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NSF Engineering Research
Visioning Alliance

The Role of Engineering to Address Climate Change

Visioning Event Report

The Role of Engineering to Address Climate Change

A Visioning Report of the Engineering Research Visioning Alliance

Report Finalized July 27, 2022

Co-Hosts:

Penn Engineering, University of Pennsylvania

UCLA Samueli School of Engineering

College of Engineering, The University of Utah

This material is based upon work supported by the National Science Foundation (NSF) under award Grant # 2048419. Any opinions, findings, interpretations, conclusions, or recommendations expressed in these materials are those of its authors and do not represent the views of the UIDP Board of Directors, UIDP's membership or the National Science Foundation.

The Engineering Research Visioning Alliance (ERVA) is a neutral convener that helps identify and develop bold and transformative new engineering research directions, directly supporting the nation's ability to compete in a rapidly changing global economy. Funded by the National Science Foundation (NSF) Directorate for Engineering, ERVA is a diverse, inclusive and engaged partnership that enables an array of voices to impact national engineering research priorities. The five-year initiative convenes, catalyzes and empowers the engineering community to identify nascent opportunities and priorities for engineering-led innovative, high-impact, cross-domain research that addresses national, global, and societal needs. Learn more at ervacommunity.org.

Suggested citation: Engineering Research Visioning Alliance. 2022. The Role of Engineering to Address Climate Change: A Visioning Report. Columbia, SC: SSRN. http://dx.doi.org/10.2139/ssrn.4173381.

Acknowledgments

The Engineering Research Visioning Alliance (ERVA) is grateful to our partners at the National Science Foundation (NSF) Engineering Directorate for their ongoing engagement and support for this work, particularly Program Director Louise R. Howe and NSF Engineering Directorate leadership Susan Margulies, Linda Blevins, and Sohi Rastegar.

ERVA visioning events enable the engineering research community to identify nascent opportunities and priorities for engineering-led innovative, high-impact research that addresses global and societal needs. Each event relies on the efforts of organizations and individuals who volunteer to lead, guide, and participate in its activities.

Gratitude is extended to the event co-hosts who supported the workshop that informed this report by providing leadership and recommendations for participants: University of Pennsylvania School of Engineering and Applied Science, led by Nemirovsky Family Dean Vijay Kumar; the University of California, Los Angeles Samueli School of Engineering, led by Ronald and Valerie Sugar Dean Jayathi Murthy; and the University of Utah College of Engineering, led by H. E. Thomas Presidential Endowed Dean Richard Brown. Special thanks to co-host lead report drafters Shu Yang of Penn Engineering and Milind Deo of the University of Utah College of Engineering.

The Thematic Task Force members contributed their time and expertise and were instrumental in framing and shepherding the workshop conversations:

- Amy Heintz (co-chair), Battelle
- Bruce Logan (co-chair), Pennsylvania State University
- David Allen, University of Texas at Austin
- Andrew Bochman, Idaho National Lab
- Eric Corey Freed, CannonDesign
- Elena Irwin, The Ohio State University
- Kimberly Jones, Howard University
- Serdar Tufekci, ENGIE North America

In particular, Bruce Logan guided content syntheses and report editing.

This visioning effort also benefitted from the expertise of facilitators and annotators in each breakout session:

- Carbon sequestration: Milind Deo, University of Utah; and Erica Smithwick, Pennsylvania State University;
- Climate justice: Kimberly Jones, Howard University; and Diana Ortiz-Montalvo, National Institute of Standards and Technology;
- Decarbonizing industrial processes: Diana Ortiz-Montalvo, National Institute of Standards and Technology; and Kevin Whitty, University of Utah;
- Ecosystem and water management: Mathieu Francoeur, University of Utah; and Kimberly Jones, Howard University;

- Energy storage: Wilson Espinoza, Georgia Institute of Technology; and Adel Nasiri, University of South Carolina;
- Geoengineering: Mark Borsuk, Duke University; and Wilson Espinoza, Georgia Institute of Technology.
- Greenhouse Gases (GHG) capture: Milind Deo and Kevin Whitty, University of Utah;
- Health and climate change: Allison Steiner, University of Michigan; and Shu Yang, University of Pennsylvania;
- Resilient infrastructure, buildings, and transportation: Andy Bochman, Idaho National Laboratory; Amy Heintz, Battelle; and Shu Yang, University of Pennsylvania; and
- Solar and renewable energy: Jesse Jenkins, Princeton University; and Bruce Logan, Pennsylvania State University.

The review of the U.S. and global R&D included in this report was prepared by ERVA's research intelligence partner, Elsevier, and presented by Bamini Jayabalasingham, Alexandre Bédard-Vallée, Christina Zdawczyk, and Celina Sprague.

The event discussions were informed by the following speakers who contributed their expertise: Linda Blevins, National Science Foundation; Daniel Calto and Bamini Jayabalasingham, Elsevier; Mikhail Chester, Arizona State University; David Hart, George Mason University; Pramod Khargonekar, UC Irvine; Benji Maruyama, Air Force Research Laboratory; Benjamin Preston, White House Office of Science and Technology Policy; and Christine Thomas, 3M.

ERVA is also grateful to all the workshop participants who contributed their time to create a valuable discussion and conference report and to their organizations for the liberty to lend their time and expertise to this effort.

ERVA executive director Jennifer Carinci led the event planning, program development, and execution under the guidance of ERVA principal investigator Dorota Grejner-Brzezinska, The Ohio State University; and co-Principal Investigators Anthony Boccanfuso, UIDP; Barry Johnson, University of Virginia; Charles Johnson-Bey, Booz Allen Hamilton; and Edl Schamiloglu, University of New Mexico. Development of the visioning session theme was informed by survey responses from nearly 500 ERVA Champions and input from the ERVA Standing Council, Advisory Board, NSF Engineering collaborators, and our research intelligence partner Elsevier.

Finally, staff and leadership from ERVA and UIDP, ERVA's administrative core partner, provided operational expertise for this event and report: Sandy Mau, ERVA communications director; Mark McGill, ERVA program coordinator; and Linda Toro, ERVA events manager. UIDP staff Natoshia Goines, Abishai Kelkar, and Melissa Drake contributed to event execution, and Mike Brizek, UIDP program director, consulted on workshop facilitation and report drafting.

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Executive Summary

More than 30 years have passed since the Intergovernmental Panel on Climate Change (IPCC) was created by the World Meteorological Organization and the United Nations Environment Programme to provide governments at all levels with scientific information they can use to address climate change. Although respected scientific bodies have produced dozens of reports in the ensuing years, few point to engineering-specific research directions and the critical role this community can play in addressing climate change.

Effectively mitigating the impact of climate change requires deliberate tools wielded by the engineering research community. Facilitated by significant and sustained investment, these tools can bring transformative change to the way society confronts the causes and impacts of climate change. This is the key recommendation of a recent visioning event coordinated by the Engineering Research Visioning Alliance (ERVA) to identify the role of engineering in addressing climate change. From this initiative, three cross-cutting thrusts emerged:

01

Focus on critical materials in all engineered systems, especially in extraction, separation, recycling and upcycling, and energy conversion, as well as carbon dioxide (CO_2) mitigation.

02

Invest in sensor, sensing, and communication capabilities to facilitate data compilation and analysis.

03

Enable and strategically exploit artificial intelligence (AI) modeling for forecasting and trend analyses.

To accelerate solutions, it is imperative to focus on *ways that engineering can lead foundational research efforts to address climate change*, with full consideration that technical solutions cannot be separated from consideration of societal impact. The event's Thematic Task Force, comprised of academic, corporate, and nonprofit experts, selected 10 discrete areas to consider. The convened scientists and engineers evaluated bold ideas, probed unexamined questions, and leveraged their combined expertise. The results were distilled into two overarching topics for this report: *synergistic engineering research priorities to address climate change* and *developing a comprehensive and inclusive vision for addressing climate change*.

Synergistic Engineering Research Opportunities to Address Climate Change

Climate change is an enormously complex topic, spanning many engineered systems that impact not only CO_2 emissions from fuels, but also the health of people, water systems, ecosystems, and infrastructure. The fundamental research topics prioritized to address climate change include:

ENERGY STORAGE, TRANSMISSION, AND CRITICAL MATERIALS

- Nanoengineered materials for critical mineral separation, extraction, and recycling;
- Chemicals or materials for non-traditional energy storage such as reversible electron shuttles in flow batteries and hydrogen gas;
- Materials for extracting additional energy from heat cycles by harvesting low-grade heat in new ways, such as thermal flow batteries and thermoelectrics; and
- Developing new ion exchange membranes to replace fluorinated membranes used in critical electrification systems, such as fuel cells, water electrolyzers, and other separation systems, with non-PFAS (per- and polyfluoroalkyl substances)-based membranes and with sufficient durability to withstand harsh conditions.

