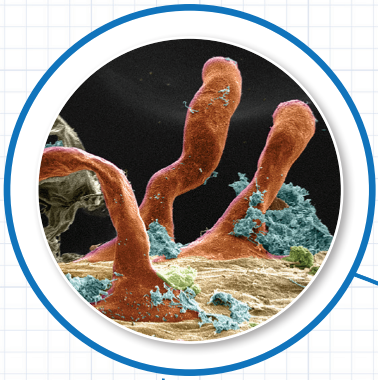
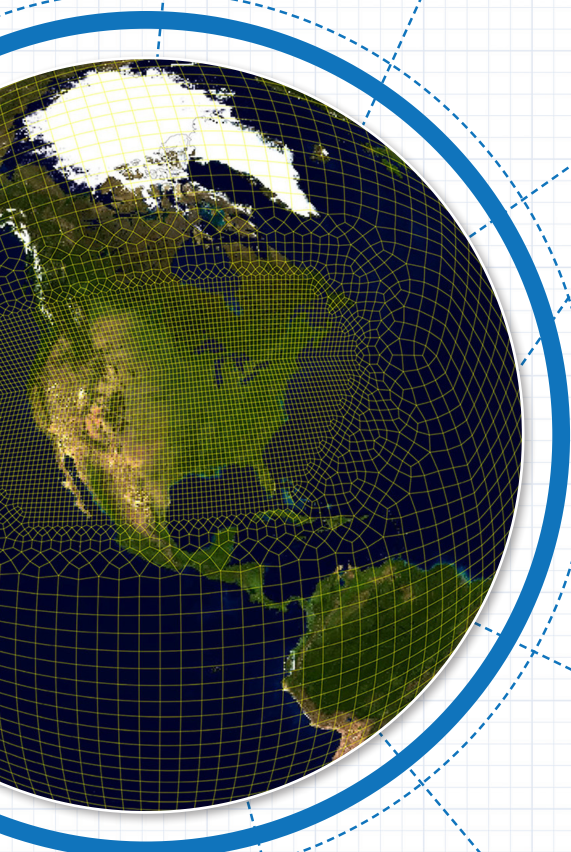
U.S. SCIENTIFIC LEADERSHIP

Addressing Energy, Ecosystems, Climate, and Sustainable Prosperity





Report in Brief from the BERAC Subcommittee on International Benchmarking

U.S. Scientific Leadership

Addressing Energy, Ecosystems, Climate, and Sustainable Prosperity

Report in Brief

from the BERAC Subcommittee
on International Benchmarking

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About this Report in Brief

This document presents components of "U.S. Scientific Leadership Addressing Energy, Ecosystems, Climate, and Sustainable Prosperity: Report from the BERAC Subcommittee on International Benchmarking," including its Executive Summary, Introduction, Findings and Recommendations, and Reflections and Conclusions. The full report contains complete details of the subcommittee's assessment of BER's main mission areas and case studies, which capture key takeaway messages. (science.osti.gov/-/media/ber/berac/pdf/BERAC_2022_Intl_Benchmarking_Report_FINAL.pdf)

About BERAC

The Biological and Environmental Research Advisory Committee (BERAC) provides advice on a continuing basis to the U.S. Department of Energy's (DOE) Office of Science director on the many complex scientific and technical issues that arise in developing and implementing DOE's Biological and Environmental Research program (science.osti.gov/ber/berac).

Front cover image credits (clockwise from left): (1) Grid view of Earth from the atmospheric component of the Energy Exascale Earth System Model. Reprinted from Rasch et al. 2019 under a Creative Commons license (CC BY-NC-ND 4.0). **(2)** Magnified view of a red pine (*Pinus resinosa*) root and associated microbiome. Courtesy Environmental Molecular Sciences Laboratory. **(3)** The Spruce and Peatland Responses Under Changing Environments (SPRUCE) research site located in northern Minnesota. Courtesy Oak Ridge National Laboratory. **(4)** Joint BioEnergy Institute researchers working on the biological production of indigoidine by *Rhodosporidium toruloides*. Courtesy Lawrence Berkeley National Laboratory.

Back cover image credits (clockwise from left): (1) Architecture of a bacterial microcompartment shell revealed by macromolecular crystallography. Reprinted with permission from AAAS from Sutter, M., et al. 2017. "Assembly Principles and Structure of a 6.5-MDa Bacterial Microcompartment Shell," *Science* **356**(6344), 1293–97. **(2)** Instruments from the Atmospheric Radiation Measurement (ARM) user facility's Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign in the Sierras de Córdoba mountain range of north-central Argentina. Courtesy ARM. **(3)** Greenhouse plants at different growth stages. Courtesy Oak Ridge National Laboratory. **(4)** Melanie Bergmann counting Arctic Ocean plastic pollution during the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition. Reprinted with permission from the Alfred Wegener Institute/Esther Horvath under a Creative Commons license.

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Report in Brief

from the BERAC Subcommittee
on International Benchmarking

December 2022

U.S. DEPARTMENT OF ENERGY | Office of Science

Biological and Environmental Research Program

Contents

Executive Summary

The research mission of the U.S. Department of Energy's (DOE) Biological and Environmental Research (BER) program is to support transformative science and scientific user facilities to achieve a predictive understanding of complex biological, Earth, and environmental systems for clean energy and climate innovation. BER mission areas are strategically situated at the nexus of critical global challenges in climate change, energy transitions, and sustainable prosperity. The program's investment portfolio supports and sustains "Big Science" to advance frontiers in genome-enabled biology and the interdependencies of physical and biogeochemical Earth system processes. BER's world-leading facilities enable major scientific discoveries across a global network of supported researchers. Unique in scale and scope, the program's mission areas range from molecular and genomic biosciences to the global dynamics of the atmosphere, oceans, and continents, with a common thread of life across environments.

In fiscal year 2021, BER's $753 million budget supported 1,510 PhD scientists and 530 graduate students at more than 140 academic and nonprofit organizations and at 12 DOE national laboratories (see Fig. 1, this page). Its facilities supported more than 3,900 users globally. BER's research investments and its experimental, observational, and computational user facilities

