The Climate Resilience Game Changers Assessment

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Advancing the National Climate Resilience Framework & Catalyzing American Innovation in Climate Resilience

The National Climate Resilience Framework, released by the Biden-Harris Administration in September 2023, set a core objective of catalyzing innovation and mobilizing investment to advance equitable climate resilience at scale.[1] Climate resilience is a major investment opportunity that also safeguards other investments. Some analysts estimate that the global market for climate resilience could be worth as much as $2 trillion by 2026. By other evaluations, however, less than 10% of global climate finance currently targets adaptation and resilience—$63 billion out of a total of $1.27 trillion—and 98% of investment comes from the public sector.

Private and philanthropic investors may perceive climate resilience projects as harder to benchmark and measure than climate mitigation projects, making returns more uncertain. Recent efforts to assess the economic returns from specific climate resilience investments, however, have indicated that certain investments could generate nearly fourfold net benefits over the course of a decade. The *Climate Resilience Game Changers Assessment* identifies a set of specific technologies and solutions for which thoughtful, targeted investments have the potential to prepare the U.S. for current and future impacts of climate change in game-changing ways.

As noted in the Fifth National Climate Assessment, "while adaptation planning and implementation has advanced in the U.S., most adaptation actions to date have been incremental and small in scale. In many cases, more transformative adaptation will be necessary to adequately address the risks of current and future climate change." An equitable and sustainable U.S. response to climate change has the potential to reduce climate impacts while improving well-being, strengthening resilience, benefiting the economy, and, in part, redressing legacies of racism and injustice. Transformative adaptation comes with challenges and trade-offs that would need to be considered to avoid exacerbating or creating new social injustices.

This assessment is designed as a companion to *U.S. Innovation to Meet 2050 Climate Goals*, a 2022 report that identified opportunities for accelerating progress to help the United States reach its 2050 net-zero emissions goal and support global decarbonization. Just as the 2022 report employs innovation to realize the vision of a net-zero nation, the *Climate Resilience Game Changers Assessment* focuses on the American innovation needed to build and empower a climate-resilient nation: one that can endure, adapt, and evolve in the face of current and future climate conditions. This assessment also implements Objective 3 of the National Climate Resilience Framework: to mobilize capital, investment, and innovation to advance climate resilience at scale.

This assessment is intended for use by a diverse set of stakeholders, including private, philanthropic, and non-governmental organizations, as well as federal, state, Tribal, territorial,

[1] In alignment with the National Climate Resilience Framework, this assessment defines "resilience" as the ability to prepare for threats and hazards, adapt to changing conditions, and withstand and recover rapidly from adverse conditions and disruptions. The term "climate resilience" is used in a matter that is intentionally broad and inclusive of the term "climate adaptation."

and local governmental entities, to help generate new ideas and align potentially catalytic investments and incentives. While this report does not comprise a final or exhaustive list of game-changing solutions for climate resilience, developing and widely deploying these solutions is critical to building a climate-resilient nation.

Developing the Climate Resilience Game Changers

This document was created through an interagency process under the Climate Resilience Game Changers Working Group, organized under the Climate Resilience sub-Interagency Policy Committee of the Recovery Interagency Policy Committee. The Climate Resilience Game Changers Working Group is co-chaired by the White House Climate Policy Office, White House Office of Science and Technology Policy, and White House Council on Environmental Quality, and includes members from the departments and agencies listed below.

Federal Emergency Management Administration (FEMA)
General Services Administration (GSA)
National Oceanic & Atmospheric Administration (NOAA)
National Science Foundation (NSF)
U.S. Army Corps of Engineers (USACE)
U.S. Department of Agriculture (USDA)
U.S. Department of Defense (DOD)
U.S. Department of Energy (DOE)
U.S. Department of Health & Human Services (HHS)
U.S. Department of Homeland Security (DHS)
U.S. Department of Housing & Urban Development (HUD)
U.S. Department of the Interior (DOI)
U.S. Department of Transportation (DOT)
U.S. Environmental Protection Agency (EPA)
White House Climate Policy Office (CPO)
White House Council on Environmental Quality (CEQ)
White House Office of Science & Technology Policy (OSTP)

References and hyperlinks throughout this document support concepts or provide examples of pilot programs, projects, or analogous initiatives to the Game Changers. Where non-governmental references are used, the authors selected examples, articles, or papers that, in their judgment, supported or illustrated the Game Changer or topic being discussed.

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The Need for Breakthrough Innovation in Climate Resilience

Climate change is causing devastating and deadly impacts across the country and around the world. In 2023 alone, communities across the United States experienced extreme heat waves that pushed temperatures to triple digits for days or weeks on end, choking wildfire smoke in areas that had never experienced fires before, and record-breaking floods that washed away property and livelihoods. Extreme-weather events drove more than 2.4 million Americans out of their homes, from Lahaina, Hawai'i to Montpelier, Vermont. Extreme events led to a record-breaking 28 disasters in 2023 that inflicted at least $1 billion of damage each—more than twice the inflation-adjusted average annual number of billion-dollar disasters from 2010 to 2019 and roughly ten times the annual average in the 1980s. At the same time, chronic climate impacts like sea-level rise, habitat loss, repetitive flooding, and changes in rain and snow patterns are creating significant long-term stress on American lives, communities, homes, and the economy. By one analysis, the costs of flooding alone are between $180 billion and $496 billion annually.

While all communities are feeling the impacts of climate change, not all communities are experiencing these impacts equally. Fossil-fuel-based energy systems have resulted in disproportionate public health burdens on communities with environmental justice concerns, including communities of color, low-income communities, Tribal Nations, and both rural and urban areas—from the coasts to former coal communities inland. Many of these same communities are also disproportionately harmed by climate change impacts. The National Climate Resilience Framework recognized the need to advance environmental justice for all, including by addressing the cumulative impacts of climate and other burdens on communities with environmental justice concerns who are most in harm's way.[2]

President Biden's historic Inflation Reduction Act—the largest-ever single investment in tackling the climate crisis—and Bipartisan Infrastructure Law dedicate over $50 billion for climate resilience, in addition to the hundreds of billions of dollars helping reach national goals of cutting carbon pollution in half by 2030 and achieving a fully net-zero economy by 2050. These historic pieces of legislation are the foundation of the American playbook to tackle climate change and advance environmental justice, and have attracted major follow-on investment in clean technologies, materials, and other climate solutions. Many of these federal dollars also benefit, through the President's Justice40 Initiative, the disadvantaged communities most impacted by climate change, pollution, and historic underinvestment.[3]

But even with a rapid reduction in global greenhouse gas emissions, some climate impacts are expected to persist for decades to come. Preparing for these impacts by investing in climate resilience as well as climate mitigation, is therefore both a social and economic imperative. As noted in the National Climate Resilience Framework, achieving the vision of a climate-resilient

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[2] See Executive Order 14096, *Revitalizing Our Nation's Commitment to Environmental Justice for All*, 88 FR 25,251 (Apr. 26, 2023).

[3] Through the Justice40 Initiative, the federal government has made it a goal that 40 percent of the overall benefits of certain climate, clean energy, affordable and sustainable housing, and other federal investments flow to disadvantaged communities that are marginalized by underinvestment and overburdened by pollution, also known as "Justice40 communities." President Biden made this historic commitment when he signed Executive Order 14008 on *Tackling the Climate Crisis at Home and Abroad* within days of taking office.

nation will require developing and deploying solutions that respond directly to climate threats and that serve as the tools in our nation's toolbox for building climate resilience.

To create a common understanding of these "tools," this assessment identifies *Climate Resilience Game Changers* that capture innovative, equitable, and scalable technologies, practices, and strategies that are ripe for research, development, and further investment by a wide range of stakeholders.

Climate Resilience Game Changers

A *Climate Resilience Game Changer* is defined here as a practice, methodology, technology, or institutional, financial, or governance structure that (1) has been identified, prototyped, developed, or significantly refined in the last ten years, (2) has not reached the point of widespread adoption, and (3) if widely and appropriately adopted, would achieve or substantially advance one or more of the objectives of the National Climate Resilience Framework.

Climate Resilience Game Changers include:

- **Management Practices and Methodologies**: Novel (limited-to-no commercial adoption) or significantly improved (much cheaper, more flexible, or more effective) practices that will improve the resilience and adaptability of various systems under changing—and often more challenging—climate conditions.
- **Technologies**: Novel or significantly improved technologies that reduce adverse effects of climate change or improve the adaptive capacity of individuals, communities, and ecosystems.
- **Institutional, Financial, and Governance Structures**: Novel or significantly improved organizational approaches that anticipate and respond to climate impacts, promote resilience-enhancing co-benefits, and reflect the interconnectedness of individuals, communities, and ecosystems.

