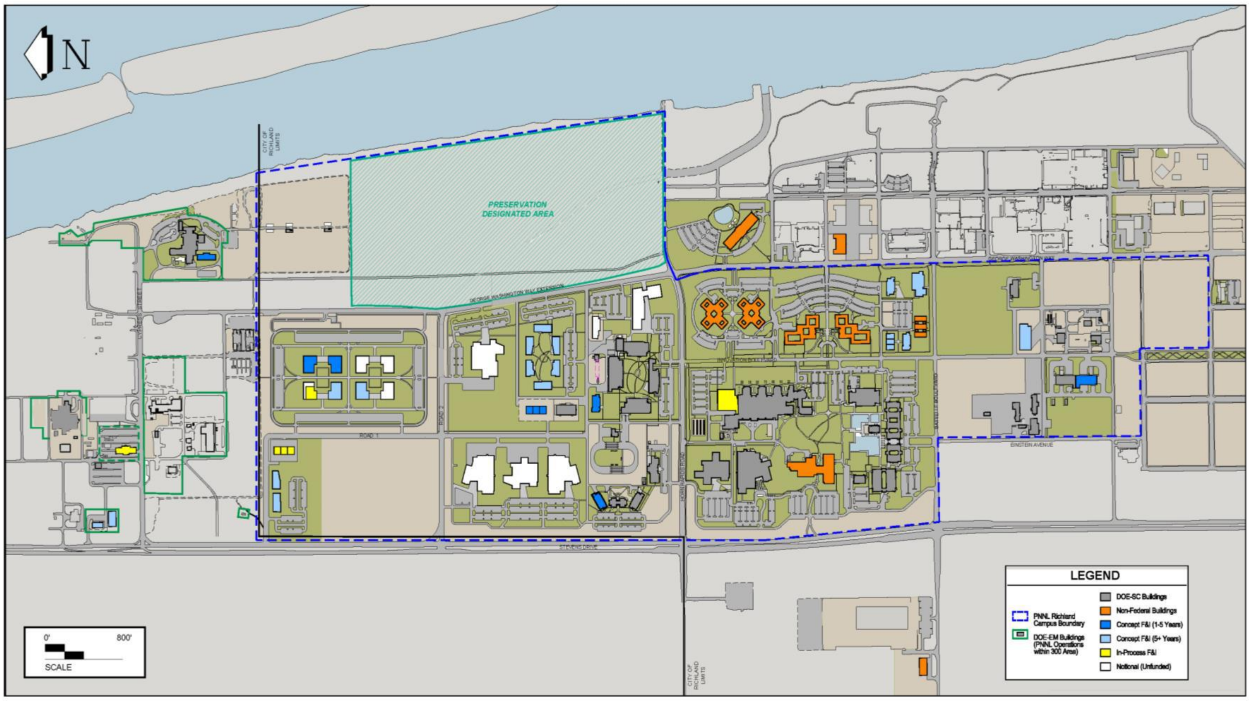


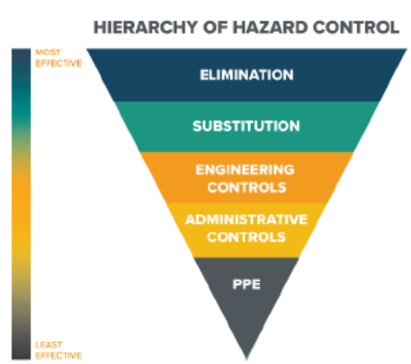
Figure: FY 2022-2035 campus development map

Renewed Focus on Safety and Construction Subcontractor Suitability

Safety is a paramount concern throughout PNNL and the DOE complex. Since the COVID-19 pandemic, there has been a noticeable increase in safety-related incidents within the industry. In response, PNNL initiated a campaign to enhance its safety culture and performance, aiming for heightened attention to safety among staff and subcontractors. Additionally, PNNL is dealing with increased attrition and turnover among its workforce, alongside growth, which has led to a substantial influx of new staff members. This trend of higher turnover rates is also observed among subcontractors and vendors.

Safety by Design

In addition to refreshing PNNL's safety culture centered around the Safe Conduct of Research (SCoR) principles, PNNL is taking a proactive approach, coined *safety by design*, that shifts the focus from reacting to incidents after they occur to preventing them through a structured approach to hazard mitigation, creating a safer work environment for all staff and subcontractors.



The safety by design methodology employed by PNNL emphasizes hazard mitigation as early as the planning or design phase and extends throughout the entire life cycle of the building. It emphasizes the importance of addressing potential dangers during the design phase rather than relying on reactive measures. This proactive strategy is founded on the hierarchy of controls, which prioritizes the most effective forms of hazard mitigation (figure to the right). Implementing proactive hazard control, such as reducing the need for work at heights, can eliminate one of the "Fatal Four" hazards—falls, being struck by something, electrocution, or being caught in or between something—contributing to 70 percent of all accidents on construction sites.

PNNL has applied the safety by design philosophy to several projects and continues to look for opportunities to improve safety by eliminating hazards before a project even gets to the field. For example, to reduce exposure to electrical hazards in locations with high incident energy, PNNL now installs external check test points to confirm de-energization and eliminate exposure to arc flash and shock hazards. Devices have been accepted by PNNL electrical safety and lockout/tagout programs as a best practice. PNNL is documenting and institutionalizing the safety by design approach by incorporating these best practices into the engineering design guidelines.

Construction Subcontractor Suitability

Navigating the complexities of subcontractor management and pipeline development has presented many challenges for PNNL, particularly in maintaining a steadfast commitment to safety. As the demand for skilled labor fluctuates and the landscape of project requirements evolves, ensuring that subcontractors align with our high standards for safety becomes increasingly critical. The industry has witnessed a notable uptick in safety-related incidents post-pandemic, highlighting the need for rigorous safety protocols and continuous training. This increase in incidents underscores the necessity for a hands-on approach in cultivating a safety culture among subcontractors by integrating safety by design principles from the onset of every project. For instance, a senior leader produced a video to educate and emphasize the significance of the SCoR principles. Additionally, PNNL has conducted a training program akin to the Lab Operations Supervisor Academy, specifically tailored for construction subcontractors. These efforts are part of PNNL's commitment to fostering a culture of continuous learning and operational excellence. By prioritizing safety in our subcontractor pipeline and onboarding processes, we not only mitigate risks but also foster a work environment that upholds our core values of security and excellence, ensuring the well-being of all involved.

Maximize Federal Ownership and Reduce Reliance on Leased Facilities

PNNL has implemented a two-part approach to achieving the objective of establishing federally owned campuses. The first part is to transition all existing contractor-owned real property to federal ownership, and the second is to minimize reliance on third-party leases by relocating staff from leased facilities to government-owned facilities and terminating leases where appropriate.

Federalization of PNNL Campuses

DOE is in the final stages of acquiring all contractor-owned facilities, the capstone of an agreement between DOE and Battelle to transfer ownership of this real property. As part of this process, the PNNL-Sequim campus transfer completed critical steps, such as the Finding of No Significant Impact and the Campus Development National Environmental Policy Act Environmental Assessment, in FY 2023. The final transitions in Richland and Sequim are anticipated to be complete in FY 2024. With this achievement, PNNL will look ahead to the next goal of transferring the remainder of the contractor-owned land to DOE by 2035 and, ultimately, completing the federalization of PNNL.

PNNL Leasing Strategy

PNNL is aggressively reducing its dependence on third-party leased facilities. The PNNL-Richland campus and adjacent areas include 17 leases totaling ~873,000 gsf and two leases totaling ~12,000 gsf at the PNNL-Sequim campus. PNNL's leasing strategy is governed by strategic reviews that are aligned with the annual campus planning process; leases are utilized as needed to fill gaps for purposes such as temporary staffing fluctuations or storage needs, with a view to eventually replace them with federally owned facilities as needs are sustained. The PNNL strategy includes thorough cost-benefit analyses to manage the leasing inventory effectively and align with future space demands.

In late calendar year 2023, PNNL completed a multiyear, complex strategy to exit Applied Process Engineering Laboratory (APEL), a third-party leased facility. The effort started with the construction of the ESC, which greatly increased laboratory space on the main campus, followed by the construction of a new warehouse facility to free up high-ceiling space for research work, and in parallel executed several concurrent laboratory upgrades in three existing facilities to support the lease exit. After 26 years of occupying ~53,000 gsf of the APEL facility, PNNL successfully exited the facility, consolidating lab and office spaces into the newly modernized spaces on the PNNL-Richland campus. PNNL also exited the ~10,100 gsf SALK third-party leased facility in early calendar year 2024 after repurposing a previously unused federal facility on the PNNL-Richland campus.

The table below outlines PNNL's actions for addressing eight leased facilities and improving the utilization of government-owned facilities and both completed and pending land transfer actions. The plan includes – pending full transfer to DOE – a complete exit of non-government-owned facilities at the PNNL-Sequim campus by the end of FY 2027.

Property ID	Gross Sq. Ft.	Planned Exit FY	Action or Leased Exit Strategy
APEL	52,697	2024	Successfully exited APEL lease by the termination date of 12/31/2023.
SALK	10,140	2024	Successfully exited the SALK lease by the termination date of 1/31/2024.
BMI Land	n/a	2024	Transfer of 15 acres of land (Parcel B) on PNNL-Richland campus is pending approval.
BMI Land	n/a	2024	Transfer of 65 acres of land, 52 acres of tidelands, and five facilities in Sequim, WA, from Battelle Memorial Institute to DOE is pending approval.
MSL6	2,166	2027	Following the construction of a new storage warehouse on the PNNL-Sequim campus, PNNL plans to terminate the agreement for the use of MSL6 (Robb House).
MSL7	9,688	2027	At the end of the current lease period, PNNL plans to exit this lease and have the landlord remove their facility from the shoreline. PNNL plans to lease new office trailers until a DOE-owned office facility is constructed.
SEF	47,712	2029	PNNL plans to exit SEF after completing the Secure Computational and Data Sciences facility.
WSUBSEL	30,000	2032	Relocate existing high-bay research to government-owned space by 2027 and request a five-year lease extension to construct additional research space planned to be completed in FY 2032.
LSB	83,846	2033	After completing a cost-benefit analysis, PNNL decided to renew the Laboratory Support Building lease for a 10-year term, ending in September 2033. The strategy is to construct a line-item replacement office facility, Operational Support Building, on the main PNNL-Richland campus and exit the lease. Depending on timing of funding, the lease may be extended to support construction of a federal facility.
BSRC	58,828	TBD	In FY 2024, PNNL will update its leasing assessment to support the Lab's upcoming research mission in Seattle, WA. This update follows the release of the PNNL Seattle Strategy in FY 2023 and will include a detailed evaluation of different options needed to meet current and future needs.
2400STV	101,414	TBD	Based on the advantageous cost analysis and inability to identify a feasible option for relocating work currently performed at the 2400 Stevens back to the PNNL-Richland campus, PNNL recommends extending the 2400 Stevens lease.
SIGMA1	20,000	2029	Maintain Sigma 1 as flexible office space to meet short-term needs until new office facilities are constructed and existing facility modernizations are complete.

Table: Real estate actions

Conclusion

At PNNL, our dedication to pushing the boundaries of scientific discovery is matched by our commitment to the well-being of our planet and the communities we serve. Our campus planning and operations strategy is aimed at creating state-of-the-art, secure, and environmentally responsible facilities. Our journey is shaped by a deep dedication to sustainability and resilience, with the goal of developing infrastructure that supports current research endeavors while remaining flexible and strong enough to meet future challenges and opportunities. Through carefully established benchmarks for maintenance and operations, we strive to achieve excellence in our facilities' upkeep, reflecting our high standards of operational efficiency and environmental stewardship.

As we look to the horizon, our plans for expanding and revitalizing our campus, with a planned investment of $1.2B by 2033, are a clear indication of our commitment to fostering an environment where cutting-edge research thrives. These plans are carefully crafted to bolster our research capabilities while prioritizing the reduction of our carbon footprint. This dual focus amplifies our role as a leader in S&T advancement. It highlights our dedication to contributing to sustainable solutions that have a lasting impact on our world. Our objectives are more than plans for mission-ready facilities, infrastructure, and future development; they embody our vision for a future in which science and sustainability go hand in hand, creating a legacy of innovation that benefits humanity and the planet alike.

Site Sustainability Plan Summary

In FY 2023, PNNL actively pursued excellence in meeting DOE's sustainability goals as delineated in Executive Order 14057, *Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability,* and DOE Order 436.1A, *Department Sustainability*.

From pioneering sustainable operational practices to achieving scientific breakthroughs with an environmental focus, PNNL actively supports DOE in realizing its sustainability objectives. These objectives include achieving carbon-pollution-free electricity, constructing net-zero-emission buildings, enhancing energy efficiency, promoting zero-emission vehicles, and advancing climate adaptation and resilience.

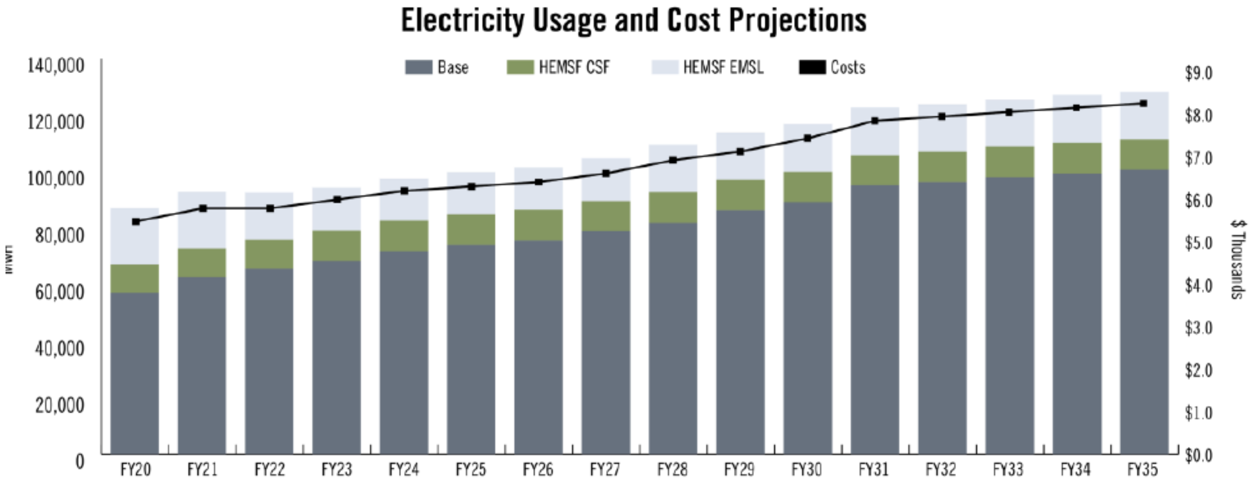
Despite ongoing challenges from the pandemic, PNNL maintained its stride toward sustainability excellence in FY 2023. Key achievements and efforts to advance DOE's sustainability goals are emphasized below.

Energy Management

Leveraging the DOE Federal Energy Management Program (FEMP) 50001 Ready Energy Management System framework, PNNL has significantly improved its capabilities in identifying, monitoring, tracking, and enhancing energy conservation measures (ECMs). Recognition from DOE's 50001 Ready program for the third consecutive year in early 2024 underscores the effectiveness of PNNL's Energy Management System at its Richland and Sequim campuses.

In FY 2023, PNNL's energy intensity for "goal subject" buildings was 187.8 thousand British thermal units (kBtu)/gsf, a 2.0 percent increase over last year. The major contributor to the increase in energy use is the start-up of the Laboratory's new facilities: ESC and HTB. The local weather also contributed to this observation. In FY 2023, PNNL experienced a warmer summer compared to FY 2022. In addition, PNNL continues to add staff back to the campus as well as grow in head count. By the end of FY 2023, PNNL has expanded from nearly 5,000 to over 6,000 staff, with just over 4,000 staff on-site at least 40 percent of their time. The increased use of PNNL facilities by on-site occupants is also a factor in the increasing energy use as plug loads increase and occupied spaces drive heating and cooling loads.

The figure below shows the total electricity use in FY 2023 in MWh and associated costs from FY 2020 through FY 2023 as well as the projection through FY 2030, assuming the successful implementation of planned electrification projects.



	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32	FY33	FY34	FY35
HEMSF EMSL	19,688	20,081	16,658	15,263	15,000	15,000	15,000	15,000	16,832	16,832	16,832	16,832	16,832	16,832	16,832	16,832
HEMSF CSF	10,102	10,030	10,199	10,763	10,770	10,770	10,770	10,770	10,770	10,770	10,770	10,770	10,770	10,770	10,770	10,770
Base	57,200	62,643	65,746	68,323	71,866	74,088	75,700	78,885	81,904	86,301	89,194	95,059	96,279	98,029	99,429	100,670
Costs	$5.3	$5.6	$5.6	$5.8	$6.0	$6.1	$6.2	$6.4	$6.7	$6.9	$7.2	$7.6	$7.7	$7.8	$7.9	$8.0

Figure: PNNL electricity usage and cost projections

Clean and Renewable Energy – Carbon-Free Electricity (CFE)

PNNL is on track to meet the 100 percent CFE goal. In FY 2023, PNNL procured 7,600 MWh of energy attribute certificates (EACs). The combination of EACs and PNNL's on-site renewables made up 8.8 percent of its electrical use, or 7.7 percent of its total electric and thermal energy.

Currently, PNNL purchases utilities from local providers, Richland Energy Services and Cascade Natural Gas Corporation, for electricity and natural gas. The PNNL-Sequim campus has utility providers local to the Sequim area, namely Clallam County PUD for electricity. Clallam County PUD is also a BPA Tier 1 customer and has essentially the same resource mix as the PNNL-Richland campus. For the purpose of setting CFE performance targets, as shown in the figure below, PNNL is applying a 78 percent grid-supplied CFE from FY 2023 through FY 2030, based on the 2021 published fuel mix data from the BPA balancing authority region. It should be noted that the 2023 CFE data from the city of Richland attested report contains nearly 90 percent clean and renewable power sources, such as hydroelectric and nuclear.

Given the existing clean power supplies and the addition of Washington State's Clean Energy Transformation Act (CETA), a 100 percent total CFE is projected with the procurement of additional EACs in FY 2030.

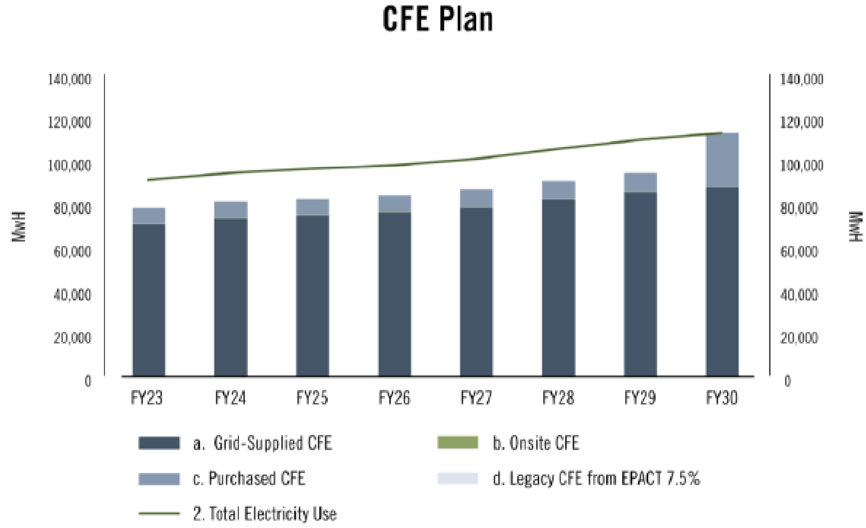


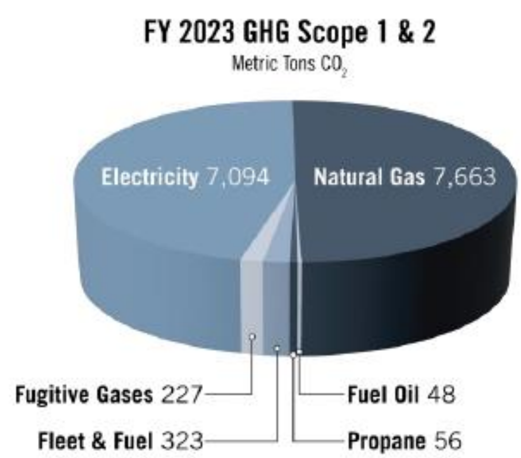
Figure: PNNL CFE plan

Net-Zero Emissions and Energy Efficient Buildings

Throughout FY 2023, the Laboratory has advanced toward its objective of achieving net-zero emissions. Notably, FY 2023 saw the completion of the net-zero emissions-ready South Campus Warehouse, equipped with air source heat pumps and backup electric heating. PNNL is on track to finalize three additional net-zero emissions-ready facilities—the GSL, the Advanced Secure Communication building, and the 300 Area Office Building—in calendar year 2024 or early 2025. PNNL's greenhouse gas emissions by category are illustrated in the figure below.

Efforts to electrify existing infrastructure included the significant renovation of Building 550 (Testing and Analysis Laboratory), where PNNL phased out a natural-gas-fired heating system in favor of backup electric boilers with the installation of air source heat pumps.

By the conclusion of calendar year 2024, PNNL anticipates expanding its inventory of net-zero emissions-ready buildings by over 135,000 gsf and will have electrified more than 213,000 gsf of its existing building stock, underscoring the Laboratory's proactive approach to sustainability and emissions reduction.



Although PNNL is committed to the net-zero emissions goals, the ability to accelerate electrification efforts across the PNNL-Richland campus has been constrained by insufficient regional and local electrical capacity to satisfy the near- and long-term demands; this subsequently will lead to a delay in PNNL’s implementation timeline. Current projections indicate that PNNL’s consumption will exceed the remaining available reserve power capacity in the next 3–5 years, causing impacts to PNNL’s ability to transition to net-zero emissions. Planned facility projects focused on electrification and increased efficiency are being prioritized; other F&I missions may be readjusted to align with the available power.

Near-term solutions being considered and evaluated to address the available power deficiency include on-site renewable generation (solar), energy/thermal storage, and implementation of energy efficient projects. PNNL has initiated an effort with the local utility to explore the benefits that on-site generation and energy storage would have on the regional electrical capacity, including consideration of how the LDES project, which is being funded by the Office of Clean Energy Demonstration, could support energy storage needs that could benefit the local utility.

PNNL also made progress toward the zero-emission vehicle (ZEV) fleet goal, with 80 percent of light-duty vehicle acquisitions ordered as ZEVs. PNNL has added additional on-site charging stations to accommodate the growing numbers of fleet ZEVs as well as personal electric vehicles. Currently, PNNL has 26 level-2 stations and has installed three additional stations as part of the GSL construction project. At PNNL, all new construction projects are required to provide charging stations for at least 2 percent of the planned building occupants. Electrical infrastructure will be provided for up to 10 percent of the parking spaces for future expansion.

Adaptation and Resilience

Resilience planning is an iterative and continuous process. During FY 2022, PNNL completed two key resilience planning processes—resiliency planning using the Technical Resilience Navigator tool and the Vulnerability Assessment and Resilience Plan, which identified PNNL top climate risks and provided the blueprint to mitigate those risks and strengthen resilient operations.

Central to this plan was the implementation of energy district energy systems as one of the solutions to elevate resilient operations. In FY 2023, PNNL began operation of its first district energy system. The ESC features an energy reducing design that captures and uses waste heat from EMSL supercomputer and research equipment via the creation of the HTB. When operation is fully optimized, the combined features of the ESC's mechanical systems and HTB potentially reduce ESC's carbon footprint by 2 million pounds of CO2 equivalent per year and energy savings of approximately 14,500 million British thermal units (MMBtu) per year. This system will be expanded with connections to the GSL building in early 2024.

Additionally, PNNL completed a wildland and fire assessment for the PNNL-Sequim campus. To elevate resiliency to wildland fire, PNNL removed trees and shrubs that were deemed vulnerable to a wildland fire and risk to the campus, developed a maintenance plan for pruning and removal, and removed parking areas along the shoreline hillside.

Performance Summary

The table below summarizes PNNL's performance status and planned actions and contribution toward DOE's goals in energy management, clean and renewable energy, efficiency and conservation measures, and adaptation and resilience.

Prior DOE Goal	Current Performance Status	Planned Actions & Contribution
Energy Management		
Reduce energy intensity (Btu per gsf) in goal subject buildings by 50 percent by the end of FY 2030.	2.0% increase versus last year due to the new ESC coming online, a warmer summer, and additional on-site staff.	PNNL will continue implementing electrification projects and cost-effective ECMs.
Achieve a net-zero emissions building portfolio by 2045 through building electrification and other efforts.	PNNL has completed the replacement of two existing steam high pressure boilers with two electric backup hot water boilers for supplemental heating in building 550. PNNL has also completed the construction of a net-zero emissions-ready building, the South Campus Warehouse.	PNNL will continue implementing electrification projects (see *Energy Management* sections for additional details).
Clean & Renewable Energy		
Achieve 100 percent CFE on a net annual basis by 2030, including 50 percent 24/7 carbon pollution-free electricity.	PNNL's combined CFE is 86 percent, using the CFE factor as reported by EPA for the BPA balancing authority region plus the EACs.	PNNL will pursue the feasibility of additional on-site clean and renewable energy systems (See *Clean and Renewable Energy* section for additional details).
Investments: Improvement Measures, Workforce, & Community		
Implement life cycle cost-effective efficiency and conservation measures with appropriated funds and/or performance contracts.	In FY 2022, PNNL partnered with Cascade Natural Gas Corporation to explore potential energy savings projects for funding under a Utility Energy Service Contract. However, this project was suspended in FY 2023, primarily due to higher interest rates and project scope.	PNNL will continue to explore opportunities to implement energy conservation projects under performance contracts.
Adaptation & Resilience		
Implement climate adaptation and resilience measures.	Completed the Vulnerability Assessment and Resiliency Plan (VARP) in September 2022. The feasibility review of the VARP solutions is in progress. Completed a wildland and fire assessment for the PNNL-Sequim campus.	PNNL will continue to evaluate the feasibility of the proposed resilience solutions are provided in the VARP.

PRINCETON PLASMA PHYSICS LABORATORY

Lab-at-a-Glance

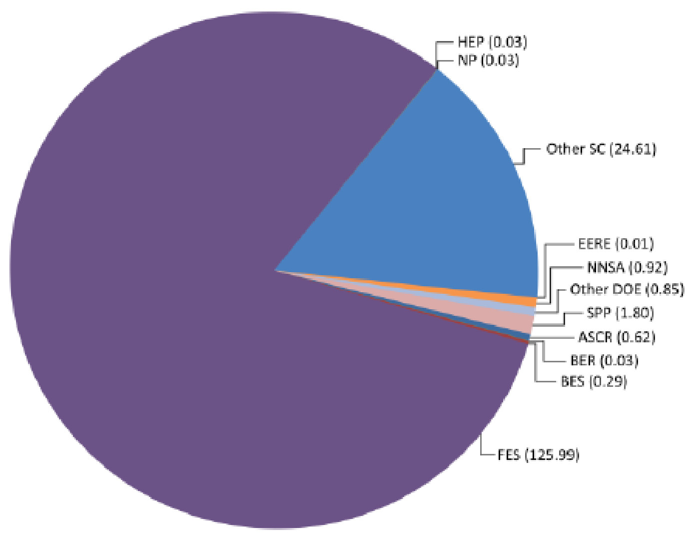
Location: Princeton, NJ
Type: Single-program Laboratory
Contractor: Princeton University
Site Office: Princeton Site Office
Website: www.pppl.gov

- **FY 2023 Lab Operating Costs:** $155.17 million
- **FY 2023 DOE/NNSA Costs:** $153.37 million
- **FY 2023 SPP (Non-DOE/Non-DHS) Costs:** $1.80 million
- **FY 2023 SPP as % of Total Lab Operating Costs:** 0.9%

Physical Assets:
- 90.7 acres and 45 buildings & trailers
- 803,000 GSF in buildings
- Replacement Plant Value: $1.232 B

Human Capital:
- 672 Full Time Equivalent Employees
- 4 Outgoing Joint Appointees, 8 Incoming Joint Appointees
- 28 Postdoctoral Researchers
- 62 Graduate Students
- 42 Undergraduate Students
- 375 Facility Users
- 26 Visiting Scientists

FY 2023 Costs by Funding Source ($M)



Mission and Overview

The U.S. Department of Energy's (DOE) Princeton Plasma Physics Laboratory (PPPL) is addressing critical national priorities through three major missions: (1) Developing the scientific knowledge and advanced engineering to enable fusion to power the U.S. and the world; (2) Advancing the fundamental science base of low-temperature plasma, plasma-material interactions, and new materials enabled by plasma, for nanoscale fabrication and sustainable manufacturing; and (3) Furthering the development of the scientific understanding of the plasma universe, from the laboratory to astrophysical scales.

PPPL's missions are supported by five core capabilities:

- Plasma and Fusion Energy Sciences
- Systems Engineering and Integration
- Large Scale User Facilities/Advanced Instrumentation

- Mechanical Design and Engineering
- Power Systems and Electrical Engineering

The Laboratory's highest priority is the completion of the National Spherical Tokamak Experiment, a world-leading user facility that is designed to deliver essential science and technology for the growing commercial fusion industry. Simultaneously, PPPL is partnering in the multinational fusion project, ITER, and working with several start-up companies to help develop alternative fusion concepts. The Laboratory is also pioneering the use of AI tools and high-performance computing to optimize and accelerate the realization and construction of future fusion pilot plants.

PPPL is enhancing U.S. leadership in critical industries through increasing basic scientific understanding that will yield innovations in plasma nanofabrication and sustainable manufacturing technologies. To serve the Laboratory and the national interest, Princeton University and PPPL are educating and inspiring a diverse workforce of world-class scientists, engineers, technicians, and operations staff.

Core Capabilities

PPPL continues to make history as a world-leading experimental and theoretical plasma physics and fusion facility, with depth and breadth of research that is unparalleled in the U.S. and the world. This status uniquely positions PPPL to lead and coordinate the multidisciplinary research needed to advance the goals of FES, and to prepare students and staff for leadership in the field.

The Princeton Plasma Physics Laboratory (PPPL) has five DOE-designated core capabilities, five additional emerging core capabilities, and one proposed emerging core capability that, together, enable the vital role of the Laboratory in executing DOE's missions, as well as in aiding the development of science initiatives that are responsive to national needs.

1. Plasma and Fusion Energy Sciences
2. Systems Engineering and Integration
3. Large-Scale User Facilities/Advanced Instrumentation
4. Mechanical Design and Engineering
5. Power Systems and Electrical Engineering
6. Computational Science *[Emerging]*
7. Chemical and Molecular Science *[Emerging]*
8. Applied Materials Science and Engineering *[Emerging]*
9. Condensed Matter Physics and Materials Science *[Emerging]*
10. Microelectronics *[Emerging]*
11. Earth, Environmental, and Atmospheric Science *[Proposed Emerging]*

PPPL has proactively strengthened and reinvigorated capabilities 2-5 for the NSTX-U Recovery Project by recruiting from both private industry and other national laboratories, and through closer interaction with experts from other national labs during project reviews. The totality of PPPL's integrated science and engineering capability make it uniquely equipped for development with universities and industry in the pursuit of the next generation of fusion concepts, innovations, and designs.