GREENHOUSE GAS (GHG) CAPTURE AND ELIMINATION

- Processes to capture and eliminate methane and nitrous oxide in agriculture operations and the environment by focusing on high emission sites such as dams and water impoundments, mines, landfills, and farms;
- Researching bio- and genetic-engineering of plants or inclusive microbial communities for selective non-CO_2-based GHG capture (e.g., for methane and nitrous oxide); and
- Exploring the feasibility of intensive biotic ocean carbon capture to deep-sea sediments with an emphasis on preventing loss of nutrients, and electrochemical methods with a focus on devising materials suitable for challenging seawater conditions.

RESILIENT, ENERGY-EFFICIENT, AND HEALTHFUL INFRASTRUCTURE

- Developing low-cost coatings for buildings, roads, and infrastructure that reduce heat island effects, increase self-cooling, and thermal energy transmission back into the exosphere;
- Infrastructure engineering that demonstrates positive impacts on health arising from de-fossilizing/decarbonizing the energy infrastructure and reducing transportation, industrial, and power-plant emissions; and
- Extensive lifecycle analyses, frameworks, or Environmental Product Declarations of embodied carbon in our infrastructure, ranging from the existing built environment to commonly used materials.

WATER, ECOSYSTEMS, AND GEOENGINEERING ASSESSMENT

- Sensing, measuring, and AI models for water flow analysis across large landscapes and proposing, through modeling and forecasting, future solutions to mitigate large swings in water availability due to increasingly disruptive events associated with climate change;
- Advancing solutions to threats of substantial losses of treated water in aging distribution systems through improved data collection and analytics, combined with novel in-line and self-powered sensing feeding forward into AI models; and
- Conceptualizing and testing at appropriate scales potential geoengineering solutions, with consideration of impacts on the environment and emphasis on economic and social costs of such technologies.

A Comprehensive and Inclusive Vision for Addressing Climate Change

The areas selected by the Thematic Task Force provide opportunities to address climate change by catalyzing the engineering research community. Encouraging pursuit of research directions for climate solutions offers an opportunity for federal agencies and the entire engineering research community to invest their resources and talent to address this problem with broader impacts on society. Engineering has unique opportunities to advance consideration of underrepresented populations through research with the potential to transform the energy and urban infrastructure in response to preventing or mitigating changes due to climate change. In this vein, participants emphasized topics of importance related to energy and climate education for all. Topics of particular importance to pursue include:

- **Convergent solutions that remove social barriers** and provide universal, affordable access to renewable energy sources and energy-saving devices;
- **Addressing the utility-scale solar and community acceptance conundrum** by enhancing multi-use land applications for solar and wind and identifying effective methods for community engagement;
- **Creating efficiencies and increasing impact** by investing the time and resources to create and leverage multinational programs of sufficient scale and that equally weigh both technical and social benefits;
- **Communicating energy use and carbon emissions without complex jargon** and confusing arrays of units for building heating and cooling, transportation systems, food systems, and consumer goods;
- **Advancing energy use tied to reduced carbon emissions in all aspects of daily life**, ranging from fossil fuels to consumer materials and goods used in daily activities; and
- **Incentivizing transitions** to energy conservation, efficiency, and renewable energy solutions.

Credit: Jeff Fitlow/Rice University

"Engineers are driven by devising elegant solutions to complex problems. Engineering research will make solutions to climate change possible – with innovations that bring our natural world, our built world and our societies into balance."

AMY HEINTZ

Chair-elect, ERVA Standing Council; co-chair of the Thematic Task Force and technical fellow at Battelle.

Credit: CasarsaGuru (used with permission)

Taking Action

There is powerful momentum to pursue meaningful steps to reduce CO_2 and other greenhouse gas emissions, build more resilient infrastructure and increase the use of solar and renewable energy, resolve energy storage challenges, improve water and ecosystem management, improve health through engineering infrastructure changes to address climate change, and explore the potential of geoengineering for CO_2 capture, storage, and conversion if it becomes needed. *Pursuing these priorities unleashes the power of engineering research to catalyze critical advances, create community awareness, and enable convergent and inclusive solutions*.

The full report is not a comprehensive review of all solutions, but instead a look at critical needs in engineering that provide unique opportunities relative to climate change. There are important ways to address climate change that do not require cutting-edge engineering research, but the ERVA report describes specific research directions through which engineering can take the lead and have impact. The aim is to inspire researchers and funders (public, private, and nonprofit) to support and pursue these priorities. ERVA challenges readers to disseminate this report and prioritize areas with potential for the greatest return on investment. Collaboration across the engineering community is needed now to seize opportunities to mitigate climate change and secure our future.

Catalyzing Engineering Innovations to Address Climate Change

The Engineering Research Visioning Alliance (ERVA), launched by NSF in April 2021, provides the engineering research community with a process for identifying bold and societally impactful engineering research directions that will place the United States in a leading position to realize a better future for all. It is an engaged, inclusive, multilayered partnership, providing a truly diverse array of voices with the opportunity to impact national research priorities. For its inaugural visioning event, ERVA convened more than 100 experts from academia, industry, and government for a virtual session Dec. 7-8, 2021, to identify priorities for engineering research that address one of the world's most vexing challenges: climate change.

More than 30 years have passed since the Intergovernmental Panel on Climate Change (IPCC) was created by the World Meteorological Organization and the United Nations Environment Programme to provide governments at all levels with scientific information they can use to address climate change. Although respected scientific bodies have produced dozens of reports in the ensuing years, few point to engineering-specific research directions and the critical role the engineering community can play in addressing climate change. This was the key rationale for selecting this theme as the focus for ERVA's first visioning event.

Visioning Event Purpose and Structure

The theme for this first ERVA visioning event emerged from a survey of nearly 500 members of the engineering research community. Participants were identified and invited based on their research and expertise and included engineers and scientists across academic disciplines, geographic location, organization sector and type, gender, race/ethnicity, and career stage. Designed to gather broad perspectives across multiple facets of climate research to identify unexplored areas where additional research could make bold, positive impacts, the ERVA visioning event was structured to spark new research directions and to catalyze engineering research for a more secure and sustainable world.