In this assessment, the Climate Resilience Game Changers Working Group identified the solutions shown below in Figure 1, organized into **sector-specific categories**. The working group acknowledges that many solutions intersect with multiple sectors. For instance, virtual power plants (VPPs) primarily support resilience of the electricity sector by stabilizing power grids and supporting integration of multiple renewable power sources. VPPs also intersect with buildings insofar as rooftop solar installations can be VPP components. For the sake of clarity and scope, the working group assigned each solution to the most relevant sector-specific category. A select number of solutions were determined to have substantial relevance to most or all sectors; these are referred to as **cross-cutting solutions**.

Consistent with the National Climate Resilience Framework, the Working Group acknowledges and emphasizes that there is no universal approach to building climate resilience. Because communities experience climate change in different ways and respond according to their unique needs, capacities, characteristics, histories, and cultures, approaches to building climate resilience must be locally-tailored and community-driven. Bolstering climate resilience often involves systemic change and integration of multiple approaches. While the individual solutions identified in this assessment each hold standalone game-changing potential, they will be most powerful if deployed as part of a thoughtful, comprehensive, and equitable climate resilience strategy that includes meaningful public engagement and aims to advance environmental justice.

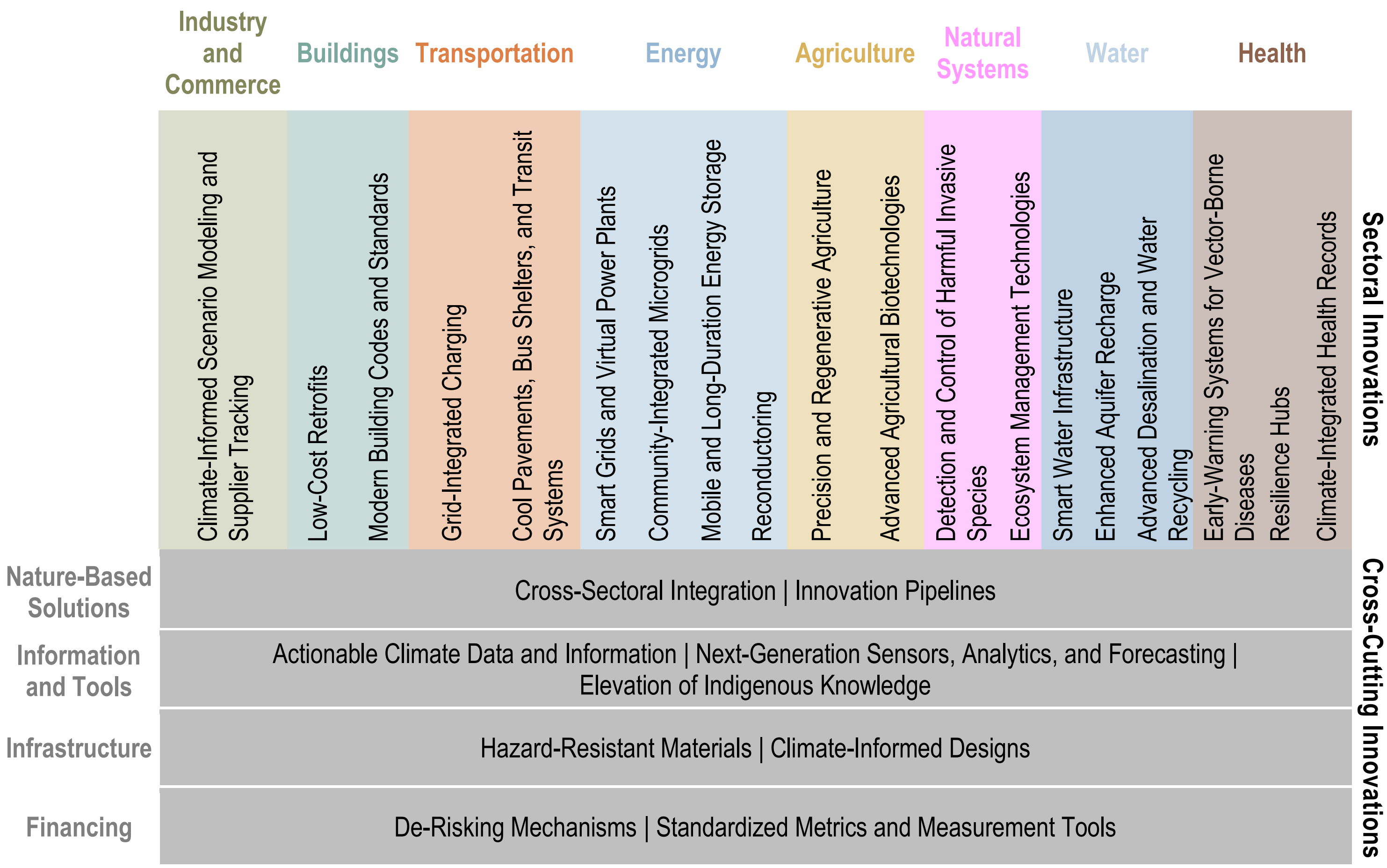

Figure 1: Summary of the 28 **Climate Resilience Game Changers** identified by the interagency Working Group.

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Principles of Climate Resilience

In developing this list of solutions, the Working Group adopted the Principles of Climate Resilience outlined in the National Climate Resilience Framework. These principles were used to curate the list of game-changing solutions and should be applied as a lens to implementing them.

Proactive. *Implement solutions that anticipate and address climate threats and impacts before damages occur. Prioritize activities and investments through risk-based approaches, including approaches that account for complex risks, like cascading impacts and concurrent events, as well as approaches that account for differences in vulnerability and response capabilities within and across communities.*

Whole-System. *Consider the ways in which communities and natural systems are interconnected, including recognizing that risks and impacts from climate change are borderless. Strive both to leverage synergies (e.g., when increased resilience of one community contributes to the resilience of others) and to avoid maladaptive activities (e.g., when efforts to increase resilience in one community impose harms on another).*

Equitable and Just. *Pursue solutions that address, and do not exacerbate, disparities between and within communities. Ensure that strategies respond to the needs of underserved and marginalized communities that have historically borne a disproportionate share of climate impacts and costs.*

People-Centered. *Position the well-being of individuals, families, communities, and society at the center of goals and solutions. Consider the needs and perspectives of all community members, including those that are most vulnerable and have been historically marginalized or disadvantaged.*

Collaborative and Inclusive. *Work across sectors to identify and pursue shared goals. Create pathways for all community members to be meaningfully involved in decision-making, and conduct active outreach to raise awareness of these pathways and address barriers to participation.*

Durable. *Implement solutions that serve current and future needs. Ensure that there is continuity of technical expertise and leadership as needed, including by enhancing or building community capacity to sustain and adapt solutions for the long term.*

Multi-Benefit. *Prioritize solutions, including nature-based solutions, that enhance climate resilience, while simultaneously advancing other community, economic, and societal objectives.*

The Climate Resilience Game Changers Assessment operationalizes these principles by proactively identifying innovative solutions that can, with additional investment, adoption, and equitable delivery, uplift local economies and enhance overall community wellbeing. The Assessment also promotes increased access to capital for solutions with the potential for transformational local impacts in frontline communities, and those communities that experience the worst effects of climate change.

Prospective Benefits of Climate Resilience Game Changers

Investing in, developing, and implementing the Climate Resilience Game Changers will strengthen our health, environment, economy, equity, and security. Several studies have documented high returns for investments in climate resilience solutions. Research from the National Institute for Building Sciences and the U.S. Chamber of Commerce, as well as a report from the U.S. Agency for International Development (USAID), the Global Resilience Partnership, and the Boston Consulting Group have concluded that every dollar spent to implement common adaptation and resilience measures can yield up to $13 in financial benefits. The Global Commission on Adaptation has similarly estimated that investing $1.8 trillion in adaptation and resilience worldwide from 2020 through 2030 could deliver $7.2 trillion in a "triple dividend" of economic, social, and environmental benefits and avoided losses. Investments in innovative resilience measures—such as the Climate Resilience Game Changers—can therefore significantly reduce the estimated costs of climate damage.