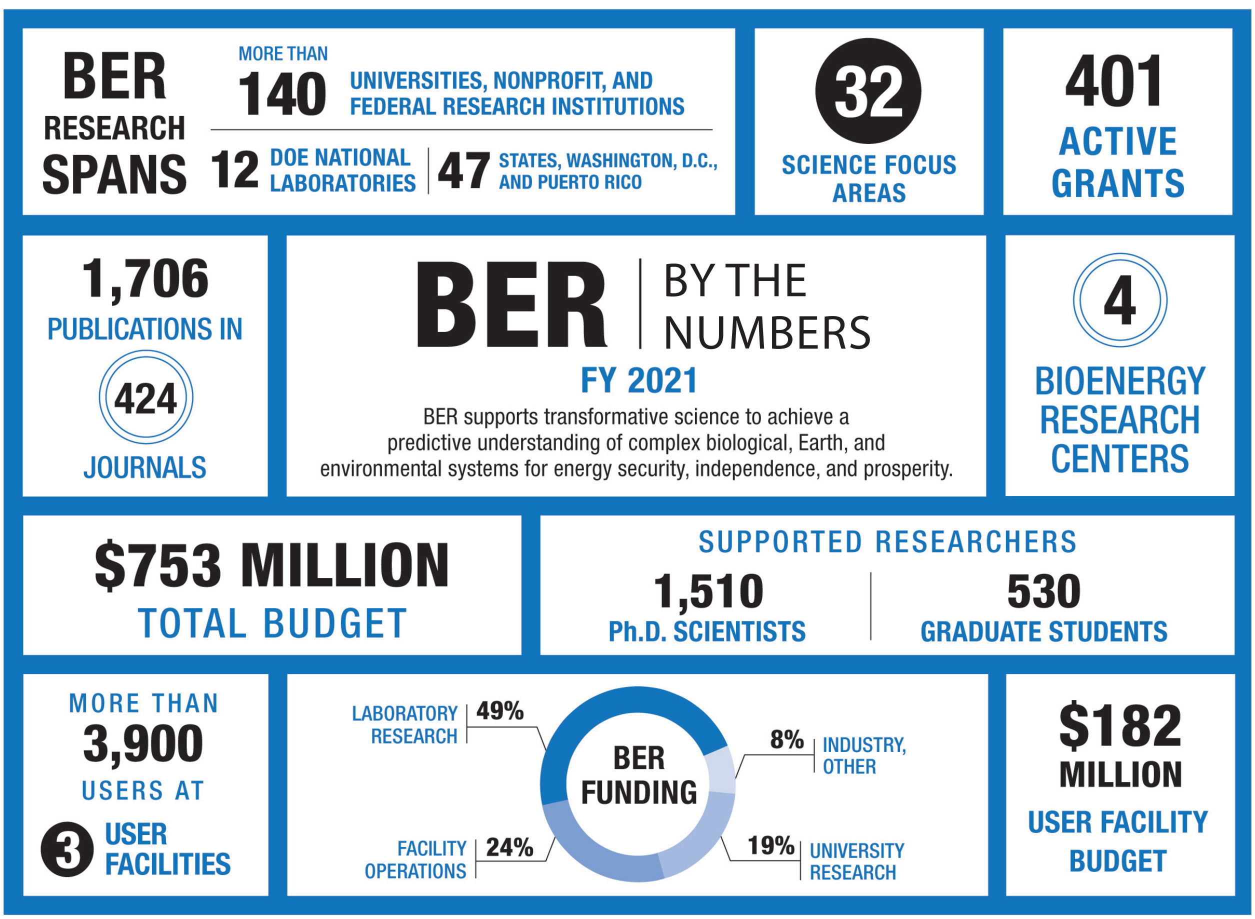


Fig. 1. BER by the Numbers. BER manages an annual research portfolio of about $750 million that encompasses research, facilities, and infrastructure.

have played central roles in (1) Nobel Prize–winning science, (2) major innovations in sustainable bioenergy, (3) world-leading ecosystem-scale experiments, (4) key global efforts addressing climate change, and (5) recent therapeutic discoveries in the fight against COVID-19. These achievements illustrate BER's unique position in the federal funding landscape as a driver of transformative and use-inspired discovery science.

Assessing BER's International Standing

Beginning in 2019, the director of the DOE Office of Science began issuing first-of-a-kind charges to the federal advisory committees of several Office of Science programs, asking them to benchmark the programs' international research competitiveness. The Basic Energy Sciences Advisory Committee (BESAC) received the charge first, completing its report in 2021. BER's Advisory Committee (BERAC) was next, followed by the Advanced Scientific Computing Research Advisory Committee.

This report describes BERAC's assessment in response to the charge letter. To develop this document, the BERAC Subcommittee on International Benchmarking has drawn heavily on the BESAC report (BESAC 2021), as it provides an excellent model for addressing the four questions posed in BERAC's charge. In particular, BESAC's insights into the most effective methodology for quantitative and qualitative metrics strongly influenced this report. Here, the BERAC subcommittee seeks to (1) benchmark BER's programmatic investments and science contributions over the last decade and (2) provide actionable recommendations to realize emerging science opportunities over the next decade.

The subcommittee's benchmarking approach combines quantitative metrics (e.g., bibliometric data and programmatic funding) and qualitative metrics (e.g., responses from expert interviews, town hall discussions, and feedback from a public Request For Information). The quantitative metrics provide a means for benchmarking BER's practices, structures, protocols, and resource investment, as well as the products and outcomes of supported science. The qualitative metrics provide diverse perspectives on national and international leadership, horizon scans for emerging opportunities, and broader workforce insights into how BER can attract and retain the top scientific talent necessary for ensuring future international leadership. Data and analyses for these findings and recommendations were gathered and developed in 2021. BER has independently acted in some cases during 2022 to address some of the issues raised.

Findings and Recommendations

This document presents the subcommittee's overarching and domain-specific findings and recommendations (see p. 8) for the next decade, identified by consensus across the full BERAC subcommittee and experts interviewed for this assessment.

Overall, BER's international leadership is well-substantiated across its mission areas and enabling infrastructure. However, BER's continued leadership, as well as that of the broader U.S. research enterprise, should not be taken for granted. The next decade could see the realization of forewarned declines in U.S. scientific competitiveness and leadership noted in previous reports (NASEM 2007; Augustine and Lane 2021) and similarly emphasized in the BESAC report (BESAC 2021).

Feedback from experts surveyed across BER mission areas also indicates that volatility in priorities, funding, and workforce retention significantly threatens BER's ability to sustain its leadership. Moreover, BER funding over the past decade has not increased commensurately with the growing scale and acuteness of the national and global challenges that its research addresses. Transformative, high-risk research[1] is required to tackle these challenges and maintain U.S. international competitiveness. The current era is one in which "… our nation cannot afford to miss opportunities, discoveries, and new frontiers that can result from bold, unfettered exploration and freedom of thought that challenges

[1] "Transformative research is defined as research driven by ideas that have the potential to radically change our understanding of an important existing scientific or engineering concept or leading to the creation of a new paradigm or field of science or engineering. Such research is also characterized by its challenge to current understanding or its pathway to new frontiers" (National Science Board, National Science Foundation 2020).

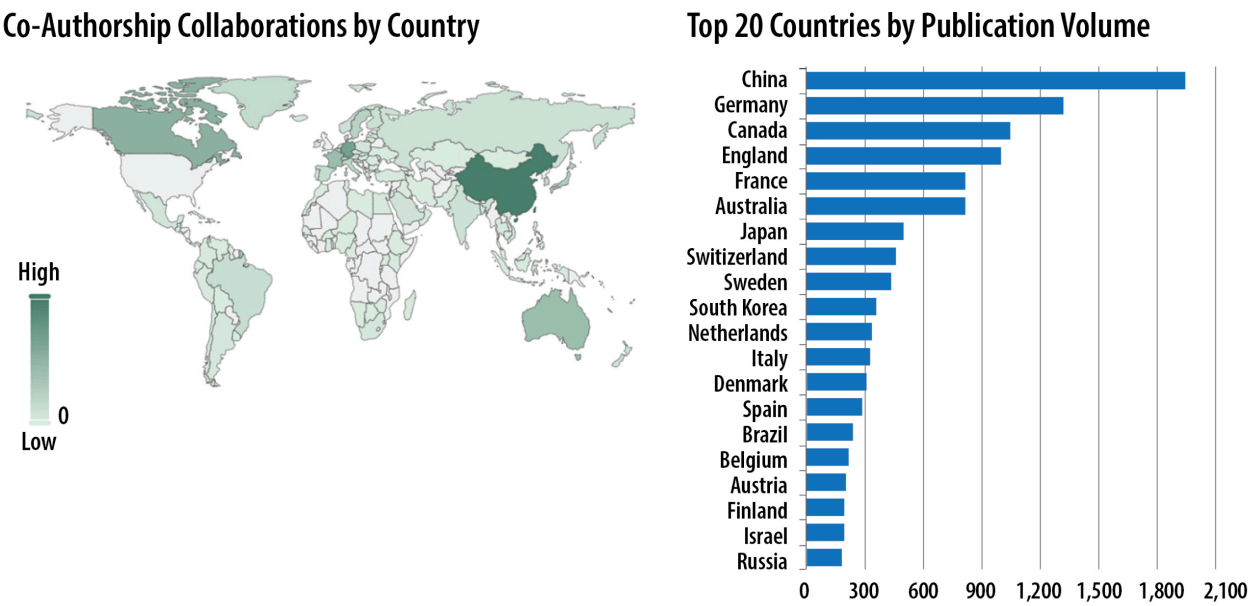


Fig. 2. International Collaborations and Publication Volumes by Country Involving BER-funded Scientists. [Courtesy DOE Office of Scientific and Technical Information]

our current understanding of natural processes" (NSB 2007).