PPPL has been at the forefront of developing numerical capabilities for fusion prediction, analysis, and design, and for plasma simulation, in general. PPPL's world-leading capabilities in diagnosing and understanding plasmas will support the next generation of nanoscale fabrication, which are central to the development of many technologies of tomorrow. These technologies require a multidisciplinary set of capabilities that PPPL is committed to strengthening and growing.

PPPL's unique capabilities in diagnosing and understanding plasmas will support the next generation of industrial plasma processing. Through the activities outlined below, PPPL is increasing efforts to strengthen and/or diversify into research areas embodied in these additional core capabilities mentioned above.

Plasma and Fusion Energy Sciences

The Laboratory continues to explore the plasma processes that take place in the universe; the high-temperature, high-pressure magnetically confined plasmas required for fusion energy production; and the use of plasmas in technological applications, including the synthesis and modification of materials. PPPL conducts research on experimental facilities located at PPPL, including the National Spherical Torus Experiment Upgrade (NSTX-U), the recently upgraded Lithium Tokamak Experiment – Beta (LTX-β), the Magnetic Reconnection Experiment (MRX), the Low-Temperature Plasma (LTP) Laboratory, and the Facility for Laboratory Reconnection Experiment (FLARE). In addition, PPPL staff members are leading significant research programs at DIII-D (San Diego), the superconducting long-pulse facilities W7-X (Germany), KSTAR (South Korea), and EAST (China), as well as smaller research collaborations at ASDEX-Upgrade (Germany), COMPASS-U (Czech Republic), LHD (Japan), MAST-U (UK), SMART (Spain), ST40 (UK), and WEST (France). PPPL is also preparing advanced X-ray diagnostics for the JT-60SA tokamak (Japan). At ITER's request, PPPL is also leading an effort to model boron transport, erosion and redeposition and prepare a pre-conceptual design of a solid boron injection system for real-time wall conditioning on ITER to support their decision to operate with a full tungsten first wall and divertor.

PPPL's Theory and Computational Science Departments, in conjunction with the new Digital Engineering group, develop and maintain state-of-the-art predictive tools and workflows to propose and analyze innovative solutions to the most challenging fusion energy problems, and to analyze and interpret experimental results. It is worth highlighting some new developments.

- The Scientific Discovery through Advanced Computing (SciDAC) Centers at PPPL are addressing the interface between plasma physics and engineering, with one of them (StellFoundry) developing a physics-engineering framework for the design and operation of fusion devices, and the two others (CEDA and CETOP) attempting to solve the Core-Edge Integration challenge by analyzing computationally different actuators.
- PPPL has installed TRANSP at ITER and updated it for use in the IMAS framework to simulate ITER operation scenarios.
- PPPL successfully completed the WDMapp simulation tool for core-edge integrated turbulence and transport simulations as part of the recently completed Exascale Computing Project (ECP).

Systems Engineering and Integration

PPPL is well positioned to lead the systems engineering and integration of new fusion facilities to incorporate innovative designs for reduction of capital costs and risk mitigation. Systems engineering and integration principles, to include requirements verification, risk management, interface control, and failure modes and effects, are ingrained in PPPL's daily work processes across the engineering staff and throughout the engineering lifecycle. This systems approach helps to develop more efficient systems with implementation cost as part of the design and establishes better lines of communication within the workforce.

In concert with ANSYS, the lead Systems Engineer has established a framework for engineers to use simulation process and data management (SPDM), material intelligence database, optical analyses, high-performance computing and optimization capabilities that functions across different engineering tools to enhance efficiencies of well-defined workflows, enhance user training/best practices, and enhance collaboration between staff, including automation and semi-automation, and gradually integrating AI capabilities into the framework. These capabilities will take advantage of high-performance computing capabilities and will help position PPPL at the forefront of digital design. PPPL Systems Engineering, in collaboration with other skill areas (Computational Sciences), is investigating concepts to integrate emerging commercial technologies, i.e., automation, extensive use of high-performance computing nodes machine learning, and eXtended Reality (XR) into the scientific and engineering processes. PPPL＇s systems and design engineering expertise allows the Lab to assume a leadership role in designing and establishing a virtual prototyping environment. These capabilities will be essential in the planning, design and integration of research and development activities leading to the conceptual design and development of ITER diagnostics and ultimately a fusion power plant.

Large-Scale User Facilities/Advanced Instrumentationn

PPPL's large facilities and extensive capabilities for plasma production, confinement, control, and measurement systems make it an ideal site for research development and collaborations. PPPL specializes in technologies to safely heat, fuel, control, and exhaust plasmas at temperatures as high as 550 M°K, with a broad application and uses beyond NSTX-U.

Technologies that are being developed as prototypes for future devices include flexible neutral beam injection and ion cyclotron range of frequency (ICRF) waves that can be used for both heating and current drive.

Gas injection at supersonic speeds will be tested as a means to efficiently fuel the deep core. Real-time plasma control methodologies are being developed that will allow for control of the plasma, and tailoring of plasma profiles, to maintain stable, high-performance plasmas for their entire lifetime. An impurity powder dropper (IPD) and an impurity granule injector have shown success on domestic and international facilities, and these will be employed to improve wall conditions, mitigate heat flux and control edge instabilities. Liquid lithium component prototypes will be tested as a basis for more expansive liquid lithium divertor concepts that would be a transformative solution to heat flux mitigation in compact, high-temperature devices.

Research on NSTX-U and LTX-beta, in particular, has led to exploration of how innovative wall coatings, such as lithium, can reduce wall recycling and lead to enhanced plasma confinement. Evidence from both machines indicates at least 50% higher plasma confinement can be achieved. Further, the testing of liquid lithium components in both devices are critical to developing a transformative path to controlling power fluxes escaping the plasma, and this will allow for operation of high-performance, long-pulse discharges.

Mechanical Design and Engineering

PPPL has extensive mechanical design and engineering expertise through its work on ITER diagnostics, NSTX-U Recovery, DIII-D, and in next-step facility design. PPPL is strengthening engineering skills required to address the emerging fields being pursued in the Laboratory plan. In particular, PPPL is targeting capability growth in the fields necessary for commercialization of a fusion device such as: Computational fluid dynamics for development of liquid metal first walls, design and fabrication of high temperature superconducting magnets and increasing the ability to evaluate effects of neutronics fluxes on materials. PPPL has also been addressing the need for growth in Mechanical Engineering skill depth through expansion of our successful Rotational Engineering program and developing a Master of Engineering Program at Princeton University that will help expand the skills of current early career staff members while also increasing ties with the University.

Digital engineering will be an important and expanding capability for the design of the next generation of fusion experiments, and the Engineering Department is establishing a strong presence in this area. Integrated simulation and workflows for optimized design, with the optimization integrating physics and engineering considerations, are being developed. The designs of the MUSE stellarator, the ARPA-E supported permanent magnet stellarator (PM4Stell), and designs derived from ongoing SciDAC modeling for stellarators will both drive and benefit from these capabilities.

Power Systems and Electrical Engineering

PPPL offers both the physical infrastructure and the technical capabilities for meeting the extraordinary power system demands intrinsic to fusion energy research machines.

PPPL’s power infrastructure includes test facilities for magnetic field testing of components with fields up to 3 Tesla and rates up to 30 Tesla/sec. Infrastructure is also in place to provide pulsed AC power, using motor-driven, high inertia generators, with the capability to deliver 13.8kV three phase, sinusoidal power for up to 20,000A for six seconds and to provide pulsed DC power, using a high-power thyristor converter, with voltages up to 2 kV and controlled currents up to 24,000A, for six seconds, for high power testing and evaluation of fusion energy coils and other high power components.

The Power Systems Group at PPPL has capabilities to study, model, simulate and evaluate various systems and subsystems related to power conversion. Computer simulations are usually done in Matlab/Simulink. The capabilities include:

- Modeling and simulation of power converters: switching strategies, development of the control
- scheme, output waveform generation, performance evaluation.
- Modeling and simulation of electric motor drives (like induction motors, doubly-fed induction motors,
- permanent magnet motors, synchronous motors). There are capabilities for the development of
- dynamic models, development of control strategies, system simulation, and performance evaluation.
- Modeling and simulation of power systems: this includes the power supplies, circuits, cables, reactors
- and coils used in plasma operation.

Emerging and Proposed Core Capabilities

PPPL’s unique capabilities in diagnosing and understanding plasmas will support the next generation of industrial plasma processing. PPPL is increasing efforts to progress and/or diversify into research areas embodied in six core capabilities:

- Computational Science (Emerging)
- Chemical and Molecular Science (Emerging)
- Applied Materials Science and Engineering (Emerging)
- Condensed Matter Physics and Materials Science (Emerging)
- Microelectronics (Emerging)
- Earth, Environmental, and Atmospheric Science (Proposed Emerging)

Computational Science

The Computational Science Department (CSD) was established in 2020 to diversify PPPL’s portfolio into foundational research in applied mathematics, computational sciences, and machine learning. All Advanced Scientific Computing Research (ASCR)-funded research, including the ASCR portion of PPPL Scientific Discovery through Advanced Computing (SciDAC) projects, are now consolidated into the CSD. In the 2022

DOE-wide Annual Laboratory Planning process, PPPL was given an "Emerging Core Capability" rating for Computational Sciences. Since the creation of the CSD, the PPPL Advisory Board has consistently ranked the research in CSD as "exceptional." The CSD and the Theory Department have produced major computational physics software, including the XGC gyrokinetic code, the M3D-C1 extended MHD code, the Gkeyll gyrokinetic/kinetic code, and the GX core gyrokinetic code, among others. Much of the present and planned work is to use these tools in design optimization, in addition to building a deeper physics understanding of various plasma devices, including fusion machines. PPPL has modularized and modernized the TRANSP code that remains critical to experimental inference for the domestic and international tokamak fusion program. These projects are funded by a mix of FES and ASCR funding sources, including the recently completed Exascale Project (that funded whole-volume modeling of tokamaks from near first-principles) to a suite of SciDAC projects. PPPL Theory, and since its inception, CSD, has been involved with SciDACs since the start of the program. Presently, PPPL is leading three SciDAC projects and contributes as a key partner in several others.

Besides the computational software we have produced, PPPL remains a leader in designing new algorithms for all areas of plasmas physics. As plasmas encompass the vast majority of the visible universe, our research in algorithms spans fusion and laboratory plasmas, to space plasma physics to plasma astrophysics around compact objects like neutron stars and black holes. Recently, Hong Qin, a member of the CSD, was jointly awarded the Dawson Award for fundamental research in symplectic and structure preserving methods.

PPPL, in partnership with Princeton University, has built two mid-sized petascale clusters for use by the national and international plasma physics communities. These clusters are managed by Princeton University's Research Computing group and hosted at Princeton University data centers. The cluster funding from DOE is matched by Princeton University, allowing significant leverage of our resources. Planning is ongoing for a third, replacement cluster of H100 GPUs.

Our recent efforts are focused on building a **sustained core research program** into applied mathematics and algorithm development (including machine-learning), making key hires, and building strategic partnerships with leading universities and other national laboratories. In particular, we have developed plans for four interconnected research areas: (a) Algorithms for Kinetic Equations, (b) Algorithms for Asymptotic (Fluid/Moment) Equations, (c) Machine Learning for solution of partial differential equations, and (d) Simulation and Experiment-based Inference. These problems are of importance across the national laboratory complex and contribute to the development of fusion as a base-power source, building deeper understanding of the plasma universe, as well as developing the core applied mathematics and algorithms for use in a broad range of problems.

Chemical and Molecular Science

PPPL is also working to establish a closely related core capability in chemical and molecular science associated with understanding and control of plasma chemistry and plasma-surface interactions. PPPL's unique capabilities in diagnosing and understanding plasmas in situ can also support development of electrified sustainable manufacturing processes that exploit plasmas and to help understand light-particle interactions in the atmosphere. Under the umbrella of the new directorate Applied Materials and Sustainability Sciences headed by Associate Laboratory Director Prof. Emily A. Carter, with Dr. Phil Efthimion as her deputy, the two themes, namely, electromanufacturing (Head: Prof. Yiguang Ju) and aerosol science for the climate (Head: Prof. Luc Deike) will help expand PPPL's expertise within the chemical and molecular science research relevant to energy sciences. In alignment with many of the Department of Energy's Energy Earthshot initiatives, we are committed to advancing carbon-emission-free technologies for a sustainable and competitive U.S. manufacturing industry. PPPL researchers are investigating ways to replace fossil-fuel energy sources with clean electricity directly or electrically driven plasmas in industrial processes. Current research foci include:

- Use of plasmas and catalysts to convert natural gas (methane) to hydrogen and carbon nanotubes
- (precursors to carbon fiber and carbon-carbon composites)
- Use of plasmas to convert methane and carbon dioxide to synthesis gas (carbon monoxide and
- hydrogen)
- Use of plasmas or electric heating to produce green ammonia from air and hydrogen
- Use of electricity to produce chemicals and fuels from carbon dioxide, air, and water

Electricity or plasmas potentially can provide the clean energy and reactive species required to sustainably produce commodity chemicals and fuels like hydrogen, ethylene, and ammonia; and construction materials like steel and cement; capture and convert carbon dioxide to minerals; and recycle plastics and batteries.

PPPL's Hydrogen Earthshot Research Center is headed by PPPL Associated Faculty Prof. Yiguang Ju, and involves co-principal investigators from PPPL (Dr. Yevgeny Raitses) and Princeton University (Profs. Bruce Koel and Michele Sarazen). Profs. Ju, Koel, and Sarazen bring to the Laboratory complementary expertise in plasma reactor design, plasma diagnostics, plasma chemistry, and materials synthesis and characterization. Additionally, a PPPL staff scientist (Dr. J. Mark Martirez) and Prof. Ju (through Princeton University) also each received significant BES funding under the ORNL-led Industrial Heat Earthshot Research Center. Dr. Martirez (via quantum mechanics based atomic-scale simulations) and Prof. Ju (via advanced optical diagnostics) will contribute to understanding (at the molecular scale) the mechanism of partial cracking of ethane and propane to ethylene and propylene under non-thermal equilibrium conditions enabled by pulsed electrified-heating-and-cooling. BES-funded research on the non-equilibrium pulsed electrified-heating-and cooling process for the synthesis of ammonia from hydrogen and nitrogen also leverages PPPL's expanded expertise in quantum-mechanics based atomic-scale simulations, which involves Prof. Carter and Dr. Martirez as co-PIs, along with Prof. Ju lending his expertise in optical diagnostics. Furthermore, as a potential boost to PPPL's modeling capabilities of plasma in the context of chemical electromanufacturing, a computational research program that will use machine learning and artificial intelligence to understand plasma-assisted H_2 production from methane has been funded, led by PPPL researcher Dr. Igor Kaganovich. Finally, LDRD research activities under electromanufacturing, e.g., on high yield, carbon-dioxide-free production of hydrogen using new chemical processes based on methane pyrolysis in an arc discharge with molten metal electrodes to produce high-value solid carbon (e.g., carbon nanotubes) and H2 (PI: Yevgeny Raitses), and computational exploration of electrochemical reduction of CO2 on Cu and alloys (PI: Emily Carter) are actively ongoing. The former LDRD-supported research (with support from BES) leverages existing nanosynthesis capabilities including plasma reactors, plasma and nanoparticle diagnostics developed at PPPL and also involves Prof. Koel. Below we summarize facilities and equipment that support these research endeavors.

The Princeton Collaborative Low Temperature Plasma Research Facility (PCRF) (Director/PI: Yevgeny Raitses) located at PPPL and Princeton University has specific capabilities germane to basic plasma science and plasma-assisted industrial processes, and provides access to specialized, world-class diagnostics, computational tools, and expertise in plasma physics and chemistry including fundamental and applied R&D. The PCRF houses several high-pressure DC arc plasma reactors, and in-situ diagnostics that can provide local measurements of gas phase and plasma including: Laser-Induced Incandescence, Laser-induced Breakdown Spectroscopy, various Laser-induced Fluorescence (LIF) and two-photon LIF (TALIF) methods, broad-band and high-resolution Optical Emission Spectroscopy, nonlinear spectroscopy (e.g., Coherent anti-Stokes Raman spectroscopy (CARS), electric field induced second harmonic generation (E-FISH), and sum frequency generation), Filtered Fast Imaging, Fourier Transform Infra-Red absorption spectroscopy, Cavity-ringdown spectroscopy, Faraday rotation spectroscopy, Raman, Rayleigh, Thomson Scattering, Laser-stimulated photo-detachment, Residual Gas Analyzers, Mass Spectrometry, and Electrostatic Plasma Diagnostics, including Langmuir probes and energy analyzers. The lab also houses equipment for measuring secondary electron emission and surface charge of materials in contact with plasma. A detailed list of the plasma sources, diagnostic instruments, and their capabilities can be provided upon request. Example facility modeling capabilities include specialized open-source kinetic particle-in-cell codes (2D EDIPIC), 3D LTP-PIC on CPU/GPU architecture, and various quantum chemistry and molecular dynamics codes.

Princeton University research collaborators with PPPL also have individual research group laboratories well equipped for plasma synthesis, diagnostics, and characterization efforts and have at hand various burners, plasma reactors, nanosecond/AC/DC plasma power supplies, jet stirred reactors, photolysis reactors, high-speed UV and IR, femtosecond and nanosecond, pulsed and continuum laser diagnostic imaging systems for species, temperature, electric field, and plasma properties, equipment for several classes of spectroscopy in the gas and condensed phases, and molecular beam mass spectrometry and gas chromatographic equipment. Labs also have equipment and instrumentation for materials synthesis.

Applied Materials Science and Engineering

PPPL's diversification into studying low-temperature plasma (LTP) applications for problems in advanced, next-generation semiconductor and quantum device manufacturing involve theoretical, experimental, and computational studies of plasma-materials interactions.

One key advanced material with applications in both quantum and semiconductor applications is diamond. Diamond is energetically metastable and requires LTP for both material synthesis and processing. To explore the science of these processes and develop new materials for applications, PPPL has established a quantum diamond synthesis laboratory, led by new hire PPPL Joint Faculty Prof. Alastair Stacey - on an international joint appointment with the Royal Melbourne Institute of Technology (Australia). This laboratory currently comprises three experimental-scale microwave-plasma chemical vapor deposition (MP-CVD) diamond growth reactors and is being provisioned to include a production-scale reactor, purchased from and in partnership with an international diamond supermaterials company - Element Six. Within these reactors, PPPL will grow new types of electronic and quantum defect doped diamond materials, investigate LTP characteristics with advanced non-invasive plasma diagnostics techniques, and support a range of semiconductor research projects with faculty at Princeton University. In particular, the laboratory's research will connect with a multitude of quantum materials and quantum device research at Princeton University, led by PPPL Associated Faculty Prof. Nathalie de Leon and integrated into the recently launched Princeton Quantum Initiative. By connecting this user/device expertise at the university with plasma engineering (theory/diagnostics/experiment) at PPPL, the quantum diamond synthesis laboratory will act as the central element in multiple co-design research projects, to amplify the discovery science associated with the development of quantum technologies and advanced microelectronics at PPPL.

The first set of diamond materials projects to use this new laboratory and PPPL/PU team include a co-design microelectronics project, focused on the development of new co-doping paradigms for solid-state quantum materials. This project leverages PPPL's strengths in plasma modeling and plasma diagnostics, to link the doping synthesis plasma conditions to functional materials properties, which are then linked in a co-design approach to quantum characteristics via quantum measurements in Prof. de Leon's laboratory at Princeton University. Of particular interest is the development of co-doped electronic and quantum-defect (qubit) materials. Device geometries under investigation include designs to maximize the quantum coherence of qubit layers while simultaneously stabilizing the qubit charge state dynamics, through novel alternate layers of electronic and qubit dopants. This expertise is then planned to be applied to the production-scale reactor when it arrives in late 2024, enabling an exciting co-design approach to production-scale quantum materials fabrication, with the opportunity to help mature the production of industrial quantum materials and accelerate quantum research.

A new collaborative experimental-computational project has also been initiated on atomic layer etching (ALE) of diamond. This project is a collaboration between Profs. David Graves, Bruce Koel, and Nathalie de Leon (Princeton University and PPPL), and University of Houston Prof. Vince Donnelly. The goals of the project are to demonstrate that ALE can shorten diamond surface preparation times, improve device performance, and expand the scope of possible nanofabricated devices based on diamond. The project aims to controllably engineer diamond surfaces to enable future advanced applications of diamond electronic and quantum devices and sensors.

In partnership with leading diamond company Element Six, PPPL has requisitioned a commercial-scale diamond deposition reactor and is planning to explore new approaches to engineering of dislocations in diamond wafers for microelectronics applications. Diamond materials are also of increasing relevance for new thermal management approaches in traditional microelectronics, including consumer electronics and neural net accelerators. This is evidenced by TSMC's interest in integrating diamond layers into future System-on-Chip fabrication strategies. Existing approaches to semiconductor-grade diamond growth are typically limited to 2" wafers in research reactors and 4" wafers in commercial reactors, far short of the 12" wafers relevant for industry applications. PPPL will combine its expertise in plasma diagnostics and modeling, with the newly established capability in diamond growth, to explore new approaches to plasma reactors for large area and low sample temperature deposition. Such approaches are expected to require new levels of control in plasma excitation and will involve collaboration with power electronics and RF device design experts, Profs. Minjie Chen and Kaushik Sengputa at Princeton University.

To extend the impact of PPPL's emerging activities in quantum diamond materials, Princeton University and PPPL are already affiliated with the DOE-funded Co-design Center for Quantum Advantage (C2QA) and are a partner in the Nordtech Hub of the newly created DoD Microelectronic Commons program. As part of the Nordtech Hub, PPPL is co-leading an application to compete for project funding to help accelerate quantum device technologies within the U.S. for defense and dual-use applications. In addition, the establishment of this capability at PPPL has spurred the preparation of joint proposals for solicitations associated with the CHIPS Act, DARPA, and a DOE Energy Frontier Research Center proposal.

In support of these applied materials goals, PPPL researchers have direct access to the Princeton Materials Institute Imaging and Analysis Center (IAC) at Princeton University, which offers high-end, state-of-the-art instrumentation and expertise for characterization of both hard and soft materials. Example IAC facility tools include optical microscopy and spectroscopy, scanning electron microscopy, focused ion beam, transmission electron microscopy, X-ray diffraction, small-angle and 3D X-ray microscopy, scanning probe microscopy, surface analysis, thermal analysis and rheometry, and sample preparation. The Princeton NanoFab and Cleanroom Facility at Princeton University houses state-of-the-art nano and micro fabrication capabilities, including, deposition (CVD, ALD, PVD), lithography (photo and e-beam lithography, direct-write, nanoimprint), plasma etching (Si, diamond, III-V compounds, metals etc.), 3D printing, packaging, thermal processing, surface and microstructure characterization, reliability testing, and electrical characterization.

These activities will also require increases in materials science capabilities, including material preparation, characterization, and processing at PPPL. Space expansion and space development activities are ongoing at PPPL for this purpose.

Condensed Matter Physics and Materials Science

The Laboratory aims to extend its capabilities and expertise in condensed matter physics and materials science, especially in the context of LTP-synthesized and modified materials. These activities fall under the purview of Associate Laboratory Director Prof. Emily Carter, who is leading the new Applied Materials and Sustainability Sciences directorate. This area has already grown significantly and has led to specific activities in Microelectronics, sustainability-focused Chemical and Molecular Science research and quantum-materials-focused Applied Materials Science and Engineering activities - which are described in more detail within their numbered sections. In addition, PPPL is increasing its collaboration activities between PPPL staff with LTP expertise and industry and academic researchers, including several Princeton University departments (Mechanical and Aerospace Engineering (MAE), Chemical and Biological Engineering (CBE), Electrical and Computer Engineering (ECE), Chemistry, and Physics).

Microelectronics

PPPL is working with the semiconductor industry to develop optimal ways to fabricate next-generation computer chips. Industry goals include a major expansion in the type and structure of materials to be used, which must be implemented with atomic-scale precision and that are likely to be enabled by controlled plasma etching and deposition. The Lab's expertise in LTPs, used in nearly half of all steps involved in fabricating computer chips, are helping transform what was a largely black-box, Edisonian approach into one based on scientific understanding and engineering control.

In 2021, three CRADAs were initiated between PPPL and two of the leading plasma equipment suppliers, Lam Research Corporation and Applied Materials Corporation.

The focus of the PPPL-Lam Research CRADA is on understanding plasma atomic layer etching (ALE) processes in semiconductor processing. This project is aimed at improving and testing molecular dynamics (MD) simulations of ALE. MD codes running on LAMMPS (open source) were validated for atomic layer etching of Si using sequential exposures of Si surfaces to Cl2 molecules followed by impacts with energetic Ar+ ions. The approach was extended to a wide range of conditions, and results were validated by comparison to experiment. Several new objectives were identified for future work: extending to high-energy (> 1 keV) ion pulses; development of a simplified near-surface model; and extension to carbon etching in oxygen plasmas. This CRADA is led by Prof. David Graves, who is an Associated Faculty at PPPL.

The focus of one of the PPPL-Applied Materials CRADAs is on modeling plasma-processing reactors using particle-in-cell (PIC) simulations. The goal is to develop and apply advanced kinetic plasma simulations employing PIC simulations that can accurately predict plasma behavior and shorten the manufacturing and design cycle of silicon-based computer chips. The focus of the study encompasses capacitively coupled, electron-beam, and microwave-produced plasmas. Igor Kaganovich's group at PPPL collaborated with the Applied Material group of Shahid Rauf. The PPPL codes were developed during three years of internal LDRD funding, producing the open-source EDIPIC-2D code that is widely used in academia and industry for modeling or industry relevant discharges. Our LTP-PIC-3D code on a hybrid CPU-GPU architecture was export cleared and will be available for users, contingent on DOE funding. For simulation of large plasma devices, traditional approaches using explicit schemes are too expensive computationally. Therefore, we explored direct implicit and energy-conserving algorithms as well as modern heterogeneous CPU-GPU computer architectures for handling large-scale and long-time 2D PIC simulations. These algorithms were implemented into the robust CPU-based EDIPIC-2D code, which is available as open-source on GitHub.

The energy-conserving method was also implemented into the high-performance, scalable, 3D LTP-PIC code, which incorporates programming best practices and multi-level parallelism. Recently this code was upgraded to operate efficiently on the latest CPU/GPU architectures for additional performance improvements. Simulation results from this upgraded code were benchmarked against other codes, and where available, analytical theory. Additionally, EDIPIC was also used to make predictions of a new electron bounce resonance phenomenon, which was later validated against experimental data. Overall, we have been able to simulate magnetized capacitively coupled plasmas, electron beam generated plasmas, breakdown in narrow holes, and kinetic effects in microwave discharges. Recently we also demonstrated that thermalization, i.e., artificial

Maxwellization of electron energy distribution function due to enhanced noise in PIC simulations is a serious issue that needs to be carefully monitored. This validated our conclusion that algorithms other than explicit methods must be used in future work and require further investigation in future studies.

The focus of another PPPL-Applied Materials CRADA is on advanced plasma diagnostics for characterization of semiconductor processing reactors and is led by PPPL's Yevgeny Raitses. The goal is to develop and apply advanced laser diagnostics (PPPL) to characterize dynamics and uniformity of plasma in state-of-the-art industrial etch reactors for semiconductor fabrication at the AMAT site in Santa Clara, CA. Accordingly, the following diagnostics have been implemented using PPPL-procured hardware: Laser Thomson Scattering for measurements of electron velocity distribution functions and to deduce macroscopic plasma properties such as electron temperature and density and Laser-Induced Fluorescence (LIF) for spatially- and temporally resolved measurements of neutral, radical, metastable and ionic species. A PPPL postdoc is on long-term assignment at AMAT Santa Clara to operate these diagnostics, and to collect and analyze data. All diagnostics are now engaged in characterization of complex plasma etching processes in the AMAT research etcher built by AMAT for this CRADA. In addition, we also compiled a comprehensive reference data of LIF transitions for more than 150 atomic, molecular and ionic species relevant to semiconductor fabrication. This valuable reference data will be available to the scientific community through publications, which we plan to submit. Moreover, we developed and demonstrated a confocal LIF configuration with a ring-shaped laser beam that makes LIF suitable and applicable for measurements on industrial reactors with limited diagnostic access. For continuation of this research, we plan to apply this approach to PPPL laser diagnostics at AMAT. We also aim to continue working with structured light laser beams (non-Gaussian laser intensity profile) and implement the optical vortex for two-dimensional laser induced fluorescence spectroscopy to characterize plasma properties, chemical composition, and uniformity in a processing reactor. Future work will use a structured light approach including optical vortex and ring-shaped beam to make laser diagnostics suitable for advanced atomic scale processing techniques in realistic industrial reactors with limited access and space. The ultimate goal is to develop a new generation of active, spatially, and temporally resolved structured light sensors for advanced processing control in these reactors.

Proposed Emerging: Earth, Environmental, and Atmospheric Science

Responding to a national (indeed global) need, PPPL will apply its expertise to understand fundamental aerosol science relevant for the climate, including radiative processes, aerosol, ice, and liquid nucleation, as well as possible implications for solar radiation management strategies. PPPL's researchers aim to study how clouds, light, and aerosols — small particles in the air — interact in controlled laboratory conditions, to inform microphysical models to be used in climate models and improve the scientific understanding underpinning possible cooling strategies, the latter being a matter of national and global security.

Under the leadership of Emily A. Carter, Senior Strategic Advisor and Associate Lab Director for Applied Materials and Sustainability Sciences, PPPL held a Princeton ecosystem retreat and then an international workshop in 2022 (the latter sponsored by the Simons Foundation) on this subject. The Princeton ecosystem retreat engaged researchers from PPPL, Princeton University, and NOAA's world-renowned climate modeling lab, the Geophysical Fluid Dynamics Laboratory (GFDL), which is one mile away from PPPL on the Forrestal campus and also managed by Princeton. (GFDL's Syukuro Manabe won the 2021 Nobel Prize in Physics for his pioneering development of the first modern, physics-based climate model that laid the roadmap for the global climate models of today.) Out of the retreat came the exciting vision of a virtuous intellectual cycle, involving: (i) Princeton and GFDL climate modelers defining needed laboratory measurements of highly uncertain and sensitive properties of aerosols and clouds that have rendered global climate models as yet unable to predict reliably phenomena involving these entities; (ii) PPPL researchers adapting their in-situ plasma diagnostics and modeling capabilities for cloud-aerosol-light interactions to measure those properties (feasible given the commonality between plasma and the atmosphere being both charged, turbulent, complex fluids); and (iii) tapping into Princeton's expertise in aerosol experiments, including ice nucleation as well as in optical diagnostics. Given PPPL's expertise in building large, high-vacuum facilities, relevant to upper troposphere or stratospheric conditions, and the PPPL-PU-GFDL intellectual ecosystem that is ideally set up to collaborate on this scientific grand challenge to improve current global climate modeling of these phenomena, critical for both natural climate evolution and any possible human intervention, PPPL aspires to build an aerosol cloud chamber to serve as a national user facility (such a facility does not currently exist in the U.S.). This facility will mimic conditions of the upper troposphere or stratosphere, varying temperature, pressure, humidity, and turbulence, along with varying aerosol type, with a suite of in-situ diagnostic tools to measure currently unknown microphysical properties, with a particular focus on ice nucleation, aerosol aggregation and aging. DOE is the natural home of such user facilities; no other agency has claimed this area as its own. For example, NOAA's focus is on modeling and fieldwork and it neither invests in such facilities nor does it undertake laboratory research as is planned in our initiative.