If implemented effectively and equitably, the Climate Resilience Game Changers can help communities avoid disruption and damage to human health and wellbeing. Investing in these promising and emerging technologies, practices, and strategies at early stages will enable their rapid deployment before, during, and immediately after disasters. For example, new sewers, flood walls, and other infrastructure improvements in Hoboken, New Jersey allowed the city to withstand 3.5 inches of rain in one day in September 2023, thanks in part to an early investment by HUD's Rebuild by Design competition, launched in 2013. This investment was the result of a game-changing policy and funding innovation—the first-ever set-aside of HUD Community Development Block Grant Disaster Recovery funding devoted to incentivizing the development of regionally-scalable and locally-contextualized resilience solutions, deployed through a competition in partnership with philanthropic, academic, and nonprofit organizations.

Finally, the Climate Resilience Game Changers Assessment is itself a novel step towards coordinating and catalyzing philanthropic and private investments in climate resilience innovation. While this document may highlight a specific set of technologies, practices, and strategies that are innovative at the time of publishing, it has the potential to be updated as technologies advance, markets evolve, and conditions change.

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Climate Resilience Game Changers

Cross-Cutting Innovations

Nature-Based Solutions

Cross-Sectoral Integration

Management practices and methodologies; Institutional, financial, and governance structures
Nature-based solutions (NBS) leverage natural features and processes to enhance resilience and produce economic, environmental, and societal co-benefits. While NBS are increasingly considered in adaptation planning—particularly, under the Biden-Harris Administration's leadership—more systematic and equitable integration of NBS into relevant projects and decision-making processes where appropriate would be a game-changing innovation. Developing replicable pathways to scale up these approaches is also a core component of the National Climate Resilience Framework. And as with the clean energy transition, strategic, purposeful, coordinated investment can accelerate new partnerships and rapid progress.

Opportunities to promote cross-sectoral innovation include:

- Developing engineering guidelines, certification schemes, manuals, and standards to facilitate strategic deployment of NBS.
- Creating a comprehensive clearinghouse of high-quality NBS information and projects to facilitate partnership development, faster permitting, technical assistance, market viability assessment, and matchmaking to funding opportunities.
- Developing consistent approaches to facilitating NBS regulatory review and permitting, which may include regional partnerships, bundling of similar projects, and consideration of net social benefits of NBS strategies over their lifespans.
- Expediting environmental impact reviews and permitting for NBS at all levels of government, especially in response to time-sensitive needs (for example, before, during, and after emergencies occur).
- Creating new or improved research, decision-support, and technical tools, particularly those designed for use by Tribal, rural, or insular communities, for developing, monitoring, and evaluating NBS outcomes. Effective tools would include comparisons against alternatives, account for short- and long-term benefits, and account for particular benefits to communities with environmental justice concerns.

Efforts in this area could build on extensive work by the Biden-Harris Administration and many non-federal stakeholders and federal agencies—including EPA, DOI, the Federal Highway Administration (FHWA), FEMA, the Millennium Challenge Corporation, NOAA, and USACE.

Innovation Pipelines

Technologies; Management practices and methodologies
While many resilience practitioners already acknowledge that NBS can have benefits, game-changing opportunities to build knowledge remain untapped in key areas.

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For example, targeted investments in research and development (R&D) of NBS that are deployable at variable scales and geographies, as well as in monitoring and quantifying the long-term effectiveness of these projects, could make scaling and replicating NBS much easier. Establishing new NBS-focused research and extension institutes, NBS incubators, and NBS prize competitions[4] targeted to this goal could drive collaborative action and signal demand to markets.

Investments could also establish new philanthropic or governmental NBS "test beds." Supporting scalable NBS pilot projects[5] would provide invaluable low-risk and high-value opportunities for modeling, monitoring, and demonstrating the value of emerging NBS applied across a range of environments. These "test beds" could also support the development of engineering standards that address performance, reliability, and maintenance costs.

Information and Tools

Actionable Climate Data and Information

Technologies; Management practices and methodologies

Local decisionmakers depend on climate information to assess and communicate risk levels, but often require extensive training, workforce development, or financial resources to use it productively. While a wealth of valuable resources for climate information on regional and national scales already exists,[6] decisionmakers may find it difficult to use this information at a local level. Enabling existing information to be more locally-tailored, accessible, and relevant for decision-making would be a game changer. Some examples include:

- Refining techniques to downscale and visualize national datasets, climate projections, and other climate risk data to make these data more actionable and accessible for community groups and local governments.[7]
- Incorporating new information and tools—such as multi-hazard exposure assessments or early-warning systems—into existing data products (such as real estate postings).
- Developing software to make climate risk visualizations more informative and easier to create, and taking full advantage of new hardware capabilities to enhance climate risk communications. For example, the U.S. Fire Administration is using augmented reality and geospatial tools to improve risk communication in the wildland-urban interface, and the Centers for Disease Control and Prevention (CDC) and the National Weather Service's experimental HeatRisk tool is integrating local climatology and public health information with temperature data to map and forecast overall heat risk.

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[4] For example, see the Department for Homeland Security's Science and Technology Prize Competitions, the NSF's Regional Innovation Engines, and the interagency Civic Innovation Challenge.

[5] For example, in partnership with city parks departments, state and territorial coastal management programs, the National Estuarine Research Reserves, the National Wildlife Refuge System, or the National Park System.

[6] For example, see the U.S. Climate Resilience Toolkit, the Climate Mapping for Resilience and Adaptation portal, and the National Climate Assessment.

[7] For example, see Argonne National Laboratory's Climate Risk and Resilience Portal, the National Climate Task Force's Federal Flood Standard Support Tool (Beta), and FEMA's Future of Flood Risk Data Initiative.

- Creating usable climate information and model curricula for integration into new courses and educational tools for use by elementary, secondary, and post-secondary school educators.
- Aligning key climate data users and producers around common standards,[8] platforms, and system architectures to make climate information more interoperable. For example, the U.S. Global Change Research Program is working to do this across the federal government through its new Subcommittee on Climate Services, and a professional society, the American Society of Civil Engineers (ASCE), has built a platform to look up hazard-specific design parameters specified in ASCE standards for buildings and structures.

These efforts could be paired with scaled-up training and technical assistance programs, including those that take advantage of increasingly sophisticated online pedagogical tools as "force multipliers" to help make climate data more actionable and encourage co-production of climate data with frontline communities. For example, the National Innovation Landscapes Network (NILN) uses immersive engagement techniques with new tools and technologies—like next-generation fire behavior models, and new tools using LiDAR to create 3D maps of forest fuels and virtual reality walkthroughs of forest plots. Regional applied science and service organizations are natural homes for innovating and scaling climate-related training and technical assistance programs.[9]

Next-Generation Sensors, Analytics, and Forecasting

Technologies; Management practices and methodologies

In an era where sensors, analytics, and forecasting tools are rapidly becoming more sophisticated and widespread, tremendous room for innovation exists to make these tools and techniques more advanced, more accessible to the public, and more suitable for climate-related monitoring and forecasting in particular. Developing and deploying these tools would unlock powerful opportunities to rapidly scale, implement, and adjust climate resilience solutions.

Emerging tools, including artificial intelligence (AI), predictive analytics, and generative algorithms, each provide new capabilities for advanced monitoring, understanding, and responding to climate-related opportunities and hazards across scales and sectors. Innovations in real-time monitoring technology (for example, to increase the quality or accessibility of remote sensing data) can help decisionmakers more accurately and easily assess the condition of utilities and critical infrastructure, and enable planners to identify, map, and analyze vulnerabilities and devise more proactive strategies to address damage from climate-related shocks and stresses. In the public sector, for example, with the help of AI, the DOE's Oak Ridge National Laboratory has developed technology to map vulnerability to climate change down to the block and building level, and DOE's Office of Electricity is developing a comprehensive resilience modeling system for all North American energy infrastructure.

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[8] For example, the American National Standard for Flood Mitigation Equipment, supported by DHS's Flood Apex Program.

[9] For example, see the collaborative network comprised of USDA's Climate Hubs, DOI's Climate Adaptation Science Centers (CASCs), and NOAA's Regional Integrated Sciences and Assessment Program (RISA).

Increasing the availability of low-cost sensors and other monitoring technologies would also be a game changer in pre-disaster resource forecasting and disaster management. For example, low-cost water quality monitors deployed widely in sewer and stormwater systems could greatly increase municipal resilience and facilitate uptake of complementary technologies like inflatable gates to divert water and avoid flooding. Similarly, developing new tools to track waste heat (for example, across a range of vehicle types) could help decision makers mitigate the urban heat island effect—waste heat from buildings, air conditioners, and vehicles contribute significantly to the extra heat added to urban environments from energy consumption. One existing tool in the context of active wildland fires, the AirNow web application, leverages community-based air quality sensor data in the Fire and Smoke Map—a collaborative effort between the U.S. Forest Service (USFS) and EPA—to provide information on active wildland fires, smoke and air quality, and recommended protective actions.