Although BER's research leadership is far-reaching and responsible for a range of cutting-edge breakthroughs, the experts did not associate these breakthroughs distinctly with BER. This lack of visibility in the research community is a missed opportunity to recruit a diverse, committed, and exceptional future workforce to BER's research mission.

Finally, many experts noted that international leadership should not be seen as adversarial. Rather, BER's research portfolio should be viewed through a collaborative lens, as it contributes to the collective commons of enabling knowledge for the world. Indeed, many of BER's impactful discoveries are generated through international partnership as shown by the subcommittee's bibliometric metric analyses (see Fig. 2, this page). Moreover, BER's goals of combating climate change, transitioning from fossil fuels to renewable resources, and achieving a sustainable bioeconomy that will ensure future prosperity are also societal goals that must be achieved on a global scale.

The full report presents specific findings and recommendations in BER's main mission areas: bioenergy and environmental microbiomes (Ch. 2), biosystems design (Ch. 3), environmental system science (Ch. 4), and climate science (Ch. 5). Chapter 6 outlines the contributions of BER-supported user facilities and infrastructure to national and international science leadership. Chapter 7 evaluates and explores opportunities for integrative science across mission areas and potential innovations to amplify BER's scientific impact. Collectively, these chapters answer the first question of the charge letter: What is the international standing of BER's science, and how can BER's leadership be strengthened? Chapter 8 addresses the remaining three charge letter questions focused on issues of workforce recruitment, international partnerships, and research enterprise management and operation. A summary of the report's Findings and Recommendations begins on p. 8. With these recommendations, the subcommittee seeks to ensure BER's continued international leadership in the next decade.

Defining BER's Leadership, Success, and Reputation

How can we measure BER science and scientific infrastructure on the world stage? Although daunting, this challenge is not impossible, as suggested by studies from the American Academy of Arts and Sciences and the National Academies of Sciences, Engineering, and Medicine (NASEM). The studies indicate that international benchmarking for a research field (NASEM 2000) and for the national research enterprise (AmAcad 2020) is both feasible and valuable, providing a sketch of research status and future directions.

To conduct such an assessment in response to the Office of Science charge, the BER Advisory Committee's (BERAC) Subcommittee on International Benchmarking established working groups in BER mission areas. Each group comprised six to eight members and co-leads, including international participants, with deep expertise spanning various institutions and backgrounds. The working groups identified international peer groups and BER-relevant focus areas for comparison. The collective goal was to benchmark performance in the last decade and to help inform BER's strategy in the next decade with actionable recommendations.

The subcommittee also identified a series of case studies that capture takeaway messages from the team's assessment (see full report, BERAC 2022). These focused stories are intended to illustrate the high-impact successes, challenges, and future opportunities for BER and its research community.

In examining BER leadership, the subcommittee structured its assessment around several questions:

- Is BER-supported research fundamentally advancing science? If so, is this impact largely internal or at an international level?
- Are BER-pioneered scientific approaches at the cutting edge and influencing scientific research more broadly?
- Are BER-supported scientists regarded as thought leaders in the global research community?
- Is BER making the necessary investments—in research, infrastructure, and training the next generation of scientists—that position it to lead now and in the future?

Assessment Methodologies Used for Benchmarking

The Basic Energy Sciences Advisory Committee's (BESAC) international benchmarking report (BESAC 2021) described a benchmarking methodology incorporating analyses of bibliometric data, interviews with experts, and community engagement at conferences. Using this methodology as a roadmap, the BERAC subcommittee analyzed both quantitative bibliometrics to provide a snapshot of research performance over the past 10 years and qualitative assessments of leadership to provide a foundation for horizon scanning in BER mission areas.

Publication and Funding Analyses

In addition to bibliometric data from public databases, such as citations and international authorships of publications, the BERAC subcommittee examined funding levels over time as another measure of BER commitment and investment in scientific leadership. The subcommittee is deeply grateful to staff at DOE's Office of Scientific and Technical Information for conducting bibliometric searches and compiling data for BER-supported scientists compared to other U.S. and non-U.S. authors across BER mission domains.

Not all potentially relevant metrics were available for this evaluation. For example, some data and software citations were too new to be applied or tallied comprehensively. Also, because BER research spans many topics, activities, and communities and given the time constraints for conducting this study, the working groups did not evaluate some potential indicators of leadership, such as (1) authorship of key reports (e.g., by NASEM and Intergovernmental Panel on Climate Change), (2) leadership in significant workshops, or (3) keynote talks at major conferences. Future benchmarking efforts could consider these indicators.

Community Input

Since quantitative metrics are insufficient for assessing leadership and scientific advancement, the subcommittee sought input from thought leaders and scientists representing all BER research domains and from different institutions, countries, and career stages. The subcommittee used these interviews with national and international experts as a primary means to assess BER's potential for international leadership in the next decade. As scientists, subcommittee members are deeply concerned about overextrapolating the findings from small sample sizes, but they captured many interesting comments from more than 60 interviews. The team then analyzed these comments to form hypotheses, and, when similar messages were heard from multiple experts, they gained confidence in a hypothesis and sought quantitative data or conducted additional interviews when possible. The subcommittee also reported instances where there was a lack of consensus or where a comment seemed particularly insightful.

To test the collected hypotheses, the team also elicited feedback from a larger pool of BER stakeholders through town halls with focus groups (e.g., Early Career Program awardees), where participants echoed and amplified many of the experts' comments. The focus groups also provided unique insights on workforce development, recruitment, and talent retention. The subcommittee received additional input in response to a public Federal Register Request For Information.

Current Status of International Leadership in BER's Mission Space

Predictions from the National Academies "Rising Above the Gathering Storm" report (NASEM 2007) might now be evident in publication and citation trends for BER mission areas. Although BER holds distinguished leadership across its mission space in terms of generating top-ranked publications and higher citation rates relative to U.S. and international peers, the leadership gap has been closing rapidly since 2010. The research community and stakeholders have raised concerns about the international competitiveness of the U.S. research enterprise over the last 2 decades, and the next decade marks a potential inflection point for U.S. global leadership. This sentiment is mirrored in the National Science Board Vision 2030 report, which notes a "case for urgency" because global R&D "… is growing faster, and consequently the U.S. share of discovery is dropping" (NSB 2020).

One clear symptom of this trend is seen in national research investment over the past decade. As global R&D funding increases to record levels (~$2 trillion as of 2019), the spending gap between the United States, European Union, and China is narrowing rapidly. The United States risks falling out of the top 10 ranked countries in terms of research workforce development rates and R&D expenditures as a percentage of gross domestic product (see Fig. 3 and Fig. 4, p. 6). Appropriated budgets for BER have remained flat in the last decade when normalized to 2010 dollars despite increased costs of performing research and a larger scientific workforce.