Our proposed work would directly benefit DOE climate models and complement current atmospheric science fieldwork and modeling at other DOE national laboratories, especially for the description of properties of clouds and natural aerosols. We have held discussions with aerosol researchers at the main DOE labs doing atmospheric science, namely PNNL and BNL, about how we may work collaboratively with them, leveraging distinct strengths at each lab to further advance aerosol science for the climate. We will be meeting with other DOE national laboratories that have projects on aerosols to ensure complementarity of effort.

Moreover, our work will enable DOE to contribute synergistically to the modeling and fieldwork done by NOAA and the fieldwork/aircraft and satellite observations by NASA related to stratospheric aerosol behavior, noting that neither NOAA nor NASA support cloud chamber research. Our planned activities thus offer an opportunity to establish important cross-agency interactions.

Examples of recent NOAA/NASA field observations include the recent SABRE mission, a component of the NOAA Earth Radiation Budget (ERB) program, in partnership with NASA. This was an extended airborne science campaign to study the formation, transport, chemistry, microphysics and radiative properties of aerosols in the upper troposphere and lower stratosphere. A recent publication in PNAS (Murphy et al. 2023) from the SABRE mission highlighted the presence of metals from spacecraft reentry in stratospheric aerosol particles and points to their unknown impact on stratospheric aerosol processes. Such chemical processes could be studied with the experimental chamber proposed to be developed at PPPL.

We aim to address the following open questions in the field of aerosol science and aerosol-light interactions, in line with some of the most pressing recommendations of the National Academies consensus report. Questions on aerosol processes will benefit our understanding of climate processes, and include:
How do dry aerosols nucleate growth of solid ice particles as a function of their size and composition, including mixed-phase conditions, and ambient temperature and humidity?

How does particle aging – including heterogeneous chemistry, wetting, and charging – impact optical and cloud-seeding properties? How is charging of aerosol (and ice) particles generated and affected by air conditions (e.g., humidity, impurities) in the presence of ultraviolet light, electric fields, etc.?

Thinking of radiation processes as well as solar radiation management, questions on aerosol-light interaction include:

- What are the light absorption and scattering properties of candidate SAI and CCT aerosols as a function of their size and composition, across the solar spectrum and infrared?

- What novel aerosol materials may feature more desirable properties for SAI and CCT while remaining practical, environmentally benign, and nontoxic?

Other examples of large field observations on aerosol processes include SOCRATES (Southern Ocean Cloud aerosol processes, NSF funded), multiple DOE synergistic observational aerosol-atmospheric science research through the Atmospheric Radiation Monitor User program (with strong focus on tropospheric processes, including marine aerosol and clouds, turbulence processes), or the NASA North Atlantic Aerosols and Marine Ecosystems Study (NAAMES). As is evident, there are many activities focused on fieldwork and modeling, within DOE and other agencies; our experimental cloud chamber proposed research would provide systematic, synergistic data under controlled laboratory conditions.

PPPL's role in understanding the science of aerosols lies in the Lab's ability to support and conduct well-controlled lab-to-pilot scale experiments and advanced computer simulations examining various physical and chemical processes under conditions mimicking different atmospheric altitudes, from molecular scale to bulk fluid scale, e.g., aerosol-cloud-light interactions. Bringing together key elements of the local Princeton ecosystem, namely PPPL, GFDL, and the many Princeton University faculty experts in fluid dynamics, aerosol and climate science, and optics together offers a unique opportunity to help furnish the needed foundational understanding of complex phenomena that may be borne out of natural and anthropogenic aerosol injection into the atmosphere. Improved knowledge of aerosol processes, including ice nucleation and mixed-phase cloud processes, as well as novel microphysical modeling stemming from the experimental work, would directly benefit DOE climate models, and complement current atmospheric science fieldwork and modeling at other DOE national laboratories, especially with respect to the description of properties of clouds and natural aerosols. PPPL Associated Faculty Profs. Marissa Weichman and Luc Deike are spearheading this effort, with Prof. Deike leading the Aerosol Science for the Climate initiative at PPPL.

PPPL has initiated a new LDRD research project in this area, led by PPPL researcher Dr. Yevgeny Raitses, to develop diagnostic tools that can characterize suspended particles. PPPL will (1) develop and evaluate the utility of photoacoustic spectroscopy (PAS), a diagnostic tool capable of detecting and measuring sizes and density of various aerosols and nanoparticles in diverse environments relevant to an aerosol-cloud chamber facility and characterizing aerosol aggregation, size distributions, and dynamic behavior; and 2) develop and test a diagnostic for characterization of the reflectivity of aerosol particles suspended in the gas phase. Both proposed diagnostic capabilities are critically important for the development of aerosol science at PPPL. The project research plan also includes the upgrade of an existing chamber to achieve conditions relevant to the stratosphere. Characterization experiments will be conducted utilizing different aerosol particles (>100 nm) made from different materials, including natural aerosol materials such as sulfate, carbon, and salts, suspended in low-pressure environments (~ a few torr), with and without plasma.

Efforts are also being made by Princeton University/PPPL researchers to advance our understanding of aerosol dynamics under stratospheric conditions and ice nucleation under lower stratosphere/upper troposphere conditions. Seed funding from the Simons foundation has enabled the team to build a small-scale pilot aerosol-cloud chamber which is currently being used to establish fundamental understanding of ice nucleation processes and develop diagnostic methods to characterize liquid-vapor content, visualize ice particles, and identify ice crystal shape and growth under stratospheric conditions. Princeton University/PPPL researchers are addressing the above-mentioned objectives by focusing on both single levitated particles and large cloud-seeding ensembles. Taken together, these experiments will provide a detailed understanding of aerosol microphysics and optical properties with the goals of directly informing climate models, i.e., providing key data that can be input into the models. Characterization of various stratospheric natural aerosols (e.g., salt, mineral dust, sulfates…) will be performed, leveraging the experimental expertise from PPPL. This small scale pilot facility will be instrumental in testing and developing novel diagnostics methods to characterize aerosol-light interaction. Characterization of ice particles nucleation and geometry (shape and size) is critical to understand the effect of possible aerosol seeding on cirrus cloud properties, and PPPL diagnostics expertise will be critical for measurement of ice crystal geometry. The knowledge gained in operating a small-scale facility and requirements for diagnostics when operating in stratospheric conditions (pressure and temperature) will be instrumental in the planning of a large-scale facility at PPPL to inform climate models as well as possible solar radiation management effects. These efforts at PPPL, while nascent, involve several PPPL research staff as well as Princeton University faculty affiliated with PPPL. As funding becomes available, we will hire full-time PPPL researchers in this area; we would also staff up the engineering side if given the opportunity to design and build a next-generation aerosol cloud chamber.

Science and Technology Strategy for the Future/Major Initiatives

PPPL's strategy and missions are rooted in two key National priorities. The first, restated in an April 2023 White House briefing: "*President Biden has set an ambitious U.S. goal of achieving a carbon pollution-free power sector by 2035 and a net zero emissions economy by no later than 2050*." The administration and the U.S. Congress clearly see fusion as an important component of the future decarbonized system. Indeed, at COP28, U.S. Special Presidential Envoy for Climate John Kerry said "*We are edging ever-closer to a fusion-powered reality. And at the same time, yes, significant scientific and engineering challenges exist*."

The second is a commitment to develop and nurture the emerging technologies that will define the future economic competitiveness of the nation. Technologies that range from artificial intelligence (AI) to microelectronics, quantum and sustainable manufacturing. Secretary Granholm articulated the Laboratories importance for this priority: *"Since their inception, DOE's National Laboratories have been central to the nation's scientific and technological advancement, and we are preparing to ensure that, as new technologies emerge, the United States leads the way in exploring those frontiers."* The unique capabilities of PPPL and its staff are needed to address key elements of these priorities and our strategy, missions and program are aligned and expanded to meet these needs.

PPPL's three missions are therefore structured to deliver on these national priorities by:

1. **Developing the scientific knowledge and advanced engineering to enable fusion to power the U.S. and the world.** Energy analysts acknowledge the need to develop fusion as a new "firm energy" source to realize the Administration's climate change goals, and in March 2022, the administration developed a bold decadal vision to accelerate fusion. In December 2023, DOE Fusion Energy Sciences (FES) released "Building Bridges: A Vision for the Office of Fusion Energy Sciences" to establish the steps needed to advance fusion energy, including addressing key science and technology gaps toward fusion commercialization. Innovation is essential to reduce the scale, cost, and time-to-construct for fusion to compete in the energy market. PPPL will lead the development of key innovations including spherical tokamaks, liquid metal boundaries for fusion devices, and optimized stellarators. PPPL's highest priority is the successful recovery and operation of NSTX-U, a spherical tokamak user facility of high interest to industry as a potentially reduced-cost pathway to commercial fusion power. NSTX-U will also develop liquid metal core-edge integration science and technology to enhance the resilience and confinement performance of all toroidal magnetic fusion pilot plant concepts. PPPL is pioneering state-of-the-art AI techniques and high-performance computing to discover and optimize low-cost fusion systems.
2. **Advancing the fundamental science base of low-temperature plasma, plasma-material interactions, and new materials enabled by plasma, for nanoscale fabrication and sustainable manufacturing.** Nanoscale fabrication for microelectronics5 and eventually sub-nanoscale fabrication for quantum systems is central to the U.S.'s future economic security and competitiveness, and industry needs have

facilitated many new partnership opportunities for the Laboratory. Understanding the basic science of low-temperature plasmas, plasma-material interactions, and the mechanisms by which chemicals and materials can be synthesized by plasmas, is critical to enable advanced nanoscale fabrication and sustainable manufacturing. To meet the Administration's net-zero carbon emission goals, PPPL's low-temperature plasma science expertise, coupled with electrochemical/plasma processing expertise at Princeton, offers a unique opportunity to build out a new program in “sustainable manufacturing.” As part of PPPL’s sustainability portfolio, PPPL and Princeton will contribute to aerosol science for the climate, an increasingly important scientific and research governance issue. This initiative will leverage PPPL’s expertise in in-situ diagnostics and modeling of complex, turbulent fluids, and Princeton’s expertise in aerosol and climate science.

3. **Furthering the development of the scientific understanding of the plasma universe, from laboratory to astrophysical scales**. A new collaborative experiment (FLARE) will enable for the first time laboratory studies of magnetic reconnection turbulent regime. Exascale simulations of ultra-relativistic plasmas will be used to study the exotic physics at the heart of multi-messenger astronomy. This mission brings PPPL into close and productive collaboration with Princeton University's Department of Astrophysical Sciences and leverages and grows DOE capabilities in exascale algorithms and computing. PPPL will also advance understanding of high-energy density laboratory plasma science of importance to astrophysical systems, fusion energy, and national security.

PPPL is developing a diverse workforce for the nation's Science, Technology, Engineering, and Mathematics (STEM) talent pool. PPPL’s SULI program has introduced many talented undergraduates to research and its joys. Graduates of PPPL’s Ph.D. program occupy leadership positions at DOE national laboratories, research universities, and business and industry. Leveraging the resources of its M&O contractor, Princeton University, PPPL has access to funded, specialized research centers and institutes, as well as world-renowned scientists in multidisciplinary fields.

Leveraging the resources of its M&O contractor, Princeton University, PPPL has access to funded, specialized research centers and institutes, as well as world-renowned scientists in multidisciplinary fields.

Infrastructure

Overview of Site Facilities and Infrastructure

The 90.7-acre Princeton Plasma Physics Laboratory (PPPL) is situated on Princeton University’s 1,750-acre Forrestal Campus located in Plainsboro Township, New Jersey. The site is punctuated by dense woods, brooks, and nearby streams. The site is leased to the DOE for operation of the Laboratory. The Laboratory is surrounded by several hundred acres of undeveloped land – including protected wetlands – and is conveniently located between Philadelphia and New York City. PPPL was constructed in 1951 with the only major growth being the construction of D-Site and associated support buildings in C-Site in the late 1970’s. The average age of the buildings for the entire PPPL campus is 51 years.

The Laboratory has a workforce and user population of nearly 800 and utilizes 806k gross square feet (GSF) of the Princeton University Forrestal Campus, with 45 government-owned buildings and trailers. There are currently no leased buildings or facilities. The University updated its land lease agreement with the DOE on April 1, 2019, extending the lease through 2056. There were no other real estate transactions during FY 2023, and there are no current plans for transactions in FY 2024. Discussions about additional access pathways to the site may have future implications.

All of PPPL's buildings and trailers are currently categorized as "operating." All of PPPL's Other Structures and Facilities (OSF) are also categorized as "operating" with the exception of one OSF asset, MG Free Cooling Ext. Pipe (Property ID # 7132030301, 400 linear feet).

Infrastructure Data Summary

Total Building and Trailer Assets	**45**
Total Other Structures and Facilities (OSF)	**35**
Total Replacement Plant Value	**$1.232 B**
Total Deferred Maintenance 2023	**$110 M**
Repair Needs (includes DM)	**$228 M**

PPPL operates and maintains a significant onsite utility distribution system including electrical, Chilled Water, Process Water, Fire Protection Water, Domestic Water, Natural Gas, Steam, Sanitary and Storm Sewer. The distribution consists of both aerial/overhead and underground components.

Electrical service to the campus is provided through multiple aerial services from the local utility company, PSE&G, at 230kV. The power is distributed through PPPL-owned equipment onsite. Onsite generation is maintained for chilled water and steam in central plants. Domestic water is provided by connection to the local water company, and gas service is also supplied by PSE&G. An on-site sanitary sewer collection system discharges to the county treatment system.

Much of the onsite generation and distribution utility system is beyond useful life, and renewal has begun under the Critical Infrastructure Recovery and Renewal (CIRR) project, which is in design. Ensuring the reliability and capacity of these utilities and systems is essential to mission readiness as well as to the execution of PPPL's expanded vision.

PPPL completed a site Campus Master Plan for the site in 2022, and the document was revisited in 2024. The goals outlined in the Campus Master Plan drive the current strategic Campus Plan which is a higher-level document that matches infrastructure to the science mission.

Campus Strategy

To achieve the vision of PPPL as a key element of the DOE national laboratory system, the Laboratory must provide the unique assets and talents that will drive innovation and breakthrough technology. PPPL is critical to the Bold Decadal Vision and has the opportunity to expand the impact of plasma technology into key areas of national importance.

The overall campus has had limited investment over many decades of operation. Existing lab spaces at PPPL are fully occupied or oversubscribed and do not support the needs of current research initiatives or the joint national and international collaborations that characterize fusion research. Adjacent office spaces that enable researchers to benefit from collaboration with subject matter experts in critical fields of interest – including computational science, data management, data analysis, visualization, and simulation – are not currently available. Many programs, including anticipated growth into low-temperature plasma, microelectronics, and sustainability sciences require unique features, such as low vibration and electromagnetic shielding. The triad of laboratory space, office space, and collaboration space are the primary infrastructure gaps that have been approached in the PPPL Campus Master Plan and our campus strategy.

Strong project execution and performance (i.e., the overall success of delivery compared to plan) is critical. PPPL has made several improvements this year to buttress project formulation and cost development including addition of a professionally-qualified cost-estimator position, standardizing cost-estimating with a procedure applicable across the lab, and benchmarking practices against other DOE laboratories.

Campus Master Plan

The PPPL Campus Master Plan provides a strategic vision for campus development over the next decade and beyond. The goals of the Campus Master Plan were developed by a broad PPPL and subcontractor team to provide direction and bounds for growth and development in a holistic, positive, and physically cohesive manner.

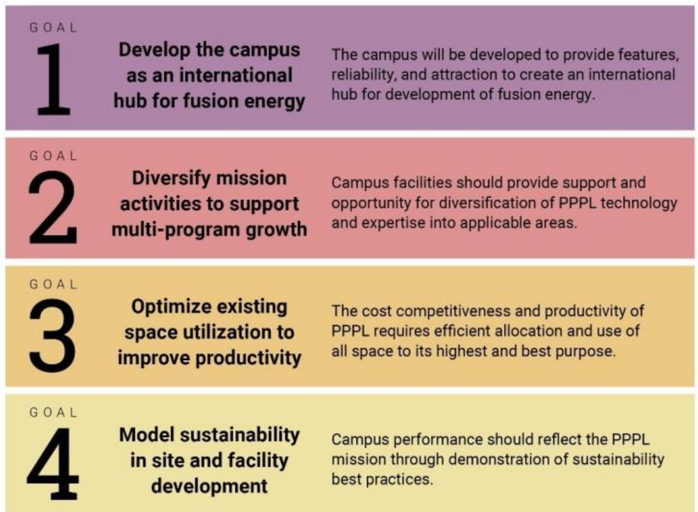


Figure: Campus Master Plan Key Goals

Campus Plan

The Campus Plan utilizes the tools and flexible framework of the Campus Master Plan for development to guide investment, facility planning and construction by incorporating five key strategies that crosscut the goals to ensure the development of integrated and optimized projects. These five strategies are:

1. Collaborative Environments
   Creating a more collaborative environment is a critical element of the PPPL vision as the international hub for fusion energy. The Princeton Plasma Innovation Center (PPIC) will be a key igniter with spaces specifically designed to promote collaboration and provide the beginning of a new "town hall center" approach through the adjoining campus. The integration of the former two sites into a single site and creation of pedestrian pathways and building linkages will promote more interaction across the full range of the campus. With partnership initiatives both on and off campus, the collaboration opportunities will expand beyond the traditional PPPL campus to serve as a cohesive and dynamic place for fusion and plasma research.
2. Site Access and Outdoor Engagement
   Ease of access and onsite productivity is important for a growing use/collaborator population, attracting future talent, and promoting science education. Celebrating the vehicular entry to PPPL with an enhanced landscape, a new gatehouse building, and enhanced lighting, will begin to improve the functionality and visitor experience. Segregation of traffic and faster check-in at the gate will promote efficiency and safety. A second service roadway into campus will separate shipments from employee

and visitor traffic and provide a second route for both evacuation and redundant services. Improvements to the perimeter loop road and the introduction of pedestrian paths and recreational areas will enhance the onsite experience.

3. Campus Realignment
   Integration into a single collaborative site is a key element of the PPPL Campus Master Plan. Long-term development of the eastern site (former D-Site) can be optimized through the elimination of the fence surrounding the site and a straightening and aligning of the existing two-way access road and the elimination of a portion of the secondary loop through the center of campus. Potential future lab and office growth on both the east and west areas of the site can recapture valuable acreage currently devoted to legacy site storage and infrastructure to help integrate a cohesive campus.
4. Optimize Utilization of Unique Assets
   Improved utilization of space enables cost effective operations through reduced maintenance of nonproductive facilities and opportunities for incubation of new and emerging programs. A review of underutilized and available smaller lab-capable spaces was recently completed in the 2023 Science Research Space Plan study. This study has created an inventory of repurposing opportunities that can be executed as projects, as needed. Future studies will also look at office and administrative inventory development
5. Research Partnership Hubs
   Public/private partnerships are an element of the FES strategy and will continue to become more prevalent at PPPL. The Fusion Research and Technology Hub (FuRTH) Test Cell initiative repurposes the home of the former Tokamak Fusion Test Reactor (TFTR) as a space and set of capabilities dedicated to advancing the next generation fusion experiments and technology. FuRTH's unique large bay capabilities coupled with the adjacency to the flagship NSTX-U and emerging Liquid Metal Core Edge (LMCE) projects pose valuable synergies with potential public/private partnerships. Renewal of adjacent spaces planned under the Fusion Systems Operations Modernization (FuSOM) project can support the staff and lab requirements for this technology hub.
   The New Jersey Economic Development Agency (NJEDA) has funded a feasibility study for an adjacent, privately-owned incubation and development center called the "Plasma Forge." The Plasma Forge would provide opportunities for collaboration with private industry and growth adjacent to the critical resources of facilities and staff at PPPL. The partnership with the Plasma Forge could drive fusion energy development, workforce development in conjunction with nearby universities, and an opportunity for plasma science market impact in areas such as microelectronics and quantum information science.

Key Transformative Projects

The PPPL 10-Year Plan achieves momentum from the ongoing execution of three significant Science Laboratory Infrastructure (SLI) projects.

The Tritium Systems Demolition and Disposal (TSDD) project has completed its threshold scope and is finishing up final objective scope items as it prepares for a CD-4 milestone towards the end of FY 2024. The TSDD project has removed the legacy tritium system that supported TFTR and now allows for reuse of this valuable asset.

The Princeton Plasma Innovation Center (PPIC) is a new multi-use building providing flexible, state-of-theart laboratories, as well as office and collaboration space adaptive to the lab's growing and expanding science program portfolio. This facility, whose primary sponsor is DOE's Science Laboratory Infrastructure (SLI) program paired with supporting funds from Princeton University, will mark the initial Town Center investment by providing an iconic building that establishes a new front door to the campus. PPIC will establish labs and valuable collaboration space for several program occupants, such as Fusion Energy Sciences (FES), Basic Energy Sciences (BES), Biological and Environmental Research (BER), and Advanced Scientific

Computing Research (ASCR). Due to its importance to all the Office of Science programs supported by this building, the PPIC project received additional financial support from the SLI program, increasing the project TPC to $109.7M. Additionally, Princeton University has provided $10 million in funding to cover the initial site enabling work which includes the demolition of the Theory and Administration (partial) building wings. The Princeton University contribution allows for construction activities to start early while awaiting approval of the fully executed construction contract. Final design is anticipated for summer 2024, while the builders contract award/start is anticipated for early 2025. Importantly, estimates for operating, maintaining, and exploiting PPIC for the PPPL mission are scheduled for incorporation into PPPL resource plans for FY 2026 and beyond.

The Critical Infrastructure Recovery & Renewal (CIRR) infrastructure project is a comprehensive utility enhancement project incorporating modern, efficient equipment and systems that will improve scientific productivity, increase site sustainability performance, and decrease the current deferred maintenance backlog. After undergoing a reprogramming effort to validate the project approach provided the highest and most useful application to upgrading the campus's most critical utility systems, preliminary design has begun with a targeted final design of summer 2025. The upgrades to the electrical and chilled water generation systems are overall most critical, while specific HVAC, IT, and underground systems are the next highest priority. Forward-looking features for artificial intelligence and machine learning will be incorporated in all these system upgrades. A major initiative of the CIRR Project, which will be integrated into future upgrade projects until completion, is a bold move away from fossil-fuel-generated steam heat toward renewable distributed energy systems. CIRR will initiate the transition to a campus-wide source-sink loop with geo-exchange fields for heating and cooling. The loop will enable energy recovery from buildings and experimental/process loads, and use renewable energy generation.

As noted above and throughout the document, PPPL's infrastructure and facility needs to advance its mission are pivotal and challenging. Some target systemic problems, others support a handful of key programs to reduce energy footprints, modernize controls, or improve flexibility for safe, secure research and development activities. A partial list of these projects on the near-term horizon include:

Site Access, Safety, and Sustainability Improvements (SASSI). The Site Access, Safety, and Sustainability Improvements (SASSI) project is a proposed SLI investment to improve campus access, functionality, and sustainability in accordance with the site Master Plan. SASSI will also mitigate safety risks for workers and visitors accessing the site supporting the increasing role of PPPL as a user site and fusion hub. The most significant component of this project is a new site entry. Regarding safety and security, PPPL is exploring the addition of a second site entrance to allow PPPL to safely segregate site access operations for employees, visitors, construction, pedestrian, and emergency traffic, thus eliminating the single point-of-failure and improving the safety for all campus occupants.

Fusion Systems Operations Modernization (FuSOM). The Fusion Systems Operations Modernization (FuSOM) project will address critical capability gaps impacting the utilization and performance of the NSTX-U and fusion test cell complex. This project will supplement the previous TSDD Project cleanout work to upgrade the 45-year-old complex for a new mission. The project will include the replacement of the fusion research center building envelope panels to a more sustainable, energy efficient building envelope to increase building energy performance. The project includes office and support space renewal that is critical to the successful operations of the NSTX-U/LMCE and other fusion research initiatives, including those with private partners. The project may also include lab and office infrastructure upgrades for the FuRTH test cell to provide necessary support capability.

C-40 Modernization for Multidisciplinary Research (C-40 MMR). The C-40 Modernization for Multidisciplinary Research (C40 MMR) project will modernize the C-40 RF building, which supports multiple research programs, including FLARE, Hall Thruster, ITER Diagnostics, Superconducting Magnet, NanoLab, and NSTX-U Radio Frequency (RF) heating and other support systems. This infrastructure is needed as a platform for the science, engineering, technology, and sustainability needed to advance the PPPL mission. C40 sits at the heart of the PPPL campus, and is the tallest, most visible structure; replacement of the envelope will substantially improve the building's R-rating.

Critical Infrastructure Renewal & Modernization (CIRM). The Critical Infrastructure Renewal & Modernization (CIRM), extending concepts initiated in the CIRR project, will replace and modernize additional utility and building systems, including expansion of the SSL and hot water heating. Upgrades are expected in electrical distribution, automation and AI/ML, and expanding site electrification.

Lab Infrastructure Modernization & Sustainability Enhancements (LIMSE). The Lab Infrastructure Modernization & Sustainability Enhancements (LIMSE) project scope will renew and enhance sustainable performance of medium and small bay laboratories. Elements of these upgrades will include optimized HVAC, utility and fume hood renewal, sustainable lighting, improved sensors and controls.

Site Sustainability Plan Summary

PPPL strives to be a sustainability leader within the DOE, while simultaneously acknowledging the challenges of executing sustainable projects for laboratories. Sustainability, in the context of integration of sustainable technologies and concepts into projects identified in the Campus Master Plan, suggests both an aspirational and realistic approach to achieve the maximum benefits using current technologies and allowing for the potential to integrate new solutions over time. The DOE sustainability goals are fully integrated into PPPL's ISO14001-certified Environmental Management System (EMS) as EMS objectives and targets. PPPL has developed a climate vulnerability assessment and resilience plan (VARP) under the DOE's sustainability reporting program. This plan identifies critical site assets, assesses their vulnerability to climate impacts, and outlines a portfolio of potential resilience strategies. The Site Sustainability Plan provides sustainability guidance for future projects in accordance with the strategic Campus Plan.

PPPL's FY 2023 Scope 1 and 2 greenhouse gas (GHG) emissions were 84.6% below the FY 2008 baseline. This is primarily due to reduced fugitive sulfur hexafluoride (SF6) emissions from experimental power systems, reduced energy usage from the curtailment of onsite staffing resulting from a hybrid workforce, and changes in experimental operations. Scope 3 GHG emissions were 14.4% below the FY 2008 baseline primarily due to pandemic limits on travel, lower site electricity usage and associated transmission and distribution (T&D) losses, and reduced employee commuting resulting from the utilization of hybrid work arrangements.

PPPL maintains a robust waste diversion program that achieved a combined recycling rate of 78% for municipal solid waste (61%) and construction waste (88%). PPPL continues efforts to facilitate the purchase of environmentally-preferable products through Lab-wide subcontracts and by enhancing sustainable acquisition guidance and resources available to employees in FY 2023. PPPL continues efforts to facilitate the purchase of environmentally-preferable products through Lab-wide subcontracts and by enhancing sustainable acquisition guidance and resources available to employees. Onsite renewable energy and high-performance building improvements continue to be an emphasis of future projects in the strategic Campus Plan.

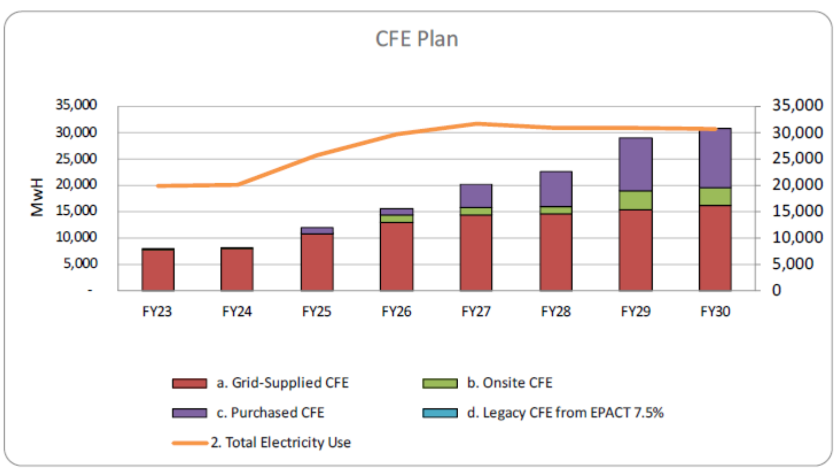
The new PPIC building will be constructed with implementation of high performance and sustainable building provisions in the design of the facility. PPPL continues to implement infrastructure projects and operational improvements to reduce its energy and water intensity. PPPL's total energy consumption for goal subject and excluded assets decreased in FY 2023 compared to FY 2022 by approximately 4.40%, due, in part, to implementation of energy efficiency projects, such as the D-Site HVAC upgrade project. PPPL's potable water intensity (Gal/GSF) for goal subject and excluded assets decreased approximately 3.9% in FY 2023 compared to FY 2022. When comparing FY 2023 potable water intensity to the FY 2007 baseline, PPPL's water intensity decreased 66.8%, exceeding the 40% reduction goal.

Recent DOE and broader federal sustainability requirements that help guide PPPL's sustainability efforts include DOE Order 436.1A, Departmental Sustainability, and Executive Order 14057 on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability. Priority efforts include increasing use of carbon pollution-free electricity (CFE), design and construction of net-zero buildings, procurement of electric vehicles and installation of electric vehicle service equipment (EVSE) and improving climate change resilience. Meeting these goals will require significant planning and investment. PPPL submitted a CFE Plan to DOE in FY 2022 that identifies specific strategies to reach 100% CFE on a net annual basis by 2030. These strategies include energy conservation projects, installing rooftop solar PV, infrastructure improvements, retrocommissioning, and CFE procurement. Other initiatives and potential projects include installing additional energy and water metering, electrification where feasible, an energy management information system (EMIS), and Battery Energy Storage System (BESS). Incorporating sustainability into the Critical Infrastructure Recovery and Renewal (CIRR) project is another important effort and along with PPIC can serve as a model for how to incorporate sustainability into all construction projects at PPPL.

PPPL ensures efficient management of its vehicle fleet through its annual vehicle and mobile/heavy equipment justification process and established local use objectives (LUOs) for each vehicle. PPPL emphasizes the use of alternative fuels in its fleet management program; heavy-mobile equipment including a 15-ton forklift, backhoe, skid-steer loader and off-road utility vehicles use a biodiesel blend (B20) for fuel. Several other fleet vehicles use an ethanol-based fuel (E85) as an alternative to traditional gasoline.

A recent parking study has identified potential locations for longer-term deployment of EV charging stations and investigations to initiate some early installations are ongoing, with broader deployment being considered as part of the CIRR project. The parking study also identified opportunities to utilize "green infrastructure" to reduce the heat island effect, manage stormwater runoff, and improve surface water quality. PPPL continues to explore opportunities to enhance its environmentally sustainable practices as it advances and diversifies research initiatives in fusion energy science, basic sciences, and advanced technology.

