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THE VALUE PROPOSITION IN INNOVATIVE ENGINEERING

The BRIDGE

LINKING ENGINEERING AND SOCIETY

NATIONAL ACADEMY OF ENGINEERING

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The
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Mission Statement of *The Bridge*

The Bridge publishes articles on engineering research, education, and practice; science and technology policy; and the interface between engineering and technology and society. The intent is to stimulate debate and dialogue both among members of the National Academy of Engineering (NAE) and in the broader community of policymakers, educators, business leaders, and other interested individuals. *The Bridge* relies on its editor in chief, NAE members, and staff to identify potential issue topics and guest editors. Invited guest editors, who have expertise in a given issue's theme, are asked to select authors and topics, and independent experts are enlisted to assess articles for publication. The quarterly has a distribution of about 7000, including NAE members, members of Congress, agency officials, engineering deans, department heads, and faculty, and interested individuals all over the country and the world. Issues are freely accessible at *www.nae.edu/TheBridge*.

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LINKING ENGINEERING AND SOCIETY

A Word from the NAE Chair

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News and Notes

A Word from the NAE Chair

Intelligent Systems Engineering?

Donald C. Winter, chair, NAE

No matter how you get your news, it seems that artificial intelligence (AI) is ever present, whether it is a report on ChatGPT's ability to pass the bar exam,[1] a flawed legal brief generated by ChatGPT citing nonexistent cases,[2] or Congress's latest attempt to regulate the AI industry.[3] While the popular press tends to focus on aspects of AI that are relatively easy to convey to the general public, they fail to report on the technology behind AI that has the potential to precipitate societal changes on the scale of the Industrial Revolution.[4] Perhaps not surprisingly, the headlines tend to focus on matters such as the forecasts for significant losses of jobs resulting from future applications of AI,[5] not on the potential benefits. All this at a time when AI is enabling incredible new products such as autonomous vehicles and radically changing the capabilities of network platforms such as Facebook.[6]

All of this has motivated me to ruminate about how AI will change the future of engineering, particularly systems engineering, a discipline that I've practiced for the vast majority of my professional career. The disciplined use of the systems engineering process is key to the successful implementation of what are termed "megaprojects": complex efforts that involve thousands of engineers and billions of dollars to address major societal issues such as climate change. Some likely applications of AI are fairly evident and can impact the systems engineering process relatively soon. For example, the use of AI to assist in software coding[7] has the potential to facilitate the development of system models and simulations that are key to the evaluation of alternate design concepts. Other aspects associated with the selection of a suitable design concept and the development of that design are much harder to assess given that AI, while it is evolving, is still in its infancy. For that reason, I will avoid making predictions on such aspects but simply pose questions in the hope of initiating a dialogue on the topic.

One of the unique aspects of the systems engineering process is the development of a suitable response to the objectives of what is often a very diverse group of stakeholders. When I taught the systems engineering process at the University of Michigan, I used a case study of the Wilson Bridge replacement, which carries I-95 and the Capital Beltway over the Potomac River.[8] It took roughly a decade to develop an acceptable design concept due to the diversity of stakeholders and their differing objectives. Besides the commuters and long-haul truckers who would use the bridge, there were boaters who needed to pass under the bridge, multiple jurisdictions providing funding, local residents concerned about construction and aesthetics, and a variety of environmental groups with differing agendas and priorities. Furthermore, the various considerations and priorities cannot be expressed as common units (such as dollars), let alone be optimized using a merit function. It took human negotiations backed up by exhaustive analyses

[1] https://www.cnet.com/tech/chatgpt-can-pass-the-bar-exam-does-that-actually-matter/

[2] https://www.legaldive.com/news/chatgpt-fake-legal-cases-generative-ai-hallucinations/651557/.

[3] https://www.npr.org/2023/05/15/1175776384/congress-wants-regulate-ai-artificial-intelligence-lot-of-catching-up-to-do

[4] Henry A. Kissinger et al. 2021. The Age of AI: And Our Human Future. New York: Little, Brown and Company.

[5] https://www.cnbc.com/2023/03/28/ai-automation-could-impact-300-million-jobs-heres-which-ones.html

[6] https://ai.meta.com/

[7] https://www.infoworld.com/article/3699140/review-codewhisperer-bard-and-copilot.html

[8] http://www.roadstothefuture.com/Woodrow_Wilson_Bridge.html

of alternatives to develop an acceptable solution. Can the AI technology of the future address such challenges?

Safety in applications such as autonomous vehicles is another critical matter. If a system concept is to be identified by AI, can the AI address the inevitable safety tradeoffs in a manner acceptable to humans? For example, might AI accept loss of life during construction or operation of a new low or zero CO_2 emission power plant, based on predictions of the potential long-term global impact of reduced CO_2 in the atmosphere? Would such a tradeoff be deemed morally correct? How can an amoral technology make such decisions to satisfy humans? These questions can become material when the consequences are adjudicated in a court of law. Who is held culpable and/or liable for the AI decision; or is the AI output deemed to be merely a recommendation for consideration by human engineers and program managers?

One aspect of AI that I find to be particularly concerning is the limited insight the user receives regarding the rationale for its output. Such insight could, for example, inform assessments of the robustness of the system concept selection. That is, to what extent will the preferred concept remain valid if changes are made to stakeholder objectives or statutory requirements? If the AI product is viewed as just one of several alternatives to be assessed and adjudicated by human systems engineers, the loss of insight may be mitigated. But if the AI-proffered solution is selected, any failure to understand the genesis of that solution can contribute to an intellectual separation between the human systems engineers and the systems engineering product.

Unfortunately, such separation is not new. The power of many computational tools in use today is such that they can provide seemingly accurate answers without the users' understanding of how the answer was arrived at or what uncertainties were associated with it. If future systems engineers lack a basic understanding of the system concept under their responsibility, what might the consequences be? How can AI evolve to better inform the user of the why behind the AI product and facilitate the development of a team, with the human aided and augmented by AI and not marginalized by it?

As I noted earlier, given the early stage of the development of AI technologies, it is unclear whether these questions will be addressed in the next few years with product evolution or whether they will need to be addressed by the way in which AI is incorporated into the systems engineering process. AI is so powerful that its incorporation into systems engineering activities can be regarded as inevitable. The fundamental question that remains is how to do so to maximize our ability to leverage AI and minimize our regrets. That question is akin to a classic engineering problem.

Editor's Note

Welcoming Changes

Ronald M. Latanision (NAE) is a senior fellow at Exponent and editor in chief of *The Bridge*.

I am pleased to introduce the editor of *The Bridge,* Kyle Gipson. Kyle joined the NAE Outreach and Communications team on June 20. He will oversee all NAE editorial projects including *The Bridge*, *Memorial Tributes*, reports, studies, marketing materials, and more. Kyle has honed his editorial expertise through his six years in scholarly book publishing at some of the nation's most renowned university presses, including Johns Hopkins University Press and the MIT Press, as well as trade publishers. His ability to edit in a manner that (1) allows authors to communicate their messages as directly and clearly as possible to readers, (2) aligns with the author's vision and voice, and (3) conforms to set standards for style, content, and format will be a great asset to *The Bridge* and to the NAE. Kyle earned an MA in English from Harvard University and a BA in sociology from Bard College.

Kyle finds that working with experts across the sciences, humanities, and social sciences has strengthened his ability to effectively communicate their ideas to a variety of audiences. "This has allowed me to become adept at distilling complex ideas into clear and concise language, and to tailor that language to different readerships. By working with experts in various disciplines, I've also fine-tuned the ability to quickly familiarize myself with specialized fields of study."

In the short time I have known Kyle he has earned my applause for the commitment, energy, and skill he has devoted to *The Bridge*. He has also won the gratitude of the authors in this issue who have responded to his editorial suggestions with such comments as "Thanks for the great feedback and comments!" and "It has been an absolute pleasure working on this." I know that we will be in good hands going forward with him as editor. You can reach him at kgipson@nae.edu or 202-334-2915.

Issue Editors' Note

Engineers Matter – But Why?

Piotr Moncarz (NAE) is vice chair and chief technologist, XGS Energy. Michael D. Lepech is professor of civil and environmental engineering, Stanford University, faculty director of the Stanford Center for Sustainable Development and Global Competitiveness, and senior fellow, the Stanford Woods Institute for the Environment.