Compounding the impact of flat budgets, major cuts in DOE's 2018 budget request represented the potential for devastating long-term losses to BER science and the BER-supported research workforce. Although final budget appropriations avoided the proposed cuts to critical programs, experts interviewed for this assessment consistently noted the more subtle and long-term effects of these potential cuts on morale, retention, and BER's reputation in recruiting scientists across all levels of seniority. These impacts are

America's Share of R&D Decreasing as Global Science and Engineering Grows

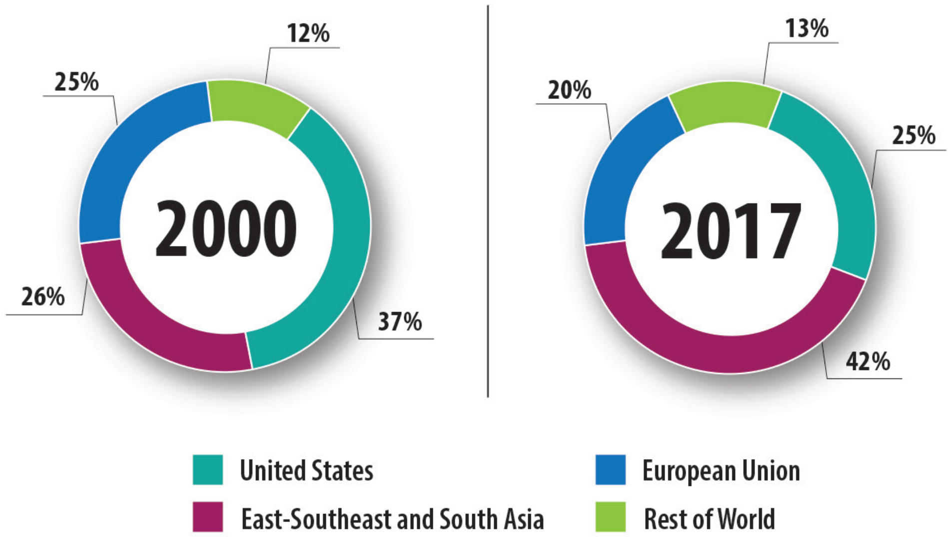


Fig. 3. Comparing U.S. and Global Science Investments. While the U.S. investment in research and development (R&D) continues to grow in absolute terms, the investment by other countries is growing faster. As a result, the U.S. share of global R&D spending decreased from 37% to 25% between 2000 and 2017. [Courtesy National Science Foundation]

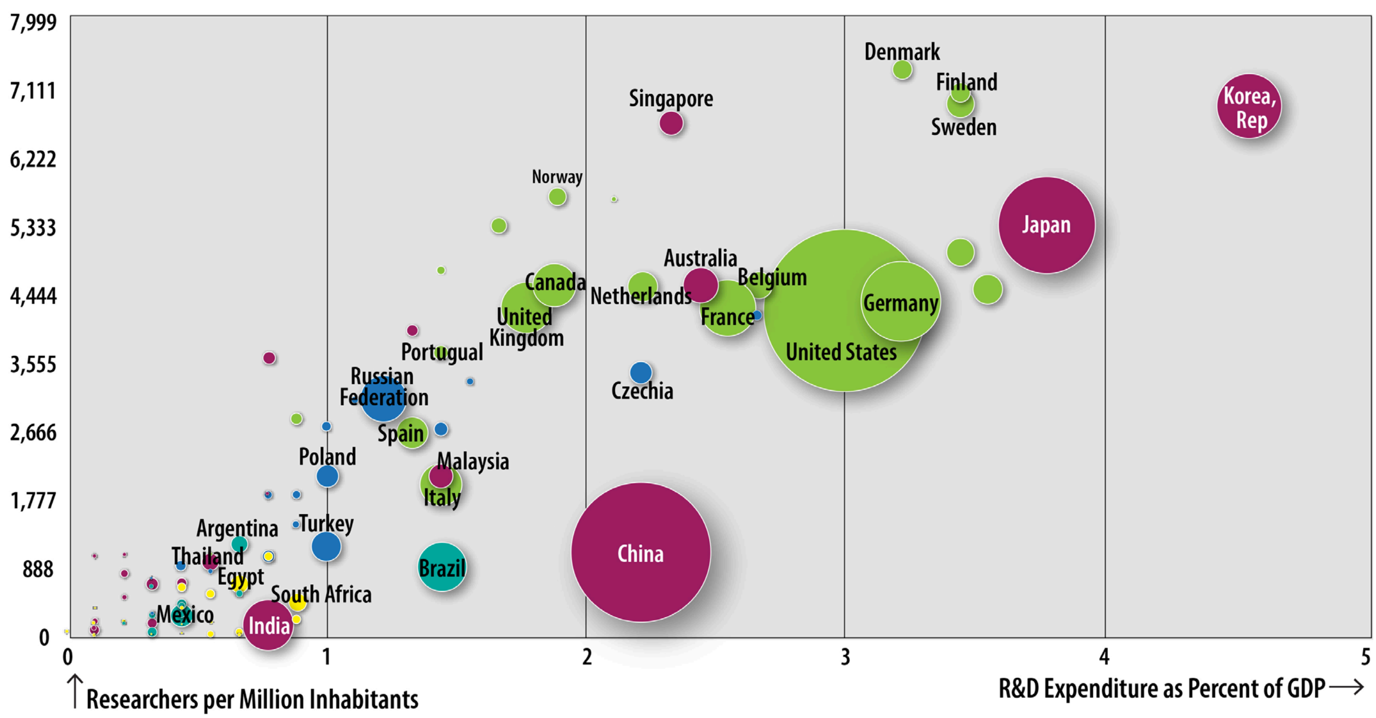


Fig. 4. Investments in Global R&D on the Rise. According to the UNESCO Institute for Statistics, global R&D has increased to record levels (~$2 trillion as of 2019) over the past decade. Countries have pledged additional substantial increases in public and private funds as well as the number of researchers by 2030 as part of their response to the United Nation's Sustainable Development Goals. [Courtesy UNESCO. uis.unesco.org/apps/visualisations/research-and-development-spending]

particularly concerning in the post-pandemic environment in which many employees are leaving the workforce for reasons that are relational and cultural (e.g., not feeling valued or recognized and not having opportunities for professional and personal growth) rather than transactional (e.g., salary increases and work conditions; De Smet et al. 2021). There is no reason to believe that the scientific workforce is immune or exempt from this trend. Although the stability of flat fiscal appropriations or even slight increases is often a focal point for BER programmatically, BER needs to consider the workforce cultural impacts of potential and realized volatility as a major structural vulnerability.

BER is tackling critical scientific challenges and global risks that no country or funding body has the singular ability to address. This perspective is reinforced by the National Science Board's Vision 2030 report, which emphasized that science and technological breakthroughs are "… now a truly worldwide enterprise, with more players and opportunities from which humanity's collective knowledge is growing rapidly. This dynamic R&D landscape is characterized by interdependence as well as competition" (NSB 2020). To conclude, the BERAC subcommittee emphasizes the critical importance of avoiding a myopic, narrow, and adversarial framing of international leadership for discovery science, the fruits of which must be realized at a global scale.