As seen in the chart below, the decrease in electric usage is linked to HEMSF-NSTX-U, which was last operational in 2016. NSTX-U's projected electric usage will increase concurrent with planned operations.



SLAC NATIONAL ACCELERATOR LABORATORY

Lab-at-a-Glance

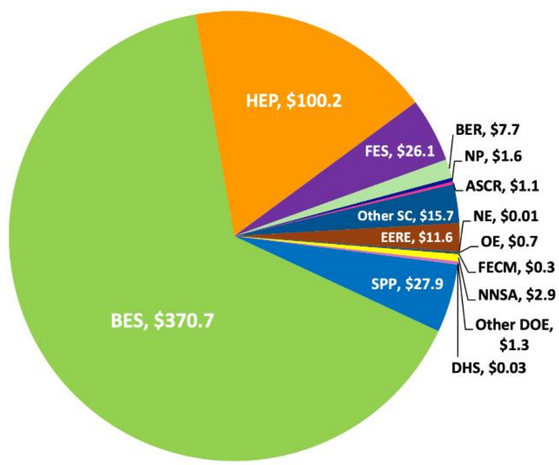
Location: Menlo Park, CA
Type: Multi-program Laboratory
Contractor: Stanford University
Site Office: SLAC Site Office
Website: www.slac.stanford.edu

- **FY 2023 Lab Operating Costs:** $568 million
- **FY 2023 DOE/NNSA Costs:** $540 million
- **FY 2023 SPP (Non-DOE/Non-DHS) Costs:** $28 million
- **FY 2023 SPP as % Total Lab Operating Costs:** 4.9%
- **FY 2023 DHS Costs:** $0.03 million

Physical Assets:
- 426 acres and 170 buildings
- 2.2M GSF in buildings
- Replacement Plant Value: $3.5 B
- 6,134 GSF in 4 Excess Facilities
- 0 GSF in Leased Facilities

Human Capital:
- 1,798 Full Time Equivalent Employees (FTEs)
- 7 Outgoing Joint Appointees, 11 Incoming Joint Appointees
- 134 Postdoctoral Researchers
- 273 Graduate Student
- 95 Undergraduate Students
- 1,456 Facility Users
- 13 Visiting Scientists

FY 2023 Costs by Funding Source ($M)



Facility users as reported to DOE by the user facilities LCLS, SSRL, FACET-II, cryo-EM

Mission and Overview

SLAC National Accelerator Laboratory is a vibrant multi-program laboratory that pushes the frontiers of human knowledge and drives discoveries that benefit humankind. We invent tools that make those discoveries possible and share them with scientists all over the world. Our research helps solve real-world problems and advances the interests of the nation.

SLAC sits on 426 acres of Stanford University land in the heart of Silicon Valley and is managed by the university for the U.S. Department of Energy (DOE). This unique partnership and support advances the work of the laboratory, providing infrastructure, capabilities, and expertise that amplify our impact across shared areas of focus, including sustainability research and industries of the future. SLAC stewards several joint research centers with Stanford, and together we educate and develop the U.S. scientific workforce in key technological areas.

SLAC is the world-leading laboratory in X-ray and ultrafast science owing to our six decades of expertise developing critical accelerator concepts and technologies and to our two user facility light sources: the Stanford Synchrotron Radiation Lightsource (SSRL) and the Linac Coherent Light Source (LCLS).

LCLS, the world's first hard X-ray free-electron laser (XFEL), is a revolutionary tool for chemistry, materials science, biology, atomic physics, plasma physics, and matter in extreme conditions. LCLS-II, a major upgrade completed in fall 2023, adds a second laser that is 10,000 times brighter and sends pulses up to one million times per second. These pulses will allow us to view how nature works at the atomic scale and help advance technologies of the future, including novel electronics, life-saving drugs, and innovative energy solutions. A high-energy upgrade, LCLS-II-HE, is presently underway and will boost our capability and maintain U.S. leadership for years to come.

SLAC started 60 years ago as a place to discover fundamental particles and forces through collider-based experiments. Today, we deploy our scientific talent and technology from mile-deep caverns to an orbiting satellite in the search for dark matter, dark energy, and the fundamental nature of the neutrino. We managed the construction of and now operate the U.S. data center for the world's largest digital camera for astrophysics and cosmology, which will produce panoramic images of the complete southern sky once installed at the Vera C. Rubin Observatory in Chile.

SLAC hosts, supports, and collaborates with thousands of U.S. and international researchers and students at SSRL, LCLS, the Facility for Advanced Accelerator Experimental Tests (FACET-II), and the Stanford-SLAC and National Institutes of Health (NIH)-funded cryogenic electron microscopy (cryo-EM) facilities.

We diversify our research programs, exploring synergies between our user facilities and core capabilities to support the missions of DOE and other federal agencies. Our connections and partnerships with DOE, Stanford, leading research centers, and Bay Area industry accelerate our progress and innovation.

Core Capabilities

SLAC's ability to deliver scientific discoveries and develop tools that transform our understanding of nature and help address the most challenging scientific and technological problems facing industry and society is grounded in the core capabilities that we steward. From a broad array of scientific and technical areas of expertise, the U.S. Department of Energy (DOE) has identified a set of core capabilities necessary for its mission and has designated which core capabilities each laboratory stewards. SLAC stewards the following twelve core capabilities:

1. Large-scale User Facilities/R&D Facilities/Advanced Instrumentation
2. Accelerator and Detector Science and Technology
3. Advanced Scientific Computing, Visualization, and Data
4. Applied Materials Science and Engineering
5. Biological Systems Science
6. Chemical and Molecular Science
7. Condensed Matter Physics and Materials Science
8. Mechanical Design and Engineering
9. Microelectronics
10. Particle Physics
11. Plasma and Fusion Energy Science
12. Systems Engineering and Integration

Large-Scale User Facilities/R&D Facilities/Advanced Instrumentation

Linac Coherent Light Source (LCLS). LCLS creates X-ray pulses one billion times brighter than those generated by synchrotrons. The LCLS takes X-ray snapshots of atoms and molecules at work, revealing fundamental processes in materials, technology, and living organisms. Movies from these snapshots allow scientists to study chemical reactions, phase changes in materials, and proteins at room temperature. Each of LCLS's nine experimental stations is equipped with a suite of specialized diagnostics tailored to the broad user communities that access LCLS. Approximately 40% of beam time is devoted to the chemical sciences (principally atomic and molecular science and catalytic chemistry), 40% to materials science (principally quantum materials, disordered materials, and materials in extreme conditions), 15% to biosciences (principally high-resolution structural biology and enzymology), and 5% to new methods development. Hundreds of users access LCLS each year, with typically 30% new users and an oversubscription rate of 4-5 times.

The LCLS facility continues to advance state-of-the-art free-electron laser (FEL) light sources. Recently, the LCLS upgrade, LCLS-II project, completed initial commissioning of the superconducting accelerator that is now providing FEL pulses up to potentially 1 megahertz. This is an almost five orders of magnitude increase of repetition rate compared to the normal conducting FEL that has been operational for more than a decade. LCLS will continue to improve the new capabilities for both the FEL source and instruments using the high repetition rate machine.

SLAC will enable and support the LCLS-II-HE project, which aims to increase the superconducting accelerator electron beam energy from currently 4 gigaelectronvolts (GeV) up to 8 GeV and implement further improvements of the LCLS experimental user facility.

The LCLS facility incorporates the Megaelectronvolt Ultrafast Electron Diffraction (MeV-UED) instrument, which has a 100 femtosecond (fs) time resolution, making it the most advanced UED facility in the world. With the additions of a terahertz (THz) to mid-infrared pump source and a three-fold increase in repetition rate, the MeV-UED facility continues to expand our ultrafast science capabilities.

Funding for this core capability primarily comes from DOE Basic Energy Sciences (DOE-BES) as well as DOE Fusion Energy Sciences (DOE-FES).

Stanford Synchrotron Radiation Lightsource (SSRL). SSRL is a synchrotron-based national X-ray user facility providing state-of-the-art research capabilities to the national and international user community. The SSRL SPEAR3 accelerator source generates extremely bright X-rays with high reliability and low emittance. At SSRL, researchers study our world at the atomic and molecular levels, leading to major advances in energy production, environmental remediation, nanotechnology, new materials, biology, and medicine. With its 25 X-ray beamlines and 30 experimental stations, SSRL enables the success of thousands of users each year, provides unique educational experiences, and serves as a vital training ground for future generations of scientists and engineers. The accelerator research and development (R&D) program aims to improve the performance and reliability of the SPEAR3 accelerator complex. We continue to develop new beamlines to meet the needs of academic, National Laboratory, and industrial users, many focusing on *in situ*, *operando,* and time-resolved studies for the understanding of functional processes of materials broadly defined.

Funding for this core capability comes from DOE-BES, DOE Biological and Environmental Research (DOE-BER), the National Institutes of Health (NIH), Stanford, and collaborative partners.

Facility for Advanced Accelerator Experimental Tests (FACET-II). FACET-II is a national user facility operated by SLAC for the U.S. Department of Energy Office of Science (DOE-SC). FACET-II combines a state-of-the-art photoinjector, three bunch compressor chicanes, and a 1 kilometer linear accelerator (linac) to deliver high-energy, high peak current electron beams to an experimental area within the SLAC linac. A broad user program is engaged in developing advanced technologies for future accelerators with the primary focus on investigating key challenges presented by plasma wakefield acceleration based colliders and light sources, as outlined in the DOE Advanced Accelerator Development Strategy Report. With the highest energy (10 GeV) and highest peak current (> 100 kiloampere) electron beams available for accelerator tests, FACET-II provides unique capabilities to develop: new accelerator technologies like plasma wakefield acceleration, novel beam diagnostics and control strategies based on AI/ML (machine learning), ultrahigh brightness beams, and strong field quantum electrodynamics phenomena. In fiscal year (FY) 2023, FACET-II served 144 unique users representing 12 experimental collaborations invited for beamtime. Half of the FACET-II users are students and postdocs, and a cornerstone of the FACET-II program is developing the future accelerator science workforce by providing a training ground for young scientists, who can get hands-on experience with cutting edge accelerator technologies.

Funding for this core capability comes from DOE High Energy Physics (DOE-HEP).

Cryogenic Electron Microscopy (cryo-EM), Cryogenic Electron Tomography (cryoET), and Fluorescence Imaging. SLAC hosts one of the world's leading scientific programs in cryo-EM research and technology development. The program's soon to be 12 state-of-the-art instruments can, at near-atomic resolution, image single particles (cryo-EM) and create three-dimensional images through cryoET. Two NIH-funded national centers, the Stanford-SLAC Cryo-EM Center (S^2C^2) and the Stanford-SLAC CryoET Specimen Preparation Center (SCSC), serve the national structural biology and biomedical user community and develop new technology. The Stanford-SLAC Cryo-EM Facility, accessible to SLAC and Stanford researchers and external collaborators, operates three instruments. DOE-BER funded programs are focused on developing technology for multi-modal imaging with high time resolution by employing various approaches of fluorescence microscopy combined with cryo-EM or other technologies. Coupling these new capabilities with SSRL and LCLS end station programs will allow researchers to use a multi-technique integrative approach, over a range of time and length scales, to investigate the structure and function of biological materials.

Funding for this core capability is provided by NIH (Common Fund), DOE-BER Biological Systems Science Division (BSSD), and initial infrastructure investments by SLAC and Stanford University.

Particle Physics Facilities and Instruments. See "Particle Physics" core capability, section A-1.10 below.

Advanced Instrumentation. Advanced instrumentation is at the core of the SLAC's mission. Over the years, we have invested in instrumentation to support our user facilities and physics experiments at our site laboratories and in collaborations. We have the capabilities and skilled scientists and engineers to conceive, design, build, and operate advanced instrumentation ranging from dedicated beamlines at SSRL and LCLS to large support facilities such as the Arrillaga Science Center and its fabrication and characterization facilities, the Detector Microfabrication Facility (DMF), Nano-X, and Detector Lab, to instrumentation projects for large physics experiments such as the 3,200 megapixel Legacy Survey of Space and Time (LSST) Camera for the Vera C. Rubin Observatory that was led by SLAC and completed this year, our contribution to the instrumentation for the Cosmic Microwave Background Stage 4 (CMB-S4) project, the LUX-ZEPLIN (LZ) project, the next generation of the Enriched Xenon Observatory (nEXO), the Light Dark Matter Experiment (LDMX), and the ATLAS Experiment at CERN.

Funding for this core capability primarily comes from DOE-BES and DOE-HEP. Other sources include DOE-BER, DOE-FES, DOE Nuclear Physics (DOE-NP), and Laboratory Directed Research and Development (LDRD) investments.

Accelerator and Detector Science and Technology

Accelerator and detector science and technology (S&T) have underpinned SLAC's mission since the laboratory's inception in the early 1960s. This core capability spans from R&D to construction to 24/7 operation of major accelerator-based user facilities and their instrumentation for diagnostics and experiments. Accelerator science and technology at SLAC falls within three broad categories: operation and improvement of accelerators at SLAC, basic science and development across the broader DOE-SC portfolio, and Strategic Partnership Projects (SPP) R&D for critical national needs. We target common threads across these categories – compact normal conducting radio frequency (RF) accelerators, next-generation power sources, etc. – to advance the state-of-the-art most efficiently.

SLAC is a recognized leader in high-brightness electron beam generation, transportation, and manipulation. We routinely deliver ultrabright beams to generate X-ray laser pulses as well as for plasma wakefield experiments and ultrafast electron diffraction. We constantly develop unique techniques to deliver ever brighter beams to improve our existing facilities and power future science applications.

SLAC is also a leader in high-power pulsed RF systems where we build and maintain the high-power klystrons for LCLS, FACET-II, and other laboratories. We continue to develop novel high-power RF sources and applications, and we partner with industry on these new technologies whenever possible.

Our renowned detector R&D program promotes an integrated co-design framework that leverages multi-disciplinary expertise across the laboratory and multiple programs to address the challenges of high-rate operation and data production in future detectors. This framework allows teams to form within agile structures and pair scientists, detector developers, and computer scientists to optimize and accelerate the development cycle.

SLAC has made significant investments in diagnostic and control systems for accelerators, particularly for the LCLS and SSRL beamlines. The LCLS-II beamline commissioning presented a challenge in control system technology, which we overcame with the development of the High-Performance Systems (HPS) control platform. SLAC is currently working on upgrading the existing control systems while also addressing the future requirements of higher performance accelerators. This includes exploring the use of edge-based machine learning (ML) algorithms to improve feedback control and reduce operational costs.

Funding for this core capability comes from DOE-SC (BES; HEP; ARDAP, Accelerator Research and Development and Production). Laboratory investments through the LDRD program are boosting the growth of this core capability. Additional SPP support comes from the U.S. Department of Defense (DOD).

Advanced Computer Science, Visualization, and Data

The advanced computer science, visualization, and data core capability supports the advanced data acquisition, edge computing and analysis, and complex systems controls needs for major experiments and experimental facilities at SLAC. Efforts in this core capability are key elements in supporting LCLS activities, including the end point of the data reduction pipeline for LCLS, and the U.S. Data Facility for the LSST/Rubin data collection effort. In addition to the historical focus on programming models, runtimes and tools for simulation, and data analytics at scale, areas of expertise now include the incorporation of AI-based methods for beamline and detector operations, and investigations into how AI/ML methods can be utilized in light sources, photon science, materials science, fusion science, and high energy physics.

Underpinning this capability are the scientists and researchers in computer science, scientific computing, and instrumentation, and the staff who manage the shared computing, storage, and scientific services resource (the SLAC Shared Science Data Facility, S3DF). The newly formed Scientific Computing Systems Division furthers the integration of all scientific computing at SLAC to utilize S3DF and enables computing support for smaller experiments across all SLAC directorates. Collaborations with Stanford University and several Silicon Valley based industrial partners are enabling the expanded work in AI/ML methods. Work done in this core capability will enable closer integration to the DOE Advanced Scientific Computing Research (DOE-ASCR) activities that are part of the newly constituted Integrated Research Infrastructure (IRI) program. This capability also drives our integrated scientific and data-intensive computing initiative (ISDCI).

Major contributions to the work in this core capability come from DOE-SC, including DOE-ASCR, DOE-BES, DOE-BER, DOE-FES, and DOE-HEP, as well as local SLAC and Stanford investments.

Applied Materials Science and Engineering

SLAC's applied materials science and engineering core capability is coordinated across multiple divisions and program and facilities efforts, and is aligned by two crosscutting themes that define our approach. Firstly, we leverage our world-leading characterization facilities – LCLS, MeV-UED, Cryo-EM, and SSRL – to understand the fundamental mechanisms governing the dynamic evolution of materials. A fundamental understanding of how atomic architectures and the electrons that bind them flex, move, and transform as raw materials come together in the synthesis of novel functional materials and how devices fabricated from them work and fail in the real world enables us to use foundational understanding to drive translational outcomes. Secondly, we are developing novel methods and applications for AI-guided acceleration of materials discovery and process optimization. We combine large-scale computations and emerging AI and ML methods with high-throughput synthesis and characterization to guide the search for new materials tailored to end-use functions and to optimize complex, multi-parameter, nonequilibrium manufacturing processing.

One major pillar is translational research driven by insights into the dynamic evolution of materials. Understanding and controlling the dynamic evolution of materials over their life cycles from synthesis to failure enables rational design of materials for end-use applications. Consistent with our facilities' focus on developing capabilities to understand dynamics across space and time, we are expanding our capability to characterize materials as they evolve in response to their environments. Our ability to look at materials systems and devices, which continuously evolve rather than remain as a static arrangement of atoms and electrons frozen in time, has informed our approach to synthesis, theory, characterization, and testing.

Another major pillar is AI-guided acceleration of materials discovery. Our approach is to combine the three materials discovery approaches – theoretical predictions, data-driven predictions, and high-throughput searches – so that their advantages compound and their shortcomings are minimized. Here, we combine all known experimental observations with physiochemical theories to train an ML model to predict the desired functionality in the target search space, providing both a prediction and a realistic estimation of the uncertainties. Using these types of models to direct high-throughput searches enables us to both accelerate materials discovery and deepen our understanding of the fundamental mechanisms governing the system.

Funding for this core capability comes from DOE-SC (BES), DOE Office of Energy Efficiency and Renewable Energy (DOE-EERE), DOE-EERE (AMMTO, Advanced Materials and Manufacturing Technologies Office; VTO, Vehicle Technologies Office; BETO, Biotechnologies Office; HFTO, Hydrogen and Fuel Cell Technologies Office), DOE Office of Electricity (DOE-OE), and DOE Office of Technology Transitions (DOE-OTT).

Biological Systems Science

SLAC's biological systems science core capability brings together a comprehensive suite of world-leading light, electron, and X-ray imaging and structure determination techniques that span subangstrom to cellular level characterization of processes occurring over a wide spatiotemporal regime, therefore enabling functional characterization of diverse biosystems. This includes our intellectual expertise and tools that drive research in DOE-BER relevant Grand Challenge science areas, including carbon dioxide (CO_2) fixation, plant metabolism, plant-pathogen interactions, biosystems design, and the impact of climate change in food and environmental security. The core capability is composed of experts developing novel imaging and structure determination modalities to study plant and microbial systems that leverage technologies and scientific expertise from the four national user facilities: SSRL, S^2C^2, SCSC, and LCLS. Our technologies and expertise are recognized for delivering cutting edge tools to solve complex problems in biological systems sciences from synthetic biology to the environmental microbiome, with unprecedented levels of details across a spatiotemporal regime that is unique to SLAC.

This core capability is composed of X-ray scientists, biochemists, theoreticians, and modelers, and takes advantage of an extensive collaborative network that has been built over the last decade within the DOE National Laboratories and Technology Centers: Environmental Molecular Sciences Laboratory, Joint Genome Institute (JGI), Oak Ridge National Laboratory (ORNL), Brookhaven National Laboratory (Brookhaven Lab), Lawrence Berkeley National Laboratory (Berkeley Lab), Los Alamos National Laboratory (Los Alamos), and Lawrence Livermore National Laboratory (LLNL). The capability interleaves complementary scientific expertise and technologies to address challenging problems at the interface of plant, soil, microbe, and water that focus on plant and rhizosphere science. This collaborative ecosystem for biological systems science research has been identified as an enabling driver in DOE-BER Basic Research Needs reports. Our strategic partnerships with the Stanford Schools of Engineering and of Humanities and Sciences and the new Stanford Doerr School of Sustainability strongly complement and drive this capability. The fundamental molecular to tissue level understanding across scale and breadth is crucial in connecting molecular level processes with their systems level impact from bioenergy crops to terrestrial ecosystems. Furthermore, this capability is closely coupled with and drives two new and emerging initiatives at SLAC – the Sustainability Research initiative and the Biosciences and Human Health initiative – and takes advantage of our advanced computing infrastructure (S3DF) and algorithm development efforts for data visualization.

Funding for this core capability comes from DOE-BER (BSSD; BCIS, Biomolecular Characterization and Imaging Science) and local SLAC and Stanford investments.

Chemical and Molecular Science

The chemical and molecular science core capability at SLAC focuses on advancing the fundamental understanding and control of physicochemical processes in their reactive environment and at relevant time scales.

One of the key components of this core capability is the ultrafast chemical science that builds on a number of different goals: enhancing the predictive power of quantum simulation and theory for electronic excited state reactivity, developing and exploiting ultrafast X-ray and electron methods to track light-driven molecular phenomena occurring on vibrational time scales and molecular length scales, transforming our understanding of correlated electron dynamics, and probing the fastest reactions in matter with ultrashort X-rays. These efforts bring together experimental and theoretical efforts in X-ray science, in accelerator science, and at LCLS.

In interface science and catalysis, we focus on capturing reaction dynamics, catalyst reorganization, and catalyst deactivation with atomic resolution; identifying key descriptors for catalyst control, reactivity, selectivity, as well as solvent control in electrocatalysis; and using data science to extract design principles for complex catalytic reactions. Synthesis of well-defined systems and structures, characterization and measurements at relevant time scales, and fundamental understanding of the processes calls for research teams spanning many of the core facilities at SLAC.

Funding for this core capability comes from DOE-BES.

Condensed Matter Physics and Materials Science

Condensed matter physics and materials science at SLAC evolved together with the development of SSRL as one of the first synchrotron light sources to address the electronic and structural properties of matter. Our research program focuses on key scientific problems that can be addressed through our X-ray, MeV-UED, and Cryo-EM user facilities, along with our world-class materials synthesis, characterization, and theory activities. Our researchers are supported by the Stanford Institute for Materials and Energy Sciences (SIMES). SIMES facilitates synergetic efforts between SLAC and Stanford across four schools and six departments, as well as the energy science education and training of the next generation of talent.

We pursue frontier issues in the assembly and design of materials, their collective quantum dynamics, and their ability to transform energy and information. Each of these lines of research addresses DOE's missions in science, energy, and security, and are advanced via integrated scientific teams combining synthesis, measurements, and theory. This includes the development and use of unique capabilities at SLAC facilities, such as *in situ* synthesis and *operando* platforms. With LCLS-II, spectroscopic probes of the ultrafast dynamics of quantum and energy materials will enable new exploration of the electronic, geometric, and excited-state properties of crystals, surfaces, interfaces, and complex nanoscale assemblies of atoms and molecules, as well as enable understanding how their physics evolves in response to external factors. This exploration not only is of fundamental scientific interest, but also is essential for designing new materials with properties tailored for a wide range of technological applications that are crucial for economic and energy security.

Funding for this core capability comes from DOE-BES, with related support from DOE-EERE, LDRD investments, and the Stanford Vice Provost and Dean of Research. It serves the DOE-SC mission in scientific discovery and innovation.

Mechanical Design and Engineering

At SLAC, the mechanical design and engineering core capability stands as a cornerstone, underpinning and propelling forward SLAC's extensive scientific agenda. This spans a broad spectrum of research areas, from astrophysics and cosmology to attosecond science, and extends into the realm of constructing state-of-the-art facilities. This core capability facilitates the realization of innovative research projects and ensures the seamless operation and advancement of our infrastructure and technological assets. For example, evolution of our large-scale user facilities such as LCLS and SSRL is a dynamic process, meticulously aligned with the advancing requirements of their diverse user communities. This continuous evolution is underpinned by our mechanical design and engineering core capability, encompassing a broad spectrum of engineering disciplines. These disciplines are fundamental in steering our discovery science mission and the development, enhancement, and operational management of intricate engineering systems. The essence of these systems lies in their precision and reliability, especially when they are required to seamlessly integrate with legacy systems that have been operational for decades and deliver science 24/7.

Our proficiency in this domain is broad and deep, covering the mechanical design of lasers, optics, metrology, magnet design, mechatronics, control systems, electrical engineering, high-power RF technology, fabrication, and rigorous testing protocols. A dedicated team of systems engineers, computer-aided design (CAD) experts, and specialists in modeling and simulation bolsters this extensive expertise. These disciplines synergize to conceptualize, design, and realize complex engineered systems that deliver our world-class scientific capabilities to the user community.

Our engineering excellence is showcased in our execution of projects such as LCLS-II, LSST Camera, MEC-U, ATLAS, and LCLS-II High Energy upgrade, LCLS-II-HE. These projects, each with its own daunting challenges, demand innovative solutions due to their complexity and the groundbreaking nature of their requirements. We tackle these challenges head-on by leveraging sophisticated multi-physics simulation tools and cutting-edge analytical and testing techniques. This holistic strategy enables the team to navigate and evaluate the design space thoroughly, optimizing the interplay among critical design elements. Through such a detailed and careful approach, we meet and surpass these significant challenges and substantially contribute to the scientific knowledge base, advancing the frontiers of science and technology. This commitment to excellence and innovation underscores SLAC's leadership role in developing complex engineering systems, ensuring they remain at the forefront of discovery science. This commitment to excellence and innovation underscores our leadership role in developing complex engineering systems, ensuring they remain at the forefront of discovery science.

SLAC is a multi-program laboratory with a diverse set of funding sources, including DOE-BES, DOE-FES, DOE-HEP, NIH, National Science Foundation (NSF), DARPA, Department of Homeland Security (DHS), and DOD.

Microelectronics

SLAC's core capability in microelectronics is at the forefront of use-inspired microelectronics research while also supporting SLAC science mission programs and other core capabilities. We are pursuing research thrusts across the entire microelectronics spectrum to identify opportunities for co-design for augmented innovation by leveraging SLAC *in situ* and *operando* characterization and synthesis resources at our photon science facilities (SSRL and LCLS), through our semiconductor design and fabrication capabilities (DMF, Nano-X, and Instrumentation Division labs), and at Stanford.

At SSRL and LCLS, novel electronic materials discovery and fundamental studies of synthesis and manufacturing processes leverage state-of-the-art capabilities including time-resolved X-ray scattering and angle-resolved photoemission spectroscopy. This research contributes to the development of new functionalities in microelectronics, including the integration of memory and logic to reduce energy consumption in computing and to facilitate new functionalities including sensors, quantum-classical computing interfaces, and on-chip optoelectronics. Over the last years, we have developed novel devices and integrated circuits for high-rate X-ray and particle sensing applications in extreme environments – high radiation, high magnetic fields, and cryogenic temperatures. We have expertise in advanced packaging, system integration, scaling, and characterization. We are expanding our research in distributed classical and AI/ML computing hardware architectures for energy-efficient real-time processing at the edge.

The microelectronics core capability at SLAC is supported by a cross-directorate workforce of about 30 scientists and engineers with backgrounds in semiconductor and microelectronics.

Funding for this core capability comes from DOE-SC (DOE-BES, DOE-HEP, DOE-FES) and DOE-EERE (AMMTO). Laboratory investments through the LDRD program and program development funds are boosting the growth of this core capability, supporting the associate microelectronics initiative. Additional SPP support is expected from participation in DOD Microelectronics Commons, U.S. Department of Commerce National Semiconductor Technology Center (DOC NSTC), and U.S. microelectronics industry.

Particle Physics

SLAC is a world leader in exploring the frontiers of particle physics, from the nature of matter at its smallest scale to its implications for the origins, evolution, and future of the universe at the very largest scales. Our comprehensive suite of experiments addresses some of the most compelling questions in the field today: What is the nature of dark matter, dark energy, and neutrinos? How did the universe evolve from the earliest moments of the Big Bang? What is the structure of matter at the most basic level, and what are the fundamental forces that govern its interactions? These questions are central to the “Report of the 2021 U.S. Community Study on the Future of Particle Physics (Snowmass 2021)” in which SLAC scientists made major contributions to help plan the future of the field. This report, completed in 2023, was then taken up by the Particle Physics Project Prioritization Panel (P5) and led to a set of recommendations to DOE and NSF in their report, “Exploring the Quantum Universe.” The recommendations in these reports are strongly aligned with SLAC priorities and are a testament to our community engagement and leadership.

In pursuit of these questions, we maintain a strong theory group in elementary particle physics and cosmology and have a high level of expertise in building instruments, detectors, and facilities, and managing and operating large-scale projects. Our programs cover a wide range of scales from deep, wide surveys of galaxies to study the evolution of cosmic structure using the recently completed 3,200 megapixel LSST Camera, which will soon be installed and operated in the Vera C. Rubin Observatory, to the inner tracker for the ATLAS experiment at the Large Hadron Collider, which will discern particle tracks resulting from the highest energy collisions ever produced in the laboratory. The liquid noble elements xenon and argon are used in several sets of experiments. The nEXO experiment studies the neutrino through subtle nuclear decay processes. The LBNF/DUNE (Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment) project studies changes in the properties of neutrinos from production in a high-energy beam to detection in far off detectors. In the LUX-ZEPLIN project, researchers use liquid xenon detectors to search for individual collisions from dark matter particles that may have been produced in the early universe and make up the missing mass in the Milky Way’s dark halo. As this established technology is scaled up to probe more deeply for heavier dark matter particles, ever more subtle superconducting quantum sensors are being developed to search for other lighter forms of dark matter with Super Cryogenic Dark Matter Search (SuperCDMS) and Dark Matter Radio. Our superconducting sensor technology and readout technology are also used to study the cosmic microwave background (CMB) with the BICEP/KEK (Background Imaging of Cosmic Extragalactic Polarization/High Energy Accelerator Research Organization) array and eventually with the CMB-S4. Toward this goal, we are constructing the Detector

Microfabrication Facility, a superconducting sensor foundry that will be used to build CMB-S4 devices and potentially future cosmology probes. Across the program, these experiments generate extraordinarily large and complex datasets that drive the need for advanced data storage, processing, and analysis tools. Increasingly, our scientists develop and employ AI/ML techniques and algorithms to interpret patterns in the data.

Funding for this core capability comes from DOE-HEP, DOE-NP, and local SLAC-Stanford investments, and synergistically from DOE-BES (Q-NEXT).

Plasma and Fusion Energy Science

SLAC's plasma and fusion energy science core capability centers on the unique diagnostics of LCLS paired with high-energy lasers to probe dynamic high-energy density laboratory plasmas (HEDLP) with unparalleled precision. Our researchers bring foundational expertise to develop the science programs and tools for the advancement of HED science and technology. We work in strategic partnership with a growing group of key faculty at Stanford, and leverage ties to the laser-plasma user communities and nationwide facilities through LaserNetUS, National Laboratory partnerships, and the LCLS open-access user program. Our research in this area explores the underlying physics needed to model complex multi-scale burning plasma systems and astrophysical phenomena and develops technologies of laser-driven radiation sources and high repetition rate energetic laser-plasma interactions.