Elevation of Indigenous Knowledge

Management practices and methodologies

Elevating and fully including Indigenous Knowledge (IK) in co-productive and collaborative projects can produce transformative shared benefits for Tribal Nations, Indigenous communities, and climate resilience. However, bolstering resilience by including IK requires building relationships based on reciprocity and trust with respect for the critical principles of causing no harm and receiving free, prior, and informed consent for the inclusion of IK.[10] These partnerships may also require new approaches to information storage, management, and protection, which might include, for example, approaches like the metadata standards in the CARE principles for Indigenous Data Governance.

Indigenous communities—both today and since time immemorial—have used nature-based strategies grounded in context-specific IK to address challenges such as wildfire, drought, flooding, sea-level rise, and the security of traditional foods and culturally important species. For instance, in the Pacific Northwest, the Karuk Tribe is blending traditional and innovative agroecological practices to build soil health and increase drought resilience. Simultaneously, the Western Klamath Restoration Partnership is combining contemporary fire ecology and forest management techniques with IK to pilot prescribed burning and fuels treatments designed to benefit cultural foods and fibers, wildlife habitats, and community wildfire protection.[11] Additional Tribal examples of this work, supported by the Bureau of Indian Affairs' Tribal Climate Resilience Awards, include:

- The Chugach Imaq, which will blend IK with aerial surveys to better-evaluate the effects of climate change on marine mammal population dynamics.

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[10] One example of local and regional coordination efforts elevating and blending resilience and adaptation best practices through peer-to-peer learning and sharing is the Bureau of Indian Affairs Regional Tribal Climate Resilience Liaison Program.

[11] Elsewhere, the Confederated Tribes of the Siletz Indians is working with the U.S. Fish and Wildlife Service to reconnect floodplains to restore Tribal fisheries in Oregon, and the San Carlos Apache Tribe is conducting research with U.S. Geological Survey scientists to develop a restoration plan for culturally important riparian areas at risk from climate change.

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- The Blue Lake Rancheria, which will expand a whole-community disaster preparedness campus to prepare for climate change impacts, including by incorporating IK in its programming.
- The Tulalip Tribes of Washington, which will use advanced technologies to support IK that enhances climate resilience and strengthens Tribal relationships by monitoring wildlife populations.

Indigenous communities manage millions of acres of land across the United States, and have ongoing and historic connections to millions more. Developing transformative, co-productive, and collaborative partnerships like these—including partnerships with Indigenous youth[12]—is essential for achieving the nation's climate resilience goals. Game-changing opportunities exist to increase Tribal access to capital and enhance investments in co-stewardship, including by funding land return to Tribes.[13] State, local, private, and philanthropic partners could work with Tribal Nations and Indigenous communities to build on these models—including the first-ever Federal Guidance on Indigenous Knowledge, published by the Biden-Harris Administration—and deploy innovative climate resilience solutions informed and guided by IK.

Infrastructure

Hazard-Resistant Materials

Technologies

Hazard-resistant materials are basic components (like wiring, cement products, and engineered wood) of walls, building enclosures, electrical systems, water systems, and heating, ventilation, and air conditioning (HVAC) systems and other infrastructure that have been strengthened to perform despite the stress of changing climate conditions and improve recovery from extreme-weather events. Once developed and mass-produced, these components can be used by a wide range of facilities and structures. Investing in mass production to make existing hazard-resistant materials cheaper—and in research to develop new materials that improve on their performance—could therefore be transformative in enhancing the resistance and resilience of much of America's built infrastructure.

In construction, some examples of hazard-resistant materials include reflective paints, green roofing layers, high-strength cladding, and building enclosure panels or window systems designed for higher wind loads, heavy rainfall, and projectile impacts—which can each help buildings cope with the impacts of extreme weather. In transportation, permeable pavements, when appropriately maintained, can mitigate the destructive impact of intense rainfall. New production and composition technologies, such as nanotechnologies (for example, applied to create fire-resistant coatings) and 3D printing, offer other important avenues for innovation that

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[12] For example, opportunities for youth-led innovation include DOI's Indian Youth Service Corps initiative, the Native Youth Climate Adaptation Leadership Congress, DOI's Bison Apprenticeship Program, USDA's 1994 Tribal Scholars Program, and the Alaska Native Science & Engineering Program, among others.

[13] For example, the Tribal Community Vision Fund seeks to raise and deploy $1.2 billion in private and philanthropic investments to expand access to capital, promote self-determination, and support sustainable economic and community development in Indian Country.

could be well-suited for investment. Hazard-resistant materials can be particularly useful for facilities that provide emergency services, such as fire stations, hospitals, emergency operations centers, and critical manufacturing venues.

Innovation in hazard-resistant materials and enabling technologies can also drive environmental co-benefits—promoting low-embodied-carbon and non-toxic materials. For example, the FHWA is advancing the use of reinforced concrete produced through innovative low-emissions manufacturing processes. Similarly, one analysis of low-carbon concrete made with recycled plastics and coconut fibers concluded that it could significantly reduce hazard loss in high-hurricane-risk areas.

Federal initiatives continue to play a significant role in developing and promoting hazard-resistant materials and technologies in federally-owned and -supported infrastructure. DOE, for example, invests in heat- and cold-tolerant power infrastructure. Additionally, FEMA identifies some building materials as flood-damage-resistant and has collaborated with ASTM International to develop several consensus standards for determining flood damage resistance ratings.

Climate-Informed Designs

Technologies; Management practices and methodologies

Climate-informed designs address future climate conditions by making design choices that factor in a range of anticipated climate risks over the lifetime of the infrastructure, or that preserve options to adjust for future climate conditions. In buildings located in warmer, drier parts of the country, for example, a climate-informed design could incorporate elements that maintain thermal comfort and conserve water, such as cool roofing with integrated stormwater capture, shade elements in the building enclosure, and wastewater treatment and reuse systems. In the transportation context, roadways in flood-prone areas might be elevated or designed with natural and/or gray elements to increase rapidly shed water, increase drainage capacity, and adaptively manage runoff. For example, DOT incorporated climate-informed planning and design in its *Post Hurricane Sandy Transportation Resilience Study in New York, New Jersey, and Connecticut*, identifying infrastructure vulnerabilities alongside solutions to enhance future flood resilience.

Investments in developing replicable climate-informed designs (particularly at cost parity with conventional counterparts) have the potential to save businesses and state and local governments money, cut energy costs, and conserve water. Creating and sharing tools that help architects, construction managers, and engineers evaluate climate risks and more fully integrate climate considerations into their designs could also promote more widespread adoption of climate-informed designs. For example, the Climate Risk Informed Decision Analysis (CRIDA) methodology developed in partnership with USACE provides a detailed tool to help water resources engineers incorporate climate uncertainty in their decisions.

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Financing

De-Risking Mechanisms

Certain investments in resilience may produce large public benefits but lower or uncertain private returns. Green banks and other clean energy finance entities have worked to close the financing gap for clean energy and energy efficiency projects through tailored financial products that facilitate mobilizing additional private capital. The $27 billion Greenhouse Gas Reduction Fund, for example, provides a new and unprecedented opportunity to capitalize clean energy transformations, particularly in low-income and disadvantaged communities. Investments supported with program funds may include resilience-enhancing projects that meet the program's eligibility criteria, including capacity building, workforce development, remediation of legacy pollution, and market development in disadvantaged communities.

Catalyzed by other sources of federal funding, green banks, related financing entities, and their implementation partners can deploy project-level de-risking mechanisms like grants, technical assistance, results-based incentives, financial guarantees, and credit enhancements to strengthen credit profiles and improve the financial predictability of resilience and NBS projects. New public-private partnerships[14] can also be established to mitigate risk by financing the purchase of parametric catastrophe insurance for critical natural infrastructure, such as coral reefs, in cases of ecosystem-disrupting extreme weather events. Novel applications of existing municipal financing tools, such as bonds and tax-increment financing, could make these investments more attractive. For example, environmental impact bonds apply a traditional bond structure but make repayment conditional on achieving specific environmental outcomes—such as the restoration of a city wetland or the creation of a stormwater-retaining park.