Piotr D. Moncarz

Michael D. Lepech

Our model world is unimaginable without the field of engineering. Yet the profession today often operates in a reactive mode of solving problems, whether large or small, defined by outside decision-makers and stakeholders. Thus, while the impact of engineers may be ubiquitous in today's world, their participation in defining our collective needs and priorities is not. This is the case even while engineers are responsible for designing and building the foundational infrastructure serving our society, developing computer algorithms and models that amaze us with new capabilities, innovating the next "must-have" products that delight us, helping craft regulations and policies that protect our society and environment, and working to solve many of today's greatest problems across temporal and spatial scales.

The application of mathematical and scientific discoveries to solving real-world problems is a central tenet of engineering, whose value in today's world seems obvious. But is it obvious? Are the contributions of engineers and the engineering disciplines really recognized by society? Defining the problems to be solved with and by engineers and communicating them to society will not only elevate the profession in the societal structure but also push society to allocate adequate resources for K-12 STEM education and collegiate engineering programs. Bringing together a group of contributors across the range of engineering disciplines, we look to explore the underlying value of engineering and engineers and the need to communicate it to the ultimate beneficiary of this value creation – our society. After all, beauty (and worth) are in the eye of the beholder.

As a roadmap for this exploration, we have selected a number of the National Academies' Grand Challenges (NAE 2008) and requested that contributing authors comment on the unique value proposition that engineering disciplines present in addressing these challenges.

How do we engineer a sustainable world?

Michael Lepech (Civil and Environmental Engineering, Stanford University) and James Leckie (Civil and Environmental Engineering, Stanford University) discuss the value of engineering in addressing the multifaceted and complex sustainability challenges facing our world. Viewed from the perspective of the IPAT equation, it becomes clear that the profession of engineering has an important role in addressing the global sustainability challenge. Engineers develop new technologies (T) that are less impactful on our natural environments and innovative products and services that allow us to consume (A) in more efficient, less polluting ways. When engineers responsibly deploy these engineering solutions to address, not exacerbate, global sustainability challenges, their value to our global society becomes even more distinct.

How do we provide carbon-free energy for all?

Piotr Moncarz (XGS Energy) and Michal Kurtyka (Atlantic Council and former president of COP24) dis-

cuss the value of engineers in developing new and innovative ways to provide carbon-free, low-cost, renewable energy around the globe. The authors present a broad picture of currently available energy sources and their future role in the 2030 and 2050 energy mix desired by most of the world. The current renewable energy pallet does not include in significant measure the virtually inexhaustible energy source GeoHeat, which is stored in the earth's crust. Neither the increase in existing renewable energy sources nor the introduction of newly developed renewable energy technologies can happen without a properly trained engineering cadre.

How do we provide access to clean water for everyone?

Glen Daigger (Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor) discusses the value that engineers provide globally in engineering clean water to quench the thirst of growing populations. The future challenges associated with a rapidly growing population (primarily in arid, underdeveloped geographies), climate change, and the scarcity of clean water can only be addressed with the help of engineering solutions based on both existing and yet-to-be-discovered technologies. The underlying principle of "one water" will lead to multiple uses of the water extracted from its resource, thus creating a sustainable system for water recycling. None of this can be done without major improvements to the existing water handling and purifying technologies, which need to be implemented through engineering processes.

How do we restore and improve our national infrastructure for both equity and resilience?

Jeffrey LaMondia (Civil and Environmental Engineering, Auburn University), Fernando Cordero (Arcadis), and Andrzej Nowak (Civil and Environmental Engineering, Auburn University) discuss the value of engineers working with planners and decision-makers, focusing the article to a significant degree on the resilience of rural communities. The discussed approach of performance measures in resilience planning provides a base for a systematic approach to including rural community-specific characteristics in the process. The transportation system is used as an example of specific conditions that need to be addressed to better serve both urban and rural populations. A similar discussion can be held for communication and utility infrastructure.

How do we manage natural and industrial flows to function cyclically and synergistically?

Benedict Schwegler (SynAppBio) discusses the value that engineering disciplines bring to the integration of natural flows and industrial flows in achieving greater efficiency, lower impact, and improved scalability. By viewing natural systems and natural cycles as the "infrastructure of the planet" and understanding that natural and industrial cycles are intimately connected, engineers take on a valuable role at the intersection of research, invention, and policy. Looking forward, engineers have the potential to design and engineer our integrated natural and industrial systems with the explicit goals of health, well-being, and sustainability.

How do we capture and store excess carbon dioxide to prevent global warming?

Birol Dindoruk (Petroleum Engineering and Chemical and Biomolecular Engineering, University of Houston) and Silviu Livescu (Petroleum and Geosystems Engineering, University of Texas at Austin) discuss the value that engineers provide in the quest to sequester carbon. Engineers are providing value in the field of carbon dioxide storage along three important axes: (i) mitigation and sequestration through subsurface storage in saline aquifers and depleted hydrocarbon reservoirs, mineralization, and within bio-domains; (ii) carbon dioxide capture technologies from industrial streams; and (iii) carbon dioxide transport pathways, including pipelines, and tankers for liquefied CO_2. More fundamentally, the next generation of engineers can provide value by being educated in the CO_2 domain, including elements of carbon footprint calculations for every step of project execution, given that emissions do not respect local, state, or national boundaries.

How do we advance personalized learning?

Craig Barrett (former CEO and chair of Intel Corporation) discusses the failure of our educational K-12 system to elevate the performance of the United States in language arts, math, and science from "near or below the middle of the pack of the OECD countries." The article points out the need to reconsider the construct of our K-12 educational system to bring together new technologies and high-quality teachers in every classroom to advance the educational journey of young people around the world. The essential point of the article is linking the quality of K-12 education and the future of

US engineering education and, ultimately, US world leadership in technology.

How do we engineer industrial cycles to retain value in critical material supply chains?

Evan Granite, Grant Bromhal, Jennifer Wilcox, and Mary Anne Alvin (United States Department of Energy) discuss the value of engineering circular pathways for abundant waste and byproduct material streams that could potentially serve as sources for materials that are critical to our economy. Engineers provide value through a focus on the "dynamic dozen," a group of elemental materials that are crucial for future clean energy and transportation systems such as renewable wind and solar power generation, electric vehicles, and hydrogen fuels. These materials can be found in wastes and byproducts from large-scale thermal processes (e.g., coal ash, steel slag), large-scale industrial wastes (e.g., mine tailings, red mud from aluminum production, e-waste), less common waste streams (e.g., garnet abrasives, phosphogypsum waste), and even novel sources such as outer space and the ocean floor. Around the world, these opportunities are being explored by engineers in government and the private sector to enhance security and improve the natural environment.

Reading these articles, consider the value proposition of engineers in addressing each of these Grand Challenges through the triple lens of relevancy, measurement, and differentiation. Specifically, ask how engineers and engineering disciplines are *relevant* to solving these Grand Challenges for the betterment of society. Are engineers and engineering disciplines an *important*, and even *necessary*, part of solving these challenges? How is the role of engineers and engineering disciplines *uniquely different* from that of other disciplines such as the physical sciences, the social sciences, mathematics, the humanities, medicine, and law in addressing these Grand Challenges? These rhetorical questions serve to illustrate the complex ecosystem in which engineers function to deliver solutions to society's greatest challenges.

We believe that this collection of diverse perspectives, which centers upon a core thesis of understanding the value of engineers and the engineering disciplines in solving our Grand Challenges, uniquely depicts the deep and broad role that engineers serve in society. We also believe that these perspectives highlight the imperative for engineers to proactively, respectfully, inclusively, and responsibly engage with academics and practitioners from diverse backgrounds and fields. Engagement with physical scientists, mathematicians, humanists, social scientists, medical professionals, lawyers, politicians, managers, leaders, decision-makers, and other individuals from across a broad spectrum of disciplines will be critical to meaningfully providing "a more sustainable, safe, healthy, and joyous — in other words, better — place" for us all (NAE 2008).

Acknowledgements

The articles in this issue were reviewed for content and relevance by us and by a host of professional colleagues. We appreciate the time, effort, and diligence of each contributor and content reviewer. They were edited by Kyle Gipson, whose efforts enhanced the clarity, accessibility, focus, and concision of all the articles. The authors graciously thank Kyle for his thoughtful insights, great help, and dedicated efforts.

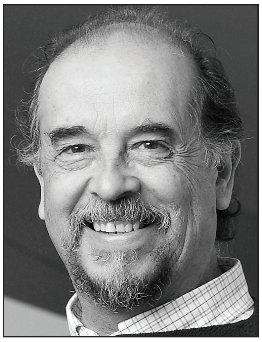
Reference

National Academy of Engineering (NAE). 2008 (updated 2017). NAE Grand Challenges for Engineering. Washington, DC: The National Academy of Sciences. Online at http://www.engineeringchallenges.org/File.aspx?id=11574&v=34765dff.