Precision Plasma State Measurement. We innovate and develop scientific techniques and diagnostics for measurement of transient high-density, high-temperature laboratory plasmas with sufficient precision to validate sophisticated *ab initio* models that in turn inform the coarser multi-scale models used to predict the behavior of astrophysical phenomena or inertial confinement fusion implosions. These include structure, radiative properties, transport properties, and the microphysics of plasma instabilities.

Plasma Technology. The execution of HEDLP experiments at high repetition rates – e.g., several Hz or more – is a frontier effort in the field and a crucial development on the path to a viable inertial fusion energy concept. SLAC innovates target and diagnostic technologies for conducting HEDLP experiments, including cryogenic and room temperature liquid targets, high repetition rate diagnostics adapted to harsh environments, and AI/ML based feedback and control. Additionally, we are continuing to lead an effort in real-time stream processing of multiple diagnostics at the flagship U.S. tokamak reactor DIII-D.

Dynamic High-pressure Materials. LCLS is ideally suited for the study of dynamically compressed matter at high strain rate and pressures, providing ultrafast measurements of phase change kinetics, atomic structure, or the microstructural response to defects. This allows access to warm dense plasmas and precise studies of inertial fusion energy target ablator physics and extreme materials in support of energy security, national security, advanced/additive manufacturing, aerospace engineering, and geo/planetary science.

Funding for this core capability comes from DOE-FES and LDRD investments and serves the DOE-SC mission in scientific discovery and innovation.

Systems Engineering and Integration

SLAC's core capability in systems engineering and integration encompasses a comprehensive range of disciplines and methodologies designed to ensure the successful development, deployment, and maintenance of complex systems. From the conception and development of advanced scientific instrumentation and large-scale user facilities to their integration, operation, and continuous improvement, SLAC has a proven record of accomplishment in delivering world-leading systems engineering practices, as well as a disciplined approach to systems engineering.

Each phase in the life cycle of an engineered system is defined in terms of the processes that dictate how systems are designed, realized, entered into operations, and supported, as well as technical management. These processes encompass the entire life cycle of engineered systems and subsystems, starting from identifying scientific requirements and extending their seamless integration into the operational environment. Within a given project, the rigor defines which of these processes are implemented and what will be needed within each phase, all of which is determined by analyzing the risks. The management of requirements plays a critical role in this endeavor. SLAC utilizes various digital tools to ensure that requirements are fully traceable, aligning the system's evolution with stakeholders' expectations.

Our strength in systems engineering and integration is especially integral to large-scale, collaborative projects. The SLAC led DOE 413.3b project, Matter in Extreme Conditions Upgrade (MEC-U), involves the complex development and integration of mechanical, controls, laser optical, and facility construction with our partnering laboratories, LLNL and the Laboratory for Laser Energetics at the University of Rochester.

Similarly, as the lead laboratory in the LCLS-II project, we facilitated the integration of numerous complex systems that we and our partners designed and constructed. We partnered with Fermi National Accelerator Laboratory (Fermilab) and the Thomas Jefferson National Accelerator Facility to design and construct cryomodules and with Berkeley Lab, Argonne National Laboratory, and other institutions to develop undulators. Moreover, we led the construction of the world's largest digital camera for astrophysics and cosmology, the LSST Camera, which is currently being integrated into the Rubin Observatory's fast-moving telescope. The LSST Camera serves as a prime illustration of systems engineering principles, particularly in configuration and interface management. This seamless integration of complex components and advanced technologies into a unified system highlights our effective coordination and integration and is exemplary of our core capability.

Funding for this core capability primarily comes from DOE-BES, DOE-FES, and DOE-HEP.

Science and Technology Strategy for the Future / Strategic Initiatives

Our core capabilities represent the foundation of our science and technology strategy, and our major initiatives represent priority focus areas in which we strive to make specific and significant impacts. Our major initiatives, spanning core mission, enabling capabilities, and emergent opportunities, in FY 2024 are:

I. Core Mission Initiatives: Advance the forefront of our core mission areas and assert world leadership, in collaboration with our principal sponsors in the Office of Science.

1. **X-ray and Ultrafast Science**
2. **Physics of the Universe**
3. **High Energy Density Science**

II. Enabling Capability Initiatives: Strengthen essential crosscutting research and development thrusts.

4. **Integrated Scientific and Data-Intensive Computing**
5. **Accelerator Research and Development**

III. Emergent Opportunities Initiatives: Seize emergent opportunities that respond to national needs and to which SLAC can make a unique contribution, often leveraging our partnership with Stanford.

6. **Sustainability Research**
7. **Semiconductors and Microelectronics**

8. **Biosciences and Human Health**
9. **Quantum Information Science and Technology**

For each initiative, we highlight our strategy and motivation, specific priority objectives within the initiative, and the associated resources needed to accomplish them. In general, these resources span commitments of leadership bandwidth and discretionary investments, including LDRD, program development and planning support, equipment acquisition, and infrastructure projects. Our partnerships (collaborations, SPP scope, and industry engagements) are key enablers as is strategic alignment with our principal DOE-SC sponsors.

Infrastructure

Overview of Site Facilities and Infrastructure

SLAC has always benefited from the extensive support of Stanford, starting with the 426 acres of prime Silicon Valley land leased from the university and located adjacent to the main campus. In 1962, DOE and Stanford signed an initial land lease agreement, which was renewed in 2010 and expires in 2043. The university has also supported the laboratory's recent science and infrastructure growth by funding construction and building improvements over the past two decades. Their latest contribution is the completion of a 15,000-square-foot expansion to the existing SRCF, providing more capability and reliability for vital scientific computing resources. The strong partnership between Stanford and DOE continues to facilitate our execution of DOE-SC core capabilities and our major initiatives, from our strongholds in X-ray and ultrafast science, physics of the universe, and high energy density science to newer areas in quantum information science, sustainability, biosciences and human health, and semiconductors and microelectronics.

Our total real property inventory consists of 372 assets, including 170 buildings, 177 other structures and facilities (OSFs), and 25 trailers. The most common land use of these assets is "mixed-use," composed of offices, laboratories, research facilities, and support structures. The largest of our facilities is the 2-mile-long Klystron Gallery and Accelerator Housing, which contains our superconducting and copper accelerators.

The utility infrastructure systems that support our science mission include electrical power, natural gas, telecommunications, and compressed air. These systems also include those for chilled and hot water, domestic water, cooling tower water, low-conductivity water (LCW), stormwater, sanitary sewer, and fire protection.

The average age of SLAC-operated facilities and utility infrastructure is 39 years old; however, it is important to note that approximately 37% of our assets were constructed 60 years ago with the initial construction of the laboratory. Since the laboratory's inception, SLAC has grown from a singular focus on particle acceleration to a multi-program laboratory, with corresponding growth in the number, type, and diversity of facilities. Supporting this physical and mission growth has been increasingly impacted by the operational fragility introduced by aging infrastructure and utility systems and a lack of adequate redundant and emergency infrastructure. As we plan for the mission needs of the upcoming decade, we need to keep in mind our infrastructure's current state.

SLAC Campus Strategy

Our goals prioritize site resiliency and reliability to support established and emerging laboratory initiatives, provide flexible and collaborative spaces for scientific exploration, and reconfigure existing facilities to support our growth and create high-impact science today and into the future. Since the construction of the core infrastructure in the 1960s, many facilities and utility systems have reached end-of-life and now have decreased reliability. The cost of infrastructure maintenance is steadily increasing, in both raw material and labor costs.

Recent lead times for critical repair parts and new infrastructure components have increased dramatically. This puts a significant strain on maintaining operational uptime, and SLAC has experienced an unprecedented frequency of utility interruption and recovery events that have significantly impacted our operations.

External environmental factors and challenges have continued in recent years, reinforcing our commitment to preparedness, resiliency, and planning infrastructure needs to include risk mitigation for various threats. Wildfires in the local area threaten the reliable delivery of power to the laboratory, and increasingly severe rain and flooding events exacerbate erosion in aged stormwater infrastructure. Given these challenges, it is critical that SLAC, DOE, and Stanford continue to aggressively reduce operational fragility while simultaneously positioning the laboratory's infrastructure to execute the science of tomorrow.

SLAC's campus strategy and associated infrastructure investments focus on optimizing the use of current assets, expanding and/or modernizing facilities to provide flexible and adaptive spaces, and synchronizing planned operations and maintenance (O&M). Our three campus strategy goals are as follows:

1. ***Configure Laboratory Infrastructure to Support Evolving Mission Needs.*** Create capable environments through renovation and new construction that will support core, new, and emerging laboratory initiatives.
2. ***Revitalize and Modernize Utility Infrastructure.*** Create a resilient, robust, and flexible campus utility system through both indirect investment and line-item construction programs to enable scientific expansion.
3. ***Modernize, Consolidate, Replace, and Repurpose Existing Facilities.*** Reimagine our spaces by maintaining a prudent investment program, aligning with our mission strategies, and applying DOE's sustainability goals.

We manage our campus proactively, with investments strategically aligned with our vision to be a world-leading laboratory. As illustrated in the figure below, SLAC's 10-year planned facility and infrastructure investments are aligned with major growth in science programs. Each project is listed under the campus strategy goal it meets, illustrating how various investments are leveraged for a unified infrastructure vision.

While the SLAC Long-Range Vision document (2015) provided a then-accurate blueprint for physical infrastructure to support DOE's science mission over the long term, it needs a comprehensive refresh to account for our core capabilities and strategic initiatives as articulated in sections 3 and 4. Our next update to the Long-Range Vision, to be completed in FY 2025, will require significant input from our science partners to calibrate the trajectory of growth and infrastructure requirements. The strategy for achieving this vision includes a near-term focus to address known vulnerabilities, current capability gaps, and deteriorating utility infrastructure, coupled with a long-term focus on renewing aging facilities in preparation for the next wave of scientific research. We will leverage both direct and indirect infrastructure investments to close capability gaps and maintain mission-ready facilities today and into the future.

Campus Strategy Goal 1: Configure Laboratory Infrastructure to Support Evolving Mission Needs

Whether we are providing new collaboration capabilities for high-data-density scientific programs and user facilities such as the Vera C. Rubin Observatory, LCLS-II, and LCLS-II-HE, or renovating and modernizing existing utilities and facility assets to support major scientific initiatives, we are focusing on adapting laboratory infrastructure in support of core, new, and emerging scientific capabilities.

Large Scale Collaboration Center

The LSCC (CD-1 Q1 FY 2020, TPC $66 million; TPC, Total Project Cost) represents a new model and vision to provide collaborative spaces for developing new science. While the ASC already delivers multi-mission laboratory and office spaces, the LSCC facility will enable deep collaboration among programs and support analysis of large data streams from LCLS-II and LCLS-II-HE (DOE-BES, NIH), Rubin Observatory (DOE-HEP, NSF), FACET-II (DOE-HEP), SSRL (DOE-BES, DOE-BER), cryo-EM (DOE-BER, DOE-BES, NIH), and associated DOE-ASCR activities and will help support growth at SLAC by co-locating approximately 100 personnel from major programs.

LSCC is currently pursuing procurement for a design-build partner to deliver the project. It will utilize a design-to-cost approach at $42 million for the 24,000-30,000 gross square feet collaboration facility. DOE CD-2/3 approval is anticipated in Q4 FY 2024 or Q1 FY 2025. Contract award is anticipated in Q2 FY 2025. The project will incorporate sustainability initiatives such as LEED Gold, high-performance sustainability buildings (HPSBs), and all-electric building design to support long-term Site Sustainability Plan goals. Beneficial occupancy is expected in Q4 FY 2027.

Notable Infrastructure

The East Campus Site & Utilities Improvement (ESUI) Project will provide improvements to the easternmost portion of the campus, supporting user facility upgrades and increasing the resilience of the utility distribution systems. Site improvements include civil work necessary for an additional access road, mechanical utility expansion, improved cooling tower water service, and electrical distribution upgrades. ESUI will provide critical support for current and future initiatives, including MEC-U, LCLS-X, and additional east campus development. Supported user science programs serve DOE-FES and DOE-BES, as well as the NSF, AFOSR, and international sources.

Civil, utility, and access improvements along the Klystron Gallery and Accelerator Housing are planned as part of the site restoration projects. These efforts will expand utility services, including appropriate shut-off capabilities along the south side of the Klystron Gallery, power availability and flexibility, communications, chilled and low-conductivity water, compressed air, sanitary sewer, and storm drainage. Roadway conditions along the North Access Road, north of the Klystron Gallery, will also be improved to support future operational needs and increased traffic volume as multiple projects (LCLS-II-HE, CUIR, and CRMF) begin heavy construction work along the Klystron Gallery and Accelerator Housing.

The Klystron Gallery Power Distribution Infrastructure project will modernize core electrical distribution to standard motor control centers, facilitating resilient power delivery and supporting various science programs along with and downstream of the accelerators.

General cleanup efforts at multiple sites throughout the laboratory have restored underutilized facilities. While these efforts fulfill an immediate operational need, they also kick-start plans to readapt and reuse this "standby" infrastructure to support new and emerging laboratory goals and initiatives. With this same goal in mind, we are installing equipment assembly facilities across the laboratory, the most recent being a prefabricated equipment assembly area installed on the east apron of the Collider Experimental Hall. The project includes the assembly area, gowning room, clean room, and associated utility connections to support installation and operation.

Non-DOE Infrastructure Projects Supporting Our Campus Strategy and Major Initiatives

As demonstrated by previous contributions, Stanford remains committed to SLAC and continues to drive the development of a "best-in-class" laboratory in support of the DOE mission. We continue to leverage this partnership to grow the laboratory, with key support facilities benefiting DOE science programs, staff, and the user community. Such facilities and areas already exist with the Kavli Building, ASC, SRCF, Stanford Guest House, Arrillaga Recreation Center, and our beautiful outdoor Quad. Stanford recently doubled the capacity at the SRCF via the SRCF-II project and is currently developing proposals for a jointly beneficial lab fit-out on the third floor of the ASC. Stanford continues to study increasing the number of rooms at the Stanford Guest House to support the visiting user community at SLAC, which is growing due to LCLS-II coming online and LCLS-II-HE being under construction.

Detector Microfabrication Facility

SLAC, Stanford, and DOE worked together to realize the DMF on the first floor of the ASC, supporting our major initiatives in physics of the universe and quantum information science and technology. This superconducting device foundry consists of 5,400 square feet of class-100 clean room space with tooling optimized for qubits, detectors, and advanced quantum devices. The DMF will allow us to improve the yield and robustness of superconducting processes to produce efficient, consistent, and high-yield superconducting quantum devices and capabilities in order to support Q-NEXT and leverage other DOE missions.

The fit-out construction of the clean room and infrastructure was completed in August 2022, and all new fabrication tools have been purchased with the majority delivered to the clean room shell. The tool hookup construction and installation effort started in September 2023, including moving and installing existing tools at Stanford's campus. The DMF clean room is expected to be operational by the end of 2024.

Stanford Research Computing Facility Expansion

Receiving beneficial occupancy in January 2024, SRCF-II represents a Stanford commitment of approximately $40 million to expand the original SRCF facility by over 15,000 square feet, doubling both the footprint and peak power (from 3 MW to 6 MW; MW, megawatt) of the existing data center. Combined, SRCF and SRCF-II support the SLAC-Stanford science research community by hosting a HPC infrastructure in an advanced data center facility. This expansion will directly support the Rubin U.S. Data Facility, enable real-time data extraction from LCLS-II and LCLS-II-HE, and provide support for numerous science programs across SLAC and Stanford. The expanded facility offers flexibility for varying HPC equipment loads within individual rack rows and improved energy efficiency with lower operational costs compared to traditional data centers.

Campus Strategy Goal 2: Revitalize and Modernize Utility Infrastructure

Utility resiliency and reliability are essential for meeting the requirements of user facilities, scientific instruments, laboratories, and experimental equipment. With the construction of next-generation systems, high-energy accelerators, process plants, and state-of-the-art equipment, world-class science requires tight tolerances and high reliability. We must transform our aging infrastructure by modernizing systems to meet the demands of the science we support. Furthermore, the modernization of infrastructure will help to mitigate emerging threats to operations and reduce carbon emissions through increased efficiency.

Critical Utilities Infrastructure Revitalization Project

As a Science Laboratories Infrastructure Line Item (SLI-LI) project, the purpose of CUIR is to modernize our utility infrastructure to provide reliable electrical, civil, and mechanical utilities for the laboratory and its accelerators. Utility improvements planned in CUIR incorporate sustainability aspects to improve the energy efficiency of our utility systems and reduce our overall carbon footprint by incorporating the use of embodied carbon and renewable fuel.

The project is organized into three subprojects to efficiently execute utility improvements in alignment with laboratory priorities and operational downtime schedules. The three subprojects are as follows:

- **Subproject 1 – Critical Electrical System Improvements (FY 2022 to FY 2030).** Modernize the electrical system through expansion of the existing Master Substation Building, replacement of the existing vintage 12.47-kV (kilovolt) transformers, switchgear upgrades, construction of a new substation (K-5B), and installation of new electrical 12.47-kV feeder pathways along the Klystron Gallery to increase power distribution capacity and overall reliability to the linear accelerator. CUIR will also install modern supervisory control and data acquisition (SCADA) hardware to further enhance energy metering and energy dashboard capabilities, aligned with DOE's energy tracking and operational efficiency goals.
- **Subproject 2 – Critical Civil Utilities Replacement and Upgrades (FY 2024 to FY 2032).** Modernize the civil utility systems along the Klystron Gallery and Accelerator Housing, including upgrading the sewer and storm drain systems and the domestic and fire protection water systems, as well as installing

metering and monitoring equipment on civil utility systems. These improvements will enhance performance and adjust usage to achieve long-term sustainability goals.

- **Subproject 3 – Critical Mechanical Utilities Upgrades (FY 2025 to FY 2034).** Upgrade and modernize mechanical utilities such as replacing low-conductivity water and process water systems along the Klystron Gallery and Accelerator Housing as well as pumps, heat exchangers, valves, and aged mechanical piping. In addition, Subproject 3 includes the installation of smart meters and programmable logic controllers (PLCs) on cooling water mechanical systems.

CUIR received CD-0 approval from the Energy Systems Acquisition Advisory Board (ESAAB) in May 2019, CD-1 from ESAAB in January 2022, and CD-3A from ESAAB in May 2023. The project has a total estimated cost (TEC) range of $160 million to $307 million. In 2024, CUIR is targeting to achieve CD-2/3 Performance Baseline and Start of Construction approval for Subproject 1. Concurrently, CUIR initiated engineering surveys and preliminary engineering design for Subproject 2 in 2024, which will continue through 2025. Scoping of Subproject 3 is currently planned to begin in FY 2025. Continued funding and support from SLI are essential for CUIR to continue to make progress and so to provide reliable and resilient utility systems to support DOE's science programs.

While CUIR is focused on the highest priority utilities requirements, a planned broader Mechanical and Civil Site Utility Improvements project (SLI-LI proposal) will continue efforts to provide reliable, efficient, and sustainable utility systems to support ongoing and future scientific research. The scope of work includes sewer system replacement (west and main campus), recycled water infrastructure, domestic water system replacements, storm drain system improvements, and cooling water, as well as HVAC (heating, ventilation, and air conditioning) system modernization.

Electrical Power

While CUIR will eliminate some vulnerabilities in primary distribution, most of our electrical distribution is aged beyond its expected lifespan. Preventative maintenance, timely inspections, and management of critical spares are key reasons we continue to be able to deliver on our scientific mission. The site is fed from two separate utility grids but is currently unable to continuously operate on both grids independently. Our backup 60-kV source is unable to fully support laboratory operations and requires load shedding when switching from our primary 230-kV source. Ensuring reliable and resilient power requires a plan designed to utilize both incoming power sources and the replacement of aged infrastructure and distribution.

A key infrastructure element is the DOE-owned 5.4-mile 230-kV transmission line. The transmission line's path travels through densely forested hillside areas, and its associated power poles are significantly lower than is typical for this voltage. Vegetation management along the 230-kV corridor is required to mitigate outage and fire hazards.

Our scientific equipment is sensitive to power fluctuations, where a voltage transient can often trip automated accelerator protection systems, and the site suffers from poor power factor correction at our Master Substation. To improve this, we have submitted a general plant project (GPP) request to correct power factor deficiencies and ensure cleaner and more efficient power delivery to the entire site. We are also assessing the installation of additional backup power capability to ensure critical systems are not damaged by short-term interruptions and to reduce possible risk to personnel and property.

Major maintenance and repair activities are focused on 12.47-kV substations throughout the site; approximately 20 substation preventive maintenance activities are completed per year. Electrical infrastructure remains a concern across the laboratory and requires diligent monitoring.

Cooling Water

The modernization of existing HVAC and cooling water systems (cooling towers and pipelines) will improve overall operational efficiency, reduce the use of fossil fuel/natural gas, and support a more active response to changing climate conditions for our science users. Some existing aging mechanical systems also create vibrations that interfere with science experiments and so impact our science mission.

Modernization of cooling tower 1701 cells A & B (SLI-GPP; direct-only TPC $11.55 million) was completed in November 2023, providing a more reliable and efficient cooling system. Additionally, this upgrade provides more energy-efficient pumps, cooling tower fans, and controls that reduce energy and water consumption, resulting in estimated savings of over 500,000 gallons of water and 1.1 MWh (megawatt hours) of electricity annually. A proposed project, Phase II, will modernize cells C & D and provide reliable redundancy and more cooling capacity to support program growth.

Additional projects underway include replacing obsolete pumps at the LCW pad, upgrading the system that provides magnet-cooling water for the accelerator beam switchyard, and fire protection upgrades all support accelerator science programs.

Underground Utilities – Sanitary Sewer & Storm, Domestic Water, and Telecommunications Systems

Significant deterioration in the storm drain, water, and sewer systems has resulted in flooding, road washouts, sinkholes, and undesirable discharges. With climate change, more extreme storm events exacerbate system deterioration. We encountered this directly during the severe winter rain events that California experienced in 2023 and early 2024, resulting in significantly accelerated deterioration that required repairs. Diagnostic efforts are in progress to assess the highest risk areas, including multiple large stormwater pipes passing directly underneath the accelerator housing, where complete collapse could pose catastrophic risks to accelerator scientific programs. This development activity will inform a targeted, risk-prioritized repair effort beginning in FY 2025.

The original water utility distribution systems do not incorporate the latest sustainability practices such as detention, infiltration, reuse, and recycling of water. In 2023, we applied for multiple Assisting Federal Facilities with Energy Conservation Technologies (AFFECT) grants. While we did receive a high-bay lighting upgrade grant, which makes us one of the few DOE-SC laboratories to become a grant recipient, we were not awarded the recycled water study grant in this cycle. The laboratory remains committed to moving forward with a study to determine recycled water chemistry, treatment, and filtration for the potential to utilize municipal recycled water in the cooling tower infrastructure. The study will also determine the life cycle cost impacts and recommended endpoints for the future use of recycled water to reduce potable water consumption.

Campus Strategy Goal 3: Modernize, Consolidate, Replace, and Repurpose Existing Facilities

We are taking a comprehensive look at the laboratory's existing space, available footprint, and current capabilities to strategically plan how our space inventory can better meet programmatic needs. With this laboratory-wide approach, we are attempting to maximize efficiency, ensure proposed renovations are well coordinated and programmed to support the next generation of scientific discovery, and be as cost effective as possible while still supporting flexibility and improved sustainability. Facilities and Operations (F&O) Building and Space Management is refining utilization standards and space management policy to promote collaboration and cross-functional team support, provide a formal mechanism for space allocation requests, and support data-gathering and space reservation tools to make data-driven decisions on utilization.

SLI-LI Proposals (Campus Building Renovation Projects)

This assortment of proposed projects includes some of our largest and most highly utilized laboratory and office buildings, already optimally located around the central Quad, constructed as part of our original campus in the 1960s and early 1970s. These Campus Building Renovation Projects include maintenance and improvements to the Central Laboratory, Test Laboratory, Central Laboratory Addition, and Computation Building (B040, B044, B084, and B050, respectively). While the basic structural core and shell construction of these buildings are sound, interior and exterior spaces, utility systems, and building envelope components are obsolete. The proposed line-item projects will look at the limitations of existing buildings and confirm if they can be cost-effectively modernized to meet the needs of future scientific demands, resulting in new capabilities, upgraded working conditions, and a reliable building shell and infrastructure. This initiative contributes to our sustainability and efficiency goals and prepares facilities to continue to support our scientific mission.

The Central Laboratory contains multiple laser, chemistry, microbiology, catalysis, geoscience, and energy storage laboratory spaces. The ESD and Fundamental Physics Directorate (FPD) staff, as well as Stanford-SLAC joint institutes including the Photon Ultrafast Laser Science and Engineering Institute (PULSE), SIMES, and SUNCAT, all occupy space in the Central Laboratory building.

The Test Laboratory building supports the TID staff and associated facilities for the development, fabrication, and testing of high-power RF sources. Also occupying the same building is the MeV-UED, a key LCLS user facility. Klystrons are high power RF amplifiers, key to the operation of FACET-II, LCLS (including the UED facility), and the NLCTA test facility. TID also develops new RF sources for other DOE and international labs, as well as strategic partnerships.

The Computation Building houses all our mission-support computing infrastructure, as well as scientific computing resources not relocated to SRCF and tape backup for scientific data redundancy.

The Central Laboratory Addition building also houses TID and FPD staff, as well as RF, elementary particle physics, and advanced instrumentation and research clean rooms and laboratories.

If the renovation of these buildings is not addressed, core building systems will continue to degrade, jeopardizing key scientific and mission support programs. In some cases, degradation of building envelope systems could result in damage to the building structure due to water intrusion, further shortening the serviceable lifespan of the facility. A comprehensive renovation and modernization program would also significantly enhance the sustainability and efficiency of the facilities, reducing operating costs and helping to meet DOE sustainability program targets.

Site Security and Access Improvements: Main Gate

The Main Gate project, authorized to proceed in August 2023, aims to address critical deficiencies in current security infrastructure and includes two major components. The first component of the project will replace the Main Gate House, which is the entrance gatehouse at the site's primary point of entry, with a modern security dispatch center, implementing updated safeguards and security systems and increasing operational efficiency for security personnel. The second phase will improve the associated ingress and egress from Sand Hill Road by reconfiguring the roads, improving walking paths, and adding bike lanes, all to provide safety for security officers, staff, and visitors. The project will install cables and utility pathways for future radiation portals at the Sand Hill Road exit lanes to reduce the risk of accidental offsite transport of activated materials.

The project is fully funded by $5.9 million from SLI-GPP/Inflation Reduction Act program funds. Execution will utilize a design-bid-build procurement, with the design partner planned to kick off design activities in Q3 FY 2024. Construction is currently slated to begin in Q1 FY 2026, with substantial completion in Q4 FY 2026 and project closeout in Q2 FY 2027.

Planning and Asset Management

Our infrastructure planning and asset management program includes efforts supporting real property data accuracy, facility condition assessments, requirements collection and tracking, and preparing proposed investments for budget prioritization and authorization. Here we describe the high-priority process improvements, most recent deferred maintenance (DM) trends, the Maintenance Investment Index (MII), overall asset condition(s) reflected in the Condition Index (CI), and replacement plant value (RPV). These ongoing efforts are key factors in the overall life cycle tracking of assets and provide the basis to achieve optimal facilities stewardship for the broader campus strategy and long-range vision.

Facilities Infrastructure Renewal and Sustainment Tracking (FIRST) Program

The electrical incident that occurred during planned maintenance in December 2022 prompted an in-depth analysis of contributing factors and root causes. The ensuing Accident Investigation Board report resulted in 16 Judgments of Need, along with corrective actions proposed as our response. One of the corrective actions included the goal of developing a facility and infrastructure renewal plan with the following objectives:

1. Sustainably implement an effective tactical and long-term infrastructure management program.
2. Consider operational risk and address all conventional infrastructure management in a risk-based approach.
3. Update the plan continuously and assess it annually.
4. Align the plan with the local budget process to ensure the allocation of sufficient resources for its sustainable implementation.
5. Specifically include electrical infrastructure as a subset of the plan.

Key focus areas for addressing this goal include the following:

Improved planning rigor. Ensure requirements are properly assessed for mission need, prioritized, and organized into proposed budgets for execution.

Improved scope development. Manage development so that requirements are ready for execution, with accurate scopes and estimates, at the right time to support operational priorities.

Improved communication. Enhance collaboration both internally within F&O as well as between F&O and supported customers, including building and area managers, directorates and programs, and the Senior Management Team (SMT).

Improved transparency. Provide open, accessible organizational information on known facilities requirements for planning, risk assessment, prioritization, and budget cycle implementation with customer friendly key metrics, dashboards, and reporting tools.

To implement progress effectively in these focus areas, F&O has formulated the Facilities Infrastructure Renewal and Sustainment Tracking (FIRST) Program. The FIRST Program's intent is to document and describe the steps to assess infrastructure readiness, receive institutional infrastructure requirements, prioritize planning and execution, develop scoping packages, review priorities with stakeholders and leadership, establish proposed annual funding profiles, and track deficiencies from identification through completion and closeout.

Maintenance and Repair

The DOE has historically assumed a "rule of thumb" maintenance target of 2-4% for the MII. The MII is defined as the percentage ratio of Annual Actual Maintenance (AAM) in relation to Replacement Plant Value (RPV) as follows: MII = AAM/RPV. For FY 2023, our reported AAM was $21 million and RPV was $3.5 billion, which results in a low MII (0.61% across all property types).

However, DOE Asset Management (MA-50) recognizes that this target is typically assumed in commercial industry but may not represent the type of industrial infrastructure within the DOE complex. At SLAC, extremely high-value but relatively low-maintenance extensive experimental tunnels, such as the operational accelerator housing, and legacy infrastructure that remain from completed science programs such as the North and South Collider Arcs and the Positron-Electron Project (PEP) Beam Housing (kept in a "standby" state) do not support the maintenance criterion of a 2% MII for conventional infrastructure.

MII values were calculated separately for operational assets by property type: buildings, trailers, and two categories of "other structures and facilities" (OSF). The results are summarized in Table 4 below. Also provided is the Condition Index (CI) for each asset type, represented as the ratio of repair needs (RNs) to RPV. While the MII is low, the overall CI is relatively good when considered in relation to the average asset age. The FY 2023 data also illustrate that our largest maintenance investment continues to be assets with the lowest CI, namely our aging utility systems. Note that we prioritize mission-critical assets in its resource allocation strategy. Currently, 15% (55) of our facilities are categorized with an operational status of “standby,” are not considered mission critical, and typically have a very low AAM, resulting in a lower MII in general for our site.

Most of the laboratory’s utility infrastructure is old and inefficient, which increases overall maintenance needs and anticipated emergent repair costs. The planned SLI-LI CUIR project closes major electrical capability gaps across the campus, with parallel and subsequent planned SLI-LI projects, SLI-GPP, and institutional general plant projects (IGPP) to continue to address mission-critical civil, mechanical, and electrical utilities. For buildings, we do not invest at the typical industry standard MII of 2%; these assets are managed to keep them in relatively good condition, as demonstrated by the average CI of 93%.