A range of potentially transformative blended finance instruments are also emerging to enable investors to capture the economic value of resilience to nearby communities. These tools could play a game-changing role in financing innovative and high-impact investments. In pursuing these transformational investments, partnerships, and financing structures, green banks can also leverage extensive federal resources in this space, including recent guidance from the Office of Management and Budget on the valuation and assessment of ecosystem services.[15]

Standardized Metrics and Measurement Tools

Management practices and methodologies; Institutional, financial, and governance structures

Two important barriers can impede private actors from financing resilience solutions: first, a lack of reliable metrics for measuring impact, and second, an uncertain financial value and return on investment timeline. While investors are beginning to gain more certainty in these areas, they still lack effective tools to measure incremental improvements in adaptive capacity.

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[14] For example, blended finance models like Forest Resilience Bonds implemented by USFS in California and a pooled fund model like the Resilience Fund implemented in Utah for watershed resilience.

[15] These resources also include the National Climate Resilience Framework, the 2023 NBS Resources Guide, and the America's Partnership Fund for Nature established by the Biden-Harris Administration in partnership with the Inter-American Development Bank (IDB).

Non-profits, philanthropies, and industry groups—along with federal, state, and local governments—are already working to standardize impact metrics for adaptation projects. As this effort moves forward, these metrics could better integrate the key federal performance indicators for climate resilience in the 2024 Federal Climate Adaptation Plans (CAPs), the Climate and Economic Justice Screening Tool (CEJST), and FEMA's Community Disaster Resilience Zone (CDRZ) designations to better align private- and public-sector impact metrics. Integrating these federal measurement tools could be the foundation of a first-of-its kind resilience investment strategy that enables federal funding to blend more easily with private capital. Additionally, by incorporating federal metrics and equity/vulnerability screening tools when scoping resilience projects, project developers would likely find it easier to unlock even more catalytic policy options like advance market commitments, offtake agreements, investment/loan guarantees, and tax credits. While these instruments have been used for emissions reductions technologies, they have yet to be deployed significantly in the context of climate resilience solutions.

Industry and Commerce

Climate-Informed Scenario Modeling and Supplier Tracking

Technologies; Management practices and methodologies

Widespread adoption of cutting-edge, climate-informed scenario modeling and dynamic supplier tracking systems could revolutionize the way organizations navigate and adapt to climate change impacts on supply chains. Traditionally, scenario modeling and supplier tracking were largely reactive and based on static historical data, limiting their usefulness in a dynamic, changing climate. Instead of relying on historical trends, today's advanced climate-informed scenario modeling and dynamic supplier tracking systems employ real-time data and predictive analytics—for example, by using Internet-of-Things sensors, AI algorithms, and cloud computing—to continuously monitor, analyze, and visualize data on climate patterns and supplier performance.

These innovations allow organizations to better anticipate, preempt, and mitigate potential disruptions before they occur, enabling business continuity planning, increasing operational resilience, and strengthening supply chain adaptability. For example, Gavi, the Vaccine Alliance employs advanced supplier tracking systems to manage the distribution of vaccines in low- and middle-income countries, where climate-related challenges such as extreme temperatures can disrupt the cold chain required for vaccine preservation. Their system allows for real-time monitoring of vaccine shipments and storage conditions, adapting routes and storage strategies based on predictive climate data and current environmental conditions. Gavi's approach helps ensure that vaccines remain viable upon delivery, despite unpredictable climate variations.

Buildings

Low-Cost Retrofits

Technologies; Management practices and methodologies

Homes and buildings across the country are increasingly at risk from more frequent and severe extreme weather events. This growing risk is making home insurance in many areas unaffordable—and in some cases, unattainable. Innovation in building retrofit approaches and technologies that account for increasing and future risks and can be deployed affordably, at mass scale, and in a variety of different building types and geographic locations, would be a game changer to effectively address the growing climate threats to the built environment.

Developing innovative, low-cost retrofits—including storm- and wind-resistant roofs and windows, floodproofing, and smoke-resistant enclosures and air filtration systems—can increase protection, reduce costs, and make properties more insurable. For example, the Insurance Institute for Business & Home Safety (IBHS) has developed FORTIFIED, a voluntary, evidence-based construction and re-roofing program to strengthen homes and commercial buildings against severe weather, such as high winds, hail, hurricanes, and even tornados. As shown in research by the DOE National Labs, investments in innovative thermal insulation, air-sealing, and energy code measures also save lives by allowing families to retain safe housing during extreme temperatures and extended power outages, and improve grid resilience.[16]

To support lower-cost retrofit methods, states, local governments, utility providers, lenders, and the insurance industry could develop new approaches to financing, permitting, approving, and incentivizing building retrofits. For example, laws in several states require insurance discounts for homeowners that have a FORTIFIED designation. Programs like Strengthen Alabama, offered through the Alabama Department of Insurance, and Louisiana Fortify Homes, offered through the Louisiana Department of Insurance, also provide grant funding that helps homeowners invest in FORTIFIED. Similar approaches include DOE's Property Assessed Clean Energy Programs (PACE), which incentivizes thermal envelope improvements, and DOE's Affordable Home Energy Earthshot, which aims to reduce the cost of energy-efficient home retrofits by 50% within a decade. These programs could also be modeled on federal investments like HUD's Green and Resilient Retrofit Program (GRRP), which provides climate resilience funding to affordable housing properties like "Revive 103," a 60-unit low-income apartment community in New York, which received GRRP funding to tighten the building envelope and seal all windows and openings—reducing heating and cooling costs, and providing more comfortable and predictable temperatures for residents during extreme weather events.

Modern Building Codes and Standards

Management practices and methodologies; Institutional, financial, and governance structures

In 2023, FEMA estimated that only 31% of hazard-prone jurisdictions in the United States have adopted modern building codes with hazard-resistant provisions. Incentivizing the development, deployment, and uptake of modern, climate-resilient, and consensus-based building codes and standards, including energy codes, will help prepare communities for climate change and natural

[16] For additional examples, see a variety of exhibitors at HUD's Innovative Housing Showcase.

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hazards. There is also evidence that adopting modern codes and standards can be a good investment: the National Institute of Building Sciences, for example, has identified $11 saved for every $1 spent in adopting the latest building code requirements.

Game-changing investments in developing and deploying modern building codes and standards could include:

- Providing technical assistance for local governments developing, adopting, and enforcing resilient modern building codes and standards. For example, DOE's State and Community Energy Program and FEMA's Building Code Plus-Up grants are supporting local adoption of building codes with technical assistance through the President's Investing in America Agenda.
- Integrating new code enforcement technology, such as through augmented reality, can increase local capacity and decrease review times after disasters, while also increasing compliance with flood and fire risk standards.
- Adopting maximum safe indoor temperature regulations as part of a state or local Renters Bill of Rights and in building design and occupancy standards.
- Adopting heating, ventilation, and air conditioning (HVAC) standards that reduce wildfire smoke infiltration to protect against increasing climate risks.
- Developing resilience rating systems for next-generation resilient neighborhoods, buildings, homes, and infrastructure (for example, like the LEED Design for Enhanced Resilience pilot program) to guide future community development.
- Incorporating temporary islanding capability for critical facilities that are equipped with renewable power generation to allow these facilities to operate during a disaster.
- Adopting energy codes alongside building codes to protect occupants during extreme temperature events and increase grid reliability.

Investments to make these innovative technologies, practices, and frameworks more available, user-friendly, and locally-customizable could support a game-changing level of adoption.

Transportation

Grid-Integrated Charging

Technologies; Management practices and methodologies

Electric vehicles (EVs) and EV charging infrastructure are actively reshaping the nation's energy infrastructure. These changes present a transformative opportunity to integrate EVs into the electric grid at a national scale, resulting in a more reliable and resilient energy system. Bidirectional charging technologies, for example, can transform EVs into mobile back-up power storage systems during extreme-weather events. And combining grid access points with other parts of the built environment—such as lampposts, in Los Angeles—can help make EV charging infrastructure itself more resilient to disruptions.

Grid-integrated charging also increases redundancy for power systems in our nation's buildings, homes, and community infrastructure. Redundant power systems save lives during extreme-weather emergencies and are particularly critical to facilities that provide health services and house vulnerable populations. Utilities in California, for example, are beginning to integrate the data, forecasting, and infrastructure required for grid-integrated charging in pilot projects, providing backup power during outages and assistance meeting peak power needs.

Taking actions to integrate charging infrastructure more fully with the grid also fulfills a goal of the National Climate Resilience Framework: to proactively build resilience and reduce disruption across critical services—such as hospitals and medical care facilities, utilities, and more—in anticipation of extreme-weather events. Brought to scale, grid-integrated charging and management practices can ensure the nation's power system and EV infrastructure work interchangeably to contribute to the safety, security, and climate resilience of communities leading up to, during, and after extreme-weather events.