Engineering disciplines present a unique value proposition in addressing the global sustainability challenge.

The Value of Engineering for Sustainability


Michael D. Lepech


James O. Leckie

Michael D. Lepech and James O. Leckie

Sustainability is one of the major existential challenges of our time. Across four broad realms of human concern (sustainability, health, vulnerability, and joy of living), the National Academy of Engineering (NAE) prioritizes sustainability-related challenges as "foremost" since they "are those that must be met to ensure the future itself" (NAE 2008). The NAE justifies that prioritization by recognizing that "sustainability is based on a simple and long-recognized factual premise: Everything that humans require for their survival and well-being depends, directly or indirectly, on the natural environment" (NRC 2011). It is clear that our global society must collectively and urgently address our needs for low-cost generation of environmentally friendly power (e.g., solar, wind, geothermal, fusion), development of effective and scalable carbon sequestration methods, stewardship of the global nitrogen cycle, and provision of ubiquitous access to clean water (NAE 2008).

Michael D. Lepech is professor of civil and environmental engineering, Stanford University, faculty director of the Stanford Center for Sustainable Development and Global Competitiveness, and senior fellow, the Stanford Woods Institute for the Environment. James O. Leckie (NAE) is Emeritus C. L. Peck, Class of 1906 Professor of Environmental Engineering and Geological and Environmental Sciences (by courtesy), Stanford University, and founding faculty director of the Stanford Center for Sustainable Development and Global Competitiveness.

Unsurprisingly, such sustainability-focused challenges are multi-dimensional and very complex, spanning various disciplines of knowledge, spatial regimes, and temporal scales. They reside in Donald Schön's classification of challenges that exist within the "swampy lowlands, where situations are confusing messes incapable of technical solution and usually involve problems of greatest human concern" (1984). If purely technical solutions are not sufficient, what is the value of engineering, a discipline that rigorously applies mathematics and science to solve real-world problems, in addressing our existential sustainability challenge? What unique value proposition do engineers offer, in concert with other fields including policy, the humanities, medicine, business, etc., in expeditiously solving our global sustainability challenge?

If purely technical solutions are not sufficient, what is the value of engineering, a discipline that rigorously applies mathematics and science to solve real-world problems, in addressing our existential sustainability challenge?

It may appear easy to claim that engineers provide unique value when addressing large global challenges like sustainability. Over the last 150 years, engineers have been responsible for some of humanity's greatest achievements and solving some of our greatest challenges. These accomplishments include electrification, automobiles, airplanes, modern water supply and distribution, radio and television, computers, telephones, spacecraft, air conditioning, and the Internet, among many others (Constable et al. 2003). There is little doubt that engineers have great potential to meet our societal needs and overcome large challenges. But is this the case for the truly global and uniquely immediate challenge of sustainability?

Given the "swampy" nature of this global sustainability challenge, it can be helpful to structure the ways in which engineers can contribute using an impact framework originally introduced by Paul Ehrlich and John Holdren (1971). They recognized that the impact (I) on the environment from human development is a function of both the human population (P) and per capita environmental impact (F), which itself is a function of per capita consumption (A) and the environmental impact associated with each unit of consumption (T). Taken together, this forms the master equation in the field of industrial ecology (equation 1), relating population, affluence and consumption, technology, and impact (Chertow 2000).

$$I=PAT \qquad \text{(equation 1)}$$

This IPAT equation provides a clear framework by which we can begin to evaluate the unique value of engineers in potentially solving our global sustainability challenge.

Engineering for Sustainability through Technology Innovation

The US Department of Labor succinctly describes engineering as the application of "the theories and principles of science and mathematics to research and develop economical solutions to technical problems." Through the invention and creation of new technological solutions to meet societal needs, many engineers are working to address our global sustainability challenge by reducing the impact associated with each unit of consumption (the "T" in IPAT). For example, advancements in mechanical engineering have significantly increased the fuel efficiency of automobiles in the United States over the past fifty years.

As shown in figures 1a and 1b, the average fuel economy and real-world carbon dioxide emissions of today's light-duty vehicles produced in the United States have improved by 32% and 25%, respectively, since model year 2004 (EPA 2022). Improvements in efficiency and emissions since 1975 have been even more substantial. Model year 2021 light-duty vehicles produced in the United States offered consumers the highest fuel economy (25.4 miles per gallon) and lowest environmental impact (grams of CO_2 emitted per mile) in the history of the US automobile industry. These trends are expected to continue as increased numbers of electric vehicles that can be charged from renewable energy sources are

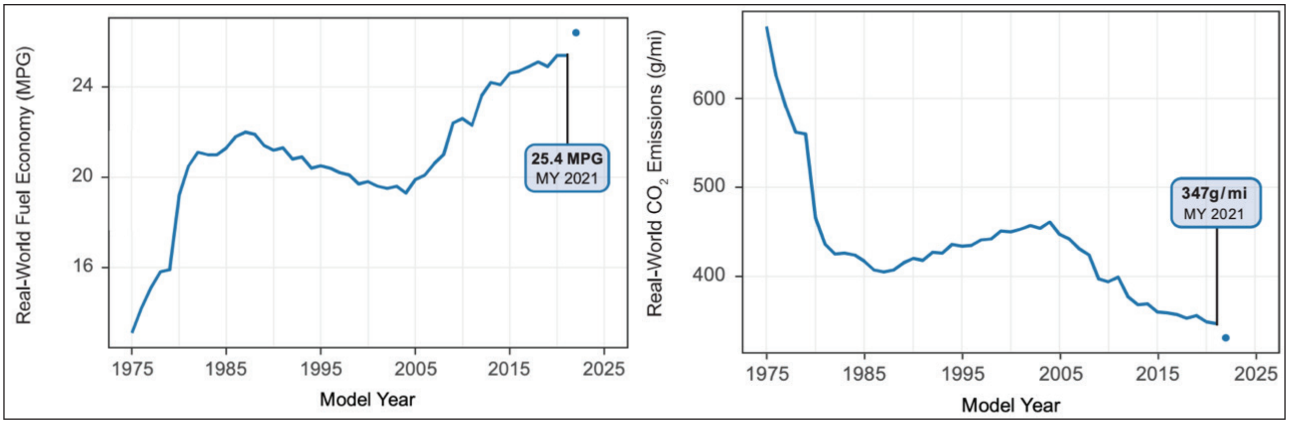


FIGURE 1 (a) Average estimated fuel economy of light-duty vehicles produced in the United States (model year 1975–2021) and (b) real-world estimated CO_2 emission rate of light-duty vehicles produced in the United States (model year 1975–2021) (EPA 2022)

introduced into the marketplace. The contribution of numerous fields of engineering (designing highly efficient internal combustion engines, building roadway infrastructure that enables automobile transit, creating new electric vehicle batteries with low-carbon charging technologies) in reducing the "T" in IPAT is different from other professions in that engineers apply principles of science and mathematics, within the context of economics and policy, to offer technical solutions.

The potential contribution of engineers to the technological portion of our sustainability challenge is not unique to automobiles or transportation. Nearly twenty years ago, Stephen Pacala and Robert Socolow identified fifteen scalable strategies to reduce annual global carbon emissions by 1GtC by 2054 (Pacala and Socolow 2004). Of these fifteen potential strategies, twelve were technology focused, recognizing the need for engineers working at industrial scales to solve this problem. These technology-focused strategies include fuel-efficient vehicles, energy-efficient buildings, efficient coal-fired baseload powerplants, efficient gas-fired baseload powerplants, carbon capture at baseload powerplants, carbon capture at hydrogen production facilities, carbon capture at synfuels plants, increased nuclear energy production, wind energy production, solar energy production, and biomass fuel production. Ever since these strategies were proposed, additional technology-focused strategies have arisen, including baseload clean energy production from geothermal heat, utility scale energy storage, and most recently clean energy production from fusion (e.g., Atzeni et al. 2022; Chen et al. 2018; Moncarz and Kolbe 2017). These are in addition to the broader sustainability needs outlined by the National Academies, including development of effective and scalable carbon sequestration methods, stewardship of the global nitrogen cycle, and provision of ubiquitous access to clean water, as mentioned earlier (NAE 2008). Developing technologies to pursue all of these strategies at a rapid, global scale is a unique contribution of the engineering profession.