Findings and Recommendations

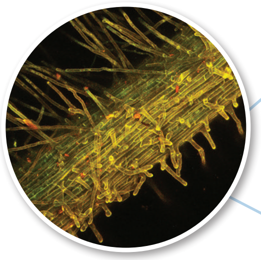
The BERAC Subcommittee on International Benchmarking developed both overarching and science domain–specific Key Findings and Recommendations based on their work to address the DOE Office of Science charge, which entailed synthesizing responses from expert interviews, town hall participants, and a public Request For Information. Data and analyses for these findings and recommendations were gathered and developed in 2021. BER has independently acted in some cases during 2022 to address some of the issues raised.

Overarching Findings

- BER's international leadership is well-substantiated across mission areas and enabling infrastructure.
- Mission areas increasingly target the critical challenges of the coming decades for which "Big Science" can and must be entrained.
- International leadership is a more meaningful goal when viewed in a collaborative versus adversarial context.
- Future leadership is not guaranteed and will require increased investments and strategic partnerships with private, public, and academic institutions; other DOE programs; other federal agencies; international collaborators; and across disciplines.
- Volatility in priorities, funding, and workforce retention significantly threatens BER's ability to sustain its leadership.
- BER's funding over the last decade has not increased commensurately with the growing scale and acuteness of the national and global challenges that BER missions and science address.
- The science community does not widely associate BER with the major research impacts and achievements it has enabled.

Strategic Recommendations

- Increase and sustain needed resources in all mission areas and in integrative science opportunities across and between these areas (risk: failure to invest).
- Improve connection between basic science and research across Technology Readiness Levels (risk: failure to capitalize on investment).
- Establish horizon-scanning mechanisms for long-range, strategic infrastructure and mission-area investments (risk: failure of imagination).
- Elevate the stature of BER mission science to ensure recruitment of the best and brightest (risk: failure to inspire).
- Prioritize, with time and investment, a culture that supports diversity and inclusion, enables early and mid-career professional development, and delivers the future workforce (risk: failure to sustain future leadership).



Chapter 2
Bioenergy and Environmental Microbiomes

Key Findings

KF2.1 BER is an international leader in fundamental bioenergy, sustainability, and environmental microbiome research, but other countries are catching up to the United States in scientific leadership and their capacity to translate basic research into practical applications.

KF2.2 BER funding of plant science studies has positioned the United States as the world leader in plant bioenergy and feedstock research.

KF2.3 BER leads in developing and applying genome- and omics-based approaches to bioenergy and environmental microbiome research. Maintaining this position requires continued support for new technologies and experimental testing of hypotheses generated from omics data. The next frontier will be combining multiomics approaches with innovations in microbial and plant biochemistry, areas where BER may lag other countries.

KF2.4 Several nations, including China, outperform the United States in developing and deploying technological applications, partly due to external policies and market trends, lower investment in fundamental bioprocessing research, and gaps in continuity between discovery, development, and deployment.

KF2.5 The DOE Bioenergy Research Center (BRC) program exemplifies the power of well-managed team science, which benefits from stable funding, a strong mission, and a collaboration emphasis. With well-integrated, multidisciplinary teams, the BRCs excel at performing and publishing research in foundational science and building collaborator networks, but their intellectual property has not been widely deployed.

KF2.6 Interagency calls, when initiated, provide a productive mechanism for fostering research collaborations.

Recommendations

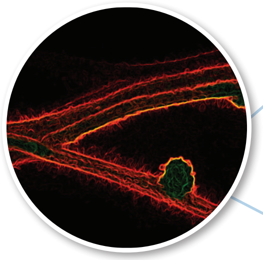
R2.1 Spearhead a renaissance in bioenergy research, the need for which is highlighted by recent geopolitical events including the war in Ukraine and U.S. economic vulnerability to disruptions in the global energy market. To maintain its international position as a research leader, BER should support and encourage the next generation of researchers to embrace innovative, high-risk approaches for achieving bioenergy goals.

R2.2 Lead efforts to provide the fundamental knowledge needed to bring products to market. BERAC does not recommend that BER support applied research, since BER's strength and preeminence lie in fundamental science. However, BER should engage in creative opportunities to catalyze communication between basic and applied researchers to speed transitions between early Technology Readiness Levels.

R2.3 Encourage interactions and interdisciplinary collaborations that better integrate the unique architecture of BER's research portfolio and provide the research community with access to established resources such as ongoing perennial field experiments and their growing data collections. These activities will generate knowledge between and across disciplines and experimental scales, from computation to experimentation and from molecules to phenotypes.

R2.4 Build on genome-enabled bioenergy and environmental microbiome leadership and knowledge to understand the complex interactions between bioenergy crops and environmental microbiomes, thereby informing sustainable management of ecosystems under climate change.

Image credit: Microbes colonizing poplar roots. [Courtesy Oak Ridge National Laboratory]



Chapter 3
Biosystems Design

Key Findings

KF3.1 The relatively recent launch of BER's Biosystems Design research program is already yielding high-profile research accomplishments.

KF3.2 BER holds a strong leadership position in microbial biodesign, particularly in bacterial systems. However, leadership is increasingly distributed across the globe, with the United States considered "one of many" leaders for yeast and other fungi.

KF3.3 BER does not lead in understanding microbial physiology during bioprocess scale-up.

KF3.4 No world region yet leads in plant biodesign, suggesting that BER could target investments to yield substantial intellectual returns.

Recommendations

R3.1 Establish new Biodesign Research Centers patterned off existing DOE Bioenergy Research Centers to leverage advancements in BER's Biosystems Design research, which encompasses multiple applications and could potentially synergize various biological platforms, including nonmodel and photosynthetic microbes.

R3.2 Explore and coordinate joint funding calls with international agencies to accelerate progress in biodesign by leveraging key expertise from other countries.

R3.3 Encourage replication of recent machine-learning breakthroughs, such as AlphaFold 2.0, and development of new deep-learning algorithms more broadly in biodesign. Target funding for curating, mining, and generating omics datasets and developing laboratory automation tools for generating high-quality datasets to train machine-learning models that support biodesign.

R3.4 Invest in disruptive, bold initiatives to accelerate plant synthetic biology and plant transformation processes in coordination with the National Science Foundation and other agencies.

R3.5 Expand support for biomanufacturing training programs for doctorate and nondoctorate workforces that critically feed the talent pipeline for the U.S. biotechnology industry.

Image credit: Transgenic roots of *Medicago truncatula* with nodules formed by its symbiont (*Sinorhizobium meliloti*). [Courtesy University of Florida]

Chapter 4
Environmental System Science

Key Findings

KF4.1 BER's Environmental System Science (ESS) research program is highly cited and internationally respected for its:

a. Multidisciplinary systems science.

b. ModEx (modeling-experimental) approach that emphasizes an iterative exchange of knowledge and discovery among predictive models, experiments, and observational field research, leading to novel discoveries.

c. Research infrastructure, including large-scale ecosystem manipulations such as the Spruce and Peatland Responses Under Changing Environments (SPRUCE) project, AmeriFlux, and watershed Science Focus Areas, which support cross-agency and international collaboration.

d. Terrestrial Ecology research, including biogeochemistry, ecosystem fluxes, and climate change responses.

e. Watershed Sciences research, including multiscale hydro-biogeochemical modeling and process studies.

KF4.2 ESS research has untapped potential for:

a. Better integrating human influence into the study of natural systems.

b. Supporting both creative discovery science and the translation of research to inform applied solutions.

c. Bridging the gaps between terrestrial sciences and atmospheric and climate sciences.

Recommendations

R4.1 Embrace coupled human-natural systems as a critical niche for ESS contributions in the next decade while maintaining the focus on mechanisms and process understanding.