Cool Pavements, Bus Shelters, and Transit Systems

Technologies; Management practices and methodologies

Urban areas featuring structures like buildings, roads, and sidewalks experience higher temperatures than natural landscapes. Walking to and waiting for public transit also exposes people to extreme temperatures and weather conditions, and particularly, extreme heat. At the same time, increasing public transit use is a key priority in lowering transportation-sector greenhouse gas emissions.

Investments to integrate heat mitigation into transportation systems could therefore have outsized positive effects, particularly on transit-oriented communities. Three areas in particular stand out:

- Efforts that focus on developing effective, low-cost, and modular transit resilience products—such as cool, reflective, high-albedo pavements and cool bus shelters—would be particularly impactful for cities seeking to install these technologies across an entire transit system. For example, FHWA's PROTECT grant program awarded nearly $24 million to the City of Davis, CA to install cool pavement technologies and replace roadway underlayment to mitigate extreme heat.
- Third-party mechanisms—like a public scorecard—to compare the effectiveness of similar products like pavement paints and commercial bus shelters in reducing heat exposure would make it significantly easier for decisionmakers to safely invest in the most promising products.
- Investments that allow transit system assets to serve a dual function during heat waves by enabling access to cooling and emergency services. For example, buses could be used to provide free access and shuttle services to hospitals, cooling centers, or shelters, or to communicate essential safety information; thoughtful design of transit system assets could integrate shade trees around public plazas and transit hubs. In 2023, for example, the District of Columbia provided free transportation to several cooling centers during a hot weather emergency. Phoenix, AZ and Jacksonville, FL have also used public buses and bus shelters as cooling facilities to protect residents during extreme heat events.

Examples of many of these interventions exist, but implementing these at lower costs and city-wide scales would be a game changer. These investments also align with a key objective of the

National Climate Resilience Framework: to “help communities become not only more resilient, but also safer, healthier, equitable, and economically strong.”

Energy

Smart Grids and Virtual Power Plants

Technologies; Management practices and methodologies

In recent years, climate-change-driven extreme-weather events have strained the U.S. power grid to the breaking point—most notably in 2021, when a severe winter storm caused hundreds of fatalities and millions of power outages in Texas.

Strategic deployment of smart grids and Virtual Power Plants (VPPs) can improve grid flexibility and reliability in the face of extreme-weather events. VPPs are aggregations of distributed energy resources such as rooftop solar with batteries, smart appliances, EVs and chargers, and commercial and industrial loads. Smart grids use advanced sensors, meters, and control systems (such as dynamic line readings and advanced switching) to track real-time information and improve operations, providing the visibility and control grid operators need to flexibly integrate new energy resources, avoid potential outage conditions, and quickly respond to disruptions.

VPPs and smart grids can optimize balancing of electricity demand and supply against grid constraints, enabling grid resilience to extreme-weather disruptions and improving the delivery of grid services under challenging conditions. For example, in Hawai'i, one company is working to aggregate 80 MW of distributed energy resources across three islands into a VPP, which could save participants thousands of dollars, enable customer control over home energy systems during outages, and provide valuable services to the grid. Together, these emerging approaches support grid reliability and resilience through integration of backup power, reduction of single-point-of-failures, and allowing optimal use of existing grid infrastructure. If integrated with traditional energy systems at scale, they could each reduce grid costs and additional infrastructure buildout needs significantly, while increasing performance and stability.

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Community-Integrated Microgrids

Technologies; Management practices and methodologies

Community-based microgrids can deliver diversified and decentralized energy production to increase the disaster resilience of communities and critical infrastructure. A microgrid is "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single, controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode." Deploying microgrids strategically in disaster-prone communities across the country, as well as developing new hardware, software, technical approaches, and regulatory structures that enable microgrids and improve microgrid performance and accessibility would be game-changing steps forward in this space.

Microgrid-enabling technologies (including distributed renewable generation, battery storage, power transmission via “multi-nodal, small-scale, high-voltage direct current, advanced demand-side management strategies,” and microgrid control systems) can significantly increase access to, and therefore impact of, microgrids during extreme-weather events and provide continuous backup power during these events. For example, advanced microgrid controllers can allow a microgrid to switch seamlessly from a grid-connected to an islanded mode and vice-versa. The Borrego Springs microgrid in San Diego County uses this technology to keep the power on in fire stations, schools, and other critical facilities during Public Safety Power Shutoffs. During a grid power outage, microgrids can also avert financial losses by businesses and support critical infrastructure, such as hospitals and emergency responders. Microgrids can also increase resilience by providing backup power and easing strain on the central grid in times of peak demand, such as a heat wave.

The global microgrid market is expected to increase rapidly in the coming decade. To maximize the impact of this growth in the United States, capital cost and project development timelines could be lowered through technological and policy advances—particularly, policies aimed at standardizing tariff structures for compensation, increasing interconnection ability, and enabling private or community-owned electric infrastructure to cross property lines. DOE’s Grid Deployment Office has supported research and deployment of microgrids, including, for example, in Michigan, where a $22.9M investment will deploy “new grid sensing and fault location devices, communications devices, and reclosers” to “lay the foundation for developing a 100% renewable adaptive networked microgrid.” In Bronzeville, on Chicago’s south side, a new microgrid supported by DOE and implemented by the local utility will connect 1,000 customers who would particularly benefit from resilience services, and also serve as a vehicle to pilot several innovative microgrid technologies.

Mobile and Long-Duration Energy Storage

Technologies; Management practices and methodologies

As described above, climate change-fueled extreme-weather events can create localized disruptions to power supplies—sometimes causing multi-day outages. Deploying affordable, mobile, long-duration, and renewable energy storage systems at scale would dramatically reduce the severity and duration of these disruptions.

Long-duration energy storage (LDES) includes storage that can shift loads by more than a few hours and that enables flexibility between generation and use of electricity. It can provide power for up to multi-day periods during extreme weather or other events that result in reduced availability of other generation resources. Mobile energy storage refers to storage technologies that can be moved and deployed quickly in areas where there are acute impacts to grid connectivity or energy generation. If deployed affordably and in complement to one another, these technologies could significantly reduce the impact of load loss due to extreme weather or disasters, which will become increasingly important as electrification of transportation, HVAC, and other vital systems advance.

While these two technologies are typically deployed separately, with different types of storage technologies optimized for each application, investments in creating energy storage at scale that is both mobile and longer-duration would be truly game-changing. Recognizing the potential of these technologies, for example, DOE recently awarded $9.5 million to bring mobile LDES systems to communities in rural Vermont with historically unreliable electric service during severe weather events. DOE has also launched a Long-Duration Storage Earthshot to reduce the cost of 10+ hour storage systems by 90% within the decade.

Reconductoring

Technologies

Reconductoring involves replacing conventional steel and aluminum grid cables with advanced cables that can deliver up to twice the power for the same-sized cable, and resist sagging under high temperatures. Advanced conductors are thus both more resilient to extreme weather and heat, and also allow for more energy transmission on a grid that will serve growing loads from increasing electrification and new customers. Reconductoring will allow for significantly more energy transmission within the existing grid footprint, easing strain on the grid and reducing the need for additional transmission siting and buildout.

For example, the Lower Rio Grande Valley's reconductoring project, completed in 2016, was motivated by rolling backouts during the South Texas Ice Storm in February 2011, partially resulting from new customers increasing strain on the grid. After considering many options, the utility reconductored two transmission lines, doubling transmission capacity without taking the existing lines out of service. DOE's Grid Resilience and Innovation Partnerships program has also funded several reconductoring projects, including one project in greater Philadelphia which will combine reconductoring with upgrades to monitoring and control technologies and installation of backup battery systems.

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Agricultural Production

Precision and Regenerative Agriculture

Technologies; Management practices and methodologies

Investments in precision and regenerative agriculture that foster soil health, optimize resource use, and decrease input costs could help farmers become more economically- and climate-resilient.

Sustainable precision agriculture includes using new and enhanced technologies and decision-support tools that leverage data to help farmers observe, measure, and respond to soil and microenvironmental variability at the farm, field, and sub-field levels. These technologies and tools—including geospatial tools, uncrewed aerial vehicles (UAVs), and machine learning algorithms—can reduce the need for water, fertilizer, and other resource inputs by allowing resources to be targeted more specifically. For example, one user-friendly toolkit developed by USDA (GRAPEX ET) combines Earth observations from satellites and UAVs such as drones to provide real-time data that can be integrated into existing irrigation schedules used by the wine industry to efficiently irrigate vineyards.