Engineering for Sustainability by Addressing Consumption

It has long been recognized that technology-focused solutions alone will not solve our global sustainability challenge (Chertow 2000). Changes in the ways we consume goods and services and the amount we consume must also take place (the "A" in IPAT). In recognition of this reality, Pacala and Socolow (2004) also identified consumption changes such as "reduced use of vehicles" as an important strategy, on par with increased fuel efficiency of vehicles, to reduce the global carbon emissions rate. Building upon our previous example of light-duty vehicles, while engineers have been effective in reducing the impact of light-duty vehicles per mile traveled (a 25% carbon emission reduction per mile since model year 2004), our nation chooses to drive increasingly more. As shown in figure 2, annual vehicle miles traveled in the United States has increased steadily since 1971 (FHWA 2023). The only exceptions to this trend are the economic downturns visible in 1974-75 and 1980-82, the Great Recession and the recovery from it (2007-2014), and (most visibly) the COVID-19 pandemic in 2021. When considered together with a nearly 200% growth in driving consumption since 1970, the technological improvements in vehicle efficiency

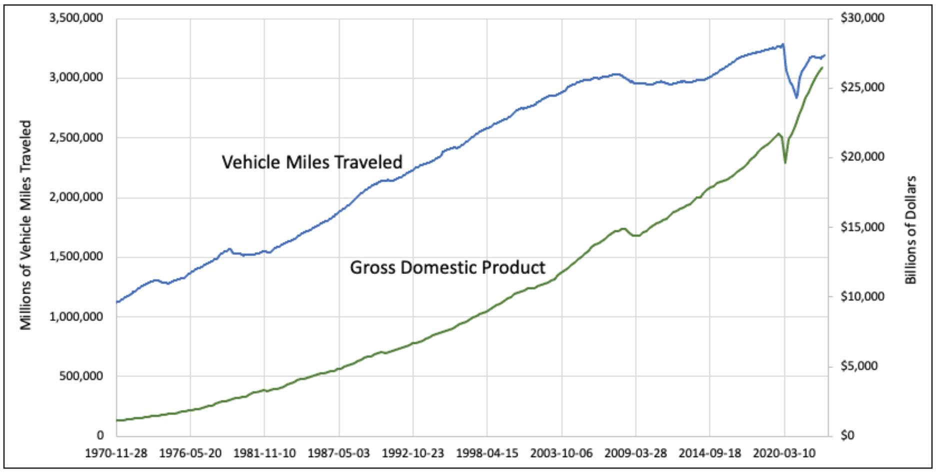


FIGURE 2 Moving 12-month total vehicle miles traveled in the United States (FHWA 2023) and US gross domestic product (BEA 2023) (1971–2023)

and emissions per mile shown in figures 1a and 1b are less impressive.

The engineers who reduced vehicle emissions per mile traveled in figures 1a and 1b also made automobile transportation more affordable by increasing fuel economy, thus making driving cheaper and unfortunately leading to increased consumption and overall environmental impact. However, this decades-long relationship between increased fuel efficiency and increased consumption may finally have been broken by technology. As also seen in figures 1a and 1b, US vehicle miles traveled have yet to return to pre-pandemic levels, even though GDP growth has recovered since the pandemic ended. During the pandemic, our need for interpersonal or business connectivity was met through advancements in new communication technologies such as Zoom, Teams, Skype, and others. This is only one example of how engineers create opportunities to meet societal needs via complete shifts in technology, while at the same time eliminating impactful forms of consumption (e.g., driving many miles for business meetings) and thus contributing to scalable sustainability solutions.

Engineering for Sustainability via Systems Thinking

While the simplicity of IPAT may provide a convenient structure for potentially dissecting the value proposition of engineers in addressing the global sustainability challenge, it fails to capture one of the most important skillsets of engineering: systems thinking. As asked previously, if purely technical solutions are not sufficient, what is the value of engineering, a discipline that rigorously applies mathematics and science to solve technical problems, in addressing our existential sustainability challenge? Phrased differently, what unique value proposition do engineers offer, *together* with other fields including policy, the humanities, medicine, business, etc., in solving our global sustainability challenge?

A foundation of engineering education, and thus engineering practice, in the United States is the application of systems thinking approaches to complex problems that include all three components of sustainability (economic, environmental, and social). Standard student outcomes for engineering programs accredited by the Accreditation Board for Engineering and Technology (ABET) in the United States reflect this foundational systems-thinking concept by explicitly requiring: (i) an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics, (ii) an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors, and (iii) an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts (ABET 2021). Engineers are uniquely educated, from the outset, to explicitly consider complexity and impact in global, economic, environmental, and societal contexts during their work, aligning well with the types of solutions that will be needed to address global sustainability challenges.

In practice, we see engineers engaging in systems-thinking and providing solutions to the complex sustainability challenge by co-creating what researchers at Stanford have termed "metastructure," a transcendent form of infrastructure that provides a platform upon which global sustainability challenges can be more

effectively addressed at scale. Metastructure includes physical infrastructures, digital IT technologies, regulations and policies, financing mechanisms, community engagements, businesses and business models, partnerships, and other institutions. This set of technologies, policies, and organizations must be created, applied, and sustained in concert with each other to provide economic, environmental, and social sustainability, in addition to a high quality of life for people around the world.

First proposed as a concept for the development of new urban transportation systems (Rogers 2016), Anne Kiremidjian and Michael Lepech (2023) describe metastructure as an integrated hierarchy of infrastructures that enable diverse disciplines to effectively collaborate on complex challenges like sustainability. Such integration increases the likelihood of successfully addressing these challenges in a more effective, scalable, and timely manner. As discussed by Kiremidjian and Lepech, metastructure is comprised of three types of infrastructure: (i) physical infrastructures that incorporate a dense sensing and data collection network (e.g., public spaces with CCTV cameras, roadways equipped with traffic sensors, smartphones providing real-time feedback), (ii) computational infrastructure that translates the ever-growing stream of data into information that can be used by individuals, businesses, and governmental agencies (e.g., machine learning algorithms, reinforcement learning processes, artificial intelligence) and (iii) engagement infrastructure that includes regulations and policies, financing mechanisms, community engagements, businesses and business models, partnerships, and other institutions. Engineers of all disciplines, working *together* with other fields including policy, the humanities, medicine, and business, are central to the creation of these systems of infrastructure and the deployment of components that link them interoperably. Thus, we see engineers as the core systems integrators that will enable society to overcome complex and urgent sustainability challenges.

The Engineering Value Proposition

When viewed through the triple lens of relevancy, measurement, and differentiation, engineering disciplines present a unique value proposition in addressing the global sustainability challenge. As described through IPAT, engineers are potentially highly *relevant* to overcoming this challenge by inventing and creating new technological solutions that meet societal needs in less impactful ways. Further, engineers are *relevant* to the sustainability challenge by creating new, less impactful goods and services that empower consumers to meet their needs in more sustainable ways.

The value proposition of engineers in addressing the sustainability challenge is uniquely *measurable*. As observed in the IPAT automobile example, the influence of engineers in improving fuel economy and reducing per-mile emissions, both of which contribute to significant reductions in carbon emissions related to automobile travel, can be measured and attributed. While more difficult to quantify, the influence of engineers on the introduction of new electric vehicle platforms, battery technologies, and renewable charging infrastructure is difficult to understate in the coming decades.

It is important that engineers (individually and collectively) realize a responsibility to use the tools of their discipline to solve, not exacerbate, global sustainability challenges.

Finally, the value proposition of engineers to addressing the global sustainability challenge is *differentiated* from that of other professions. As discussed previously, engineers apply the theories and principles of science and mathematics to research and develop economical solutions to problems. Engineers bridge the chasm between scientific and mathematical discovery and meeting the consumption needs of our society. Engineers create the tools and infrastructure systems that enable the effective societal engagement of many other professions through regulations and policies, financing mechanisms, community engagements, businesses and business models, partnerships, and other institutions (i.e., metastructure).

An Engineer's Responsibility and Call to Action

While there may be real value for engineering disciplines to address the global sustainability challenge, it is important that engineers (individually and collectively) realize a responsibility to use the tools of their

discipline to solve, not exacerbate, global sustainability challenges. While the CO_2 emission rate of light-duty vehicles produced in the United States has decreased significantly over the past few decades (figure 1b), absolute CO_2 emissions from the United States transportation fleet (including medium- and heavy-duty trucks) have increased over the same time period (CBO 2022). Engineers have a responsibility to recognize their potential value in solving global sustainability challenges and to *realize* this potential through responsible practice and engagement, acting with urgency since time is truly "of the essence."

Beyond individual actions, this responsibility includes a call to work with colleagues around the world to address global sustainability. In many cases, the provision of basic services (e.g., electricity, water, food) overwhelms considerations of environmental sustainability and social equity. Leveraging the technological parts of IPAT, engineers are called to develop and disseminate viable solutions that elevate quality of life while not sacrificing natural environments. Indeed, this may be the most challenging role for engineers to play when working to address the global sustainability challenge in a timely fashion.