R4.2 Elevate and integrate tools for data discovery and analysis at a level commensurate with ESS data volume and complexity to accelerate scientific impact.

R4.3 Facilitate the translation of ESS research into solutions and innovations by the DOE offices with a mandate for applied work and other potential partners.

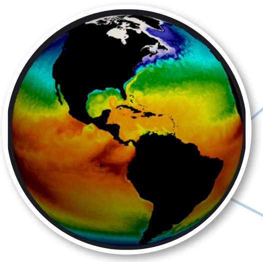
R4.4 Create avenues for the research community to communicate and interact across the DOE science and technology pipeline, leading to breakthroughs, greater inclusivity, improved efficiencies, and reduced time lags between needs assessment, fundamental science, and application.

R4.5 Become an international leader in providing safe and inclusive fieldwork by building on existing ESS accomplishments, developing and sharing ESS resources, and modeling the successes that arise from equitable professional environments.

R4.6 Maintain global leadership in large-scale ecosystem manipulation experiments, a hallmark of BER science, which integrate ESS domains, promote ModEx, and foster collaboration among domestic and international institutions.

R4.7 Ensure that ESS strategic priority and funding paradigms support foundational research opportunities to continue international domain leadership.

Image credit: Catlett Islands water sediment site. [Courtesy Pacific Northwest National Laboratory]



Chapter 5
Climate Science

Key Findings

KF5.1 BER-funded climate science publications are among the most highly cited papers in the field, garnering a higher rate of citations than non-BER publications, particularly for the top 1% and 5% of papers.

KF5.2 BER has demonstrated international leadership in developing and interpreting climate model intercomparisons through the DOE Program for Climate Model Diagnosis and Intercomparison (PCMDI) and was a leading contributor to research earning the 2007 Nobel Peace Prize awarded to the Intergovernmental Panel on Climate Change and former U.S. Vice President Al Gore.

KF5.3 BER is a world leader in climate change and cloud feedback research through its application of the "fingerprint" method to identify signatures of human influence on climate and its development of innovative techniques to quantify cloud feedbacks and pin down equilibrium climate sensitivity.

KF5.4 BER has advanced exascale computing to become one of the world's leading developers of kilometer-scale Earth system models, such as the convection-permitting Energy Exascale Earth System Model.

KF5.5 BER has successfully developed capabilities in crosscutting energy-related research and coupled human-Earth system models, such as the Global Change Analysis Model.

KF5.6 BER leads internationally in capturing ground-based and aerial atmospheric measurements through its Atmospheric Radiation Measurement (ARM) user facility and in advancing physical understanding of atmospheric systems through the associated Atmospheric System Research program.

Recommendations

R5.1 Increase investment in development of kilometer-scale Earth system modeling by advancing exascale computing, artificial intelligence and machine-learning approaches, and model-observation integration.

R5.2 Strengthen international leadership in modeling the coupled human-Earth system by providing more decision-relevant insights and better accounting for model uncertainties.

R5.3 Sustain international leadership in ground-based and aerial measurements and their use in advancing physical process understanding by strengthening collaborations with the satellite community, supporting integration of national and international field-observing systems, and potentially establishing synergistic leadership in laboratory chamber facilities.

R5.4 Strengthen international leadership in model intercomparison activities and in climate sensitivity research by increasing support for PCMDI, the Earth System Grid Federation, and process-oriented exercises that use ARM observations.

R5.5 Establish sustained and substantial funding for expanded collaboration between U.S. agencies and universities to improve research outcomes and integration of efforts to meet societal needs.

R5.6 Create additional means for supporting "blue sky" proposals from DOE scientists to stimulate innovation and workforce engagement.

Image credit: Energy Exascale Earth System Model (E3SM) representation of sea surface temperature. [Courtesy E3SM]

Chapter 6
Enabling Infrastructure

Key Finding

KF6.1 The review showed that BER research is currently supported by six world-class infrastructure capabilities:

a. **DOE Joint Genome Institute (JGI).** BER's JGI is the world's largest center for nonbiomedical genomic science research, supporting DOE missions in clean energy and environmental characterization and cleanup. It provides integrated high-throughput sequencing and computational analysis that enable systems-based approaches to these challenges.

b. **Atmospheric Radiation Measurement (ARM) User Facility.** BER's ARM is internationally recognized for its long-term ground-based observation facilities, which have been advancing global atmospheric and climate research for 40 years. ARM's long-term data records, breadth of conditions and locations over diverse climate-relevant areas, and influence in the study of the climate system are unmatched by any other ground-based programs around the world.

c. **AmeriFlux and the AmeriFlux Management Project.** BER-supported AmeriFlux is a collection of long-term, eddy flux stations that measure ecosystem carbon, water, and energy fluxes across the Americas. One of two leading global flux networks, AmeriFlux is part of the international FLUXNET project and has taken the lead in creating the FLUXNET synthesis data products, the most impactful international observational product.

d. **National Synchrotron Light Source II (NSLS-II).** Supported by DOE's Office of Basic Energy Sciences, NSLS-II is the newest and most advanced synchrotron in the United States. The facility's design optimizes the creation of tightly collimated, high-flux light beams, covering the spectral range from infrared to high-energy X-rays. This unique combination of performance characteristics has allowed the creation of world-leading instruments, such as imaging with high spatial resolution (~10 nm) and chemical sensitivity, opening up novel possibilities for the study of biological material dynamics. Additional BER co-funded instruments with small beams (1 μm) are enabling high-resolution structural information from tiny protein crystals.

e. **DOE Leadership Computing Facilities.** Supported by DOE's Advanced Scientific Computing Research program, the Argonne Leadership Computing Facility, Oak Ridge Leadership Computing Facility (OLCF), and National Energy Research Scientific Computing Center are critical parts of the enabling infrastructure on which BER scientists rely. In June 2022, the high-performance computing community's international benchmarking effort ranked OLCF's Frontier supercomputer as the fastest in the world after it became the first system to break the exascale barrier. What distinguishes these DOE systems from international comparators is the science support ecosystem around them, provided by the DOE Exascale Computing Project (ECP). BER science has benefited from ECP in both its climate (Energy

Exascale Earth System Model) and biology (ExaBiome) research.

f. **Environmental Molecular Sciences Laboratory.** EMSL delivers leading facilities, advanced instrumentation, and scientific leadership that empower and enable a national and international community of researchers to advance BER's mission to achieve a predictive understanding of complex biological, Earth, and environmental systems.

Recommendations

R6.1 Establish an oversight board to assess strategic decisions about creating, continuing, and sunsetting all BER infrastructure capabilities. This board should develop and publish a regularly updated 5- to 10-year strategic roadmap for infrastructure capabilities that support mission-critical science, coordinating with other DOE offices and national and international agencies to maximize investment and impact.

R6.2 Promote greater integration across user facilities—including harmonization of data management and analysis services—to enable researchers to easily schedule and use different infrastructure capabilities.

R6.3 Consider creating data user facilities and providing long-term support for their governance, planning, policy development, and technological needs.

R6.4 Establish a cross-facility working group to develop and share a foundational BER data policy and best practices for data use, licensing, and citation.

R6.5 Increase computational and storage capacity for BER researchers.

Image credit: ARM cloud radar in Brazil. [Courtesy ARM]

Chapter 7
Integrative Science

Key Findings

KF7.1 BER leads internationally in integrating climate observations and modeling, and its Atmospheric Radiation Measurement (ARM) user facility and Atmospheric System Research (ASR) program are international leaders of integrative science involving short-term field campaigns.