Regenerative agriculture focuses on improving soil health as a means to increase ecosystem services and crop resilience. Healthy soils store more water, and thus can help plants withstand intense drought, while also reducing runoff and erosion during extreme rainfall events. Healthy soils can also sequester carbon. Regenerative practices include diverse cropping systems, crop rotations, extended living cover, integrating livestock through prescribed grazing and grazed cropland, compost production and application, reduced- or no-tillage, interseeding, agroforestry, and more. These practices have both climate adaptation and mitigation benefits. For example, cover crops can increase resilience to drought and extreme rainfall while also providing other ecosystem services such as improved soil fertility, weed control, and soil erosion control.

Advanced Agricultural Biotechnologies

Technologies

Climate change presents many challenges for our nation's farmers—from altering growing zones, to stressing plants and animals with extreme temperatures and more variable precipitation, to impacting crops with smoke taint from wildfires, to wind damage from derechos. Advanced agricultural biotechnologies can help enhance adaptation to climate change and address global food security.

Advanced agricultural biotechnologies include genomics-informed breeding, gene editing, biotechnology risk assessment tools, advanced plant regeneration methods, and functional microbes. These technologies can provide a transformative boost for farmers, ranchers, and foresters seeking to enhance the resilience of their plants and animals to increased temperatures, drought, new diseases, or other stresses resulting from climate change. For example, plant scientists are beginning to use CRISPR technology to develop new varieties of drought-tolerant wheat, corn, rice, tomatoes, soybeans, and cotton seeds.

These technologies can improve agricultural resilience and sustainably increase the yield of nutritious food and other biobased products, particularly when combined with regenerative

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practices. For example, enhanced soil microbes can help produce a wide variety of ingredients for food production, support plant growth, and reduce crop dependence on fertilizer. So-called precision fermentation can reduce agriculture's impact on the environment, while increasing predictability and yields in the face of more challenging weather conditions. New investments could also refine and improve existing biotechnologies, such as transgenic herbicide tolerance traits that reduce the need for tillage and pest-resistant traits that reduce pesticide use.

USDA's Agricultural Research Service supports this work through a wide range of programs, and the National Institute of Food and Agriculture similarly supports advances in agricultural biotechnology through multiple funding programs. President Biden has also announced federal support for the North Dakota Advanced Agriculture Technology Engine, which will spur the responsible development of advanced agricultural biotechnologies in partnership with local communities. However, widespread adoption will require additional work to develop clearer paths to market and more streamlined, science-based regulatory regimes. Innovations will also need to be affordable, sustainable, and accessible for smaller agricultural producers.

Natural Systems

Detection and Control of Harmful Invasive Species

Management practices and methodologies; *Institutional, financial, and governance structures*
Harmful invasive species impact America's environment, economy, public health, recreation, and overall livelihood at a cost of $21 billion annually. They challenge efforts to build resilience to climate change by compromising natural climate solutions (such as carbon sequestration and storage), undermining built and natural infrastructure (for example, through wildfires fueled by invasive grasses, tree mortality from invasive insect pests, degradation of coral reefs and wetlands by aquatic invasive species), threatening public health (for example, through new or expanding disease vectors such as ticks and mosquitoes), and stressing ecosystems.

Investments in innovative invasive species detection, control, and eradication techniques could facilitate rapid responses when introductions of new invasive species inadvertently occur and could also help slow or halt the spread of established invasive species across a landscape. For example:

- Emerging technological solutions, including genomic data and tools, AI used for rapid data processing, remote sensing, and automated delivery mechanisms for treatments could dramatically increase monitoring and control capabilities. For example, the Biden-Harris Administration is supporting the Chickasaw Nation in using satellite imagery to address invasive red cedar trees and increase the accuracy of prescribed burns.
- Environmental DNA (eDNA)—organismal DNA that can be found in the environment—and early-warning sensors can support national biosecurity at ports of entry (for example, testing imported goods and shipping containers) and early detection (for example, surveillance for aquatic invasive species and forest insect pests).
- R&D in integrated pest management, including in applying machine-learning-assisted monitoring and detection to improve targeting, efficacy, and specificity of treatments; as

well as in leveraging biological processes like RNAi; and in using new molecular and other novel technologies and techniques to complement classical biocontrol tools.
- Demonstration projects to effectively spotlight novel technologies and techniques, which can increase access to these management options for federal agencies, states, Tribes, territories, local governments, the private sector, and other impacted groups.

DOI, NOAA, USDA, and other agencies under the National Invasive Species Council are critical partners in responsibly developing, regulating, and disseminating these technologies.

Ecosystem Management Technologies

Technologies; Management practices and methodologies

In a changing climate, restoring, conserving, and improving the health of natural systems can foster resilience to a wide range of climate challenges. This can include the "rewilding" of degraded ecosystems, replacing species that have become locally extinct, providing new pathways for species movement, or pursuing assisted migration. However, in the context of a changing climate, conservation, restoration, and rewilding increasingly require novel approaches based upon the latest advances in technology, Indigenous Knowledge, and scientific understanding.

The ability to understand animal populations and current and changing habitat needs is currently limited by traditional resource-intensive tracking methods. Developing new approaches and technologies that incorporate machine learning for species identification, new UAV technology to remotely map habitats, telemetry and tracking methods (for example, long-range wide area network tracking), and eDNA to measure and monitor biodiversity would give managers a much broader information base with which to make management decisions.

Vulnerable coastal and marine habitats could benefit from a wide range of innovative and resilience-enhancing technologies and practices, including improved early-warning systems, innovative approaches to measuring blue and wetland carbon, new coastal change modeling approaches using machine learning and artificial intelligence, and satellite monitoring of climate-stressed fisheries. Developing new techniques for coral restoration, such as bioengineering corals resistant to increased temperatures and ocean acidification, producing artificial reefs using recycled materials, and 3D-printing cost-effective and accessible reef structures, would enhance coral reef resilience.

For agriculture, forestry, and land management, new and expanded technologies are needed to identify genotypes resistant to climate-related stressors and to determine genetically appropriate seed transfer guidelines for climate-informed revegetation. Conservation and restoration of natural systems, especially native species of vegetation like the five North American Ash, will benefit from using innovative technologies (such as gene editing), climate-informed management strategies (including selective breeding and adaptive silvicultural techniques), and improved seed technologies. Supporting the National Seed Strategy, a collaboration between 12 federal agencies and over 300 non-federal partners, will also ensure a diverse supply of seeds to restore and rehabilitate native plants across ecosystems.

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Water

Smart Water Infrastructure

Technologies; Management practices and methodologies

Smart water infrastructure, incorporating SMART (self-monitoring, analysis, and repairing technology), is a transformative approach to water management. By integrating advanced sensors (in network and in upstream watersheds) and valves, along with regulatory innovations like stormwater utility programs, smart water infrastructure optimizes water supply, hydropower generation, and stormwater management, while also being able to monitor and assess supporting physical infrastructure.[17]

Case studies, including the installation of smart water meters in cities like Los Angeles and Seattle, demonstrate efficacy in reducing water wastage and improving service delivery. President Biden's Bipartisan Infrastructure Law has also provided new transformative support for smart water infrastructure—including a recent investment of $179 million in innovative water reuse projects across the West. Further increasing public, private, and philanthropic investment in developing and deploying SMART water technology, as well as complementary approaches, such as dynamic pressure management and variable speed drives to reduce water loss, would be extremely impactful. Deploying smart water infrastructure at scale will require addressing challenges, including data privacy, cybersecurity, financial planning, and workforce transition, as well as robust safeguards and strategic approaches to ensure equitable and sustainable deployment.

Enhanced Aquifer Recharge

Climate change, urbanization, and population growth have challenged the aquifers that millions of Americans rely on. One analysis last year of 80,000 wells across the country found that 45% had experienced statistically significant water level reductions since 1980. Enhanced aquifer recharge (EAR) systems can play an important role in replenishing, stabilizing, and buffering these critical systems against drought. According to EPA, EAR techniques, including a variety of surface infiltration systems and injection wells, have "tremendous potential" to "augment water supplies, replenish groundwater, and restore streamflow" in the face of climate change and other stresses.

Initiatives like EPA's Science to Achieve Results research grants, Water Infrastructure Finance and Innovation Act (WIFIA) program and the U.S. Geological Survey's Groundwater and Streamflow Information Program support EAR advancement and highlight innovation in EAR-related water management and monitoring technologies. Non-federal initiatives like Orange County's Groundwater Replenishment System demonstrate the efficacy of EAR through a state-of-the-art water purification project that has been able to produce 130 million gallons of high-quality water every day. Additional innovations in the recharge technology itself, alongside the development of new applications for alternative water sources and advances in groundwater monitoring and management, would be productive areas of further investment.