Conclusion

When viewed through the frameworks of IPAT and value proposition, it becomes clear that the discipline of engineering is critical to addressing our global sustainability challenge. When combined with the comprehensive systems-thinking approach that is required in US engineering education, the value of engineers in rapidly addressing this collective challenge only grows. While the profession of engineering cannot solve the global challenge of sustainability alone, engineers provide a unique value proposition for solving sustainability-focused challenges that are multi-dimensional and very complex, spanning various disciplines of knowledge, spatial regimes, and temporal scales. Working across professional silos in aspirational ways, the field of engineering will be key to the goal of delivering more sustainable economies, environments, and societies around the globe for centuries into our future.

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Engineers are vital to the development of new and innovative ways to provide carbon-free, low-cost, renewable energy around the globe.

Engineering Carbon-Free Energy for All

Piotr D. Moncarz

Michal Kurtyka

Piotr D. Moncarz and Michal Kurtyka

Three decades have passed since the 1992 United Nations Earth Summit produced the Rio Conventions[1]—an action plan intended to confront climate change, biodiversity loss, and desertification. These existential threats can only be met with a massive shift in individual and collective human accountability for the health of the planet, in tandem with powerful engineering solutions that are implemented globally. The pursuit of sustainable energy solutions has seen important advances, but even the leading technologies—including solar, wind, and nuclear power—have major limitations where supply and distribution are concerned. A new approach to extracting heat from the earth's core—GeoHeat harvesting—has the potential to eclipse many of our existing energy sources and to do so without excluding large parts of the world based on income level and geography. This article reviews the advantages and limitations of today's leading energy technologies as well as the relative advantages of GeoHeat extraction.

[1] https://unfccc.int/process-and-meetings/the-rio-conventions

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Climate-Benign Energy through Engineering and Technology Breakthroughs

The challenge at hand is how to move from fossil fuels, characterized by their heavy carbon footprint and concentrated in a limited number of geographic locations, to a system capable of satisfying energy demand with a drastically lighter carbon footprint and fewer geopolitical strings attached. The options to be considered fall into two groups: those based on improving the systems available today and those of accelerated technological development with feasible rapid dissemination. Figure 1 summarizes some of our existing and emerging energy options, including fossil fuels, nuclear, solar, wind, and photovoltaics. Figure 1 also depicts opportunities from simple water circulating through hot rock to advanced geothermal systems, including closed-loop, "dry" GeoHeat harvesting and transport to the surface, which is represented in the bottom row.

FIGURE 1 With so many options available and so many more on the horizon, can we make a choice for the fifty years ahead?

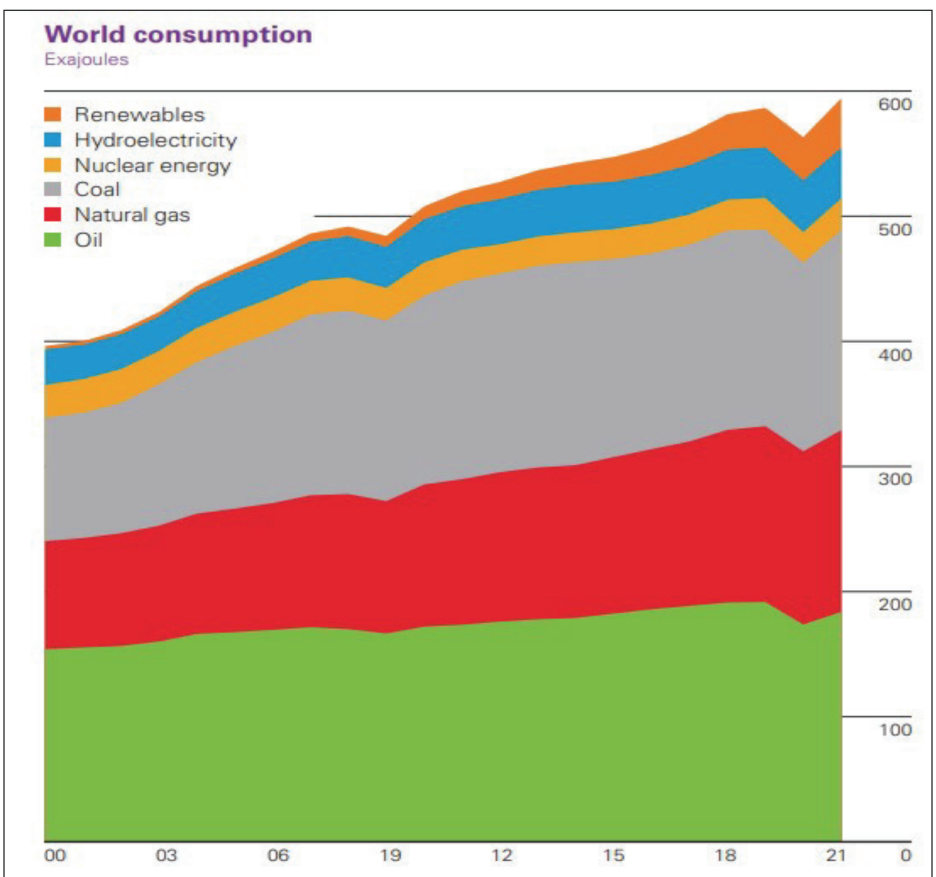

FIGURE 2 World energy consumption. Adapted from BP (2022).

The Energy Revolution

The primary combustion systems, starting with coal and moving into oil and natural gas, have provided sources of heat energy used throughout most of the electric energy generation. Figures 2 and 3 demonstrate the parallel growth of the total energy consumption relative to the total growth of electricity use

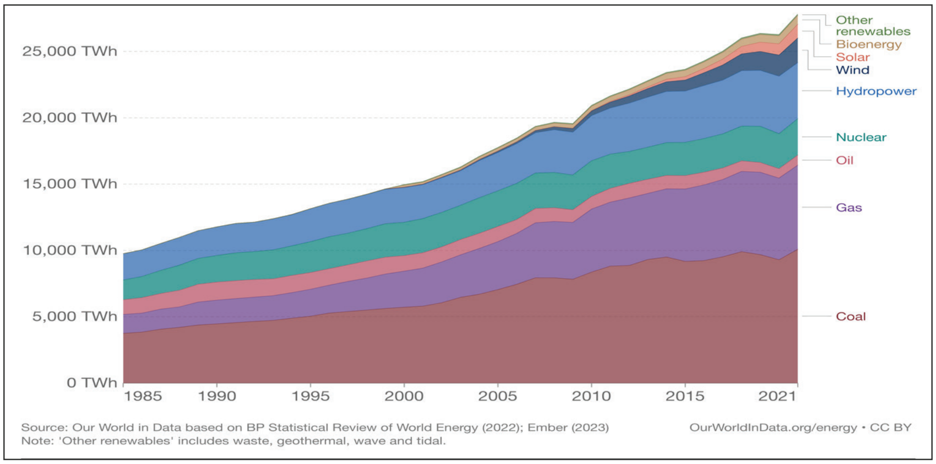

FIGURE 3 World electricity production by source. Sources: Our World in Data (2022); Ember (2023).

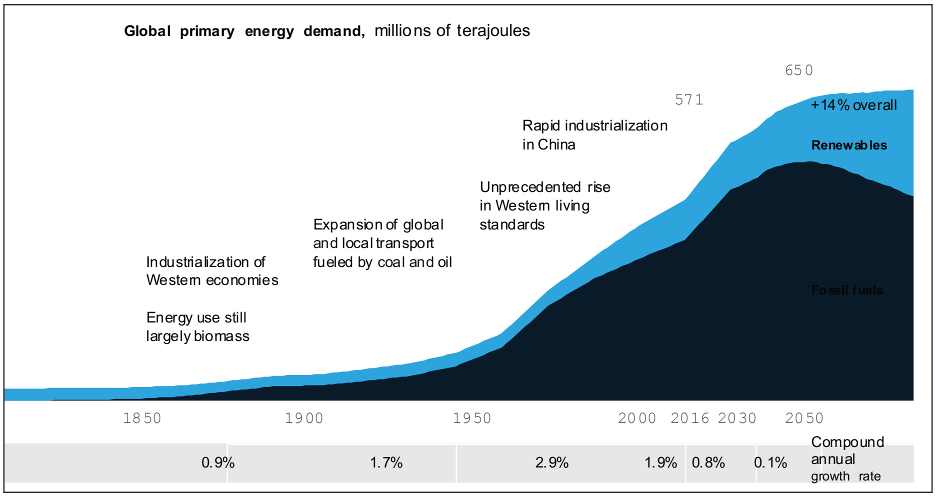

FIGURE 4 Energy demand predicted to plateau despite population growth from 8 billion to 11 billion by 2100, predominately in underdeveloped (i.e., energy hungry) regions. Adapted from McKinsey & Company (2019).