Maintenance Investment Index and Average Condition Index (CI)
by Property Type for Operational Facilities

				OSFs					
		Buildings		**Utilities**		**Other**		**Trailers**	
AAM	**MII**	$12,557,739	0.53%	$7,530,631	0.84%	$886,823	0.47%	$28,148	0.26%
RPV		$2,353,260,990		$893,439,771		$190,345,209		$10,773,066	
Average CI (percentage)		92%		93%		96%		77%	
Source: FIMS Year-End Data FY 2023									

Deferred Maintenance Trends

As an integral part of our campus strategy, reducing DM is a weighting factor that drives the development of projects ranging from significant SLI-LI construction efforts to smaller institutional minor repair projects. The FIRST Program discussed above will improve the ease and transparency of project initiation and tracking, including implementing a mapping system to capture DM and RN from the Condition Assessment Information System (CAIS) and associating specific deficiencies with planned projects throughout the project life cycle, aiding in retiring DM and RN from CAIS at project closeout.

SLAC reported a DM cost of $94.2 million for FY 2023. However, the DM value is subject to many variables in any given year. Each year, deficiencies are removed as projects and maintenance activities are completed and added as the annual condition assessment cycle takes a fresh look at facilities. We have been proactively reducing the DM backlog with laboratory indirect investments in infrastructure projects, including repair or replacement of electrical substations, roofs, mechanical pumps, compressors, elevators, and sanitary sewer lift stations. Cumulatively, these efforts will retire as much as $12 million when completed by the end of FY 2025.

Site Sustainability Plan Summary

The SLAC Sustainability Plan is driven by goals from DOE’s most recent Executive Order-14057. In this executive order, two main points drive decision-making for sustainability projects:

- Achieve 100% carbon pollution-free electricity (CFE) on a net annual basis by 2030, including 50% 24/7 CFE.

- Achieve a net-zero emissions building portfolio by 2045 through building electrification and other efforts.

SLAC has a separate annual Site Sustainability Plan that covers all DOE sustainability goals in further depth. DOE has asked us to categorize efforts under the following elements:

Energy Management

- Reduce energy use intensity (BTUs [British Thermal Units] per gross square foot) in goal-subject buildings – in FY 2024, increases in building occupancy and clean room usage, including the build-out of the DMF, resulted in increased building energy use compared with the previous year. Successful recommissioning of HVAC controls reduced cooling/heating energy use by 18% on average in six buildings. For future planned efforts, SLAC plans to continue recommissioning and energy efficiency measures and to incorporate energy efficiency with the proposed modernization projects. There is a medium risk of nonattainment of this goal.
- Achieve a net-zero emissions building portfolio by 2045 through building electrification and other efforts – in FY 2024, SLAC submitted a SLI funding request to modernize multiple aged office and laboratory facilities that included plans to eliminate natural gas in these facilities and update inefficient equipment and the building envelope. For future efforts, we plan to target select natural gas-heated buildings for load analysis study as a first step toward electrification. We will also conduct life cycle-cost analyses to maximize efficiency features in proposed building modernization projects. Many facilities utilize central plant gas boiler hot water heat, which is challenging to upgrade cost-effectively. There is a high risk of nonattainment due to the financial cost of this goal.
- Energy Independence & Security Act Section 432 continuous (four-year cycle) energy and water evaluations – we have completed 13 facility energy and water audits that included the 40 facility evaluations required in the 2020-2024 audit cycle. For future efforts, we plan to pursue recommissioning in facilities with energy savings potential. There is a low risk of nonattainment of this goal.
- Meter individual buildings for electricity, natural gas, steam, and water where cost-effective and appropriate – currently, energy use intensity (EUI) goal subject buildings are metered for electricity and water usage. Natural gas metering is currently limited to main endpoints. In the future, domestic water metering improvements are planned. Installing meters in three facilities to measure natural gas loads is underway. There is a low risk of nonattainment for this goal.

Clean and Renewable Energy

Achieve 100% CFE on a net annual basis by 2030, including 50% 24/7 CFE – current electricity procurement includes renewable electricity on the electricity grid and hydropower through Western Area Power Administration (WAPA), which results in our electricity totaling 58% CFE. A renewable electricity power purchase agreement (PPA) was pursued through WAPA. However, the effort was canceled in 2023 due to failed contractual negotiations. We are part of the DOE California Laboratory Electric Power Consortium consisting of SLAC, Berkeley Lab, and LLNL that initiated a fresh effort in 2024 to explore renewable electricity PPAs to meet the goal. Despite best efforts, there is a risk of PPA contracts and construction lead times resulting in not achieving 100% CFE by 2030. There is a high risk of nonattainment for this goal.

Efficiency and Conservation Measure Investments

Implement life cycle cost-effective efficiency and conservation measures with appropriated funds and/or performance contracts – for FY 2024, SLAC implemented efficient lighting upgrades to reduce energy use and maintenance.

Implemented energy audits and building automation control systems recommissioning successfully – for future efforts on this goal, SLAC plans to continue strategy on cost-effective project implementation within the constraint of competing prioritization with infrastructure upgrades. There is a medium risk of nonattainment for this goal.

Adaptation and Resilience

Implement climate adaptation and resilience measures – for FY 2024, SLAC identified our highest climate-related risks, including wildfires, severe weather, and electricity interruptions, which are mitigated through planning and controls. For future efforts on this goal, SLAC will continue planning and mitigation through the established Business Continuity Program. There is a high risk of nonattainment of this goal.

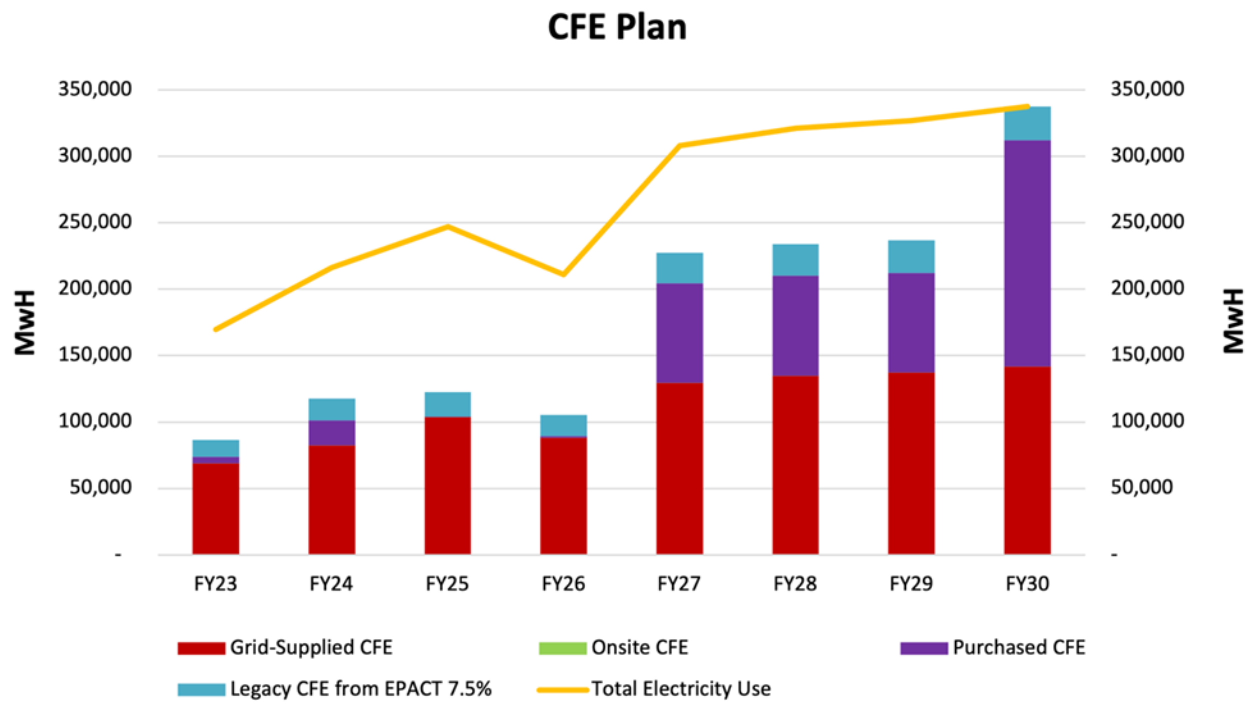


Figure: Carbon pollution-free Electricity (CFE) Plan. Note: EPACT, Energy Policy Act of 2005.

Carbon-free electricity and hydro power account for approximately 58% of the grid electricity purchased. Renewable power on the grid is projected to grow in California; however, this alone will not meet the Executive Order goal for 100% CFE by 2030. Therefore, additional options are being explored.

Large scale on-site CFE generation, carbon capture, and battery storage would incur construction-related interruption and come at elevated costs due to the economy in the local San Francisco Bay Area. The electricity consortium members agree that CFE goals are best achieved through long-term solar PPA contracts and that the option to purchase annual energy attribute credits is not cost-effective. The consortium partners have been meeting to estimate total annual greenhouse gas (GHG) profiles going forward and are working with the consortium's electricity management consulting firm, Exeter Associates, toward matching the need for long-term cost-effective electricity procurement and meeting the goal. If successful, we propose completing one PPA by 2027 and a second PPA by 2030.

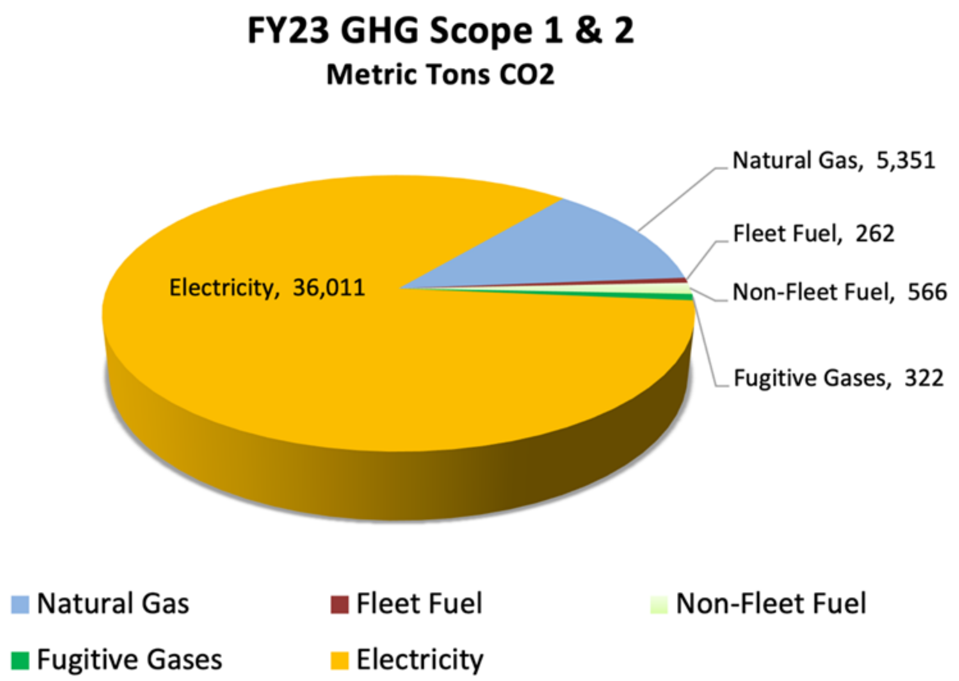
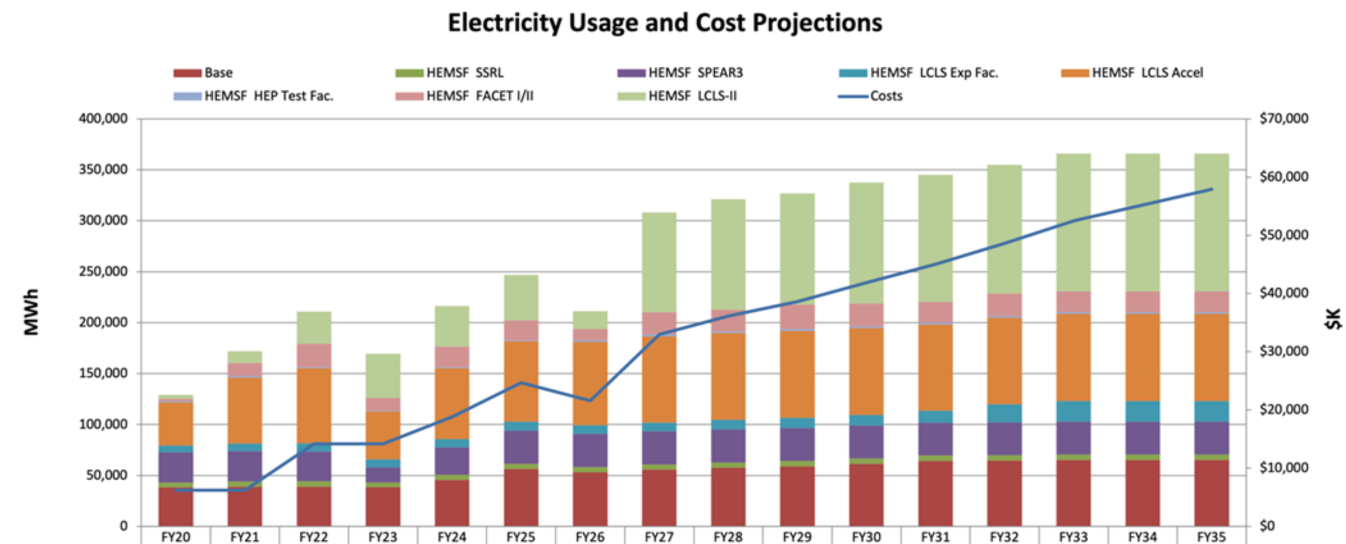


Figure: FY 2023 usage of greenhouse gases (GHGs)

Purchased electricity accounts for approximately 70% of sitewide GHG emissions, as illustrated in Figure 4 above. The CFE strategy described previously targets eliminating these emissions by the end of 2030.

SLAC is formulating a strategy to support electrification and GHG reduction through the following initiatives:

- Approximately 5,000 metric tons of SLAC GHG emissions come from natural gas. Main gas usage is at the two central plants that supply heated hot water through an extensive underground piping network to laboratories, offices, and science facilities. Ahead of creating a long-term strategy for replacing the central plants to meet the 2045 goal, SLAC is first investigating a strategy for electrifying the many stand-alone gas-fired heaters and boilers.
- SLAC initiated an internal study to quantify all gas-burning equipment and is increasing metering to support electrification, efficiency, and maintenance and operations improvements.
- Fleet services, in partnership with the Sustainability Program, has prioritized rotation of petroleum-fueled vehicles to plug-in and all-electric vehicles and was recognized with a DOE zero-emission fleet award in 2023. Using the award funds, site planning is underway to expand electrical vehicle charging to support fleet electric mobility.
- SLAC is exploring reduction in emissions from fuel used for forklifts and diesel generators by proposing utilizing renewable diesel (R-99) for select equipment. In addition, we have planned to replace aged forklifts with electric forklifts and have created a replacement plan.
- Emission-reduction efforts include pursuing energy efficiency through recommissioning audits. SLAC has requested SLI funding for modernization of aged facilities and to transform them into net-zero emission buildings.
- As noted earlier, SLAC was awarded an AFFECT Grant for $740,000 to supplement SLAC funding of $500,000 to upgrade lighting in high-bay science facilities that meet the deep-energy reduction goal for four of the five planned upgrades.



	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32	FY33	FY34	FY35
HEMSF LCLS-II	3,810	11,700	31,670	43,320	40,000	44,710	17,410	97,650	108,410	108,890	118,880	124,870	126,350	135,010	135,010	135,010
HEMSF FACET I/II	2,110	12,600	23,230	12,380	20,200	19,470	11,000	21,960	21,470	24,180	22,220	20,370	22,230	20,540	20,540	20,540
HEMSF HEP Test Fac.	1,300	1,600	820	700	770	900	1,560	1,700	1,700	1,700	1,700	1,700	1,700	1,700	1,700	1,700
HEMSF LCLS Accel	42,300	64,800	73,730	47,230	69,620	79,030	81,700	84,710	84,920	85,330	85,330	84,730	84,990	85,510	85,510	85,510
HEMSF LCLS Exp Fac.	6,720	7,700	8,130	7,720	8,260	8,760	8,760	8,670	9,440	10,050	10,250	11,660	17,390	20,130	20,130	20,130
HEMSF SPEAR3	29,600	29,600	29,130	14,830	26,900	32,570	32,270	32,340	32,450	32,340	32,340	32,340	32,340	32,340	32,340	32,340
HEMSF SSRL	4,800	5,100	5,140	4,630	5,130	5,260	5,260	5,260	5,260	5,260	5,260	5,260	5,260	5,260	5,260	5,260
Base	38,410	39,000	39,150	38,600	45,500	56,290	53,170	55,710	57,540	59,040	61,580	64,300	64,740	65,350	65,350	65,350
Costs	$6,200.0	$6,200.0	$14,200.0	$14,200.0	$18,800.0	$24,700.0	$21,600.0	$33,000.0	$36,100.0	$38,600.0	$41,900.0	$45,000.0	$48,600.0	$52,500.0	$55,200.0	$57,900.0

Figure: SLAC electricity usage and cost projections

Commissioning and start-up of High Energy Mission Science Facilities (HEMSF) such as LCLS-II, the Cryoplant Building, and the ASC laboratories and fabrication center will result in the site peak electrical load increasing from the current 33 MW. LCLS-II operations will be limited through FY 2026 for the LCLS-II-HE completion and commissioning. Once operational in FY 2027, the LCLS-II-HE doubles the LCLS-II beam energy, raising LCLS-II from 9.7 MW to an estimated peak load of 17 MW. This increase in operations, with the addition of completing the remaining planned science upgrades, leads to an estimated peak electrical load of 54 MW for the SLAC site. Load increases have been translated to annual megawatt-hour (MWh) power consumption in the graph in Figure 5 above.

Site base electricity includes estimated increases to account for process water cooling that supports multiple science programs. In addition to the multiple science program support, the site base includes the expanded computing facility, SRCF-II. The site base also includes offices and laboratory buildings for which energy efficiency is prioritized and tracked in the EUI goal. Increases in the demand to convert more spaces to laboratory clean rooms and proposed building renovations to electrify heating are also projected.

THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

Lab-at-a-Glance

Location: Newport News, VA
Type: Single-program Laboratory
Contractor: Jefferson Science Associates, LLC
Site Office: Thomas Jefferson Site Office
Website: www.jlab.org

- **FY 2023 Lab Operating Costs:** $204.8 million
- **FY 2023 DOE/NNSA Costs:** $202.1 million
- **FY 2023 SPP (Non-DOE/Non-DHS) Costs:** $2.7 million
- **FY 2023 SPP as % Total Lab Operating Costs:** 1.3%
- **FY 2023 DHS Costs:** $0 million

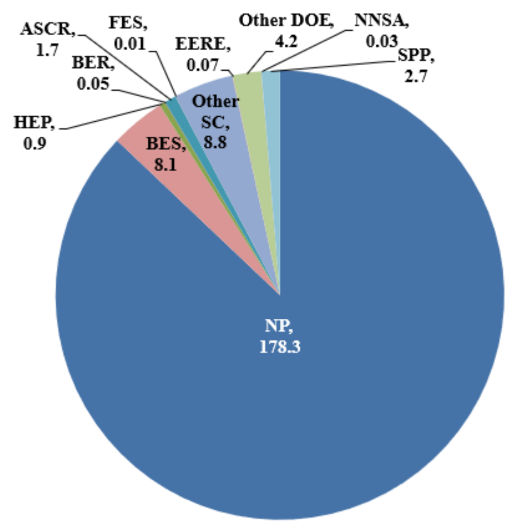
Physical Assets:

- 169 acres and 69 buildings
- 885,835 GSF in buildings
- Replacement Plant Value: $943 M
- 0 GSF in Excess Facilities
- 86,705 GSF in Leased Facilities

Human Capital:

- 873 Full Time Equivalent Employees (FTEs)
- 22 Joint Faculty (Incoming)
- 35 Postdoctoral Researchers
- 56 Graduate Student
- 20 Undergraduate Students
- 1,904 Facility Users
- 1,770 Visiting Scientists

FY 2023 Costs by Funding Source ($M)



Mission and Overview

Thomas Jefferson National Accelerator Facility's (TJNAF) expanding mission is to provide the nation with unprecedented capabilities to further human understanding of the tiniest constituents of matter through the Department of Energy (DOE) Office of Nuclear Physics, while developing advanced computing capabilities to fully exploit the power of data across the DOE Office of Science (SC). Recently, the Office of Advanced Scientific Computing Research (ASCR) chose TJNAF to a lead the development of a new capability dedicated to data intensive computing: the High Performance Data Facility (HPDF).

Nuclear Physics research at TJNAF reveals the fine details of the constituents of matter, from the familiar protons, neutrons, and electrons in the atom, to the lesser-known quarks and gluons inside the atom's nucleus.

Enabling these studies is TJNAF's world leadership in the development and deployment of large-scale superconducting radiofrequency (SRF) technology. SRF technology powers TJNAF's flagship facility, the Continuous Electron Beam Accelerator Facility (CEBAF). To reach higher energies, and thus more fully investigate the gluons, TJNAF is a partner with Brookhaven National Laboratory (BNL) in the designing and establishing the Electron Ion Collider.

The technical and research successes accomplished with CEBAF as a unique SRF particle accelerator have made possible a wide array of applications, from ever more powerful free-electron lasers for research to detectors that enable life-saving advances in nuclear medicine.

TJNAF attracts and retains a diverse and talented workforce to support its mission and maintain its core capabilities in Nuclear Physics; Large-Scale User Facilities/Advanced Instrumentation; Accelerator Science and Technology; Advanced Computer Science, Visualization, and Data; Mechanical Engineering and Design; and Systems Engineering.

TJNAF actively partners with industry to advance critical technologies to benefit the nation. The lab also invests in the next-generation science, technology, engineering, and mathematics (STEM) workforce, training one-third of U.S. PhDs in nuclear physics annually. TJNAF's outreach programs positively impact thousands of students and teachers while helping them build critical knowledge and skills for a brighter future.

TJNAF was established in 1984 in Newport News, Virginia, and is operated by Jefferson Science Associates, LLC (JSA), for the Department of Energy's (DOE) SC.

Core Capabilities

Nuclear Physics

(Funding: DOE SC Office of Nuclear Physics)

TJNAF is a unique, world-leading user facility for discovery studies of the structure of nuclear and hadronic matter using continuous beams of high-energy, polarized electrons. The nuclear physics program at TJNAF spans a broad range of topics in modern nuclear physics. LQCD calculations predict the existence of new exotic hybrid mesons that can be discovered with the new 12 GeV experiments, and elucidate the nature of confinement. New phenomenological tools have been developed that produce multidimensional images of hadrons with great promise to reveal the dynamics of the key underlying degrees of freedom — a new science program termed Nuclear Femtography. Development of measurements of exceptionally small parity-violating asymmetries with high precision has enabled major advances in hadronic structure, the structure of heavy nuclei (through measurement of the neutron distribution radius), and precision tests of the Standard Model of particle physics, including a measurement of the electron's weak charge.

The theoretical research program at TJNAF pursues a broad program of theoretical research in all areas of QCD and hadron physics, promoting and supporting the physics studied at Jefferson Lab's 12 GeV program, and providing leadership for national and international nuclear physics research efforts. It is a key component of TJNAF's research program. Excellent synergy exists between the TJNAF experimental, theoretical, and computing programs. The Joint Physics Analysis Center (JPAC) develops theoretical and phenomenological understanding of production and decays of hadron resonances, which helps bridge the analyses and interpretation of experimental data from TJNAF with the results of LQCD calculations. The Jefferson Lab Angular Momentum (JAM) and CTEQ-Jefferson Lab (CJ) collaborations pull expertise in QCD theory, phenomenology, and HPC to develop new and better tools to help extract the 2D and 3D tomography of hadrons from TJNAF data. TJNAF was the first to make use of GPUs for HPC based on heterogeneous architectures (for LQCD calculations) and continues this innovative approach to present needs, including wide embracement of AI/ML in nuclear physics techniques.

TJNAF leads the world in enabling technology development such as high-power polarized targets and high rate detector deployment. For the latter, the laboratory is working toward becoming a national resource for micro-pattern gaseous detectors (MPGDs). An MPGD facility has been proposed to be located at TJNAF. The research and development of new MPGD-based detectors for a range of applications has been rapidly increasing in recent years, with ever-larger deployments of such detectors in nuclear and particle experiments, as well as for such varying applications as muon tomography, materials science, security inspection and medical imaging. The envisioned facility would provide expertise, design support, testing, training to interested researchers for the purpose of R&D, and prototyping of new detectors – and would aim to further MPGD detector technology with new capabilities and implementations. Additionally, this facility would become a curator of institutional knowledge on the design of MPGD detectors and the production of MPGD amplification layer production in the US.

TJNAF actively partners with BNL to provide important expertise and capability to ensure successful implementation of the EIC, including taking responsibility of scope that benefits from TJNAF's longtime intellectual investment in the EIC, TJNAF's core expertise, and its wide international user community.

Large-Scale User Facilities/Advanced Instrumentation

CEBAF (Funding: DOE SC – Nuclear Physics)

The CEBAF electron beam can be simultaneously delivered to the experimental halls at different energies. With the completion of the 12 GeV Upgrade, the beam energy can be up to 12 GeV, converted to 9 GeV photons for Experimental Hall D, and up to 11 GeV to Halls A, B, and C. Each experimental hall is instrumented with specialized experimental equipment designed to exploit the CEBAF beam. The detector and data acquisition capabilities at TJNAF, when coupled with the high-energy electron beams, provide the highest luminosity (10^{39}/eN/cm^2/s) capability in the world. The TJNAF staff designs, constructs, and operates the complete set of equipment to enable this world-class experimental nuclear physics program, in close collaboration with a large domestic and international user community of more than 1,900 users annually.

Hall D is dedicated to the operation of a hermetic large-acceptance detector for photon-beam experiments, known as GlueX. Hall A houses two high-resolution magnetic spectrometers of some 100 feet in length and a plethora of auxiliary detector systems, including the large-acceptance Super BigBite Spectrometer. Hall B is home to the CLAS12, with multiple detector systems and some 100,000 readout channels. Hall C boasts two roughly 80-foot-long, high-momentum magnetic spectrometers that allow for precision scattering experiments, and has housed many unique large-installation experiments. Maintenance, operations, and improvements of the accelerator beam enclosure and beam quality, and the cavernous experimental halls and the multiple devices in them, are conducted by the TJNAF staff to facilitate user experiments. Important capabilities related to the experimental program include state-of-the-art particle detection systems, high-power cryogenic targets, polarized targets, high-speed readout electronics, and advanced data acquisition technology.

HPDF Hub (Funding: DOE SC — Advanced Scientific Computing Research)

Scientific computing at TJNAF is entering a new era with its selection as the site of the hub of the ASCR-funded High Performance Data Facility (HPDF) and lead laboratory for the HPDF project in partnership with LBNL. The integrated HPDF project, though in its early stages, is already showing strength and fruitful promise. The project is working toward a conceptual design and CD-1. TJNAF is participating in the Integrated Research Infrastructure (IRI) working groups to ensure alignment between the IRI and HPDF. TJNAF anticipates that HPDF will become the nation's 29th Office of Science user facility in the coming years.

Accelerator Science and Technology

(Funding: DOE SC – Nuclear Physics, Basic Energy Sciences, High Energy Physics, Department of Defense (DoD) Office of Naval Research, Commonwealth of Virginia, and Industry)

SRF Accelerators. The SRF accelerator system consists of multiple integrated technologies with expertise spread throughout multiple disciplines and departments. TJNAF maintains collaboration and communication among all associated subsystems essential to maintaining and enhancing SRF capabilities. System integration essential to an effective SRF system includes cavity fabrication and processing, cryomodules, low-level RF controls, high-power RF, cryogenics, software and hardware controls, and monitoring systems. Ensuring that each of these subsystems maintains state-of-the-art capabilities is critical to maintaining a world-leading program in SRF accelerator system capabilities. To accomplish the mission, the SRF Institute must maintain a comprehensive set of expertise and facilities to support SRF technologies at TJNAF and be ready to respond to current and future needs of TJNAF, the DOE complex, and other partners. TJNAF's SRF facilities occupy approximately 60,000 SF of contiguous space all under one roof, which includes 30,000+ SF of new work centers, 25,000 SF of renovated high bay assembly and test work centers, and approximately 5,000 SF for parts inventory and storage. A unique feature of the SRF facility is the ~8600 SF chemroom/cleanroom suite. The SRF research labs host a vapor diffusion Nb_3Sn furnace and several vacuum coating systems for synthesis of advanced SRF materials and cavities, with some of them unique and not available in other DOE labs. This state-of-the-art facility is fully engaged to support cryomodule construction and refurbishment needs of CEBAF, LCLS-II-HE, SNS PPU, and planning for the EIC project SRF production; strongly contribute to critical fundamental SRF R&D; and prepare for future projects such as PERLE, ILC, or FCC-ee.

The ability to use the TJNAF LERF as an accelerator R&D testbed for ERLs and techniques required to establish cooling of proton/ion beams, or other future initiatives, provides a mutually beneficial cross-fertilization between the TJNAF LERF and nuclear physics. The LERF vault has recently been configured to enable higher throughput of cryomodule testing for LCLS-II-HE.

Cryogenics. Over the past 30 years, TJNAF has developed a unique capability in large-scale cryogenic system design and operation that is a critical resource for the U.S. national laboratory complex, including the design of construction projects requiring large-scale cryogenics at SLAC (LCLS-II), Michigan State University (Facility for Rare Isotope Beams), Oak Ridge National Lab (SNS), TJNAF (12 GeV Upgrade), and NASA (James Webb Space Telescope testing), as well as improving the cryogenic efficiency of existing systems (BNL). In the process, several inventions have been patented, and one has been licensed by Linde (one of two companies that build cryogenic systems) for worldwide applications on new and existing cryogenic plants. TJNAF provides commissioning support to SLAC and routine operational support to ORNL.

Advanced Computer Science, Visualization, and Data

(Funding: DOE SC – Advanced Scientific Computing Research and Nuclear Physics)

TJNAF utilizes its expertise in detector readout and data processing workflows by continuing an R&D partnership with ESnet and new partnerships with NERSC and ORNL. TJNAF and ESnet have developed a low-latency transfer mechanism, essential for real-time streaming and data analysis at scale. TJNAF has established a streaming readout facility to remove the distinction between offline and online computing. TJNAF is developing computational and data science technology toward the scientific understanding the structure of the protons, as a complement to advanced experimental facilities and techniques. Funding from these pilot projects enables TJNAF to build the talented workforce that will be needed successfully deploy the HPDF.

TJNAF has developed world-leading applications in AI-based controls for particle accelerator applications. Efforts are underway to apply AI-based controls techniques, developed with funding from the ASCR DnC2S project, for applications at SLAC/DESY, SNS ORNL, BNL, and FNAL. TJNAF data scientists continue to explore new techniques in AI-based controls to address ill-posed problems, improve uncertainty estimations, and involve policy models' explainability. TJNAF has developed automated detector controls for monitoring experimental data quality and calibrating detectors. That work is being extended to experimental beamline components.

