BUILD A RESILIENT PLANET

Description and Rationale

Resilience is the watchword as the U.S. and the world increasingly feel the impacts of a changing climate and the growing need for clean, reliable, sustainable energy. Without the resilience to withstand and recover quickly from these impacts, we are at the mercy of heat waves, droughts, floods, wildfires, rising oceans, and other extreme events, as well as power disruptions, economic instability, food and water insecurity, and the deleterious effects on human health. NSF's Build a Resilient Planet initiative will take on the multifaceted challenges of:

- Predicting the response of Earth's systems to a changing climate and how natural and built systems respond to increased environmental variability;
- Innovating clean energy technologies, and associated infrastructure that can adapt to a changing planet;
- Improving climate adaptation and resilience to maximize resource utilization and sustainability within the food-energy-water system;
- Developing nature-based solutions to combat climate change; and
- Enhancing national efforts in greenhouse gas (GHG) measurement, monitoring, and verification of emissions and GHG removal from the atmosphere.

The magnitude of these challenges demands a whole-of-NSF approach to engage scientists and engineers through convergent research that addresses societal needs and integrates research and education. NSF will invest strategically in emerging areas to ensure U.S. leadership for an economically strong, nationally secure, sustainable, and equitable future. NSF will also leverage and enhance investments in essential research infrastructure needed to drive the discoveries that will build a more resilient planet.

Accelerating climate research and developing solutions to reduce the impacts of climate change, inventing energy systems of the future and developing solutions to the interconnected challenges of resilience requires bold thinking, convergent approaches, and an overarching commitment to environmental equity, justice, and workforce development and education. NSF will take action to advance knowledge, empower and engage communities, grow a capable and diverse scientific workforce, and generate innovative technological solutions; this includes learning with and from likeminded international partners at all scales. Through strategic investments, NSF will implement President Biden's promise to take aggressive action to tackle climate change while addressing the economic and national security threats posed by the climate crisis. Investments proposed are consistent with the U.S. Global Change Research Program (USGRP) and Clean Energy Technology (CET) crosscuts. Furthermore, investments in NSF's major facilities that target study of Earth's biosphere, atmosphere, and oceans, contribute to USGCRP, and will be a core element of this activity.

Transformational action in this decade is essential to enabling a resilient future. Increases in GHG, largely because of the combustion of fossil fuels, have altered the Earth's atmosphere, leading to warming temperatures and rapidly changing biological and physical environments. Because these climate-driven changes influence processes at a range of spatial and temporal scales across terrestrial, atmospheric, freshwater, and ocean systems, it is imperative that a "whole Earth" approach is taken to understand the impacts.

Climate change impacts the health, prosperity and welfare of people and communities, posing a major economic and security threat to the Nation. The changing climate often makes extreme events, such as hurricanes, wildfires, and drought, more severe and frequent. Such events also result in damaging effects on water supplies, air quality, housing, and critical infrastructure such as power, communication, and transportation. Oftentimes the impacts of extreme events fall disproportionately on disadvantaged communities. NSF's approach to resilience explicitly includes the concept of environmental justice, reaching and involving the most at-risk or vulnerable communities to play a lead role in their resilient future through community-driven engagement as agenda-setters and active participants in resilience research. Disadvantaged and underserved communities will directly build, and benefit from, Build a Resilient Planet.

The grand challenges of enabling a carbon-neutral energy system and understanding, forecasting, mitigating, and adapting to the Earth's changing climate at global to local scales can only be met through scientific, engineering, and technological advances. To achieve a carbon-neutral, equitable, and sustainable economy, clean energy must increasingly dominate energy sources. Critical technological advances are needed to maximize access and utilization of renewable energy, enable grid security and storage, and electrify manufacturing, transportation, and chemical processing. To advance climate adaptation and resilience, new technologies are needed with equitable access to create well-being and health across the U.S. NSF will invest in research and engineering that integrate and translate knowledge regarding climate change risks to health, national security, and the economy and translate this understanding into decision-making tools to enable greater predictability of impacts and resilience for the U.S. and ultimately the world.