KF7.2 Sustaining leadership in the integration of the ARM, ASR, and Earth system modeling programs requires both maintenance of cutting-edge observational capabilities and continued access to adequate computational resources.

KF7.3 Additional leadership gains would be achieved by improving integration across the Energy Exascale Earth System Model (E3SM), the Program for Climate Model Diagnosis and Intercomparison, research in Regional and Global Model Analysis, ARM, and MultiSector Dynamics modeling efforts.

KF7.4 The DOE Bioenergy Research Centers (BRCs) exemplify interdisciplinary research ranging from detailed molecular analysis to ecosystem modeling.

KF7.5 DOE's Environmental Molecular Sciences Laboratory (EMSL), Joint Genome Institute (JGI), and light source user facilities, along with their numerous collaborators, are international leaders in integrating omics research, molecular and structural analysis, and systems biology.

KF7.6 BER is a leader in systems-level understanding such as the linkages between plant microbiomes and ecosystem function.

KF7.7 EMSL successfully integrates atmospheric science and physical chemistry with potential expansion into biological aerosols.

KF7.8 Citation analysis demonstrates integration success: BER-sponsored papers are 1.5 times more likely than non-BER papers to span two BER science areas and 3 times more likely to span three.

KF7.9 BER research could be further integrated by developing opportunities embodied in crosscutting user facility programs such as the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) project and the Facilities Integrating Collaborations for User Science (FICUS) initiative.

KF7.10 Integrating efforts across U.S. agencies is a formidable challenge leaving unrealized opportunities for further integration across BER's portfolio.

Recommendations

R7.1 Improve BER's capacity for integrative research within and beyond its research portfolio.

a. Solicit support from the National Academies of Sciences, Engineering, and Medicine for synthesizing capabilities, needs, and opportunities across BER-relevant user facilities and field sites funded by DOE and other U.S. agencies to accelerate groundbreaking integrative research.

b. Create sustained funding opportunities across BER, DOE, and other agencies (where possible) to advance a more integrated understanding of biological and environmental systems at multiple scales.

c. Strengthen workforce capacity for integration by better supporting integrative research with targeted funding opportunities, particularly among early career researchers.

R7.2 Advance a more complete understanding of coupled human-natural systems in BER science areas.

a. Include coupled human-natural system dynamics in BER funding opportunities.

b. Launch a multiagency research program to improve integration across both the MultiSector Dynamics and Earth and Environmental Systems Modeling programs.

c. Establish research sites for integrated long-term studies that span genomes to landscapes and the subsurface to atmosphere.

R7.3 Build international collaborations to strengthen BER's global leadership in the genomic, environmental, and climate modeling sciences.

a. Work jointly with other U.S. agencies to develop an internationally coordinated effort that will provide public and private stakeholders with urgently needed climate and environmental data.

b. Explore the potential for coordinating and promoting international collaborations that would leverage BER's investments in the genomic and environmental sciences, including the BRCs.

R7.4 Support integration through existing and new user facilities.

a. Establish a computational synthesis center to support the pursuit of questions that demand targeted integration across disciplines and scales.

b. Dedicate a cross-facilities operational budget to fund integrative science projects spanning multiple BER user facilities.

Image credit: Researcher working on lignin digestibility.
[Courtesy Great Lakes Bioenergy Research Center]

Chapter 8
Strategies for People, Partnerships, and Productivity

Key Findings

PEOPLE

KF8.1 BER funds academic scientists across the nation who contribute exceptional talent and new expertise to the program's mission.

KF8.2 The DOE national laboratory complex provides many positive career opportunities for BER-funded scientists.

KF8.3 Programs for undergraduates, graduate students, and postdoctoral students effectively recruit scientific talent for BER missions.

KF8.4 The lack of workforce diversity significantly limits BER's long-term leadership and the necessary growth of its scientific workforce.

KF8.5 BER frontier research successes and impacts lack visibility.

KF8.6 BER funding for high-risk discovery science and paths to independent work are rare at the national laboratories, and increased funding flexibility is desired at all career levels.

KF8.7 Real and perceived volatility in funding levels and research topics hampers workforce recruitment and retention at all career stages and impedes long-term productivity.

KF8.8 Current funding models produce high levels of professional anxiety among national laboratory programmatic staff who feel pressure to continuously secure projects that support their own salaries.

KF8.9 At some user facilities, limited opportunities exist for support staff advancement, independent research, and future career choices, leading to overwork and professional burnout. These challenges vary significantly depending on the operational model of a given facility.

KF8.10 Over the last decade, BER has seen attrition of scientific workforce talent, particularly among academic Early Career Research Program awardees, half of whom are no longer funded in the BER mission space.

KF8.11 Some BER-supported Early Career awards are limiting workforce development due to their timing and topical volatility, providing only narrow windows of opportunity in a scientist's career pathway. This impact is more pronounced for the Earth and Environmental Systems Sciences Division than the Biological Systems Science Division and its more stable approach.

PARTNERSHIPS

KF8.12 Although international collaborations are critical for strengthening BER scientific output and increasing global visibility, such partnerships are difficult for BER-funded institutions due to funding restrictions between countries.

KF8.13 BER program staff and BER-supported scientists have few resources to travel or engage internationally.

KF8.14 Meeting societal needs requires more domestic and international collaborations for ground-based observations and high-resolution Earth system modeling to improve research outcomes and ensure integration of efforts.

KF8.15 Because of its mobile facilities and ability to fund international partners, the Atmospheric Radiation Measurement (ARM) user facility excels in collaborations—both in the United States and abroad.

PRODUCTIVITY

KF8.16 BER user facilities are specially positioned to integrate researchers across BER because of their unique expertise, leadership positions, and ability to attract users.

KF8.17 The Bioenergy Research Center (BRC) program achieves strategically important BER mission goals, and its model could be applied to other relevant research areas, such as environmental microbiomes. With their integrative focus, the BRCs have excelled at building impactful and highly productive researcher networks working toward a common goal.

KF8.18 BER should maintain team-based projects combining researchers from academic institutions and DOE national laboratories.

KF8.19 Silos and mission boundaries within DOE and across agencies block the potential for science accomplishments to inform innovation and applied solutions.

KF8.20 U.S. agencies should consider opportunities to expand collaborative climate science research beyond the current facilitating role of the U.S. Global Change Research Program, which lacks allocated funding.

Recommendations

PEOPLE

R8.1 Incentivize efforts to increase workforce diversity and provide a culture of inclusivity, explicitly measuring successes and evaluating outcomes continually for further improvements using processes with broad participation.

R8.2 Invest in effectively communicating BER scientific successes and proactively convey the importance of the program's research mission to better recruit and retain top global talent.

R8.3 Support Early Career award researchers in their future and post-award career paths by providing training and opportunities for research leadership.

R8.4 Provide incentives to the national laboratories for creating and sustaining professional development opportunities for early and mid-career scientists.

R8.5 Develop and demonstrate balanced models for providing BER-supported researchers with options for both collaborative teaming paths and individual successes.

PARTNERSHIPS

R8.6 Enhance international partnerships and cross-agency cooperation by developing new funding modalities, such as joint calls with the National Science Foundation and other agencies.

R8.7 Increase opportunities for BER program managers and supported scientists to engage with their international counterparts.

R8.8 Develop new international programs and consider establishing a formal office for international activities.

R8.9 Increase fellowships, scholarships, and international exchange opportunities.

R8.10 Optimize resources and efficiencies by bridging across agencies and nations.

PRODUCTIVITY

R8.11 Promote more effectively BER's world-class programs; unique facilities; and leadership in creating synergies across observations, process studies, and system modeling.