(BP 2022; Ember 2023; Our World in Data 2022). The use of energy could also be plotted against GDP and the associated life expectancy and quality of life. However, in recent years, the electricity energy source has begun to deviate from the total energy used; renewables are becoming an important part of power generation. Based on a report released by the International Energy Agency (2021), in 2021, renewables made up 28.7% of global electricity generation, with an annual growth rate of almost 7% (or 522 TWh with PV), with wind accounting for 90% of that change. In 2021, wind and solar exceeded 10% of total electric power generated (World Economic Forum 2022). This encouraging trend is, however, not fast enough to put the electric sector on track to achieve the goal of 60% renewables by 2030, a goal that is part of the net zero plan. Moreover, the trend is mostly based on the low-hanging fruit of wealthy nations installing fashionable wind and solar energy collectors, which are often well subsidized by public money. Also, the more weather-dependent energy sources are installed, the more acute the problem of intermittency becomes. Synchronizing production and consumption of electricity becomes a major concern as the tools to attenuate it are either extremely costly (storage, starting with batteries) or cause the existing energy assets to deteriorate (worsening of economics, technical difficulties through modulation). Getting energy at the right time and right location becomes a major challenge of the energy transition.

The Fossil Fuel System

Coal, oil, and natural gas are fighting for survival in the modern, climate-control-influenced energy sector (Dieter 2017). The clear "survivor" of the war on fossil fuels in the energy sector is natural gas. The use of coal by the electricity generation systems in most countries is steadily declining (in the United States, it has dropped from 42% in 2014 to about 20% in 2022). Natural gas has become the main replacement of coal in the United States since the production of shale gas began in the 1990s. The share of natural gas in US electricity generation has increased from 10% in 1988 to 40% today. As McKinsey & Company (2019) states, energy demand is likely to plateau around 2030, with a rapid decline in the use of fossil fuels substituted by renewable energy (figure 4). At the same time, oil

is maintaining its dominant position in the world's energy consumption.

Modern Wonder, Nuclear – A Major Player but Not a Fit-for-All Solution?

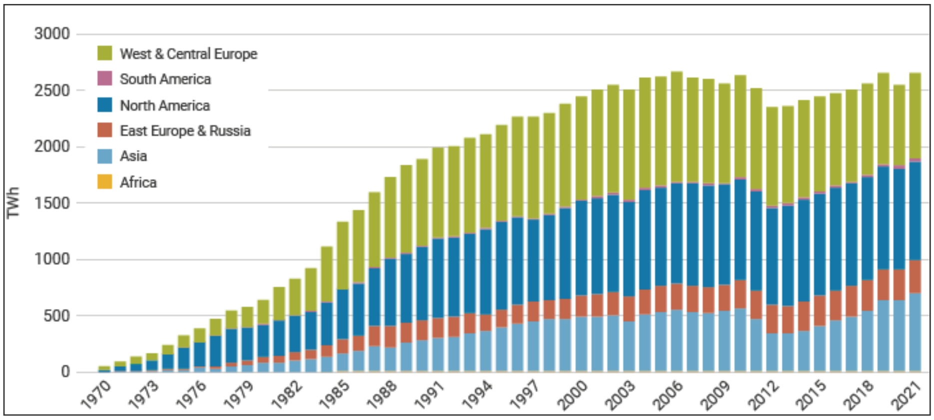

FIGURE 5 Nuclear electricity production. Adapted from the World Nuclear Association (2023).

Today, worldwide nuclear power plant electricity generation capacity is 393,351 MW with an annual electricity generation of 2,653,344 GWh (figure 5). In 2022, nuclear energy provided the United States with about 19% of electricity, and it provided only 4% of electricity worldwide. The engineering and economics related to the large size of each individual nuclear power plant project (gigawatts)—and hence the need for extensive transmission infrastructure, cooling water, reliability, safety, the long construction time, and high initial capital demand —make it a solution that might not be viable for every economy. The question of the safety of nuclear power plants is yet another element imposing some of the extremely conservative requirements that lead to the very slow adoption rate for new sites and new projects. The promise of small nuclear reactors (about 300 MW) is approaching reality, although many questions remain to be answered.

Sun- and Wind-Driven Energy Supplies – Intermittency

The spectacular increase in recent years in the amount of electricity generated through wind and solar should not be misinterpreted as an answer to our electricity supply needs. The intermittency of both of these electricity generation sources demands a large supply/demand balancing effort, which, at least for the foreseeable future, can only be provided by batteries. The probability that battery production will reach a level proportional to that of wind and solar intermittency is extremely unlikely for many reasons. Among those reasons are the raw material supplies required, the complexity of operation, and the most basic question of whether we should present the next generation with the daunting responsibility of recycling this monstrously large chemical system. Other energy storage options, while much less environmentally burdensome, have their own limitations. For example, the simple and logical pump-storage approach of seamless exchange between kinetic and potential energy has one fundamental limitation: the difference in elevation required. Not many places with suitable natural topologies exist that would be allowed for use by a modern, environmentally protective society. Similarly, large-capacity hydropower plants are not likely to continue being installed in large numbers due to awareness of the environmental consequences. They are potentially even less likely to continue being installed in large numbers due to the concerns surrounding water supplies in times of climate-driven hydrological changes such as droughts.

The GeoHeat Energy Supply – Baseload Under Our Feet

The earth's temperature varies from ambient to over 500ºC in the lithosphere (the top layer of the crust), to 1000ºC at the crust-mantle boundary, to some 5000ºC at its center. While the temperature of the earth's crust varies with depth, the local variation gradient depends on geological and tectonic conditions. The crust could—and, as scientific and technological developments strongly suggest, will—become one of the principal sources of energy for humanity. Figure 6 shows the abundance of locations around the earth where locally obtained GeoHeat energy could become the answer to renewable energy needs.

In stark contrast to the potential presented in figure 6, even prominent, forward-thinking renewable energy studies seem to neglect GeoHeat as an important element of the energy revolution (this is illustrated by *Renewable Power Generation by Technology in the NetZero Scenario, 2010-2030* [IEA 2022]). This discrepancy stems from the engineering challenge of how to

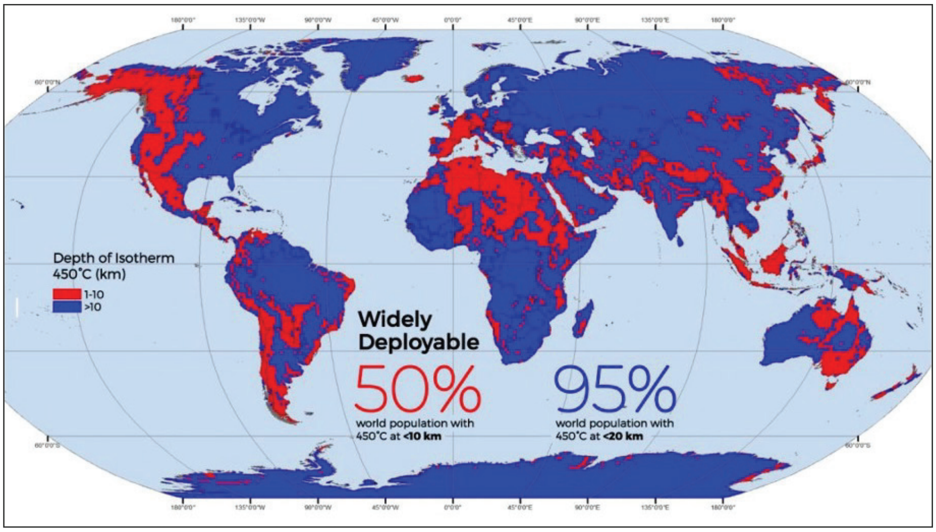

FIGURE 6 Pacific Northwest Laboratory defining the opportunity. Source: Bonneville (2022).

enable access to the hot rock at depths and temperatures that would allow GeoHeat to become the ubiquitous supply system—one without political boundaries, price constraints based on supply, water use, or environmental strain. A word of caution is called for: most GeoHeat supplies work best in the baseload mode; thus, in a cyclic offtake condition, storage becomes necessary. A co-located GeoHeat plant with a supply of green energy from either storage (e.g., batteries) or a green electric grid would provide balancing support. The use of residual heat would further increase the efficiency of the system, thus creating a truly sustainable energy supply system.