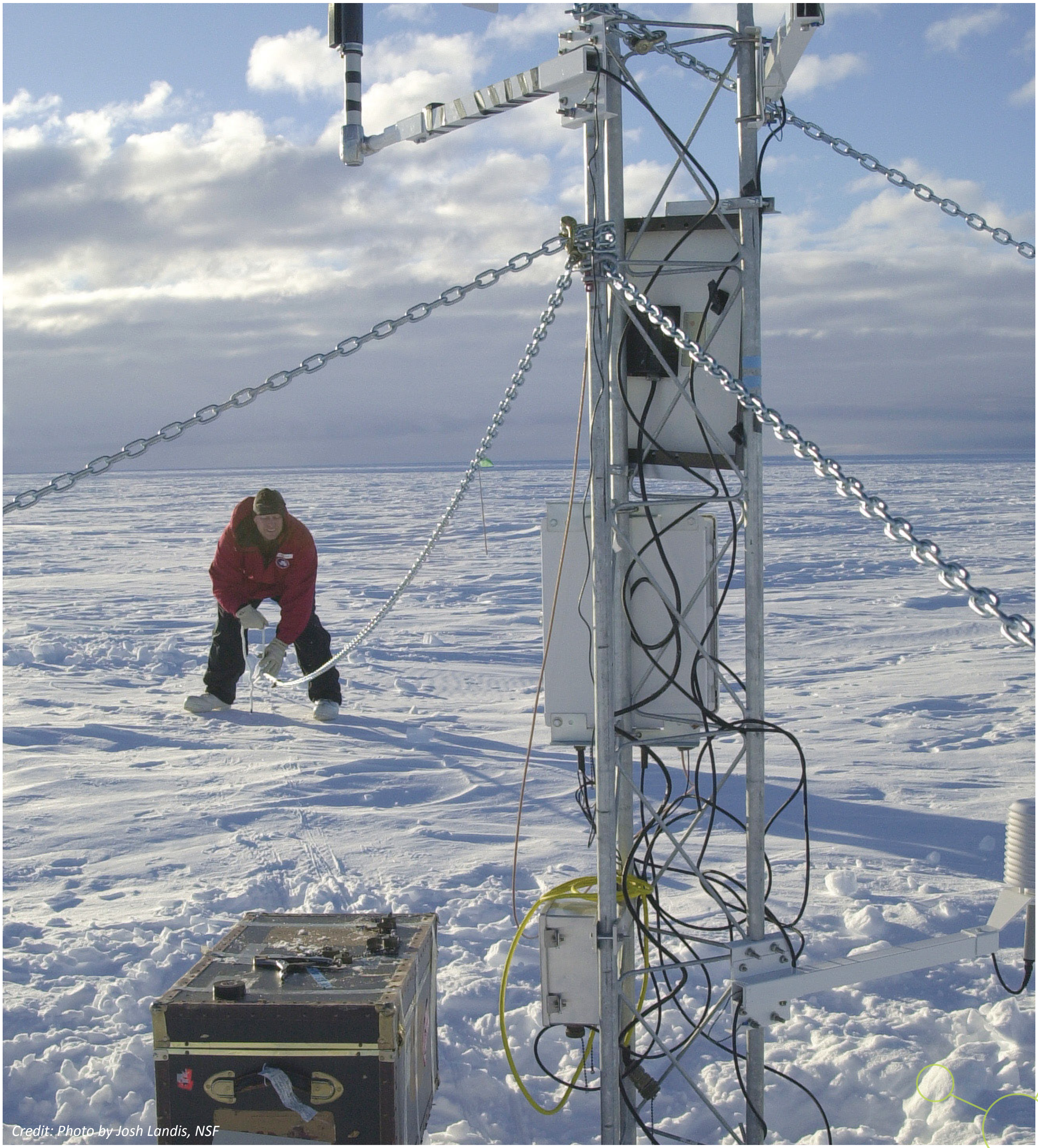
To frame this visioning event, a Thematic Task Force of experts was assembled to identify salient topics for discussion. The enormous level of current research activity in climate change mitigation and adaptation science posed both a challenge and an opportunity to seize on nascent areas ripe for engineering research leadership. Ultimately, 10 discrete areas were framed for the convened engineers and scientists to envision bold ideas, probe unexamined questions, and focus their combined expertise; participants were placed, based on their scientific expertise, into breakout groups to facilitate interdisciplinary discussions around needed fundamental research in the identified areas (see list below). Following workshop breakout group reporting, these 10 areas were distilled into six topics with related engineering-focused research directions and two topics that are important for expanding impact and inclusiveness as climate change solutions are developed.

Original theme topics for workshops

- Carbon Sequestration
- Climate Justice
- Decarbonizing Industrial Processes
- Ecosystem and Water Management
- Energy Storage
- Geoengineering
- Greenhouse Gas (GHG) Capture
- Health and Climate Change
- Resilient Infrastructure, Buildings, and Transportation
- Solar and Renewable Energy

Workshop participants recognized that addressing today's critical scientific and societal challenges requires increasingly collaborative, cross-disciplinary, and convergent approaches through new modes of engagement to ensure broad participation across the entire engineering research ecosystem.

The ERVA event keenly focused on *ways engineering can lead fundamental research efforts to address climate change*. Over the course of the visioning event, nascent research directions ripe for engineering research community investigation emerged, which are discussed in the following sections.



Credit: Photo by Josh Landis, NSF

Engineering Research Opportunities to Address Climate Change

Climate change topics receiving the most attention

An analysis of the proposed workshop topics by ERVA and Elsevier was conducted to assess the relative attention that different topics are receiving in the climate change literature. Research focused on mitigation of climate change and its effects includes a broad array of specific areas. All research where findings might serve to mitigate climate change or its impacts was identified by leveraging a library of queries developed to identify climate change-related research. This library of queries was developed as a result of a literature review on climate change topics and resulted in the creation of thousands of queries, each designed to identify research aimed at addressing specific aspects of climate change mitigation and its effects.[1] The selected queries[2] resulted in the retrieval of a publication set from the Scopus database that consists of 3,124,275 peer-reviewed publications published during the period of interest.

Classifying climate change research into selected topics of interest reveals that the solar and renewable energy topic represents 30% of climate change research, making it the most highly represented issue in the literature (Figure 1). Research on ecosystems and agriculture represents 23% of the literature, resilient infrastructure represents 17%, and energy storage represents 10%. Research on carbon sequestration, decarbonizing industries, geoengineering, and health and climate change each represented less than 2% of the climate change literature.

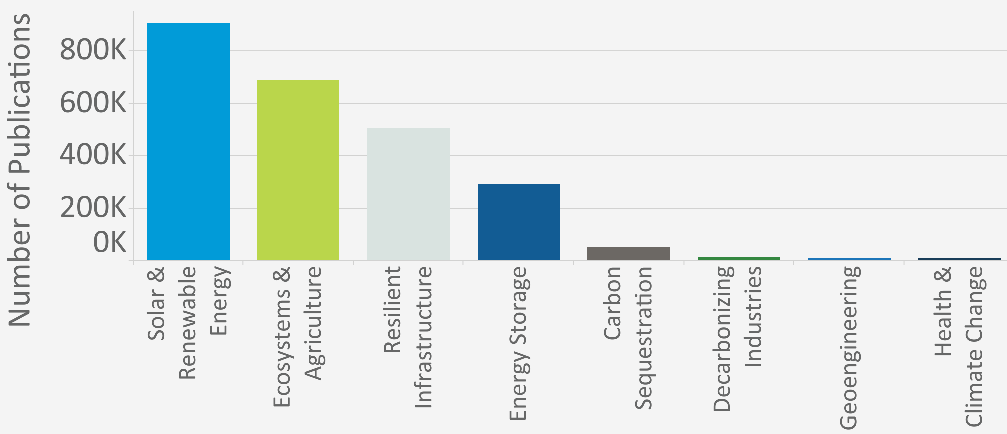


Figure 1: Total number of publications related to selected climate change topics, 2001–2020. Source: Produced by Elsevier from Scopus data for ERVA.

This literature analysis indicates that energy technologies are receiving far more attention by researchers around the world than those topics focused on carbon removal (carbon sequestration and decarbonizing industries), mitigating the effects of GHGs through geoengineering, or addressing the impacts of climate change on health. Based on the number of publications, there are strong efforts aimed at developing a more resilient infrastructure and addressing impacts on agriculture and ecosystems. Further analysis of the existing literature relative to the individual climate change topics examined is available as a separate report prepared by Elsevier for ERVA and for use by the engineering research community.

Identifying the climate topics most relevant for engineering solutions

The event's Thematic Task Force selected 10 discrete themes for the convened scientists and engineers to consider and evaluate bold ideas, probe unexamined questions, and leverage their combined expertise. These 10 discussion themes were further distilled into six topic areas with identified priorities for engineering research to pursue.

Energy Storage, Transmission, and Critical Materials

Renewable energy is a rapidly growing research topic, but the ability to store and move energy (spatially and temporally) is critical for reducing both reliance on fossil fuel sources and transmission losses through infrastructure. Electrochemical storage systems encompass a wide range of battery chemistries. Mechanical storage systems include pumped water, compressed air, and other emerging gravity storage solutions. Electrical storage systems refer to the direct storage of electricity using capacitors and superconducting magnetic coils. Chemical and thermal storage are related to media and repositories that may be used to convert chemical or thermal energy to electricity. These technologies can also be bidirectional. Thermal energy storage possibilities include geothermal resources, phase change materials, molten salt storage, and lower temperature geothermal systems. Chemical storage may involve producing and storing energy-carrying fluids like hydrogen or graphene. The third set of technologies of flexible generation and controllable loads enable flexibility of production, storage, and consumption.