NSF's investments in Build a Resilient Planet will advance the priorities of the CHIPS and Science Act. They will improve our understanding of climate systems and related environmental and human interactions, water quality and food-energy-water systems, and natural hazards and community resilience, including social and behavior dimensions. Build a Resilient Planet will advance sustainable chemistry, the provision of critical minerals, engineering biology, and biomanufacturing to enable economic growth that protects people and the planet. NSF investments will lead to innovative data-driven solutions for climate adaptation and mitigation; new technologies and strategies for clean, abundant energy, water, and food, such as precision agriculture; and rural and urban infrastructure that is resilient to wildfires, droughts, extreme storms, and other natural and anthropogenic disasters. Innovations in high-performance computing, semiconductors, and advanced computer hardware and software are essential to enable computational approaches to modeling, simulation, visualization, analysis, and prediction at the speed and scale needed for climate and clean energy systems. While these computing-based technologies have the potential to be transformative, it is also important that they should be designed to be sustainable with respect to energy consumption, depletion of rare earth elements, creation of toxic byproducts, and other sustainability metrics. To be a global leader in the research needed to build a resilient planet, NSF will rely heavily on current and proposed research infrastructure investments. Furthermore, NSF's Build a Resilient Planet portfolio will grow a diverse workforce across the Nation that will continue building knowledge and sustainable U.S. infrastructure and industry.

Goals of Investment

- To catalyze convergent research at speed and scale with an integrated systems approach that focuses on the causes and predictable impacts of climate change while also developing paradigm-shifting clean energy technologies and infrastructure systems; other non-energy related technologies aimed to improve sustainability and reduce environmental impacts; sustainable food and water sources and waste management; and adaptation and mitigation strategies. These efforts will be tailored to a local/regional scale with the ability to scale for global impact.
- To integrate foundational and use-inspired science and engineering research with translational approaches to clean energy and climate resilience, adaptation, and mitigation, with attention to predictive modeling and experimental testing.
- To engage effectively and respectfully with communities through the incorporation of local, traditional, and indigenous knowledge in research programs co-designed with impacted stakeholders.
- To enhance research investments in resilience through support for an integrated, mission-oriented approach beyond approaches traditional for NSF with the goal of rapidly stimulating research for deployment of solutions within the coming decade towards a sustainable Earth. These new investments will build on existing climate- and energy-related activities supported through the Foundation's research portfolio.
- To develop and enhance research infrastructure investments that are essential to advancing science and engineering that will build a more resilient Earth system.
- To develop systems-thinking capacity in the training of a skilled, globally competitive, and diverse generation of scientists and engineers while actively engaging communities and the public.
- To democratize resilience and the ability for all communities to engage in climate resilience research regardless of socio-economic or geographical circumstances.
- To establish integrated and equitable public and private partnerships among local communities, researchers, educators, communicators, industry, international partners, and policy makers to advance knowledge, empower communities, and catalyze resilience solutions towards a sustainable earth.

Potential for Impact, Urgency, and Readiness

The Nation is poised to embark on the urgent mission of building a resilient planet, as highlighted in numerous recent reports:

- The Intergovernmental Panel on Climate Change[1] found that the world is today facing unprecedented challenges because of climate change, with impacts more severe than expected.
- The recent Engineering Research Visioning Alliance report "The Role of Engineering to Address Climate Change"[2] focuses on investments in critical materials, energy storage and transmission, resilient and energy-efficient infrastructure, GHG capture and elimination technologies, ecosystem sensor and sensing applications, and exploiting artificial intelligence modelling in forecasting and trend analyses.
- As envisioned in the National Academies of Sciences, Engineering, and Medicine (The National Academies) report on "Next-Generation Earth Systems Science at the NSF,"[3] a systems-thinking

[1] https://report.ipcc.ch/ar6/wg2/IPCC_AR6_WGII_FullReport.pdf
[2] www.ervacommunity.org/visioning-report/visioning-event-report/
[3] https://doi.org/10.17226/26042

approach is needed, identifying the mechanisms and opportunities that interrelate understanding of the climate system, clean energy technologies, and society in holistic solutions to the growing climate and clean energy crisis.
- As recommended in the National Academies report on Accelerating Decarbonization of the U.S. Energy System,[4] bold and decisive action is urgently required to address the need for clean energy. New resources are necessary to both initiate and accelerate new discovery and insights as well as the translation of research results to technological solutions.

NSF's support of all fields of science and engineering make it uniquely capable of advancing the integrated, interdisciplinary research needed to enable a resilient nation and planet. NSF investments in cyberinfrastructure, computing, communications, and information systems will support the interconnected areas of the Resilient Planet portfolio. Likewise, NSF investments in education, diversity and inclusion will prepare a future workforce that understands the complex interdependencies of changing Earth systems and the built environment and that can innovate clean energy and related green industries. These investments will ensure that the U.S. continues to be a global leader in the management, mitigation, and adaptation to climate change for an economically strong and secure future.