At discrete geographic locations, humans have used GeoHeat for thousands of years. This was done through conventional "wet" geothermal systems in which water and steam were extracted from underground either through natural flow (hot springs and geysers) or through man-made systems. Those typically consist of large-diameter wellbores with a high flow of steam and hot water driven by the underground pressure. However, as the flow declines from the initial production state, the well needs to be decommissioned or the reservoir replenished with water pumped from the ground. Identifying the location with rock characteristics that promise good production of steam and hot water is the first step in geothermal plant development (Gonzalez et al. 2023). The processes of drilling and maintaining the well are adequately understood and have been tested thousands of times. Maintaining the flow of the hot fluid, with or without water re-injection into the ground and mineral-scale buildup inside the extracting pipe, are some of the problems the conventional "wet" geothermal system faces. Most often, conventional geothermal wells take advantage of pressure maintenance through re-injection, thus relying on large quantities of surface water supplies and the potential need to address resultant seismic events. Other adverse effects are those related to toxic gas emissions, such as sulfur and carbon dioxide, and noise. In addition to these environmental effects, corrosion or scaling problems caused by high in situ fluid acidity or mineral solubility destabilization often diminish the economic value of the projects.

A more advanced form of extraction of steam and water from hot rock formations is the enhanced geothermal system (EGS), which relies on heating the water injected into a channel of fractured rock connecting the injection well(s) with the production well(s). The many years of trial-and-error efforts to help make EGS a solution to the problem of bringing high-temperature heat to the surface have shown weaknesses of this convection-based, wet geothermal system: the need for major rock fracturing and refracturing, the need to resupply water lost in the injection-production channel, mineral deposit precipitation in the production well, and the need to handle leached-out minerals brought to the surface. Nonetheless, the dream of EGS becoming a major source of US energy supply is supported by the GeoHeat mapping presented in figure 7 (NREL 2018).

The effort to provide access to GeoHeat without the constraints listed above resulted in the pursuit of closed-loop geothermal systems (CLGS) introduced in the 1970s by the Los Alamos National Laboratory's Hot Dry Rock Program (1971). Such a system relies on the heat conductivity of rock and, as such, is confronted by one basic dilemma: rock's low intrinsic heat conductivity. The conductivity of rock (2-4 Watt per meter per degree Kelvin – W/m°K) is far too low to support long-term heat delivery at the rate required to make such a system economical. In recent years,

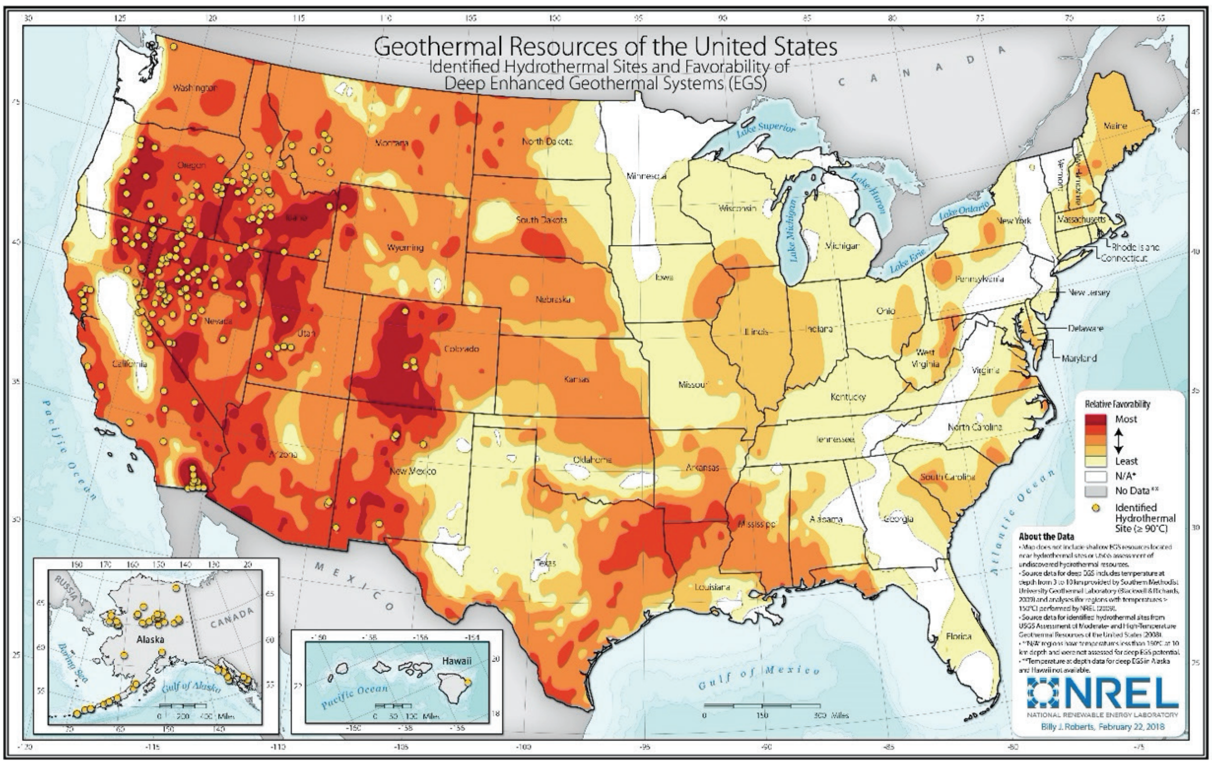

FIGURE 7 Hydrothermal sites and EGS attractive locations. Adapted from NREL (2018).

the California-based company XGS Energy (formerly Geothermic Solution) has introduced a method of enhancing the conductivity of the rock in the vicinity of the borehole in which the closed-loop heat harvester is installed. However, tapping into GeoHeat through a closed-loop system also has many very significant technical challenges, including drilling in very hot rock, installation that assures continuous contact between the rock and the closed-loop casing, and, most importantly, stimulating more robust heat flow from the rock to the borehole than that provided by the rock's intrinsic conductivity. Building on years of experience in the shale gas industry and the mining industry, the method introduces high-conductivity solid material into the rock surrounding the borehole, thus providing for stable heat collection.

This method, when disseminated commercially, will deliver heat energy around the world with no environmental impact and with no demand for the scarce resource of water. The hot (>300°C) rock of the earth's crust at a depth between a few kilometers and more than 10 kilometers could, in the not-too-distant future, become a major supply of truly renewable energy. The ensuing concept of medium-sized plants (50 MW electric or up to 200 MW thermal) in a system of delivery close to the point of use will provide the additional advantages of system reliability and robustness through independence from fuel and water supplies and high-voltage transmission systems.

Heating and Cooling

The amount of energy used per capita varies by the standard of living, climate, and state of the economy, but a whopping 25 percent of the total energy used worldwide is consumed for the purposes of heating and cooling residential and commercial buildings. With the modernization of our urban systems, a lot of that energy goes through the most grotesque, wasteful process: we use fossil fuels to generate heat, then we convert the heat into electricity, then we ship the electricity through energy-losing wires, and *then* we convert the electricity into heating or cooling. The solution of potentially much more efficient central heating and cooling plants is difficult to implement in already-built environments

or in suburban and rural buildings of various sizes and spacing. While many cities operate based on centralized heat energy centers, most of them use either fossil fuels directly or electricity.

The heat exchange systems for urban developments require significant, even if relatively simple, underground installation. The geothermal heat pump installed at Google's new Bay View campus in Mountain View, California, with its heat exchange tubes reaching a cumulative length of 69 miles, is the largest such system in the world to date. Heat exchange tubing installed at a depth of some 20 meters within structural piling provides efficient harvesting of needed heat or effective storage of rejected heat. The geo-heat pump will likely become a widespread system in single-family and small residential buildings, as proven by the enormous popularity of the system in Europe. Poland is an outstanding example of this "nearly self-made," energy-balancing approach. There, hundreds of thousands of property owners have installed the heat pump systems—mostly as an economy- and reliability-driven investment.

Conclusions

Achieving a carbon-neutral, net-zero society requires nothing short of an energy revolution—a shift in individual and collective mindset to usher us into an age of ecological civilization (Kurtyka 2023). For this transformation to succeed, three related challenges must be addressed simultaneously: First, how to develop, select, and disseminate environmentally friendly technologies that limit the need for combustion of fossil resources—economically feasible *engineering solutions* that can contribute to raising standards of living in ways less harmful to our planet. Second, how to transform the current economic model, which is based on fossil fuels, into a new model that utilizes ecologically friendly technologies in a *just* way, engaging people locally and globally to craft solutions, including new models of production and consumption, and garnering social acceptance (on a global scale) of those new models. And third, how to keep the world *united* and *synchronized* in its pursuit of carbon neutrality, ensuring that access to associated technologies and their benefits will be just and balanced (Kurtyka 2023).