R8.12 Secure leadership in both the science areas where BER already excels (e.g., observation and modeling integration) and in new growth areas.

R8.13 Assign facilities the responsibility of coordinating and storing the data relevant to their main area of expertise.

R8.14 Increase emphasis in modeling activities related to uncertainty quantification and uncertainty propagation for complex, multiscale systems.

R8.15 Build a productive, creative workforce by supporting interdisciplinary research opportunities for early and mid-career scientists, as is done by crosscutting organizations such as the Max Planck Institutes in Europe or Chinese institutes for environmental and climate science.

R8.16 Manage volatility, potential and realized, in funding levels and award topics.

R8.17 Use inter- and intra-agency cooperation and co-funding to foster interdisciplinary collaborations, maximize large-scale resources, and bridge Technology Readiness Levels (TRLs).

R8.18 Create a culture of communication and interaction across the TRL spectrum in DOE and among BER, businesses, and nongovernmental organizations.

R8.19 Develop integrative science opportunities as a signature area for BER.

Image credit: Researchers examine plant-microbe interactions to improve biomass feedstock growth. [Courtesy DOE Joint Genome Institute]

Reflections and Conclusions

DOE's origin story is rooted in response to national needs. The agency evolved from its first iteration in 1946 as the U.S. Atomic Energy Commission, which assumed leadership of the Manhattan Project after World War II, to its 1974 reinvention during the energy crisis as the U.S. Energy Research and Development Administration, tasked with developing new energy technologies. Ultimately, in 1977, President Jimmy Carter's administration drew an equivalency between energy security and national security and formed DOE to unite these two missions under a new federal agency.

Similarly, DOE's BER program began in 1947 under a different name and has evolved since then to become an international leader in diverse fields relevant to DOE missions. In the 1950s, BER contributed to studies of chemical dispersion, atmospheric global circulation, and environmental remediation of nuclear waste. By 1987, BER had partnered with the National Institutes of Health to sequence the human genome, partly to understand the impacts of radiation on DNA but also to develop the capability to sequence any organism's genome. In the 2000s, BER responded to DOE's intention to transform the nation's energy system and secure leadership in clean energy technologies; pursue world-class science and engineering as a cornerstone of economic prosperity; and enhance nuclear security through defense, nuclear nonproliferation, and environmental efforts. Toward those goals, BER research has increased understanding of biological systems and Earth and environmental systems. Due to these efforts, BER now occupies a unique position in the global scientific funding landscape at the nexus of energy transition, climate change mitigation, and sustainable economic prosperity.

This report reflects the BERAC Subcommittee on International Benchmarking's dedication to addressing the Office of Science director's four charge questions, an effort requiring 40 colleagues to commit themselves to a task encompassing more than a year of their time. From the subcommittee to the many experts who provided a wealth of input, the scientific community's engagement and enthusiasm for this effort signifies deep respect for how BER manages and operates its research enterprise to support DOE missions. On the global stage, respondents provided unequivocal evidence of BER's international leadership across its mission areas. In developing this study, the subcommittee and its colleagues became enriched by a new appreciation for BER's practices, structures, protocols, resource investment, and scientific outcomes.

Across the various mission areas, the subcommittee identified five strategic recommendations and associated risks for the next decade:

1. If our nation *fails to invest* adequately in transformative and use-inspired discovery science, it risks undermining future capabilities to mitigate climate change impacts, manage energy transitions, and promote an emerging bioeconomy enabled by recombinant DNA technology. The integration of science across BER mission space in a true systems approach is an opportunity to amplify and accelerate progress.

2. If BER and DOE *fail to capitalize on investments* in translating fundamental science to market, they risk the international competitiveness of U.S. companies in the sectors of energy, agriculture, chemicals and materials, carbon capture technologies, and associated data and services.

3. If BER and DOE *fail to imagine* the consequences of science and innovation trajectories, they risk other nations reaping the benefits of technologies that drive step changes in the global economy. As the pace of discovery accelerates across the life sciences, regular horizon scanning is critical to ensuring that BER makes informed investments in research and infrastructure to remain at the forefront.

4. If BER and DOE *fail to inspire* their stakeholders and the public, they risk diminished stature and impact at a juncture when communicating the benefits of science in addressing societal needs is critical.
5. If BER and DOE *fail to sustain future leadership* through recruitment and retention of the best and brightest in the BER mission space, they risk the nation's international leadership in biological, environmental, and Earth systems science.

Given the urgency of addressing societal grand challenges by using "Big Science" to drive solutions, failure is not an option.

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References

AmAcad (American Academy of Arts & Sciences). 2020. *The Perils of Complacency, America at a Tipping Point in Science and Engineering*. Rice University's Baker Institute for Public Policy. (amacad.org/publication/perils-of-complacency).

Augustine, N. R., and N. Lane. 2021. "America on Edge: Settling for Second Place?" *Issues in Science and Technology*, Arizona State University.

BERAC. 2022. *U.S. Scientific Leadership Addressing Energy, Ecosystems, Climate, and Sustainable Prosperity: Report from the BERAC Subcommittee on International Benchmarking*, DOE/SC-0208. M. McCann and P. Reed, eds. Biological and Environmental Research Advisory Committee. DOI:10.2172/1895129.

BESAC. 2021. *Can the US Compete in Basic Energy Sciences? A Report of the BESAC Subcommittee on International Benchmarking*. (science.osti.gov/-/media/bes/pdf/reports/2021/International_Benchmarking-Report.pdf).

De Smet, A., et al. 2021. "Great Attrition or Great Attraction—the Choice Is Yours," *McKinsey & Company*.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2000. "Experiments in International Benchmarking of US Research Fields." The National Academies Press. DOI:10.17226/9784.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2007. "Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future." Washington, DC: The National Academies Press. DOI:10.17226/11463.

NSB (National Science Board). 2007. *Science and Engineering Indicators*. National Science Foundation.

NSB (National Science Board). 2020. *Vision 2030: National Science Board*. (nsf.gov/nsb/publications/2020/nsb202015.pdf).

UNESCO (United Nations Educational, Scientific, and Cultural Organization). 2022, August 10. *How Much Does Your Country Invest in R&D?* (uis.unesco.org/apps/visualisations/research-and-development-spending).

Acronyms and Abbreviations

ARM	Atmospheric Radiation Measurement user facility
ASR	Atmospheric System Research
BER	DOE Biological and Environmental Research program
BERAC	Biological and Environmental Research Advisory Committee
BES	DOE Basic Energy Sciences program
BESAC	Basic Energy Sciences Advisory Committee
BRC	Bioenergy Research Center
COVID-19	coronavirus disease 2019
DOE	U.S. Department of Energy
E3SM	Energy Exascale Earth System Model
ECP	DOE Exascale Computing Project
EMSL	Environmental Molecular Sciences Laboratory
ESS	Environmental System Science
FICUS	Facilities Integrating Collaborations for User Science
JGI	DOE Joint Genome Institute
ModEx	model-experiment
MOSAiC	Multidisciplinary drifting Observatory for the Study of Arctic Climate
NASEM	National Academies of Sciences, Engineering, and Medicine
NSB	National Science Board
NSLS-II	National Synchrotron Light Source II
OLCF	Oak Ridge Leadership Computing Facility
PCMDI	Program for Climate Model Diagnosis and Intercomparison
R&D	research and development
SPRUCE	Spruce and Peatland Responses Under Changing Environments
TRL	Technology Readiness Level
UNESCO	United Nations Educational, Scientific, and Cultural Organization