Impacts will be realized across several key areas:

<u>Advancing Climate Science</u>
Understanding climate change and the associated impacts on human and environmental systems is the central thrust to much of NSF's resilience research and is essential to identifying, developing, and ultimately implementing solutions to mitigate climate change impacts. One of the critical keys to the resilience puzzle is predicting tipping points; the point at which a series of small changes or incidents becomes significant enough to trigger a larger, more impactful change. Understanding and predicting tipping points reveals how changes in climate lead to drought, wildfire, thawing of permafrost, ice loss and sea-level rise, coastal flooding, and severe storms.

A scientific understanding of climate and the ability to predict impacts of climate change are not sufficient to catalyze resilience. Research results will be translated into actionable information allowing policy makers to understand regional and local threats and enable the development of implementable mitigation strategies. NSF brings tremendous energy and focus to the challenge of resilience and through coordination with USGCRP, as NSF's efforts are leveraged and built on by other government stakeholders enabling a whole-of-government effort to build a resilient future.

<u>Innovation in Clean Energy Technology and Infrastructure</u>
The discovery, development, and deployment of clean energy solutions remains a primary mechanism to attenuate the impacts of climate change and provide a path to thrive in a world that is increasingly reliant on dependable, cost-effective, on-demand energy. NSF will invest in foundational research, translation, and collaboration for a new generation of sustainable energy technologies that speed the U.S. on our race to net zero emissions, benefit human health and the environment, and serve society equitably and without disproportional impacts.

NSF's clean energy investment will focus on enabling and advancing the transformation of energy

[4] https://nap.nationalacademies.org/catalog/25932/accelerating-decarbonization-of-the-us-energy-system

systems for the future, including new energy sources, hydrogen at scale, energy-efficient technologies, energy storage and transmission, and secure and sustainable energy systems. These investments will advance fundamental physics, chemistry and next-generation materials science research pertaining to energy, as well as research related to social, cultural, and individual acceptance of energy system transitions. Themes will include energy security and reliability; interconnection of built infrastructure, energy infrastructure, and cyberinfrastructure for overall resilience and efficiency; biotechnology, eco-manufacturing, industrial efficiency technologies, and the circular economy (including critical minerals and materials); modeling and tools; social and behavioral aspects; and development of a diverse workforce.

Advances in theoretical, computational, and experimental research on topics such as plasma science, thermoelectrics, and superconductor research provide new opportunities to reconceptualize clean energy systems globally. Advances in fundamental materials and device research are also needed, which will lead to deployment of superconducting-based technology at ambient conditions would most directly influence and reduce waste in energy transport. Advancing the fundamental understanding and utilization of superconductivity as well as other phenomena such as multiferroicity, piezoelectricity, and thermoelectricity positions the U.S. to redefine other industrial sectors, such as semiconductors, optoelectronics, wireless information transmission, and smart health. Cross-cutting contributions from artificial intelligence (AI), cloud, wireless networking, and other computational based technologies have already surfaced new advances in these important areas and expanded funding can accelerate these further. Similarly, advanced manufacturing of materials that can operate in extreme environments, such as non-equilibrium multi-component alloys, is needed for next generation energy systems.

NSF's clean energy approach will be further advanced by systems-oriented studies of clean energy generation and use. These include new smart wireless sensor-based technologies to enhance operation, storage, integration, and distribution of different types of clean energy. Likewise, large-scale data analytics and AI techniques will allow for more efficient monitoring, management, and maintenance of decentralized energy grids, especially in remote locations or hazardous conditions. NSF will also advance novel research that addresses the substantial environmental impacts that computing technologies have through their entire lifecycle from design and manufacturing to deployment and operation, and finally into reuse, recycling, and disposal.

<u>Climate Change Adaptation and Resilience</u>

Build a Resilient Planet will utilize a holistic approach that pulls together the interconnected systems of climate, biosphere, and the built environment, along with understanding of human behavioral, economic, and international dimensions, to predict change and inform and advance equitable adaptation, mitigation, and resilience strategies. Only by harnessing and integrating physical, biological, computing, and social sciences and engineering can we create truly resilient, sustainable systems. In a warming climate, multidisciplinary research is crucial for advancing our predictive understanding of the response of living and engineered systems at all temporal and spatial scales. It is also crucial for developing capabilities to mitigate negative environmental impacts through, for example, emissions capture and reuse, energy efficiency, extreme design for a changing climate, and alternative chemicals, materials, and manufacturing processes. Research on climate change mitigation and adaptation systems that includes environmental, educational, infrastructural, health, and community elements will create sustainable and resilient strategies to manage and engineer the changing world. In a virtuous cycle, some climate change mitigation and adaptation strategies may be

independent of or indirectly related to clean energy solutions while some clean energy research investments will yield new climate change mitigation and adaptation strategies.