Credit: Matthew Henry on Unsplash

IDENTIFIED RESEARCH PRIORITIES

Identified topics that could have the greatest return on investment and should be prioritized by the engineering research community are:

- **Basic materials and separations research.** This priority is one of the three cross-cutting thrusts and covers development of new materials to engineer better batteries; improving mining and production aspects (including advanced separations) of the minerals currently being used in batteries; and improving the overall environmental footprint from recycling. It includes finding new ways to separate lithium and other precious minerals from raw streams in energy-efficient and economically feasible ways.
- **Thermal storage.** Geologic energy storage, which includes storing hydrogen in the subsurface, has been less explored than other thermal storage approaches. Areas ripe for exploration include:
  - » identifying the most cost-effective thermal storage method for a given application; and
  - » determining the feasibility of energy storage in appropriate subsurface geological systems (including geothermal).
- **Systems research.** Energy storage technologies must be seamlessly integrated with energy production and consumption. Areas for further exploration include:
  - » manufacturing innovations in engineering energy storage devices and systems that will reduce costs;
  - » research in data systems, communication, and networking to enable efficient use of energy storage in the utility grid; and
  - » whether distributed or concentrated energy storage for the utility grid yields the most benefit.

Greenhouse Gas (GHG) Capture and Elimination

GHG Capture

There are essentially two major pathways for carbon capture: **biological pathways** that utilize and enhance the ability of natural carbon sinks to work more effectively, and **engineering devices, processes, and systems** to capture GHGs. Coastal carbon removal and sequestration has been widely studied.[3] Tidal wetlands remove and sequester carbon at a rate of about eight tons per hectare-year. Terrestrial carbon removal by better managing forests and by afforestation and reforestation have also been studied for effective carbon removal; these technologies also offer the promise of rapid scaleup.

On engineered separation and capture of carbon dioxide (CO_2), the U.S. Department of Energy has categorized research into pre-combustion capture and post-combustion capture.[4] More recently, there has been some focus on CO_2 capture from the air (direct air capture or DAC).[5] In post-combustion capture, flue gases from either coal or gas-fired power plants are targeted for capture. Pre-combustion CO_2 capture is used where first a solid fuel is converted to gaseous fuel (synthetic gas or synthetic gas). CO_2 from synthetic gas is captured prior to the combustion of hydrogen to generate power. Primary technologies that have either been developed or are in the process of development are capture using solvents, sorbents, and membranes. Advanced, more comprehensive methods being pursued are systems that combine attributes of all the three methods or process intensification where there is an effort for integration, energy savings, and improved performance.

Addressing GHGs must move the focus beyond fossil fuels alone to consider all sources and chemicals. Carbon sequestration for CO_2 by injection into geological reservoirs is important, but there are opportunities to further advance long-term biological storage methods for CO_2 as well as develop elimination methods for other GHG chemicals. New approaches are needed for direct capture of all GHG molecules from air and water sources in addition to industrialized processes.

IDENTIFIED RESEARCH PRIORITIES

Identified topics that could have the greatest return on investment and should be prioritized by the engineering research community are:

- **Reducing other GHG emissions, particularly methane.** Methane is more than 25 times (100-year impact) to 82 times (20-year impact) as potent as CO_2 at trapping heat in the atmosphere. More targeted efforts must be made to explore specific engineering solutions to eliminate or reduce methane and nitrous oxide emissions.
- **Plant genetic engineering or terrestrial plant management to help capture additional CO_2.** Participants also considered genetic engineering as a relatively unexplored area that will yield significant benefits over a reasonable period of time. Genetic engineering of crops, plants, and other forms of biomass for high carbon input phenotypes, understanding soil dynamics with respect to carbon change at depths of interest, and studies on biochar may also help realize the vision of using natural environments more effectively. These methods also have potential to address other GHGs like methane and nitrous oxide. For example, biochemical approaches using enzymes expressed by plants or microorganisms, such as nitrous oxide reductase and methane monooxygenase, may be more effective dispersed over large areas than dedicated large engineered industrial processes for chemical capture.

- **Developing solvents and sorbents for CO_2 that are cost-effective and environmentally benign:** amines are regenerated and recycled, but there are losses, and most commonly used amines are toxic. Specific recommendations are to improve the engineered separation processes by improving thermodynamic understanding of the processes, reducing energy penalties for separation, and improving materials of construction and separation. Research must continue on environmentally benign materials for CO_2 separation; materials research for energy conversion and CO_2 mitigation specifically is a cross-cutting thrust. These novel materials could also be used to reduce costs of DAC.
- » There is a need for more engineering research in minimizing the parasitic load of separation of CO_2.
  » Electrochemical reduction of CO_2 using electrolysis is a technology that also merits further investigation.
- **Integrating removal at the source through design or process intensification.** Process intensification will create more efficient energy utilization, thus reducing the process carbon footprint. Significant potential exists in using this method to reduce CO_2 generation.
- **Re-purposing CO_2 utilization** at the source into useful chemicals or conversion into materials that will not contribute to atmospheric CO_2.

Carbon Sequestration

Technologies for carbon capture and sequestration go hand in hand. There are essentially three components of CO_2 sequestration: geologic, biologic, and chemical (both biologic and chemical sequestration are also CO_2 capture methods).

There was discussion on enhancing sequestration in oceans, which are the largest natural repositories for CO_2. Biological engineering to sequester more CO_2 in forests may be key to large-scale efforts to address the crisis, although potential effects on biodiversity are a concern. The use of sensor and sensing capabilities in conjunction with strategic use of AI modeling for forecasting and trend analysis, two cross-cutting thrusts raised by the visioning participants, would support research in this area and reduce the risk of negative impact on biodiversity.

IDENTIFIED RESEARCH PRIORITIES

Identified topics that could have the greatest return on investment and should be prioritized by the engineering research community are:

- **Carbon mineralization**, which has emerged as a promising area for not only storing carbon but also capturing CO_2. In this context, in-situ mineralization in igneous and meta-igneous rocks that are rich in minerals containing magnesium and iron and with low silica content offers the promise of fast mineralization and secure storage. A great deal of data on mineralization in various natural materials and industrial waste is available. Additional data on carbon mineralization rates in alkaline industrial wastes is needed. There is significant potential to sequester CO_2 by mineralizing in mine tailings, industrial wastes, and sediments.
- **Chemical sequestration.** Specifically, engineering research on graphitic conversion of CO_2 is less explored. Other chemical conversion pathways for natural gas may also help reduce the impact of methane.
- **Oceanic sequestration**, or how to enhance the carbon uptake of the oceans. Among the abiotic approaches, research on ocean alkalinity enhancement, including electrochemical alkalinity enhancement, has priority over electrochemical approaches that only seek to achieve CO_2 removal from seawater (also known as CO_2 stripping). Biotic approaches, research on ocean iron fertilization, and seaweed cultivation offer the greatest opportunities for evaluating the viability of possible biotic ocean CO_2 removal approaches; bioengineering research on potential CO_2 removal and sequestration permanence for ecosystem recovery would also be beneficial in the context of ongoing marine conservation efforts.

Credit: Photo by Marita Kavelashvili on Unsplash

Decarbonizing Industrial Processes

Industrial processes are significant sources of CO_2, and thus their decarbonization offers opportunities for mitigating GHG emissions, particularly CO_2. The top five GHG-intensive industries are iron and steel, chemicals and plastics, cement, aluminum, and petroleum refining. Many decarbonization approaches can be implemented by industry, such as using green hydrogen and renewable electricity. Industrial processes are embedded in a much broader set of energy systems and networks, resulting in a need to understand the implications of changes at industrial locations at the system level. Classical control theory does not get to the optimization of the process, nor to an understanding of how local changes create global changes. The solution requires a level of automation; therefore, engineering research at the intersection of control theory and AI becomes essential and reflects a cross-cutting thrust.

IDENTIFIED RESEARCH PRIORITIES

Identified topics that can have the greatest return on investment and should be prioritized by the engineering research community are:

- **A new look at thermal conductors in general.** There is a need for a better understanding of thermal conduction in insulating materials. Ultimately, this means developing a fundamental understanding of phonon transport.
- **Material alternatives that are carbon-neutral or that never decompose.** Critical materials research is a cross-cutting thrust with applications in the decarbonization topic area. For example, use materials that can be landfilled effectively as carbon sequestration. If they are not renewable, they should at least not go back to the atmosphere (ability to easily capture it).

Resilient, Energy-Efficient, and Healthful Infrastructure

Climate change impacts will severely test the resilience of infrastructure, which ranges from homes, workplaces, and community buildings to large-scale grid systems for gas, power, and transportation. Fossil fuel emissions can be reduced by increasing energy efficiencies, but solutions are needed for other infrastructure aspects that enhance resiliency and infuse renewable energy solutions directly into communities. Priority engineering research directions identified for infrastructure and renewable energy solutions must therefore be focused on convergent topics at the human-technology-environment level, thus the merged focus on these topic areas (resilient infrastructure, renewable energy, and health).