Mechanical Engineering and Design

(Funding: DOE SC – Nuclear Physics)

TJNAF has a long-established ability to define, design, engineer, test, and operate advanced engineered systems. CEBAF, its four experimental halls, multiple cryogenic plants, and SRF Institute reflect the commitment to the processes and capabilities of its technical staff to transform the mission need into a world-class electron beam accelerator with advanced detector systems, focused on exploring the nature of matter. CEBAF contains more than 10,000 elements and operates 24/7 for >30 weeks a year. This has paved the way for technical expertise in several areas of accelerator technology, each sought out by a variety of scientific labs and accelerators around the globe. Examples of these world-leading technologies are:

- High-current, polarized, electron sources
- Superconducting RF (SRF) cavities and cryomodules
- Low-level RF (LLRF) control systems
- 4.5 K and 2 K cryogenic plants – enabling superconducting magnet and SRF accelerating systems for more compact, higher-performing, and higher-efficiency accelerators
- Nuclear physics targets, detector systems, and associated “Fast Electronics”

Having demonstrated the ability to design, construct, and operate a 6 GeV CEBAF with three experimental halls, TJNAF further expanded the capabilities of CEBAF with advanced SRF technology and detector systems to the current 12 GeV CEBAF, adding a fourth experimental hall. These design and engineering capabilities have not been used solely for the advancement of CEBAF, but for other major science facilities as well. SRF cryomodules developed at TJNAF are operating at LCLS-II, FRIB, and SNS. LLRF systems are deployed at LCLS-II, PIP-II, and the Pohang Light Source. Cryogenic plants have been developed for RHIC, SNS, FRIB, LCLS-II, and NASA.

Current and future major programs will benefit from TJNAF’s abilities toward advanced engineered systems. The MOLLER experiment, planned for installation in Experimental Hall A, is a complex system of beamline elements, experimental torus magnets, target, and detectors. It also requires upgrades to several accelerator systems to achieve and measure the required beam parameters. Future upgrades for CEBAF are being investigated toward accelerating positrons and a 22 GeV upgrade. TJNAF is also a partner on the Electron-Ion Collider facility, sited at Brookhaven National Lab, to provide an array of technical systems: SRF accelerating cryomodules, SRF crab cavities, superconducting detector solenoid, complete detector system, normal-conducting beamline magnets, LLRF control system, 2-K satellite refrigerators, and 2-K cryogenic distribution systems.

Systems Engineering and Integration

(Funding: DOE SC – Nuclear Physics)

TJNAF has a history of participating in major projects under the guidance of DOE O413.3B. The associated rigor in following this project stage gate development process translates to a systems engineering approach to developing complex technical systems. This drives the systems engineering process from requirements development, design advancement and maturity, to system verification. Examples of these projects are the CEBAF 12 GeV Upgrade, LCLS-II cryomodules, LCLS-II cryogenic plants, SNS PPU cryomodules, and the End Station Refrigerator 2 (ESR2). Current projects following this methodology are LCLS-II-HE cryomodules, the MOLLER experiment, and the Electron-Ion Collider. All of these major system development activities methodically follow the approach of appropriate R&D, thorough assessment of a concept design, well-defined requirements and interface definition, detailed design and engineering to full design maturity with associated technical design reviews, procurement/fabrication, installation, and the ultimate commissioning of the overall integrated systems.

An active Engineering Council is chartered to formalize a systems engineering framework that is scalable to smaller, internal projects to assure the same measure of thoroughness is applied. In all cases, well-defined methodologies and tools, such as 3D computer-aided design, finite element analysis for structural and thermal analyses, computational fluid dynamics, and circuit schematics/layouts/simulation, are employed. Beyond standard engineering efforts, the process also engages Environment, Safety, & Health (ES&H) and Quality Management organizations into all the engineered systems.

Science and Technology Strategy for the Future/Major Initiatives

The TJNAF science strategy for the future involves pursuit of four major initiatives (Table 4.1) that advance key objectives in the field of nuclear physics and enable TJNAF to contribute to the SC programs more broadly, particularly with the development of the HPDF for ASCR.

The four major initiatives form a compelling and coherent vision for TJNAF. Starting from its strong heritage in nuclear physics and motivated by grand challenges within the field as outlined in the 2023 Long Range Plan (LRP) for Nuclear Science, such as the quest to image the nucleon, TJNAF'S strategy brings together fundamental nuclear physics, computational science, and the underlying accelerator technology to 1) drive discovery in nuclear science; 2) design and build the facilities of the future; and 3) power new methods and facilities to integrate experiment, theory, and computation — enabling a new paradigm of scientific discovery.

Table 4.1: TJNAF Major Initiatives

Strategic Areas	5-7 year goals
Maintain and strengthen global leadership in nuclear physics R&D	• Ensure that TJNAF maintains a role as the premier cold QCD laboratory in the world through a world class experimental program and theoretical leadership in hadron structure and spectroscopy. • Advance world-leading cryo-SRF and accelerator research capabilities to enable new accelerator concepts, while exploiting performance gains in CEBAF .
Ensure excellence in delivering on the EIC partnership	• Demonstrate leadership in the EIC scientific program and deliver on TJNAF Project Partnership responsibilities. • Develop a strong R&D effort that encompasses the physics covered by the EIC in both theory and experiment.
Advance S&T to enhance particle accelerator capability at CEBAF and beyond	• Based on world-leading cryo-SRF and accelerator research capabilities, continue delivering 34 weeks of EBAF operation at 12 GeV with reliability realized. • Develop concepts for future upgrades of CEBAF. Develop applications of SRF to a variety of sciences and industries
Deploy HPDF and develop an associated R&D program	• Deliver the High Performance Data Facility including its supporting organization. • Establish strong research programs in Data Science and AI/ML with HPDF spoke development in mind. • Develop a coordinated approach to the Integrated Research Infrastructure implementation in collaboration with Other ASCR facilities.

The first major initiative is Nuclear Physics at CEBAF, a premier Office of Science national user facility. As stated in the 2023 LRP, "[T]he highest priority of the nuclear science community is to capitalize on the extraordinary opportunities for scientific discovery made possible by the substantial and sustained investments of the United States … The recommendation requires … continuing effective operation of the national user facilities." The currently planned program of experiments will require the better part of the next decade to execute. Here, CEBAF will continue to provide unique capabilities to advance our understanding of hadronic matter at high luminosity far beyond what will be available at the future EIC. The planned CEBAF experimental program is launching a new era in three-dimensional imaging of the nucleon to facilitate solutions to long-standing anomalies in nuclear medium modifications, and to provide benchmarks for quantum chromodynamic calculations. Furthermore, advances in nuclear theory, particularly first-principles calculations in LQCD, provide essential support for future developments at CEBAF and EIC. TJNAF will continue to advance the role of computation in nuclear physics, particularly in the areas of lattice QCD and AI/ML techniques applied to increase the speed and efficiency of experimental data interpretation.

The second major initiative involves leadership in EIC science, a higher-energy extension of our ongoing R&D efforts at TJNAF. The third recommendation in the 2023 LRP was that "[W]e recommend the expeditious completion of the EIC as the highest priority for facility construction." TJNAF has established itself as a major partner in the development, construction, and scientific utilization of the new EIC Project. This effort is both synergistic and complementary to the Nuclear Physics program at CEBAF, and it exploits TJNAF's world-leading expertise in utilizing electron scattering in experimental nuclear physics as well as accelerator science and technology. The theory program at TJNAF is well-equipped to provide leadership in guiding and interpreting eventual EIC experimental results.

The third major initiative is Accelerator Science and Technology. TJNAF will continue to be a world-leading center for SRF technology research and production, both for fundamental scientific research and for applications to industry, medicine, and national security. To reach its full potential, TJNAF will fully develop and staff the SRF, cryogenic, and accelerator research capabilities, thus enabling delivery on new accelerator projects across the DOE complex. Examples of additional elements of this initiative include machine learning for accelerator operations, development of a polarized positron source, advanced photocathode development, and application of plasma processing to enhance SRF accelerator capabilities.

TJNAF is embarking on a new and exciting fourth major initiative with the ASCR program to establish the High Performance Data Facility in partnership with LBNL. The vision for the HPDF distributed architecture is that it will connect hub resources and ASCR computational facilities to spokes and other Office of Science user facilities via existing Energy Sciences Network (ESnet) pathways. The model aligns with the Integrated Research Infrastructure (IRI) goal of empowering researchers "to seamlessly and securely meld DOE's world-class research tools, infrastructure, and user facilities in novel ways to radically accelerate discovery and innovation."[37] TJNAF and LBNL will provide management and operational support for HPDF, focusing on hub deployment and operations, coordination of national federated architecture operations, and development of strategic directions for HPDF and IRI efforts in partnership with ASCR and other stakeholders in SC and DOE.

Infrastructure

Overview of Site Facilities and Infrastructure

TJNAF is located on a 179-acre DOE-owned federal reservation within the City of Newport News in southeast Virginia. Adjacent to the federal reservation is the Virginia Associated Research Campus (VARC), a five-acre parcel owned by the Commonwealth of Virginia and leased by SURA, which subleases five acres to DOE for TJNAF use as the Service Support Center (SSC). Also adjacent is a 37-acre parcel owned by SURA, where it operates a 42-room Residence Facility at no cost to DOE.

TJNAF consists of 71 DOE-owned buildings comprising 1,010,744 gross square feet (GSF) of office, shop, technical, and storage space. JSA leases additional office space in the SSC (34,739 GSF) and storage space in three warehouses (37,627 SF). Distribution of net usable space by type is summarized in Table 6.1. There are currently no excess facilities and none are expected within the next 10 years. In addition to real property assets, 38 personal property shipping containers represent 11,640 SF of added storage. While the Lab-at-a-Glance table in Section II represents physical assets as of the end of FY 2023, these figures have been updated to reflect acquisitions that occurred in FY 2024, which included transferring two leased buildings to DOE-owned along with 10 acres of land.

Type of Use	Total Usable Square Feet, Owned and Leased
Technical and Laboratory	290,203 (39%)
High Bay	140,910 (19%)

[37] High Performance Data Facility (HPDF) DOE National Laboratory Program Announcement, March 10, 2023

Office	143,409 (19%)
Storage	110,267 (15%)
Common	64,162 (8%)
TOTAL	748,951 (100%)

Table: Distribution of Usable Space by Type of Use

TJNAF provides office and workspace for approximately 900 JSA contractor, JSA, and federal government employees, plus more than 1,900 transient users and visiting scientists. With a growing workforce and mission, facility space is considered over-utilized. The condition of TJNAF facilities is generally good as summarized in the table below. The infrastructure investment strategy includes executable plans to transition substandard facilities to adequate condition.

Condition		Mission-Unique Facilities		Non-Mission-Unique Facilities		Other Structures and Facilities	
		Number	SF	Number	SF	Number	SF
Rating	Adequate	36	339,976	32	394,098	39	N/A
	Substandard	0	0	7	349,036	4	N/A
	Inadequate	0	0	0	0	0	N/A
	TOTAL	36	339,976	38	734,134	43	N/A
Utilization	Underutilized	0	0	0	0	0	N/A
	Excess	0	0	0	0	0	N/A

Table: TJNAF Facility Rating and Utilization Assessment

TJNAF is entirely dependent on public utility service. Electric utility service is sourced from Dominion Energy at an average blended rate of $0.09/kilowatt-hour (kWh) and water is sourced from Newport News at a blended rate of $5.13/Kgal (Kgal = thousand gallons). Additional sewer charges are $4.54/Kgal; however, this rate is not applied to all of the supplied water. A vast majority of this water is evaporated by cooling towers; therefore, this rate is applied only to the water that is estimated to go to sewer. Wastewater charges are approximately $10.25/Kgal totalized across three wastewater accounts with HRSD. Utility services meet mission requirements although occasional, unplanned electric utility outages periodically disrupt operations.

The Land Use Plan is maintained on the TJNAF website and summarized in Enclosure 1. The Land Use Plan accommodates infrastructure improvements identified to support CEBAF operations and HPDF. In addition to DOE-owned land, further opportunities for campus expansion exist on adjacent SURA- and Newport News-owned land parcels, which have been reserved for TJNAF interests.

The SLI-funded CEBAF Renovation and Expansion (CRE) project received CD-1 in March 2020. The project includes the acquisition and renovation of the Applied Research Center (ARC) and renovation of CEBAF Center. In FY23, an additional offsite warehouse (18,597 SF) was leased. Additional real estate actions are being considered, to fill critical shortages in available office space and high-bay space in the coming fiscal years as the laboratory mission expands.

Campus Strategy

Modern science relies heavily on robust and dependable infrastructure. A revitalized and efficiently managed physical infrastructure not only enhances scientific output but also fosters the attraction and retention of employees and the user community at TJNAF. Together with the lab's operational excellence, this infrastructure forms the backbone of its scientific facility portfolio.

A key component of the lab's operational strategy is excellence in safety performance and continuous improvement in its safety culture. As TJNAF continues to see more infrastructure investment and requests additional investment to support its needs, the lab has been proactive in its approach to safely prepare to execute this work. In 2024, a new hazard-based Work Planning and Control Process and tool was rolled out to facilitate staff focusing on hazards for every job regardless of the perceived risk level. TJNAF developed an ES&H Observation tool that allows substandard conditions found throughout the site to be easily entered into the system with pictures and sent to the appropriate lab group for resolution. Finally, TJNAF wanted to ensure it was learning from events more quickly, so a Rapid Incident Analysis process was developed to evaluate certain events quickly and enter corrective actions into the tracking system to resolve.

Planned investments in infrastructure aim to bolster and facilitate scientific endeavors across a diverse array of facilities crucial to TJNAF's core capabilities. Priority is given to projects critical to maintaining operations while acknowledging the importance of future endeavors to enhance mission readiness. TJNAF acknowledges that a sustained commitment to investing in both areas is imperative to ensure the effective practice of routine maintenance and infrastructure stewardship.

TJNAF's campus strategy is aligned with the S&T strategy described in Section 4 of this plan, thus enabling the lab's research mission. The resulting strategy consists of five major elements:

- Enhancing Cryogenic Infrastructure: Enhance capacity and reliability of cryogenic infrastructure to ensure consistent delivery of liquid helium to support operations at the accelerator, four experimental halls, and advanced research and development facilities.
- Expanding High-Bay Space: Expand high-bay space to accommodate the increasing demand for assembling, testing, and modifying superconducting radiofrequency accelerator components, detectors, and target systems for the CEBAF experimental program and other DOE projects.
- Providing Office and Collaboration Facilities: Develop office and collaboration spaces to accommodate the expanding workforce, user community, and the evolving mission of the laboratory.
- Investing in Campus Infrastructure for Computational Research: Direct campus infrastructure investments toward advancing a new era of scientific computational research.
- Achieving Efficient and Sustainable Operations: Implement efficient, sustainable, and resilient infrastructure strategies to achieve net-zero emissions, as well as ensure energy- and water-resilient operations.

Presented in the table below is the correlation between S&T mission requirements, required infrastructure capability, current shortfall in this capability, and optimum solution.

Core Capability (SC-X)	Infrastructure Requirement	Current Shortfall	Optimum Solution and Need Date
Accelerator Science and Technology (SC01)	Provide liquid helium to the Test Lab to enable the development, production, and testing of SRF components and cryomodules, both for use by TJNAF in CEBAF and projects for other labs.	The Cryogenics Test Facility (CTF) has experienced heavy utilization due to the CEBAF upgrade and BES multi-lab partnership projects. Approximately $5.2M of system components have reached end-of-life	Complete the CTF Upgrade. Funding was provided in FY20 under the SLI-GPP program and is currently being executed.

		and others require upgrading to maintain adequate capacity for projected workload.	
	Provide sufficient high-bay and office space needed to design, produce and test SRF components and systems.	10,000 SF of high-bay space in the Test Lab is unavailable for SRF needs due to occupation by Physics' large-scale assembly and testing activities. SRF office space needs in the Test Lab exceed available capacity.	The TJII project will construct a new 45,000-SF Test Lab High-Bay Annex with the required floor loading, utilities, and crane coverage to support Physics' large-scale assembly and testing activities. Relocation of Physics large-scale assembly and testing activities to this new facility will make existing Test Lab high-bay space available for expanding SRF activities which require immediate adjacency to associated work centers in the Test Lab such as the cryomodule test cave, production chemistry rooms, and R&D chemistry rooms. The Experimental Equipment Lab (EEL) Renovation project will relocate Physics' engineering office space to the EEL to ensure adequate space is available for SRF in the Technology and Engineering Development Facility (TEDF).

	Operate the Low Energy Recirculator Facility (LERF) for dedicated cryomodule testing for DOE projects and R&D on electron guns and future accelerator concepts.	Mechanical systems are at end-of-service-life and electrical systems are at or past capacity. Finishes are well-worn and need to be renewed.	The LERF Renovation will ensure the facility can meet its planned operational use.
Advanced Computer Science, Visualization, and Data (SC02)	Additional data center space is needed to support the High Performance Data Facility (HPDF).	CEBAF Center data center (6,000 SF) is at capacity.	Construct the warm-lit-shell of the Jefferson Lab Data Center (JLDC) using $46M of funding provided by the Commonwealth of VA. Additional funds for infrastructure necessary to run the data facility (appropriate electricity, HVAC, and cooling water) in JLDC will be part of the HPDF project.
	Administrative space for 100+ staff to grow core capabilities in computational science.	Insufficient administrative and office space exists in CEBAF Center to support the growth of the Computational Sciences and Technology (CST) Division.	The CEBAF Renovation and Expansion (CRE), including acquisition of the ARC, renovates ARC and CEBAF Center and provides an additional 121,000 SF of space. Initial project funding was received in FY20 and ARC renovation work is expected to commence in FY 2025.
Large-Scale User Facilities/R&D Facilities/Advanced Instrumentation (SC16)	210 tons of cooling capacity are required in each of the two linac service buildings to support CEBAF operations.	Existing cooling system is 36% undersized for current loads. Shortfall is 75 tons in each linac.	The LINAC Additional Cooling project increases chilled water capacity, improves air flow, reduces infiltration of unconditioned air, and increases air conditioning.
	45,000 SF of environmentally controlled high-bay and technical space to support SRF production, cryogenics fabrication, detector and equipment assembly and staging for four experimental halls operating at 34 weeks/year, Electron Ion	High-bay space in the EEL, Test Lab, and TED buildings is heavily overutilized. Overcrowding increases the safety risk to staff and visiting scientists. Off-site space is	The TJII project will construct a new 45,000-SF Test Lab High-Bay Annex for Physics' large-scale assembly and testing activities.

	Collider (EIC) support activities, and other DOE projects.	currently being leased to meet the demand.	
Mechanical Design and Engineering (SC17)	New core capability – no infrastructure gaps have been identified at this time		
Nuclear Physics (SC21)	End station refrigeration capable of supplying Halls A, B, and C with 4000W of 4 K cooling and 40 g/s of LHe at >85% reliability.	Current End Station Refrigerator serving Halls A, B, and C only has 1500W of 4 K cooling and 11 g/s of LHe, has been operating nearly continuously for 20 years and is near end-of-life.	Complete installation of the SSC Cold Box to activate the End Station Refrigerator 2 (ESR2). This will close the capability gap and provide a long-term solution to meet the experiment plan. GPP funding was provided by NP in FY20 and the project is nearly complete.
	Up to 210,000 SF of office and collaborative space that meets DOE high-performance, sustainable building standards to house staff, students, and visiting users.	CEBAF Center (127,000 SF) is overutilized and substandard due to aging mechanical systems that require immediate replacement.	The CEBAF Renovation and Expansion (CRE), including acquisition of the ARC, renovates ARC and CEBAF Center and provides an additional 121,000 SF of space. Initial project funding was received in FY20 and ARC renovation work is expected to commence in FY 2025.

	The EEL provides 54,800 SF of technical and lab space for Physics, Engineering, and Facilities staff and is integral to the campus plan.	EEL has end-of-life mechanical systems and code deficiencies. Office and technical space is insufficient, poorly distributed, and not integrated with the campus.	The EEL Renovation project fully renovates and modernizes the EEL facility to meet mission needs.
Systems Engineering and Integration (SC25)	New core capability – no infrastructure gaps have been identified at this time		
Support Facilities and Infrastructure (SC25)	Provide 100,000 SF of outside storage to accommodate large experimental assemblies, support structures, and equipment for future experiments and operations.	Current laydown space is scattered in multiple locations around site. Stored material in some of these sites is visible from off-site and creates an eyesore. Some 70,000 SF of existing laydown area will be lost due to future building construction.	The Laydown Yard Expansion significantly increase an existing storage area on the accelerator site. Consolidation will improve material management and provide an opportunity to eliminate unneeded material. Infrastructure Reinvestment Act (IRA) funding was provided in FY 2022 and construction is scheduled to begin in FY 2024.
	Relocate Facilities Maintenance and Operations functions.	Functions are located in two substandard buildings (13 and 19) located in the administrative core of the campus. Critical spares are inefficiently scattered across the campus as well as offsite warehouses.	The Integrated Maintenance and Logistics Center (IMLC) project provides a fully integrated solution and relocates these functions to a new facility located in the lab's service corridor.

	Relocate Logistics functions.	TJNAF logistics functions are primarily located in high-bay space within the EEL building, which is already oversubscribed and needed to support research and technical operations.	The Integrated Maintenance and Logistics Center (IMLC) project provides a fully integrated solution and relocates these functions to a new facility located in the lab's service corridor.
	Onsite, centrally managed warehouse space to fully support multi-program storage needs.	Approximately 40,000 SF of technical storage is leased in warehouse space remote from TJNAF. This introduces additional labor and time requirements to control and access this high-value material. In addition to the offsite leased space, there are 4 temporary fabric tents (8,800 SF) and 38 deteriorated shipping containers (11,640 SF) onsite which do not reliably meet storage needs and also pose a safety and health risk to staff.	A new Infrastructure Storage Facility includes 20,000-30,000 SF of warehouse space to primarily address the temporary tents and shipping containers as well as partially relieve the demand for remote, off-site leased storage. A new Integrated Maintenance and Logistics Center (IMLC) includes 15,000-20,000 SF of warehouse space to further relieve the demand for remote, off-site leased storage.
	Suitable access roads, parking, and pedestrian walkways to facilitate collaboration and meet safety and regulatory requirements.	Continued expansion of the TJNAF campus as outlined in this plan along with development of property immediately surrounding TJNAF requires expansion and alteration of campus access and	Roads, Parking, and Sidewalk Improvements project increases parking capacity, enhances the central pedestrian corridor, and supports future campus plan growth and development.

		parking to support vehicle loads, and maintain compliance with safety and regulatory requirements.	
	Provide 1,900 gal/hr of chilled water to cool R&D equipment in the Test Lab, EEL, CEBAF Center, and Accelerator service buildings.	Existing Test Lab chillers are approaching the end of their service life and use refrigerant that will no longer be available after FY30.	The Central Utility Plant (CUP) Upgrade project includes replacing the existing chillers with new chillers to be installed in the CUP. Construction is scheduled to begin in FY 2025.
	Achieve the 50% reduction in water usage intensity by 2030 relative to a 2021 baseline as outlined in the DOE Buildings Strategic Plan.	TJNAF requires a reduction of nearly 69 million gallons/year in potable water consumption.	A Water Conservation Strategies project contains scope items capable of saving up to 16 million gallons/year.
	Suitable potable water distribution to reliably meet need for 90-100M gal/year use.	Portions of the after system exceed 50 years and have experienced severe corrosion. The site lacks a full water loop with isolation valves to allow for normal maintenance without severely affecting operations.	The Potable Water Utility Upgrades project replaces aging sections of piping and provides for completion of the site water distribution loop with adequate isolation valves for system operations and maintenance.
	Meet carbon pollution-free energy (CFE) and renewable energy goals established by DOE.	TJNAF currently relies on the purchase of renewable energy credits to meet DOE sustainability goals, which require that renewable electric energy account for not less than 7.5% of a total agency electric consumption.	The Renewable Energy Integration project provides a 6-MW photovoltaic system on-site, which will assist to meet CFE and renewable energy goals and provide a resilient microgrid for the campus.

Table: Campus Strategy Reflecting Realistic Solutions to Address Infrastructure-Capability Shortfalls to Meet TJNAF S&T Strategic Objectives

The gaps identified above can be closed using a combination of GPP, SLI-GPP, SLI, and alternative sources of funding of $280M over the next decade. The Commonwealth of Virginia has already committed $43M to the construction of the Jefferson Lab Data Center (JLDC) in support of the HPDF project. In addition to providing essential capabilities for mission performance, these investments will increase sustainability and climate resiliency as well eliminate more than $5M of deferred maintenance.

The primary focus of the indirect-funded Facilities Maintenance and Operations program is to increase the mean time between failure of facility systems through accelerated replacement of end-of-life systems and adding redundancy for critical systems to eliminate downtime from single-point failures. Similarly, when failures occur, TJNAF will reduce the mean time to repair by making sure sufficient stock of critical spares is on hand to immediately restore operation, rather than accept lengthy downtimes to source replacements.

The most recent TJNAF Condition Index is 97% (excellent). However, this rating will drop over time if the Maintenance Investment Index continues to be limited to 0.89% of Replacement Plant Value (RPV). The DOE target is to spend 2%-4% of RPV in maintenance each year. Modernization projects funded through GPP and SLI have enabled TJNAF to maintain a modest deferred maintenance value ($10M in FY 2023). Over the next decade, no significant increase in deferred maintenance is expected if TJNAF implements the capital spending plan.

Site Sustainability Plan Summary

TJNAF remains strongly committed to supporting and achieving the targets in the DOE Sustainability Strategic Plan. Evidence of this commitment is demonstrated in the significant progress already made in achieving many of the established interim goals, and TJNAF remains on target to meet or exceed interim and long-term sustainability goals for most identified categories. Sustainability goals are integrated into the Environmental Management System (EMS) in accordance with DOE O 436.1A to ensure that goals are met in a timely manner and to identify areas for improvement prior to the requirement deadlines.

Understandably, expansion of the scientific mission at TJNAF with CEBAF operations has led to significant increases in electricity and water requirements when compared with data from established baseline years. The addition of HPDF is expected to create additional increases, which are actively being taken into consideration. Therefore, while achievement of electricity and water reduction goals represent a significant challenge, multiple reduction strategies have been identified and are under consideration for implementation as part of the overall Campus Strategy.

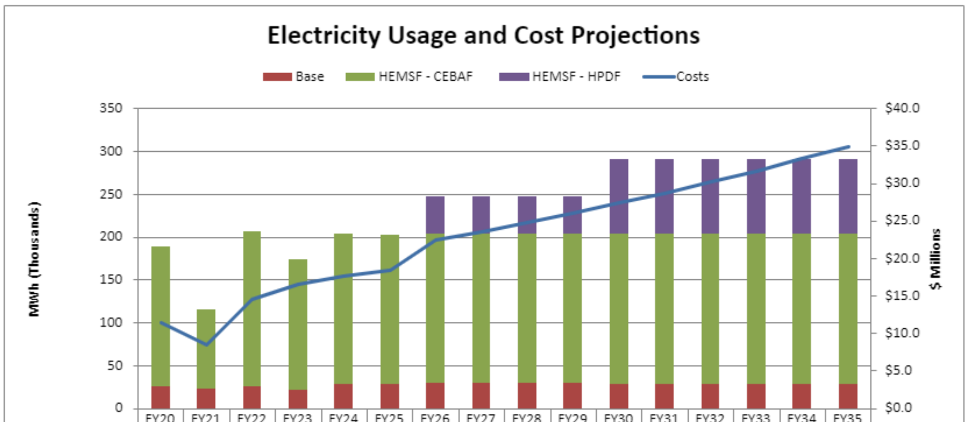
Energy Management

TJNAF takes a holistic approach to energy management, acknowledging that goal-subject buildings, excluded buildings (high-energy mission-specific facilities and high-performance computing facilities), and non-fleet vehicles and equipment (V&E) are all separate categories that need to be understood, tracked, and managed independently.

In FY 2023, TJNAF completed American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Level 2 energy and water evaluations in 21 EISA-covered facilities (634,557 GSF). Goal-subject facilities were prioritized as a part of TJNAF's efforts to meet energy utilization intensity (EUI) reduction goals. Results and proposed energy conservation measures (ECMs) and water conservation measures (WCMs) were uploaded into the Sustainability Dashboard ECM pipeline per the Energy Independence and Security Act Section 432 (EISA S432) evaluation deadline in February 2024. For FY 2025 and beyond, TJNAF plans to conduct these energy and water evaluations on 25% of the required facility portfolio annually to balance the workload.

TJNAF uses several tools as a part of the overall energy management strategy. Benchmarking of covered facilities in Energy Star's Portfolio Manager was started in FY 2021. Commissioning further supports efforts to identify and improve energy and water inefficiencies in all facilities. To comply with the metering requirements set forth in Energy Act of 2020 (EAct 2020) and expand benchmarking of covered facilities, TJNAF currently has 88% of all buildings at least partially metered for electricity, potable water, and natural gas. Roughly 40% of buildings are designated as fully metered. In FY 2024 and beyond, TJNAF will continue efforts to integrate all new and existing meters into an established internal utility dashboard, which has an infrastructure consistent with the Federal Information Security Modernization Act (FIMSA) of 2014. Metering data, in addition to energy and water evaluation results, will inform future energy management initiatives and priorities, such as the implementation of advanced energy management software to consolidate and optimize energy- and cost-saving data and strategies.

In October 2023, TJNAF acquired the Applied Research Center, which will affect the goal-subject energy consumption and, ultimately, the EUI score for FY 2024. Renovations of the Applied Research Center will be complete by FY 2027 and CEBAF Center by FY 2029. Both buildings will meet the High-Performance Sustainable Building Guiding Principles. Within the next five years, TJNAF plans to construct a new High Performance Data Facility (HPDF). The facility is expected to provide sufficient space to house the HPDF, and TJNAF expects this project to substantially increase the electricity and water consumption on-site. TJNAF will implement sustainable building requirements consistent with DOE O 436.1A and DOE O 413.3B and seek opportunities for energy efficiency as well as opportunities for on-site renewables to reduce overall energy consumption and emissions. Historical and projected electricity consumption and costs for Site Base and high-energy missions-specific facilities (HEMSFs) are documented in the figure below.



	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32	FY33	FY34	FY35
HEMSF - HPDF							43.8	43.8	43.8	43.8	87.6	87.6	87.6	87.6	87.6	87.6
HEMSF - CEBAF	164.07	91.53	180.73	153.57	176.61	174.69	174.69	174.69	174.69	174.69	174.69	174.69	174.69	174.69	174.69	174.69
Base	24.67	23.05	25.9	20.48	27.41	27.41	29.09	29.09	29.09	29.09	28.09	28.09	28.09	28.09	28.09	28.09
Costs	$11.5	$8.5	$14.6	$16.6	$17.7	$18.4	$22.5	$23.6	$24.8	$26.1	$27.4	$28.7	$30.2	$31.7	$33.3	$34.9

Figure: TJNAF Electricity Usage and Cost Projections

Clean and Renewable Energy

TJNAF invests and implements clean and renewable energy technologies. Several existing facilities utilize geothermal heat pump systems (GTHP), which vary in thermal consumption from year to year since changes-in-degree days impact the thermal energy production of the system. Additionally, approximately 18% of TJNAF's total electricity (174,048 MWh's) consumption in FY 2023 was accounted for with renewable energy certificates (RECs). In all, 11,962 RECs were transferred from the Commonwealth of Virginia to TJNAF related to the renewable portfolio standard (RPS) rider in the existing utility contract. A portion of these RECs are generated from solar facilities in Virginia that went into operation after October 1, 2021, allowing them to qualify as energy attribute credits (EACs). These RECs scale in size based on TJNAF's annual demand and consumption, meaning that as operations increase, TJNAF's Carbon Pollution-Free Electricity (CFE) RECs will also increase. An additional 20,000 RECs were purchased from the market, which allowed TJNAF to meet the interim clean energy goal. Currently, there are no EACs generated in the Pennsylvania-New Jersey-Maryland (PJM) grid region, where TJNAF is located, available on the market.