Maximizing the use of resources and developing emission mitigation technologies is central to limiting the severity of negative impacts of climate change. Technologies beyond clean energy, such as emissions mitigation and environmental remediation technologies, could lead to a strengthened and sustainable infrastructure. NSF will invest in fundamental science and technologies that support a circular economy by mitigating GHG emissions; developing overall carbon-neutral or carbon-negative processes; improving product circularity and efficiency, including reclaiming precious resources and advancing precision agriculture; addressing emerging new contaminants, and developing new chemicals, materials, technologies, and processes that minimize the production or enhance remediation of waste to support clean water, air, and soil. NSF will invest in innovative, foundational, use-inspired, and translational research in several areas including electrochemistry, catalysis, fusion and plasmas, photochemistry, photonics, enhancements in efficiencies of chemical reactions, chemical separations, surface chemistry, and subsurface flow and transport by using innovative computational, data science and experimental approaches.

The role of high-performance computing, AI, and data sharing in advancing research on climate change, natural resource depletion, loss of biodiversity, extreme events, and sustainable energy is undeniable. Advances in computation, from smart sensors to cloud-based data aggregation and analytics, to high precision computational modeling, improves our understanding of environmental trends and play an intrinsic role in global efforts to understand, analyze, and mitigate the effects of climate change, moving society towards intelligent adaptations and greater resilience. However, the widespread, intensive use of computing technologies introduces sustainability challenges and motivates new approaches across the lifecycle of technology design, use, and decommission. To balance opportunities of advanced computation with computing's own GHG emissions, which are on par with mid-sized countries, NSF will support investments that treat GHG emissions and sustainability impacts as first-order metrics for computing design and use, along with broader research directions including discovery of new sustainable materials for manufacturing digital devices, seamless integration of renewable energy, and methods for safe recycling and reuse of e-waste.

Ensuring the success of these resilient solutions requires continuous engagement with stakeholders; this engagement will help ensure that research answers questions and designs solutions that are relevant at the local and regional scales and enhance decision making. Further, through interaction with stakeholders, NSF's investment will facilitate science-based risk communication, citizen science, and community-engaged research programs, enhancing the investment's overall impact. An added benefit of local and regional engagement is the direct conduit that is built to disadvantaged communities. Build a Resilient Planet will explicitly focus on developing proactive and accessible resilience and adaptation strategies for historically underserved and disadvantaged communities to co-create resilience solutions that are just, inclusive, and equitable. The effects of climate change, such as extreme natural hazards, exacerbate existing environmental and societal inequities and contribute to cumulative burdens on vulnerable communities; NSF's investments will advance economic and environmental justice, equity, and public health through reduced vulnerability to climate impacts. Research infrastructure will also be a core element in NSF's goal of expanding access to facilities for traditionally underserved groups and communities. This infrastructure will enable underserved STEM researchers to significantly contribute to helping their communities become more resilient. Research infrastructure will also be central to developing the next generation of researchers and engineers that

are essential for ensuring the U.S. continues to be a world leader in climate and clean energy research and to ensure a strong economy and secure nation.

Nature-based Climate Solutions

Build a Resilient Planet will include research to understand the effectiveness of nature-based climate solutions, including terrestrial, freshwater, coastal, and ocean ecosystems that provide carbon sequestration and storage and which can enhance ecosystem and human community resilience. Understanding how living systems respond and adapt to climate change can help us design and implement solutions that go beyond mere survival under adverse conditions to enable robust resilience in the face of continual change. Taking advantage of knowledge at multiple scales of biological organization—from molecules to genomes to cells to organisms to populations and ecosystems—as well as how biological systems interact in diverse environments provides a foundational basis to use the information to improve life on our warming planet. By sustaining and restoring valuable ecosystem services, research funded by NSF will create economic opportunities for farmers, ranchers, fishers, and foresters and will also contribute to improving national security. In addition, NSF investments in precision agriculture, biotechnology, food-energy-water systems, control of nitrogen and methane emissions from agriculture, and other research areas will mitigate climate change impacts and increase the sustainability of future U.S. agriculture.