Resilient Infrastructure, Buildings, and Transportation

In this context, resilience is defined as the ability of the physical infrastructures (e.g., buildings, roads, bridges, networks, facilities) and society to withstand, adapt to, and mitigate the changing conditions, and recover quickly from damages, disruptions, and stresses, whether they arise from natural hazards or are attributable to human error. Ideally, we can engineer a sustainable and resilient infrastructure that considers environmental, economic, and social impacts on local, regional, and global systems, addresses present needs, and doesn't sacrifice the future.

Advances in fundamental and applied science and engineering over the next decade will significantly benefit from increased integration of physical sciences and social sciences, improving the balance among physical climate research, ecosystems research, and human systems research. To increase the resilience of infrastructures and avoid or mitigate potential vulnerabilities of human and natural systems to climate change, it is important to reconcile these systems for adaptation. These human and natural systems are dynamic, independent, yet interconnected through complex feedback loops; potential impacts must be considered in infrastructure planning and design practices.

IDENTIFIED RESEARCH PRIORITIES

Identified topics that can have the greatest return on investment and should be prioritized by the engineering research community are:

- **Extensive life cycle analyses** of embodied carbon in infrastructure, ranging from the existing built environment to commonly used materials.
- **New low-cost coatings** for buildings, roads, and infrastructure that reduce heat island effects, increase self-cooling, and thermal energy transmission back into the exosphere.
- **Next generation AI tools** for forecasting and trend analysis, a cross-cutting thrust, to better manage grid operations and enhance resilience.
- **Bio-based and bioengineering-based solutions using synthetic biology and engineered living materials.** Evolutionary biologists should collaborate with physical scientists and engineers to consider system-level questions and mine nature for its structures, materials, and processes. Synthetic biology and bio-based solutions should be jointly explored to engineer living materials and their hybrids with synthetic analogs. Research priority should be placed on how bio-based and synthetic biology processes inform each other and improve sustainability and resilience in the infrastructure.
- **Processes to extend the useful life of infrastructures when they age**, for example, developing self-healing concrete. This requires continuous monitoring of performance, waste generation, emissions from the environment, buildings, transportation, and using this information to accurately predict the future life of materials. It underscores the cross-cutting thrust of investing in sensor, sensing, and communication capabilities as tools for future research.

Solar and Renewable Energy

Energy infrastructure is essential for daily life and continued prosperity in industrialized nations. Improving accessibility to energy and increasing the efficiency of energy conversion from natural resources (e.g., sunlight, heat, wind)[6] will enable longer, more productive lives. Harnessing nature's power has long been practiced for heating/cooling, transportation, lighting, and more. Compared with energy generated from burning fossil fuels such as oil, gas, and coal, renewable energy is considered "clean" as it emits no or low GHGs or air pollution.

Meeting the goal of reducing fossil fuel emissions by 50% or more by 2030 requires planning and coordination for the integration and implementation of solar and other renewable energy resources into the electrical grid. Both a clear understanding of the impact of change and systems to mitigate grid vulnerability must be developed. Engineering solutions should be synthesized with socio-technical systems, social science, policy, and macro-energy approaches. It is essential to understand the barriers to and successful paths for siting and permitting of solar and wind generation and transmission infrastructure; how technology and sector change in highly structured and regulated industries could impact the future electricity market; and ways that market design solutions, institutions, and processes impact innovation/technology adoption.

IDENTIFIED RESEARCH PRIORITIES

Identified topics that can have the greatest return on investment and should be prioritized by the engineering research community are:

- **Dual-use renewable energy technology development through intentional collaboration.** Solar and renewable energy systems are interdisciplinary/transdisciplinary in nature; because of language/community/culture barriers between disciplines, collaborative research must be proactively catalyzed.
- **Use of materials in different climates.** Engineering passive cooling materials and new ways to manufacture them at scale in different localities are areas for exploration; critical materials in engineered systems is a cross-cutting thrust.
- **Materials life cycle analysis.** Topics include local and global availability to reduce carbon footprint, what materials will offer high durability and lifespan enhancement, and how to reduce materials supply bottlenecks to scale up into a circular economy.
- **Advanced geothermal energy.** Topics in this area include improved drilling for depth/pressure/temperature, basement rock; improved lithium and materials recovery and reuse from brines; updated resource potential for deep closed-loop, enhanced geothermal, and use of deeper heat-oriented wells; and use of hydraulic fracturing for an enhanced geothermal energy system.

Health and Climate Change

Climate change affects people, their property, and their way of life. It affects both urban and natural ecosystems and their interactions and thus impacts the health and well-being of Americans. Key health risks include increased morbidity and mortality from heat waves and other extreme weather events, adverse effects from exposure to poor air quality (including excessive GHG emissions, pollution, and aeroallergens), rate of emergence of air-, water-, and food-borne infectious diseases, food supplies, and risks to biodiversity. Climate change also affects mental health and well-being. Health risks may increase with more severe and prolonged climate change.

Health risk predictive intelligence is critical to analyzing, mitigating, or preventing future health crises inflated by climate change. Such predictive capabilities require multi-modal, real-time sensing and monitoring of indoor and urban environments (air quality, relative humidity, and temperature); investments in these capabilities is a cross-cutting thrust across many of the topics included in this report. Questions remain as to whether existing low-cost sensing technology for pollutants accurately produces data needed to evaluate ecosystems and their relationship


Credit: Sarah Dillingham, Texas Tech University

to human health. Correlating and quantifying the effects of climate change on human health is necessary to raise community awareness and increase receptivity to in-home or even on-body sensors.

The climate health-engineering linkage is relatively unexplored. The ERVA-Elsevier analysis indicated that only 6% of climate-health research is published in engineering journals and that the publications in this area are the most diverse.[7] Collaborations between health scientists and engineers who can identify problems and solutions will help promote infrastructure changes that protect human health despite greater challenges produced by climate change.

IDENTIFIED RESEARCH PRIORITIES

Identified topics that can have the greatest return on investment and should be prioritized by the engineering research community are:

- **Multi-mode sensors and communication systems.** These are needed to assess human health stressors (e.g., heat, humidity, and airborne contaminants). Real-time monitoring of indoor air quality and the existence of pathogens is critical to improving data analysis and communication capabilities when changes merit response in local communities. An example is when increased flooding combines with excessive heat and drives mold growth in buildings, which in turn produces adverse health consequences that can disproportionately affect vulnerable populations. Monitoring temperature, humidity, and airborne biotic particles would strengthen the infrastructure for greater human health security.
- **New ways to use big data and machine learning to improve understanding of climate change and its risks/co-risks to health.** One of the three cross-cutting thrusts identified by visioning participants, data measurement capabilities and AI applications that can identify and differentiate climate change impacts as they relate to discrete communities are critical to improve data accuracy and enable intelligent prediction of future events.
- **Engineering solutions for healthier cities.** Research is needed to discover ways to both modify existing and develop new infrastructure to reduce the negative impacts of climate change on health. Dense urban systems and buildings need engineered approaches to minimize infectious disease transfer and the development of antibiotic-resistant organisms. Relieving fossil fuel use will result in improvements in biodiversity and air quality, as will reductions in roadway, industrial, and power-plant emissions.

Water, Ecosystems, and Geoengineering Assessment

Water and Ecosystem Management

All freshwater ultimately depends on the continued healthy functioning of ecosystems and sustainable water management. With an increasingly hotter planet, more uncertainty in fresh water availability, a higher frequency of extreme weather events, and a more rapid return flow of water to the atmosphere are expected, breaking the equilibrium of ecosystems. Water required for irrigated agriculture will grow at a slower pace (approximately 11% by 2050).[8] Preventing water losses in distribution systems will also require advances in monitoring and detection in order to identify engineering solutions.

Ecosystems are dynamic, complex communities of organisms linked together through water, nutrient cycles, and energy flows. While the external processes control the resource inputs (e.g., climate, soil, air, and water), the availability of these resources is controlled by internal factors (e.g., decomposition, disturbance, succession, and the types of species present). Ecosystems are subject to periodic disturbances such as human activities and climate change, but they tend to remain in the equilibrium state (e.g., by mitigating flooding and drought), which is important to system health and productivity.