Although TJNAF will benefit from the electricity provider transitioning to 100% CFE by 2050, the site is investigating opportunities to increase on-site CFE. By producing CFE on-site, TJNAF will be able to minimize the cost of utility bills and energy attribute credits. In FY 2023, TJNAF completed an on-site renewables feasibility study to identify renewable energy technology options and potential siting of new systems. Through collaboration with Dominion Energy, TJNAF clarified the Virginia State Code for net-metering, which was previously believed to limit TJNAF to 3 MW of on-site renewables located behind the meter. It was determined that the net-metering requirement applies to each electric service account that meets the minimum electric demand required for enrollment, rather than the entire site. Therefore, TJNAF can leverage two existing accounts for a total of 6 MWs on-site. Additionally, TJNAF will be able to invoke net-metering on any potential new service accounts related to expansion of the lab mission.

TJNAF will continue to benefit from cleaner grid electricity in future fiscal years as the electricity provider increases its percentage of CFE. Although TJNAF operations are expected to increase, the scalability of RECs from COVA will also ensure that TJNAF is able to meet CFE goals on the prescribed timeline. TJNAF anticipates 88% CFE by 2030 solely based on these benefits. However, TJNAF has identified installing on-site renewables and purchasing off-site CFE as high-level priorities in order to cover the remaining 12% and meet the 2030 deadline. The current and projected timeline for TJNAF to achieve 100% CFE is documented in the figure below.

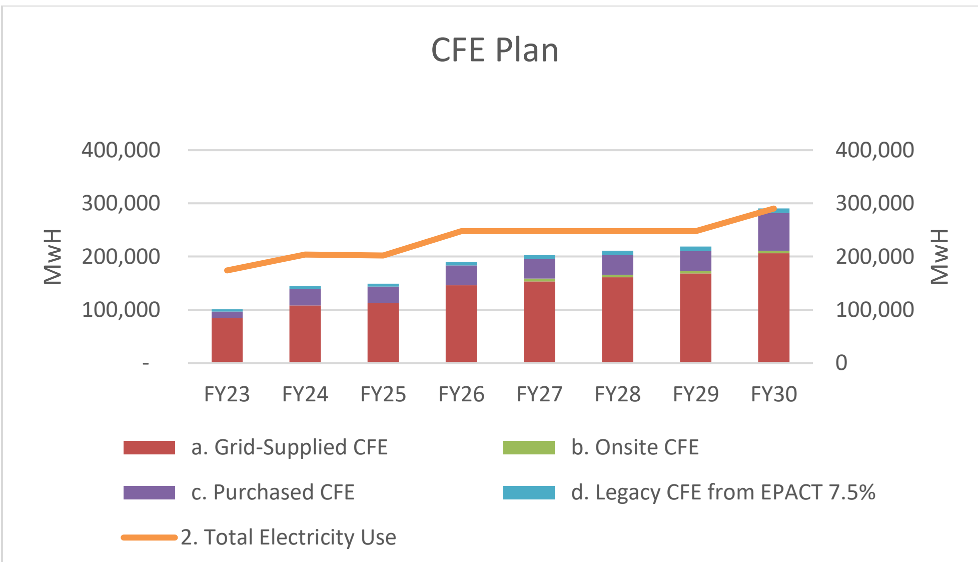


Figure: TJNAF CFE Plan

A majority of energy consumption at TJNAF is electric; however, a small percentage of heating and emergency generation relies on natural gas. TJNAF is investigating opportunities for electrification given the additional benefit of the electricity provider also pursuing CFE. To eliminate the potential for additional natural gas consumption, TJNAF has incorporated the Federal Building Performance Standard (FBPS) into the design requirements for all newly constructed buildings to ensure only electric equipment is selected. TJNAF projects construction of two new facilities that will adhere to the FBPS as well as the Federal Guiding Principles for High Performance Sustainable Buildings (HPSB) to minimize each building’s lifecycle greenhouse gas (GHG) emissions. Additionally, increases in site-wide CFE directly support the implementation of Net-Zero Emissions Buildings (NZEBs) by reducing the Scope 2 emissions related to electricity generation.

In addition to designing and constructing new facilities that comply with FBPS, TJNAF began long-term planning for a NZEB portfolio by examining existing buildings that will require electrification retrofits to eliminate Scope 1 emissions. In FY 2023, TJNAF performed a comprehensive review of all existing buildings utilizing natural gas to determine applicable facilities as defined by the FBPS. The review concluded that seven DOE-owned buildings will require electrification by 2030 in order to achieve compliance. While four additional facilities in TJNAF's building portfolio currently use natural gas — three of them DOE-leased and one DOE-owned — these facilities are anticipated to be eliminated from the portfolio prior to the 2030 deadline and, therefore, do not require electrification. The identified facilities were then prioritized based on economic and technical feasibility in conjunction with the 2030 deadline. The Applied Research Center (ARC) and CEBAF Center are expected to be electrified under the CEBAF Renovation and Expansion (CRE) project, which is currently at CD-1. The Chiller Building, Physics Storage, General Purpose Building, and the TED Building are anticipated to require minimal retrofits to achieve complete electrification and will be completed using indirect funds over the course of three fiscal years. As the highest natural-gas consuming facility at TJNAF, the Test Lab has been identified as a high priority and would require a dedicated, direct-funding source to complete an electrification retrofit. TJNAF included this project in a SLI funding request data call in FY 2023.

TJNAF has transitioned to electric carts, where feasible, in an effort to minimize fleet vehicles and fuel consumption. However, forklifts and generators that use diesel or liquified petroleum gas (LPG) will need to be transitioned. While electric forklifts are commercially available, TJNAF continues to investigate alternative fuel technologies that will meet the emergency power demands fulfilled by generators. TJNAF plans to continue investigating and developing strategies for non-fleet vehicle and equipment replacements in FY 2024. A complete profile of TJNAF's FY 2023 Scope 1 and 2 emissions is available in the figure below.

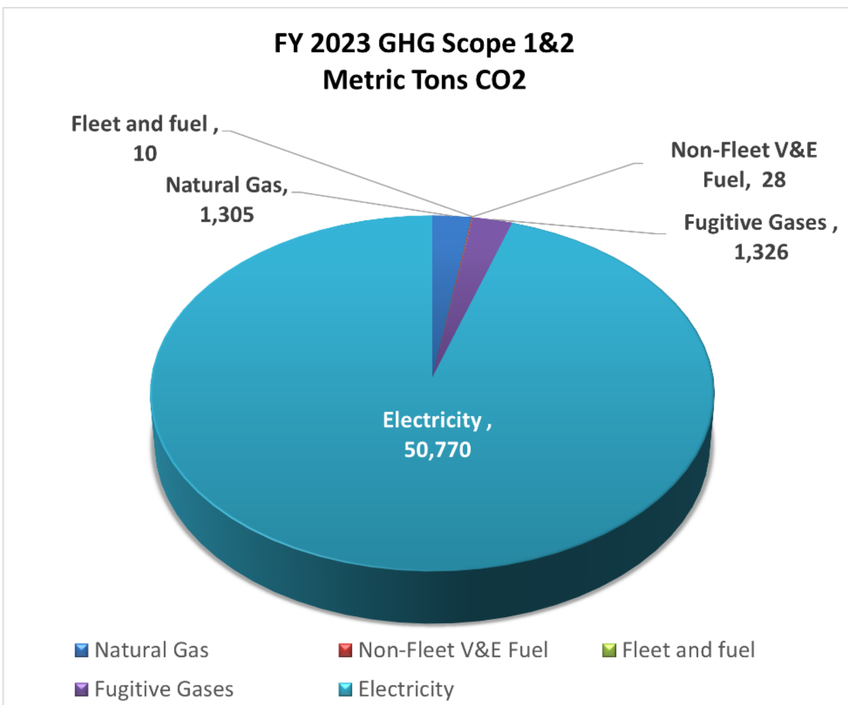


Figure: TJNAF FY 2023 GHG Scope 1&2

Adaptation and Resilience

In FY 2023, TJNAF invested $737,195.70 of indirect funds to complete several preliminary items related to previously identified resilience solutions. As identified in TJNAF's Vulnerability Assessment and Resilience Plan (VARP), flooding due to precipitation presents a significant risk to the underground experimental halls — categorized as critical assets. During a SAD period, flow tests were conducted to validate performance of the drainage system that protects the experimental halls, and the system was determined to be not functioning at full design capacity. Further tests will be performed during an upcoming FY 2024 SAD to determine the exact cause in order to make appropriate recommendations to resolve the issue and mitigate risk. Additionally, a site-wide storm water condition assessment was conducted along with an associated storm water management model (SWMM), in order to better understand current and projected storm water conditions at TJNAF. In FY 2024, data from the SWMM will inform ongoing sustainability and resiliency planning efforts related to alternative water reuse.

TJNAF has integrated adaptation and resilience planning into its overall campus planning process and recognizes the opportunity to align objectives that enhance infrastructure efficiency, sustainability, and resiliency to achieve net-zero emission and resilient operations. In addition to making progress toward the federal CFE and net-zero operations goals, TJNAF would benefit from increased energy and water resiliency and security by utilizing on-site renewables and alternative water sources.

APPENDIX 1
SCIENCE AND ENERGY CORE CAPABILITIES

The Programs reporting to the Under Secretary for Science and the Under Secretary for Energy have together identified twenty four categories of core capabilities that comprise the scientific and technological foundation of its national laboratories. There are three criteria to define core capabilities. They must:

- Encompass a substantial combination of facilities and/or teams of people and/or equipment;
- Have a unique and/or world-leading component; and
- Be relevant to a discussion of DOE/NNSA/DHS missions.

Below is a table of the core capabilities that have been affirmed by DOE at each of the thirteen Science and Energy national laboratories. The following pages give a detailed definition of what each core capability encompasses.

Figure: Distribution of Core Capabilities across the Science Laboratories

	Core Capabilities	AMES	ANL	BNL	FNAL	LBNL	ORNL	PNNL	PPPL	SLAC	TJNAF	INL	NETL	NREL
1	**Accelerator and Detector Science and Technology**		✓	✓	✓	✓	✓			✓	✓			
2	**Advanced Computer Science, Visualization, and Data**		✓	✓	✓	✓	✓	✓		✓	✓	✓		✓
3	**Applied Materials Science and Engineering**	✓	✓	✓		✓	✓	✓	E	✓		✓	✓	✓
4	**Applied Mathematics**		✓	✓		✓	✓	✓						✓
5	**Biological and Bioprocess Engineering**		✓			✓	✓	✓				✓		✓

	Core Capabilities	AMES	ANL	BNL	FNAL	LBNL	ORNL	PNNL	PPPL	SLAC	TJNAF	INL	NETL	NREL
6	Biological Systems Science		✓	✓		✓	✓	✓		✓				✓
7	Chemical and Molecular Science	✓	✓	✓		✓	✓	✓	E	✓		E		✓
8	Chemical Engineering	E	✓	✓		✓	✓	✓				✓	✓	✓
9	Computational Science		✓	✓		✓	✓	✓	E				✓	✓
10	Condensed Matter Physics and Materials Science	✓	✓	✓		✓	✓	✓	E	✓		E		
11	Cyber and Information Sciences		✓			✓	✓	✓				✓		E
12	Decision Science and Analysis		✓			✓	✓	✓				✓	✓	✓
13	Earth and Energy Systems and Infrastructure Analysis and Engineering					✓	✓	✓						✓
14	Earth, Environmental, and Atmospheric Science		✓	✓		✓	✓	✓	E			✓	✓	
15	Isotope Science and Engineering		✓	✓		✓	✓	✓				✓		
16	Large Scale User Facilities/Advanced Instrumentation		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
17	Mechanical Design and Engineering		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
18	Microelectronics		✓	✓	E	✓	✓	✓	E					
19	Nuclear and Radio Chemistry		✓	✓		✓	✓	✓				✓		

	Core Capabilities	AMES	ANL	BNL	FNAL	LBNL	ORNL	PNNL	PPPL	SLAC	TJNAF	INL	NETL	NREL
20	**Nuclear Engineering**		✓	**E**			✓	✓				✓		
21	**Nuclear Physics**		✓	✓		✓	✓				✓			
22	**Particle Physics**		✓	✓	✓	✓				✓				
23	**Plasma and Fusion Energy Science**				**E**	✓	✓	✓	✓	✓		✓		
24	**Power Systems and Electrical Engineering**		✓	**E**		✓	✓	✓	✓			✓		✓
25	**Systems Engineering and Integration**		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

✓ = DOE Full/Endorsed Core Capability

E = Emerging Core Capability

1. **Accelerator and Detector Science and Technology:** The ability to conduct experimental, theoretical, and computational research on the physics of particle beams and to develop technologies to accelerate, characterize, and manipulate particle beams in accelerators and storage rings, as well as to detect and characterize particles with next-generation instrumentation technologies. The research seeks to achieve fundamental understanding beyond current accelerator and detector science and technologies to develop new concepts and systems for the design of advanced scientific user facilities. This capability requires scientific and/or engineering expertise from several underlying areas, including cryogenics, magnet applications, microelectronics, computational modelling, and in developing computational architectures for collecting, storing, and analyzing high volumes of scientific data.

2. **Advanced Computer Science, Visualization, and Data:** The ability to support basic research in computer science and engineering. This research includes areas such as programming languages, models and environments, software tools for high-performance computers, including novel architectures such as neuromorphic or quantum computers, scientific data management and scientific visualization, artificial intelligence, distributed computing infrastructure and workflows, co-design of intelligent devices and advanced computers, and automatic tuning for improving code performance, with unique and/or world-leading components in one or more of these areas. The capability requires access to a high-end computational facilities with the resources to test and develop new tools, libraries, languages, etc. In addition, linkages to application teams in research domains of interest to the Department of Energy and/or other Federal agencies would be beneficial to promptly address needs and requirements of those teams.

3. **Applied Materials Science & Engineering:** The ability to conduct theoretical, experimental, and computational research to understand and characterize materials with focus on the design, synthesis, scale-up, prediction and measurement of structure/property relationships, the role of defects in controlling properties, the performance of materials in hostile environments to include mechanical behavior and long-term environmental stability, and the large-scale production of new materials with specific properties. The strong linkages with molecular science, engineering, and environmental science provide a basis for the development of materials that improve the efficiency, economy, cost-effectiveness, environmental acceptability, and safety in energy generation, conversion, transmission, energy storage, and end-use technologies and systems. Primary supporting disciplines and fields include materials synthesis, characterization, and processing; chemical and electrochemistry, combinatorial chemistry, surface science, catalysis, analytical and molecular science; and computation science.

4. **Applied Mathematics:** The ability to support basic research in the development of the mathematical models, computational algorithms and analytical techniques needed to enable science and engineering-based solutions of national problems in energy, the environment and national security, often through the application of high-performance computing and emerging architectures such as quantum or neuromorphic computing. Laboratory capabilities in this area would involve expertise in such areas as linear algebra and nonlinear solvers, discretization and meshing, multi-scale mathematics, discrete mathematics, optimization, complex systems, scientific machine learning and artificial intelligence, emergent phenomena, and applied analysis methods including but not limited to analysis of large-scale data, uncertainty quantification, decision-support, and error analysis.

5. **Biological and Bioprocess Engineering:** Applies understanding of complex biological systems and phenomena to design, prototype, test and validate processes components, technologies, and systems relevant to (1) bioenergy production, (2) environmental contaminants processing, and (3) global carbon cycling and biosequestration. Primary supporting disciplines include chemical engineering, agricultural science, fermentation science, and systems science.

6. **Biological Systems Science:** The ability to address critical scientific questions in understanding complex biological systems via the integration of laboratory-specific research facilities, instrumentation and/or leadership-class computational systems, and individuals with expertise in biological systems research and related disciplines to advance DOE missions in energy, climate, and the environment. This unique combination of tools and people is the foundation for research of scale and breadth unmatched by other facilities world-wide, for example, on research that employs systems and synthetic biology and computational modeling approaches enabled by genome sequencing and functional characterization of microbes, plants, and biological communities relevant to (1) bioenergy production, (2) carbon/nutrient cycling in terrestrial environments and (3) microbial biogeochemical controls on contaminant transport and biosequestration at DOE sites. Primary supporting disciplines include systems biology, plant biology, microbiology, biochemistry, biophysics, and computational science.

7. **Chemical and Molecular Science:** The ability to conduct experimental, theoretical, and computational research to fundamentally understand chemical change and energy flow in molecular systems that provide a basis for the development of new processes for the generation, storage, and use of energy and for mitigation of the environmental impacts of energy use. Areas of research include atomic, molecular, and optical sciences; gas-phase chemical physics; condensed phase and interfacial molecular science; solar photochemistry; photosynthetic systems; physical biosciences; catalysis science; separation science; actinide chemistry; and geosciences.

8. **Chemical Engineering:** The ability to conduct applied chemical research that spans multiple scales from the molecular to macroscopic and from picoseconds to years. Chemical engineering translates scientific discovery into transformational solutions for advanced energy systems and other U.S. needs related to environment, security, and national competitiveness. The strong linkages between molecular, biological, and materials sciences, engineering science, and separations, catalysis and other chemical conversions provide a basis for the development of chemical processes that improve the efficiency, economy, competitiveness, environmental acceptability, and safety in energy generation, conversion, and utilization. A core capability in chemical engineering would underpin R&D in various areas such as nanomanufacturing, process intensification, biomass utilization, radiochemical processing, dielectric materials, advanced conducting materials, high-efficiency clean combustion, and would generate innovative solutions in alternative energy systems, carbon management, energy-intensive industrial processing, nuclear fuel cycle development, and waste and environmental management.

9. **Computational Science:** The ability to connect applied mathematics and computer science with research in scientific disciplines (e.g., biological sciences, chemistry, materials, physics, etc.). A core capability in this area involves expertise in applied mathematics, computer science and in scientific domains with a proven

record of effectively and efficiently utilizing high performance computing resources to obtain significant results in areas of science and/or engineering of interest to the Department of Energy and/or other Federal agencies. The individual strengths in applied mathematics, computer science and in scientific domains in concert with the strength of the synergy between them is the critical element of this core capability.

10. **Condensed Matter Physics and Materials Science:** The ability to conduct experimental, theoretical, and computational research to fundamentally understand condensed matter physics and materials sciences that provide a basis for the development of materials that improve the efficiency, economy, environmental acceptability, and safety in energy generation, conversion, transmission, and utilization. Areas of research include experimental and theoretical condensed matter physics, x-ray and neutron scattering, electron and scanning probe microscopies, ultrafast materials science, physical and mechanical behavior of materials, radiation effects in materials, materials chemistry, and bimolecular materials.

11. **Cyber and Information Sciences:** The disciplines, technologies, and practices designed to protect, analyze, and disseminate information from electronic sources, including computer systems, computer networks, and sensor networks. A core competency in this area would involve recognized expertise in one or more of the following topics: cyber security, information assurance, information analytics, knowledge representation, and information theory, control systems design and engineering, embedded systems, reverse engineering, and advanced hacking techniques. This core competency would be applied to: the protection of information systems and data from theft or attack; the collection, classification, analysis, and sharing of disparate data; and the creation of knowledge from heterogeneous information sources; securing control systems integrated into critical infrastructure; and increasing security, reliability, and resilience of automated processes and systems.

12. **Decision Science and Analysis:** Derives knowledge and insights from measured and modeled data sets to further the understanding of and tradeoffs among resource and technology options, to identify and quantify the risks and impacts of current and emerging technologies on environmental systems, and to assess the impact of market dynamics, human behavior and regulations, policies or institutional practices on the development and uptake of technology. Primary supporting disciplines include engineering, environmental science, applied math, finance, business, social and political science, and market and behavioral economics. This capability provides credible and objective information to support DOE and others to support strategic planning and program direction, policy formulation and implementation, efforts to remove market barriers to deployment and engagement with stakeholders.

13. **Earth and Energy Systems and Infrastructure Analysis and Engineering:** The ability to understand environmental and ecological systems, processes, and interrelationships to predict, assess, and mitigate the impacts of past, current, and future energy production, transmission, distribution, and use on subsurface, terrestrial, coastal, and marine environments. Knowledge is used to develop technologies that minimize emissions and/or control technologies that protect these environments.

14. **Earth, Environmental, and Atmospheric Science:** The ability to apply knowledge of atmospheric, oceanic, terrestrial, ecological, hydrological, and cryospheric processes, that combine with human activities and anthropogenic emissions, in order to understand and predict climate change and different patterns of meteorological conditions, with a particular focus on (1) understanding and describing the causes, impacts, and predictability of climate change via the integration of laboratory-specific research facilities, instrumentation and/or leadership-class computational systems, and individuals with expertise in future

climate change research and related disciplines. This unique combination of tools and people is the foundation for research of scale and breadth unmatched by other facilities, world-wide, for example, on (1) atmospheric-process research and modeling, including clouds, aerosols, and the terrestrial carbon cycle; (2) climate change modeling at global to regional scales; (3) research on the effects of climate change on ecosystems; (4) integrated analyses of climate change, from causes to impacts changes, including impacts on energy production, use, and other human systems; (5) understanding and predicting future extreme weather as the climate evolves, that in turn introduces risk and vulnerability to energy and related infrastructures; (6) understanding the carbon cycle, with focus on the interdependence of a changing climate and terrestrial ecosystems; (7) predict the influences of terrain and atmospheric processes and systems on the availability, behavior, and quality of energy resource and operations, and (8) the structure and function of subsurface environments to enable systems-level environmental prediction and decision support and provide a scientific basis for the long-term stewardship of nuclear waste disposal, and in the functioning of terrestrial ecosystems.

15. **Isotope Science and Engineering:** The ability to produce, process, enrich or separate isotopes for distribution, and the research that enables this core competency. This includes technologies, byproducts, and surplus materials for production and processing of radioisotopes using reactor or accelerator facilities, material separation, or enrichment of radioactive and stable isotopes. The ability to conduct theoretical, experimental, and computational research to develop isotope production, processing, enrichment, and separations capabilities and technologies, and to translate to routine production of new isotopes with specific assays. This core competency may include the production of isotopes following current Good Manufacturing Processes, and knowledge to operate reactors, particle accelerators, processing equipment or enrichment devices. Areas of research needed to develop this core competency include chemical processing, analytical chemistry, nuclear and radiochemical processing, catalysis science, separation science, material science, biology, actinide chemistry, computational science, reactor physics, accelerator science, advanced manufacturing, targetry, mechanical engineering, chemical engineering, robotics, enrichment science and engineering.

16. **Large-Scale User Facilities/R&D Facilities/Advanced Instrumentation:** The ability to conceive, design, construct and operate leading-edge specialty research facilities available to universities, industry, and national laboratories customers to conduct groundbreaking research and development activities and/or 'at scale' testing and demonstration of technology. This includes the ability to effectively manage construction of $100 million or greater one-of-a-kind scientific facilities, and to host hundreds to thousands of U.S. and international users in addition to carrying out world-class research at the facility itself. The ability to conceive, design, build, operate and use first-in-class technical instruments intended for a particular research purpose, often requiring the material expertise of multiple scientific disciplines. Instrumentation that can be created by a small number of individuals or that would sit on a laboratory benchtop is not considered part of this core capability.

17. **Mechanical Design and Engineering:** Applies the principles of physics, mechanics, and materials science to analyze, design, test, validate, and enable operation of advanced engineered systems, machines, and tools.

Includes equipment used in DAC systems and CO_2 fluid management, as well as equipment used to convert energy to useful services (e.g., electricity, mobility, home heating and cooling, robotics, imaging devices, H2 turbines, pollution control equipment, etc.) or to manufacture products. Primary supporting disciplines include physics, materials science, aerospace engineering, mechanical engineering, chemical engineering, electrical engineering, and computational science.

18. **Microelectronics:** The ability to use a broad range of capabilities to conduct experimental, theoretical, and computational research to advance the development of next-generation microelectronics. Includes both fundamental research capabilities to establish the foundation for transformative innovation in microelectronics technologies and development of capabilities for fabrication of prototype devices. Also included are development of tools and integration of advanced microelectronics into applications required for DOE's missions, e.g., technologies in computing, communications, sensing, and power. Areas of research and development include semiconductors and related materials, processing chemistries, design, fabrication, lithography, packaging, sensors, devices, integrated circuits, processors, memory, computing architectures, and modeling/simulation across scales. Required capabilities include system-level integration of the components required for microelectronics, including "co-design" approaches for innovation in devices, architectures, and systems, with the ultimate goals of enhancing functionality while simultaneously improving energy efficiency of microelectronic technologies.

19. **Nuclear and Radio Chemistry:** The ability to use a broad range of facilities, instrumentation, equipment and, often, interdisciplinary teams that apply the knowledge, data, methods, and techniques of nuclear chemistry, mechanical engineering, chemical engineering to missions of the Departments of Energy and Homeland Security. The elements of this capability are often brought together in unique combinations with those of other disciplines to address high priority needs such as new and improved nuclear systems; radioisotope production and advanced instrumentation for nuclear medicine; development of methods and systems to assure nonproliferation and combat terrorism; and environmental studies, monitoring, and remediation.

20. **Nuclear Engineering:** The ability to use a broad range of facilities, instrumentation, equipment and, often, interdisciplinary teams that apply the knowledge, data, methods, and techniques of nuclear engineering, mechanical engineering, nuclear reactor physics, measurable science, and risk assessment to missions of the Departments of Energy and Homeland Security. The elements of this capability are often brought together in unique combinations with those of other disciplines to address high priority needs such as new and improved energy sources and systems; advanced instrumentation for nuclear systems; accelerator science and technology; nuclear forensics; and development of methods and systems to assure nonproliferation and combat terrorism.

21. **Nuclear Physics:** The ability to carry out experimental and theoretical research to provide new insights and advance our knowledge on the nature of matter and energy. This includes the design, operation, and analysis of experiments to establish the basic properties of hadrons, atomic nuclei, and other particles, and the development of models and theories to understand these properties and behaviors in terms of the fundamental forces of nature.

22. **Particle Physics:** The ability to carry out experimental, theoretical, and computational research to provide new insights and advance our knowledge on the nature of matter and energy, and the basic nature of space and time itself. This includes the design, development, and operation of facilities and experiments

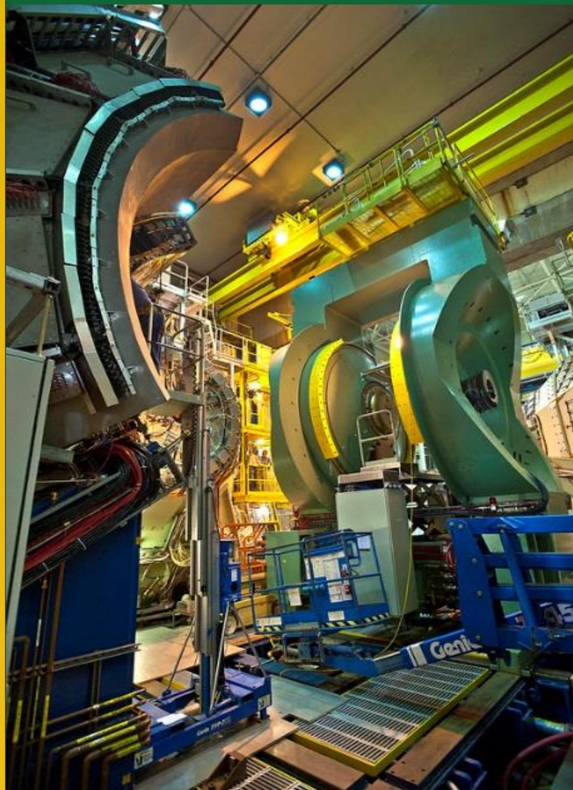
to discover the most fundamental building blocks of matter, probe their interactions, and investigate fundamental forces, as well as the development of theoretical models to understand their properties and behaviors. These initiatives vary dramatically in both scale and methodology, from astrophysical surveys of the sky that study the structure and evolution of the universe to the use of ultra-sensitive particle detectors at powerful accelerator facilities or ones buried deep underground that enable the study of the elementary constituents of matter and energy.

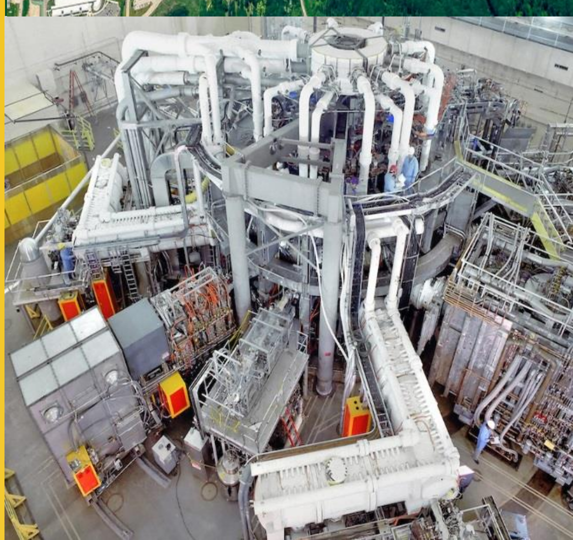
23. **Plasma and Fusion Energy Sciences:** The ability to control, maintain, and utilize matter in the state of plasma across a range of conditions to conduct world-leading research. This includes low-temperature plasmas which are utilized in applications such as microelectronics fabrication and nanomaterial synthesis and can have significant spinoff applications, and high temperature/high pressure plasmas, also known as burning plasmas, which are critical for developing the scientific foundation for fusion as a future energy source. This ability can be demonstrated across this entire range of plasma conditions in the operation of state-of-the-art experimental facilities that can support research on the fundamental physics of plasmas; in theory and advanced simulations which are critical to the full understanding of the plasma phenomena being studied and on how plasmas can be best controlled and utilized; and in enabling technologies that allow experiments to reach the necessary conditions where new discoveries can be made.

24. **Power Systems and Electrical Engineering:** Applies understanding of electromagnetic phenomena to design and engineer circuitry, electrical and electronic devices and equipment, sensors, instruments and control systems to address the efficiency and reliability of power transmission and distribution systems, and the interface of the grid with variable generation and modern loads. Primary supporting disciplines include electrical engineering, power systems engineering, computational science, and materials synthesis, characterization and processing.

25. **Systems Engineering and Integration:** The ability to solve problems holistically from the concept and design phase to ultimate deliverable and completion phase, by synthesizing multiple disciplines, and to develop and implement optimal solutions. The ability to develop solutions that address issues of national energy and environmental security. Areas of application of this capability include development of programs in energy supply, storage, transportation, and efficiency; and deployment of novel solutions to materials and sensor problems in fields of interest to the Department of Energy and/or the Department of Homeland Security.

Back cover photo credits (top to bottom): Brookhaven National Laboratory, Argonne National Laboratory, and Princeton Plasma Physics Laboratory





Consolidated Report Prepared by

U.S. Department of ENERGY | Office of Science