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[17] Initiatives like the EPA's Drinking Water System Infrastructure Resilience and Sustainability Program support the development and adoption of smart water infrastructure nationwide.

EAR at scale also poses challenges related to energy consumption and land use. Managing these challenges will require additional innovations in groundwater and surface water monitoring technologies. Stakeholder engagement, adoption, and planning are important to navigate these risks, maximizing EAR's climate resilience benefits, while addressing environmental justice concerns. If implemented carefully, EAR should promote equity and environmental justice by ensuring access to clean water for disadvantaged communities.

Advanced Desalination and Water Recycling

Technologies

Innovations in desalination and water reuse technologies could advance equitable access to clean water and be a pivotal game changer in addressing water scarcity and building climate resilience.[18] Investments to make advanced desalination and water recycling processes like reverse osmosis, advanced greywater recycling, hydropanels, and stormwater harvesting, more accessible and affordable could open up a new suite of opportunities for communities experiencing longer and more severe droughts. These innovations maximize resource efficiency, diversify water sources, and reduce strain on ecosystems.[19]

Some examples of these technologies, recently supported through the Bureau of Reclamation's Desalination and Water Purification Research program, include:

- Sustainable solvents for use in desalination;
- Advanced desalination and purification membranes;
- Enhanced evaporation systems with selective precipitation; and
- Improved electrodialysis technologies.

Additionally, game-changing investments could be made to mitigate environmental challenges associated with desalination and water reuse projects. For example, desalination plants commonly employ open intake systems, which can potentially pose ecological issues. Improved technologies, such as submerged and cable intake systems and beach wells, are alternatives that, if fully developed and deployed, could minimize these impacts. Developing ecologically and economically viable desalination concentrate management practices also has the potential to expand the use of the technology in cultivating new water supplies, including inland brackish sources. Investment in research to minimize the life cycle greenhouse gas emissions associated with the manufacturing, materials, and operation of these technologies is also key.

[18] DOE, EPA, DOD, DOI/Bureau of Reclamation, and NOAA conduct research to improve the desalination process, including intake technology, and develop it as a more viable water supply source, including addressing energy consumption, brine disposal, and environmental impact challenges

[19] EPA, DOE, and DOI/Bureau of Reclamation invest significantly in research projects to explore the benefits of water reuse, while also providing resources to track the National Water Reuse Action Plan and better understand state regulations and guidelines. Through programs such as the Title XVI Water Reclamation and Reuse Program and the new Large-Scale Water Recycling Program, DOI/Bureau of Reclamation also invests in construction of innovative water recycling projects that allow communities to develop local, drought-resistant supplies through treatment and distribution of municipal wastewater.

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Health

Early-Warning Systems for Vector-Borne Diseases

Technologies; Management practices and methodologies

Warmer winters, increases in extreme weather events, and other physical stressors with widespread significant impacts on ecosystems have widened the distribution of many vector-borne diseases. This is especially concerning in parts of the world where new species interactions could enable disease emergence.

Enhancing public health early-warning systems using both biosurveillance tools and predictive modeling would be a game changer in reducing the climate-driven risks of vector-borne diseases. This could incorporate, for example, improving monitoring and surveillance of human systems (like wastewater and syndromic surveillance), such as by layering and more fully integrating data collection and analysis platforms, and increasing the quality and availability of rapid, at-home, multi-pathogen diagnostic tests. For example, the National Institutes of Health's Rapid Acceleration of Diagnostics (RADx) initiative has helped accelerate innovation in mobile and accessible SARS-CoV-2 testing and reporting that could be replicated in the context of other vector-borne diseases and by non-governmental actors.

Similarly, the federal and Ohio Environmental Protection Agencies jointly developed new targeted methods for detecting SARS-CoV-2 in wastewater using RNA markers, and these approaches could be expanded to emphasize metagenomic-based, pathogen-agnostic approaches to surveil climate-related disease outbreaks. Linking monitoring systems to the CDC's growing National Wastewater Surveillance System and National Syndromic Surveillance System could also enhance data quality and improve surveillance capabilities for communities across the country. Finally, the development of sophisticated artificial-intelligence-enhanced algorithms could more generally improve the effectiveness of early-warning systems.

Resilience Hubs

Institutional, financial, and governance structures

Resilience hubs are trusted physical sites in neighborhoods that serve as gathering spaces, information centers, and places of recreation, gathering, or community connection in everyday life. During disruptions like extreme weather events, resilience hubs assist the community in partnership with local emergency managers—for example, by providing shelter, communications support, or emergency supplies—and can also assist in post-disruption recovery.

Co-locating a resilience hub with health services or trusted staff from community health centers or hospitals can streamline access to basic health programs and increase the uptake of health care and social services simultaneously. More effectively integrating resilience hubs with community health care workers and promotores from community-based organizations or healthcare systems can also increase access to care during times of disruption. For example:

- A resilience hub in Boyle Heights, Los Angeles provides art programs and youth-led radio programming. During local disruptions, the hub provides outreach services, including multilingual emergency broadcasting.

- A resilience hub in Ward 7, District of Columbia provides workforce development programs and youth and senior services. During disruptions, the hub uses a Community Emergency Response Team to connect people most at risk of adverse health outcomes in the community with site resources.
- A resilience hub in Sacramento, California provides youth-focused behavioral health services, youth and adult education, and job training and placement. In the event of a disruption, the hub is able to provide emergency behavioral health services or serve as an emergency warming or cooling shelter.

Additional resilience hubs can be identified with the DHS Resilience Hub Finder tool.

While resilience hubs are already being developed across the United States,[20] providing long-term, sustained, and coordinated public-private support to establish permanent and well-equipped resilience hubs in communities nationwide would be a game changer.[21] It also would require flexibility in program design, as different communities of varied population density, geographies, community needs, and climate hazards would require different resources from resilience hubs. Developing a system to link individual hubs into a resilience network would also improve sharing of resources, local knowledge, scientific data, and tools, which would further enhance the effectiveness of individual hubs.

Climate-Integrated Health Records

Management practices and methodologies

Electronic health records (EHR) are used by doctors and health officials to understand patient needs and to monitor and predict trends in public health. Linking climate services information with EHR and informatics methodologies to identify at-risk patients, especially in populations most at risk from climate-related hazards, could be a game changer for clinical providers working to tailor care.

No integrated system currently exists that links information on climate risk directly with information on at-risk patients or to health care providers and patients, but initiatives such as the HHS emPOWER Program hold promise. If developed and adopted, this kind of system could help care providers share location-specific climate risk information with at-risk patients through EHR health portals, including predictions or warnings of extreme heat, wildfire smoke, vector-borne disease outbreaks, and flood risks. Care providers could also use this kind of system to develop more sophisticated plans of care for patients before, during, and after extreme-weather events.

Climate-integrated health records could reduce exposure to a variety of risk factors, for example, by enabling prescriptions for air filters or cooling devices. They could also play a role in raising patient awareness of increased risk during and after events. Care providers could also make use

[20] For example, see the City of Austin's Resilience Hub program, which plans to leverage funding from President Biden's American Rescue Plan.
[21] For example, through its Community Change Grants, EPA provides free technical assistance and $2 billion in implementation grants for disadvantaged communities, which can include climate resilience projects that create or upgrade community-level resilience hubs.

of the data from these health records to better manage healthcare availability, for example, using the data to improve planning and surge staffing during and directly after wildfire smoke or extreme heat events. HHS (including CDC and NIH) and EPA are supporting innovative research linking EHR with environmental data in some locations and health systems. A national real-time system linking climate risk and EHR data could facilitate innovative research to understand and mitigate climate impacts on health, greatly benefiting overburdened populations at the frontline of climate change impacts.

Conclusion

The United States has always been a nation of innovators. Our world-leading universities, pioneering national laboratories, and competitive marketplaces have fostered breakthroughs in computing, batteries, healthcare, artificial intelligence, robotics, and more. This assessment highlights the tremendous opportunity to harness that ingenuity to strengthen the resilience of our nation—across communities, natural systems, small businesses and schools.

By making thoughtful and targeted investments in the *Climate Resilience Game Changers*, private, philanthropic, and non-governmental organizations, as well as federal, state, Tribal, territorial, and local governmental entities have the opportunity to continue this legacy of innovation, and to work to build a better and more climate-resilient future for all Americans.