Always present in NSF activities is the theme of investing in the next generation of researchers, scientists, and citizens. Build a Resilient Planet will strengthen the development of the workforce to design, implement, and manage effective nature-based solutions and hybrid options that integrate traditional and nature-based approaches.

GHG Monitoring, Measurement, and Verification

Measurement, monitoring, reporting, and verification of GHG emissions and removal is critical to understanding and enhancing the progress and effectiveness of local to global actions to address drivers of climate change. These strategies can serve as a foundation for assessing success of biotechnologies capable of using waste gases as substrates for sustainable synthesis of fuels and chemicals, thereby contributing to mitigation of the warming effects of such gases. Through Build a Resilient Planet, NSF will continue to develop sensors, imaging tools, and technologies for GHG detection, understanding of the impacts of proposed solutions, to develop new technologies for capturing, converting, and sequestering GHG, and to work with partner agencies to transition NSF-funded research tools and technologies to operational use by other agencies or industry.

Budget Justification

All NSF units are essential to the success of Build a Resilient Planet. Investments include ideas from researchers across the science and engineering spectrum to create broad new understanding and innovations that will increase energy resilience, enhance sustainability, mitigate climate change, and lead to other societal benefits. NSF's Build a Resilient Planet theme is being initiated in FY 2023 with investments in the National Discovery Cloud for Climate, Design for Environmental Sustainability in Computing, Future Manufacturing, Critical Aspects of Sustainability, and Global Centers.

FY 2024 will build on these and other efforts through key targeted investments, including:

- Fundamental and convergent research with increasing investments in themes such as life on a warming planet, extreme events and climate thresholds, computational climate science and

prediction, sustainable computing design, technologies for decarbonization, and co-production of knowledge. NSF will also initiate new activities in design for extreme environments.

- Cross-cutting interdisciplinary research will continue and expand to encourage creative and collaborative research in areas such as sustainable regional systems, and innovative solutions to climate change and sustainable chemistry to address critical aspects of sustainability (CAS).
- Research infrastructure essential to advancing research for enhancing resiliency will be a core focus of this activity. BIO will continue to invest in the National Ecological Observatory Network (NEON) by expanding the biorepository capacity. GEO will continue support for the National Center for Atmospheric Research (NCAR), the Academic Research Fleet (ARF), infrastructure and logistics to support access to the Arctic, Antarctic continent, and Southern Ocean, the seismic and geodetic services of the SAGE/GAGE facility, and continued development of the design for the Antarctic Research Vessel (ARV). CISE, through its Office of Advanced Cyberinfrastructure, will oversee continued implementation of the National Discovery Cloud for Climate.
- Centers and hubs for research, testing, coordination, and translation will be established to address complex challenges in adaptation and resilience, the bioeconomy, clean energy, wildfires and drought at the urban/rural interface, sustainable chemistry, connections with the environment and society, and other topics. Likewise, connectors will be funded to couple foundational advances across and within other large-scale NSF research and infrastructure investments into these new centers and hubs.
- Innovation and translation investments will continue to accelerate new research discoveries, technologies, and solutions into the market and society.
- Research infrastructure investments in more energy-efficient facilities, advanced computing, digital simulations, electric grid testbeds, *in situ* environmental observation technologies, and Natural Hazards Engineering Research Infrastructure (NHERI) will continue, and new opportunities for access to facilities and testbeds will begin. NSF's National Discovery Cloud for Climate as well as the National Artificial Intelligence Research Resource (NAIRR) are envisioned as shared computing and data infrastructure that democratizes access to advanced cyberinfrastructure and will serve to expand the geography of innovation by enabling researchers everywhere in our Nation to engage fully in and advance these topics.
- Education and workforce development investments will prepare diverse students across the country for climate and clean energy careers. Preparing a future workforce that understands the complex interdependencies of the climate, human, and other earth systems and that can innovate in clean energy and related green industries is critical for the U.S. Also important will be efforts to engage the public through informal learning on climate and clean energy topics. In FY 2024, NSF will start a special initiative to support Climate Equity Fellows. This program will train students and researchers in science important for addressing climate change and to be knowledgeable about the disparate impacts of climate change on disadvantaged or underserved communities and to integrate these perspectives into the design of their research projects.
- NSF's partnerships with other agencies and the private sector will help accelerate fundamental and translational research and prepare the future workforce to Build a Resilient Planet.