Achieving a more sustainable and water-secure future will require changes in consumption and conservation of water, food, energy, and other goods and services. It requires science, technology, and engineering innovation for space-based environmental monitoring and real-time feedback, better and more reliable prediction of future weather and climate events, renewable energy that will replace fossil fuels entirely (e.g., solar and wind energy, biofuels), reduced energy use in wastewater treatment, and holistic lifecycle approaches to how products are produced, consumed, recycled, and reused with reduced waste and loss.

IDENTIFIED RESEARCH PRIORITIES

Identified topics that can have the greatest return on investment and should be prioritized by the engineering research community are:

- **Accurate, low-cost, real-time sensors for water flow and distribution over a range of spatial and temporal scales.** This is a cross-cutting thrust and is critically important to accurately sense and measure water quality and quantity in water treatment facilities and water flow and flow distributions. Current water sensors are often unreliable, yet costly. They do not offer real-time sensing and are typically designed for single use. Engineering testing infrastructures for water management using real-time (or near real-time sensing) will not only improve the data for analytics across different scales, but also make it possible to share the data and understand community needs and implications of climate change for water management.
- **Modeling the ecosystem and water usage.** Modeling the interactions between engineering systems (water, power, transportation) and the changing ecosystems around them (wildfire, ignition, drought, flooding, invasive species) creates the basis for predictive modeling and simulations of the impact of climate change on water availability and scarcity. Social factors play important roles in water management, and individual and collective behaviors should be incorporated into models.
- **Energy-efficient methods for wastewater treatment.** The aim is to both lower energy use and to save more water than current state-of-the-art systems.

- **Capturing new water sources.** A substantial amount of atmospheric water in the form of fog, cloud, and moisture indicates potential research value in efficient technologies to harvest atmospheric water. Converting salt water into cooled and condensed pristine freshwater with help from the sun is another promising research direction. Any new water technologies should be developed at scale and at low cost to accelerate technology translation.
- **AI/machine learning to reconstruct missing data or fill gaps.** There is a need to improve and expand the resolution and extent of historical and future data sets using novel monitoring technologies and analytics; this may be accomplished using AI/machine learning, a cross-cutting thrust in this report. This data and resulting analysis may be used to prioritize, accelerate, and scale-up response to protect communities, economies, and ecosystems.

Geoengineering

Geoengineering, also known as climate engineering, is the deliberate and large-scale intervention in the Earth's climate system.[9] Cloud dynamics and brightening schemes, ocean whitening, seawater engineering, surface reflectivity modifications, mechanisms for climate mitigations through space, and stratospheric particle themes are all possible research directions that would require massive engineered systems. The discussion of geoengineering is invariably tied to societal acceptance as well as risk evaluation and governance. Research in large-scale geoengineering must be coupled with consideration of how the public would perceive the use of such technologies. Because of its large-scale potential effects on water and ecosystems, geoengineering is grouped with those topics in this report.

As complex as the individual solutions and technologies are, interaction with existing technologies and possibly with other engineered solutions is complicated and must be studied. For example, how would solar radiation management interact with other possible offerings? What impact will manipulating solar radiation have on water, food growth, and supply? The governance of such technologies is also a significant consideration since the implementation is expected to cross state and often national boundaries. Intentional manipulation of the climate without collective agreement is not fully accepted because climate and carbon systems are interconnected. Traditionally, this is a controversial area and as noted by the ERVA-Elsevier analysis, geoengineering has relatively few publications compared to other climate-focused areas.

IDENTIFIED RESEARCH PRIORITIES

Identified topics that can have the greatest return on investment and should be prioritized by the engineering research community are:

- **Cooling potential, deployment speed, cost, and risk (environmental/human) of marine cloud brightening, stratospheric aerosol injection, and cirrus thinning**, to include field and modeling research.
- **Assessment of which biophysical mechanism works best and can be most efficiently engineered** (cirrus thinning, stratospheric aerosol injection, cloud brightening), as well as which regions for deployment give the most "bang for the buck" in terms of maximum cooling potential and engineered system deployment. This would likely require a modeling study because of the implementation costs and unknown risks and is another example of the cross-cutting thrust of AI modeling for forecasting and trend analysis.
- **Geoengineering's effects on socio-economic systems and systems transitions**, including energy, water, and food. The unintended consequences for any of the geoengineering mechanisms proposed must be considered. The framework used in climate research may or may not be applicable in understanding the implications of geoengineering methods such as solar radiation management or ocean engineering.

Behind each of these priorities is the power of engineering research to catalyze critical advances, create community awareness, and enable convergent and inclusive solutions.

Credit: Kelly Speelman

A Comprehensive and Inclusive Vision for Addressing Climate Change

Every focus area selected by the Thematic Task Force for topic ideation provided opportunities to address climate change through more inclusive, comprehensive research approaches. Encouraging the engineering research community to pursue research directions for climate solutions provides an opportunity for federal agencies and the entire engineering research community to invest their resources and talent to address this problem with broader impacts on society.

Engineering has unique opportunities to advance consideration of underrepresented populations through research with the potential to transform the energy and urban infrastructure in response to preventing or mitigating changes due to climate change. In this vein, participants emphasized topics of importance related to energy and climate education for all. Topics of particular importance to pursue include:

- **Convergent solutions that remove social barriers** and provide universal, affordable access to renewable energy sources and energy-saving devices;
- **Addressing the utility-scale solar and community acceptance conundrum** by enhancing multi-use land applications for solar and wind and identifying effective methods for community engagement;
- **Creating efficiencies and increasing impact** by investing the time and resources to create and leverage multinational programs of sufficient scale and that equally weigh both technical and social benefits;
- **Communicating energy use and carbon emissions without complex jargon** and confusing arrays of units for building heating and cooling, transportation systems, food systems, and consumer goods;
- **Advancing energy use tied to reduced carbon emissions in all aspects of daily life**, ranging from fossil fuels to consumer materials and goods used in daily activities; and
- **Incentivizing transitions** to energy conservation, efficiency, and renewable energy solutions.

Climate change must be viewed as a global challenge; therefore, research must provide solutions for the world through collaborative proposals with agencies in other countries that equally weigh both technical and social benefits.

Overall Assessment and Moving Forward

There is powerful momentum to pursue meaningful steps to reduce CO_2 and other greenhouse gas emissions, build more resilient infrastructure and increase the use of solar and renewable energy, resolve energy storage challenges, improve water and ecosystem management, improve health through engineering infrastructure changes, and explore the potential of geoengineering for CO_2 capture, storage, and conversion if it becomes needed. Behind each of these priorities is the power of engineering research to catalyze critical advances, create community awareness, and enable convergent and inclusive solutions.

New, targeted focus is needed for fundamental engineering research in many areas related to climate change. Some workshop attendees expressed concern over greater investment in applied technology than in basic research. The ERVA-Elsevier analysis on climate change revealed that applied technology is indeed the most prominent research classification represented within the climate change literature, representing 47% of global research and 43% of U.S. research published from 2001 to 2020 (Figure 2). Applied technology represents the highest share of literature for each climate change topic of interest except for energy storage and ecosystems and agriculture. Decarbonizing industries holds the highest share, with 83% of global (82% of U.S.) literature classified as applied technology.

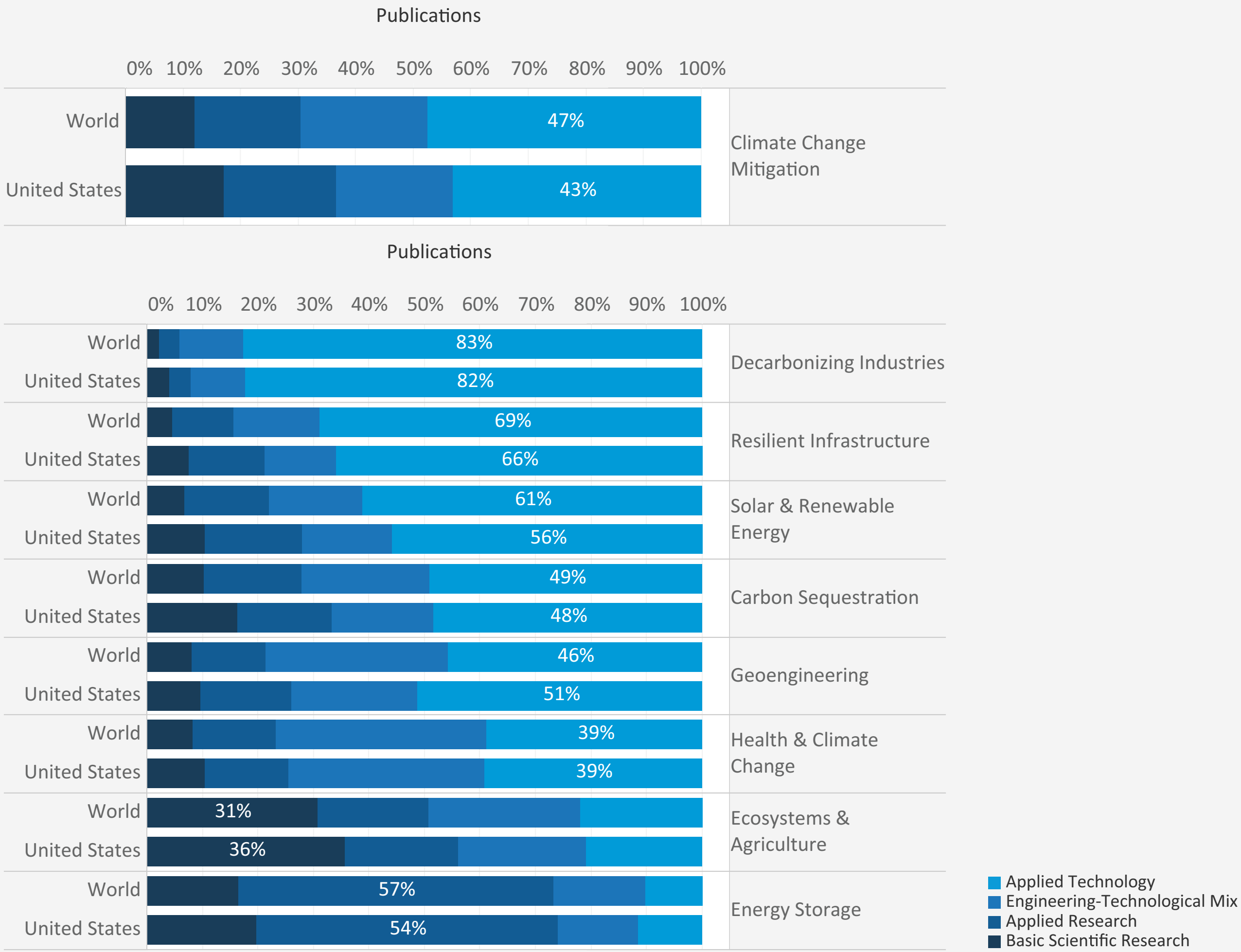


Figure 2: Global and U.S. research on climate change mitigation classified across the basic to applied research spectrum, 2001–2020. Classification representing the highest share of publications is labeled. Climate change topics are listed from top to bottom in order of descending percentage of publications classified as applied technology. Produced by Elsevier from Scopus data for ERVA

The engineering research priorities identified in this report range from fundamental to use-inspired. The complexity of the climate change challenge requires increasingly collaborative, cross-disciplinary, and convergent approaches through new modes of engagement to ensure broad participation across the entire engineering research ecosystem. An array of voices representing disciplines across the engineering research community identified the primary areas of scientific opportunity delineated in this report, represented by three high-level themes woven through the identified research priorities:

- **Focus on critical materials in all engineered systems**, especially in extraction, separation, recycling and upcycling, and energy conversion, as well as CO_2 mitigation.
- **Invest in sensor, sensing, and communication capabilities** to facilitate data compilation and analysis.
- **Enable and strategically exploit artificial intelligence (AI) modeling** for forecasting and trend analyses.

Now is the time for engineering-led innovation to enable high-impact, cross-domain research that addresses national, global, and societal needs. This report aims to elevate the priority research areas with the potential for the greatest return on investment so the nation may seize today's opportunities to mitigate climate change and secure the future.

Endnotes

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6 The renewable energy discussion did not include consideration of nuclear energy.

7 Based on a single Scopus query that identifies research relevant to the effects climate change can have on human health, across health, engineering, and other disciplines, defining health and climate change based on an extensive list of query terms. Bédard-Vallée, Alexandre; Zdawczyk, Christina; Jayabalasingham, Bamini (2022), "Queries to identify climate change research that takes an engineering approach," Mendeley Data, v1, doi: 10.17632/gxgj4kmsvz

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Appendix A: Visioning Event Participants

Lilia Abron, PEER Consultants, P.C.

Alan Allgeier, University of Kansas

William Ampomah, New Mexico Tech

Nadine Aubry, Tufts University

Gretchen Baier, The Dow Chemical Company

Filbert Bartoli, Lehigh University

Andrew Bochman, Idaho National Lab

Mark Borsuk, Duke University

Stephen Chae, Samsung Semiconductor Inc.

Junhong Chen, University of Chicago

Mikhail Chester, Arizona State University

Ismaila Dabo, Pennsylvania State University

Milind Deo, University of Utah

Melanie Derby, Kansas State University

Duane Detwiler, Honda

Kirk Dimond, University of Arizona

Jennifer Dunn, Northwestern University

Tamar Eilam, IBM Research

Marwa El-Sayed, Embry-Riddle Aeronautical University

Efrie Escott, KieranTimberlake

Wilson Espinoza, Georgia Institute of Technology

Mathieu Francoeur, University of Utah

Eric Corey Freed, CannonDesign

Dipankar Ghosh, 3M Co.

Amit Gokhale, BASF Corporation

Peter Goodwin, University of Maryland Center for Environmental Science

Kimberly Gray, Northwestern University

Erika Gupta, U.S. Department of Energy

Amy Halloran, Sandia National Laboratories

David Hart, George Mason University

Amy Heintz, Battelle

Eric Hoek, University of California Los Angeles

Julia Hsu, University of Texas at Dallas

Liangbing Hu, University of Maryland College Park

Kimberly Huguenard, University of Maine

Matthew Ide, ExxonMobil Research and Engineering

Elena Irwin, The Ohio State University

Shaleen Jain, University of Maine

Ankur Jariwala, Evonik Corporation

David Jassby, University of California Los Angeles

Jesse Jenkins, Princeton University

Manoj Jha, North Carolina A&T State University

Concepcion (Conchita) Jimenez-Gonzalez, NC State University/GSK

Kimberly Jones, Howard University

Colleen Josephson, VMware

Zakya Kafafi, Lehigh University

Maryam Khanbaghi, Santa Clara University

Pramod Khargonekar, University of California Irvine

Eleftheria Kontou, University of Illinois at Urbana-Champaign

Vijay Kumar, University of Pennsylvania

Bob Kumpf, Deloitte

Saniya LeBlanc, The George Washington University

Elaine Lee, Lawrence Livermore National Laboratory

Kunlei Liu, University of Kentucky Center for Applied Energy Research

Bruce Logan, Pennsylvania State University

Julian Marshall, University of Washington

Benji Maruyama, U.S. Air Force Research Laboratory

Claire Monteleoni, University of Colorado Boulder

Juan Moreno-Cruz, University of Waterloo

Alex Moyes, Dominion Energy

Eric Mueller, Mercury Marine

Francisco Munoz-Arriola, University of Nebraska-Lincoln

Jayathi Murthy, University of California Los Angeles

Adel Nasiri, University of South Carolina

Philip Odonkor, Stevens Institute of Technology

Diana Ortiz-Montalvo, National Institute of Standards and Technology

Indrani Pal, Columbia University and CUNY

Salimifard Parichehr, Oregon State University

Jim Pinkelman, Microsoft

Arturo Pizano, Siemens Technology

Benjamin Preston, White House Office of Science and Technology Policy

Sara Pryor, Cornell University

Dorothy Reed, University of Washington

Line Roald, University of Wisconsin Madison

Amy Robertson, National Renewable Energy Laboratory

Abhishek Roy, National Renewable Energy Laboratory

Mojtaba Sadegh, Boise State University

Parichehr Salimifard, Oregon State University

Jane McKee Smith, U.S. Army Corps of Engineers

Erica Smithwick, Pennsylvania State University

Armin Sorooshian, University of Arizona

Melissa Stark, Accenture

Allison Steiner, University of Michigan

Stuart Strand, University of Washington

Barry Sullivan, Electrical and Computer Engineering Department Heads Association

Patricia Sullivan, New Mexico State University

Xin Sun, Oak Ridge National Laboratory

Cristina Thomas, 3M

Serdar Tufekci, ENGIE North America

Jian Wang, Washington University in St. Louis

Ben Wender, California Energy Commission

Christopher White, NEC Labs America

Erin Whitney, Alaska Center for Energy and Power University of Alaska Fairbanks

Kevin Whitty, University of Utah

Scott Wisler, Siemens Energy

Thorsten Wuest, West Virginia University

Eli Yablonovitch, University of California Berkeley

Guirong (Grace) Yan, Missouri University of Science and Technology

Shu Yang, University of Pennsylvania

Observers

National Science Foundation Directorate for Engineering

Linda Blevins

Aranya Chakrabortty

Nakhiah Goulbourne

Bruce Hamilton

Louise R. Howe

Kemi Ladeji-Osias

Sohi Rastegar

Contractual Partners

Alexandre Bédard-Vallée, Elsevier

Daniel Calto, Elsevier

Bamini Jayabalasingham, Elsevier

Christina Zdawczyk, Elsevier

Todd Zoblotsky, University of Memphis

ERVA Principal Investigators and Operations Team

Anthony Boccanfuso, UIDP

Jennifer Carinci, ERVA

Dorota Grejner-Brzezinska, The Ohio State University

Barry Johnson, University of Virginia

Charles Johnson-Bey, Booz Allen Hamilton

Mark McGill, ERVA

Sandy Mau, ERVA

Linda Toro, ERVA

Edl Schamiloglu, University of New Mexico

Appendix B: Event Presentation Summaries

Engineering for a Climate Change-Resilient Future

Presented by Benjamin L. Preston, Ph.D., Assistant Director for Climate Services, Adaptation, and Workforce, White House Office of Science and Technology Policy

Background

Scientists have long warned of the future risks of climate change. In the United States, there has been a long-standing legislative agenda to address the climate change phenomenon. Founded in 1990, the U.S. Global Change Research Program (USGCRP) is a confederation of 13 federal agencies mandated to "assist the nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change." The USGRCP leads in coordinating research, provides information regarding policy decisions, delivers mandated products such as the National Climate Assessment, and supports international mandates and secretariats. Recently, the White House proposed legislation within the federal budget and through the Infrastructure Investment and Jobs Act to address the challenges arising from climate change.

Rapid changes in the environment produce many challenges in the global ecosystem but may also present new opportunities for engineering research to lead. These include strategies to promote and advance infrastructure resilience, hardening, and "greening," along with innovative materials redesign. Opportunities are abundant in the fields of carbon sequestration, mapping, and storage, as well as in clean energy deployment through technologies that promote mobility and storage.

Challenges arise not only with addressing and mitigating climate change, but also with promoting an evolving engineering mindset that combines innovation with reflexivity, intersectionality, and equity. Intersectionality strategies converge in interrelated climate change mitigation research topics from social sciences, public policy, and civic engagement. Through reflexivity, engineers must recognize and balance their past achievements and advancements in infrastructure design and environmental adaptability with present needs. Innovative approaches to address climate change require a multi-faceted approach involving advancements in data analytics and AI, automation, additive manufacturing and bioprinting, sensors, battery technologies, and nature-based solutions. Policy addressing climate change mitigation through innovation must include considerations for equity and inclusion. Equity will have ongoing importance in engineering solutions to ensure they provide access to green sources of energy, clean water, sanitation, and public services to all.

KEY TAKEAWAYS

- Rapid changes in the environment resulting from climate change have produced many challenges in the global ecosystem but may also present new opportunities for engineering research to lead.
- Opportunities abound in carbon sequestration, mapping, and storage, as well as in clean energy deployment through technologies that promote mobility and storage.
- The evolving engineering mindset must combine innovation with reflexivity, intersectionality, and equity.

The Great Infrastructure Decoupling: Rigid Designs Confront Climate Uncertainty

Presented by Mikhail V. Chester, Ph.D. Associate Professor, Civil, Environmental and Sustainable Engineering and Director of the Metis Center for Infrastructure and Sustainable Engineering School of Sustainable Engineering and the Built Environment, Arizona State University

Background

Our rigid infrastructure systems (technologies, governance, and education) are increasingly out of pace with changes in the world around them. Complex systems in a symbiotic relationship with the environment must consistently evolve with changes in the ecosystem to maintain relevance and impact. The uncertainty of climate change and its potential detrimental effects is a primary disruptor to a rigid infrastructure. To respond with agility rather than rigidity, we must consider design together with responsive policy change and education.

Another consideration is the rapid pace of climate change and effects on infrastructure, balanced against the pace of response. A decoupling effect occurs, resulting in a widening gap between rigid design and climate uncertainty. There is a fundamental challenge to align innovative ideas and strategies with rigid infrastructure design. Five factors in infrastructure design should be considered to address this challenge: complexity, agility and flexibility, knowledge, leadership, and consciousness in extremes and failures.

Consider the fundamental shift in thought from systems being complicated to being complex. This requires a higher level of system design, testing a probe of events rather than evaluating the cause-and-effect nature of a response to events. Future infrastructure systems and design must evolve to become more agile and flexible to meet the pace of environmental change. Think of infrastructures as knowledge systems designed to meet the complexity of environmental systems and these rapid ecosystem changes. Currently, organizations are not structured to address the complexity of change and mitigate climate change events. Instability in the environment requires us to set aside status quo design thinking and to embrace an innovative, entrepreneurial school of thought. Finally, we must recognize that our current infrastructure system will not reach optimization at the pace of climate change. Future infrastructure systems designed to be less structurally rigid allow considerations for institutional and social capacities to address changes in the ecosystem. Systems must also consider failure in addressing change and how to navigate through these systems failures toward improved mitigation efforts.

KEY TAKEAWAYS

- Rigid infrastructure occurs in technologies, governance, and education.
- Current infrastructure systems are not designed to meet today’s environmental challenges.
- Change in infrastructure design must consider policy and education.
- Because of rigid infrastructure, pace of response to environmental change has been decoupled from the rapid pace of environmental change; realignment is a fundamental challenge.
- Five factors in infrastructure design should be considered to address this challenge: complexity, agility and flexibility, knowledge, leadership, and consciousness in extremes and failures.

Panel: Envisioning Engineering Climate Change Institutes of the Future

Moderated by Vijay Kumar, University of Pennsylvania, with panelists David Hart, George Mason University; Pramod P. Khargonekar, University of California, Irvine; Benji Maruyama, Air Force Research Laboratory; and Cristina Thomas, 3M Corporation

Panelist's comments highlighted a range of opportunities for a new organizational model, Engineering Climate Change Institutes, to contribute to climate change mitigation and adaptation by focusing on specific topics. Advances in a number of areas where engineering research advances could lead in mitigating climate change include:

- Decarbonization of the electric power grid;
- Decarbonization of the transportation system, specifically improvements in electric vehicle efficiency and progress toward renewable liquid fuels with lifecycle sustainability;
- Elimination of use of fossil fuel in manufacturing of metals, cement, and chemicals;
- Precision, sustainable agriculture with reduced GHG emissions;
- Negative carbon technologies, now in their infancy;
- Resilience and adaptation to respond to extreme events such as droughts, flooding, storms, etc.; and
- Advances in interdependent infrastructures such as the energy-food-water nexus.

Panelists highlighted critical aspects in the vision, design, and potential execution of Engineering Climate Change Institutes. Climate change problems are inherently multidisciplinary, and solutions require collaboration between engineering, social science, business, law, and the arts. Engineering research can lead or be a part of collaborative teams in the convergence research paradigm. Industry involvement in research teams holds the promise to accelerate technology development and transitions at scale.

There are many examples of research areas (e.g., materials science and engineering) where the time to market for research, development, and innovation is currently too slow. For example, discoveries in autonomous materials research may catalyze innovation in related areas where similar materials can be applied to combat global climate change. Automation and machine learning allow engineers to explore potential technology solutions faster, decreasing the time for discovery (a technique that has been used successfully in combinatorial chemistry for drug discovery).

Panelists focused on the critical issue of diversity, inclusion, and equity in their vision for Engineering Climate Change Institutes, noting that institutes so envisioned would offer a prime opportunity to educate the next generation of engineers from diverse backgrounds and enable it to contribute to the transformation necessary to address climate change problems.

Notes

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Our mission is to identify and develop bold and transformative new engineering research directions and to catalyze the engineering community's pursuit of innovative, high-impact research that benefits society.

ERVA IS FUNDED BY THE NATIONAL SCIENCE FOUNDATION THROUGH AWARD NUMBER 2048419

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This material is based upon work supported by the National Science Foundation under Grant # 2048419. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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