The strength of GeoHeat as an energy source is that it moves us away from dependence on fossil fuels without leaving large parts of the world behind. It is environmentally benign, free of demand for precious water, and can be extracted from nearly every region of the globe.

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Engineers are deeply involved in and essential to vital transformations in our water management system.

Engineering Clean Water

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Glen T. Daigger

The provision of water for human use is in a state of transition (Daigger 2011). The One Water paradigm reverses the historic one-use approach of managing the individual components of the water cycle on a "siloed" basis and shifts to an integrated approach valuing the various "waters" on an equal basis. The resource recovery paradigm strives for greater resource use efficiency and recovery while minimizing adverse impacts such as greenhouse gas emissions. Implementing these paradigms requires significant changes to water resource management and service delivery systems, the required infrastructure, and the technologies used. Engineers are deeply involved in this water management system transition and are essential to its realization. Engineers evaluate and select higher-performing and more integrated water management systems, develop the allied technologies, and are essential to the implementation and operation of the supporting infrastructure. While much remains to be done, substantial progress is being made.

Why Is Water Important?

A sufficient quantity of clean water is essential to a healthy environment. The importance of water quantity in the environment, and the adverse impacts of withdrawing too much water, are well demonstrated (Yao et al. 2023). The benefits of effective water pollution control are also well demonstrated by, for example, the restoration of the Great Lakes and Chesapeake Bay.

Effective water management, consisting of water supply, stormwater, and wastewater management, is essential for human life. Moreover, people are drawn to water for a variety of services beyond the simple provision of water needed for life. Consider the water features defining major metropolitan areas—San Francisco Bay, Sydney Harbor, Chesapeake Bay, Puget Sound, and the San Antonio River Walk. Water-based recreation brings people and families together, providing both physical health from recreational activities, and emotional and mental health from familial and other relationships. That the value of property adjacent to and/or within eyesight of water is significantly greater than similar properties lacking these features demonstrates the value that humankind places on water.

While many disciplines are needed to plan and manage water service delivery infrastructure, engineers are essential to designing, constructing, operating, and maintaining it.

The essential nature of water becomes evident when viewed through the lens of the triple bottom line of sustainability. Effective water service providing a sufficient quantity of clean water is essential for the environment, society, and the economy.

Water Service Provision and the Role of the Engineer

We are all familiar with the water cycle. Water evaporating from lakes, rivers, oceans, and snowpacks is the source of precipitation that provides the flow of water into lakes and streams, recharges aquifers, and eventually flows into the oceans. Evapotranspiration by plant life also cycles water to the atmosphere. While we commonly say that water is not created or consumed, this is not entirely true. Water interacts with the carbon cycle by serving as the source of hydrogen for carbohydrate formation during photosynthesis. This water is returned to the environment when organic matter is oxidized. For our purposes, however, we can consider that the quantity of water on the planet is constant.

The quantity of water available for human use is limited (only about 1 percent of the total) but still substantial. Historically the issue has been the location of water, not the quantity of water available. Additionally, water is often not available in the quantity and quality desired for human use at the time that humans wish to use it. In the past, the solution was storing water and transporting it from where the water was available to where humans wished to use it. Water quality issues were addressed by simply sourcing water of the desired quality and returning used water to locations that did not directly interfere with human activities. More recently, the increased human population and the resulting escalation in water use and pollution of water bodies led to the process of water treatment, either to make water acceptable for use or to return used water to the environment. The combined processes of treating water, moving it from one location to another, and storing it, are referred to as water service.

Civilizations have risen and fallen based on their ability to source, transport, and store the water they need. We are all familiar with significant engineering feats constructed over the centuries that enabled the development of notable societies. The emergence of civilization in the Middle East provides important examples, along with the aqueducts in Rome and water management by the peoples of Central America, South America, and Asia.

Why is such large-scale water service infrastructure needed? Two factors make this necessary: the quantity of water needed for human use and the fact that water is heavy. Because of these factors, effective water service requires a robust and complex infrastructure. They also explain why engineers play such an essential role in water service provision. While many disciplines are needed to plan and manage water service delivery infrastructure, engineers are essential to designing, constructing, operating, and maintaining it. Service that delivers a sufficient quantity of high-quality water requires the infrastructure that engineers make possible.

Engineers and Water Challenges

The historic approach to water management functioned satisfactorily until the middle of the twentieth century when the human population and the global economy began to increase dramatically. Since then, the global

population has increased more than threefold,[1] and the per-capita GDP has increased more than 4 ½ times over this same period, resulting in a more than tenfold increase in the global economy.[2] The resulting increase in water demand significantly exceeds the natural water supply produced by historic water management approaches, leading to increasing water stress, which is adversely affecting water uses (MacAlister et al. 2023). Climate change, of course, further exacerbates this stress.

Water use need not increase in response to increasing demands. While US water use increased between 1950 and 1970, it then leveled off and, in fact, has declined somewhat during the 2020s, despite the more than doubling of the US population.[3] Agriculture (largely irrigation) and thermoelectric power generation are the two largest water users in the United States, representing nearly 80 percent of the total. Engineers are essential to satisfying increased demand with the same water supply by developing technologies to use water more efficiently. Advances in agricultural water use include new generations of drip irrigation systems and laser leveling of fields, coupled with local and remote sensing and control to deliver water (and nutrients) to plants as they need them. Application of technologies such as these can increase agricultural water use severalfold. Water demands for thermoelectric power generation need not increase and may decrease if renewable energy sources that are less dependent on water (e.g., solar and wind) can be increased sufficiently to meet growing demands as we electrify our economy.

Engineers are developing new manufacturing technologies that use much less or even no water. Consider, for example, textile dyeing, which has historically required significant quantities of water and resulted in a highly polluting waste stream. Emerging technologies such as supercritical carbon dioxide and ultrasound dyeing can essentially eliminate the use of water for this purpose. While water use by industry in general is modest, dramatically reducing or eliminating it significantly reduces this water pollution source. More water-efficient (and energy-efficient) products, such as washing machines, are also being developed.

While urban water represents a modest proportion of the total use, it exerts a disproportionate impact on the natural water supply due to the potential to pollute available water resources. The historic approach to urban water management depends on natural processes to treat returned water for its next use. Population growth over the second half of the twentieth century challenged natural recycling systems, leading to technological developments, which, coupled with methodologies to demonstrate reliable compliance with product water quality standards, have enabled engineered water recycling systems. Water is used multiple times before it is returned to the environment, thereby reducing the quantity of water removed and the environmental impacts of used water discharges. Large-scale water reclamation and reuse systems are now implemented in the United States, Singapore, and Israel and are becoming more widespread elsewhere. Water reclamation and reuse partially close the urban water cycle and mitigate the impacts of water shortages and drought on urban water management.[4]

Engineers are intimately involved in defining and implementing the infrastructure needed to manage floods, another form of water stress. Traditional flood management approaches are challenged by the combined effects of population growth and urbanization, leading to increased human occupation of flood-prone areas, and climate change, which is increasing the frequency and intensity of precipitation events.

Engineers are essential to satisfying increased demand with the same water supply by developing technologies to use water more efficiently.

The One Water paradigm is the urban water sector's response, recognizing that alternate approaches to one component of the human water system can often be a solution to another (Daigger et al. 2019). For example, stormwater capture and water reclamation and reuse not only address stormwater and wastewater but also provide additional water supplies. This broader system-wide perspective, referred to as the "portfolio approach," exam-

[1] https://www.un.org/en/global-issues/population

[2] https://ourworldindata.org/economic-growth

[3] https://www.usgs.gov/special-topics/water-science-school/science/trends-water-use-united-states-1950-2015#overview

[4] Sedlak provides an interesting and informative description of the evolution of water service in his book *Water 4.0* (2014).

TABLE 1 An increasing range of practices are being incorporated into the core functions of urban water service systems*

Source Water	Store Water	Provide Water Services	Recover Resources
• **Surface Water** • **Groundwater** • Stormwater • Reclaimed Water • Seawater	• **Surface** • Aquifer	• **Potable** • **Sewage** • Non-Potable • Greywater • Blackwater • Yellowater	• **Organic Matter** • **Nutrients** • **Energy** • **Biogas** • Water • Heat • Other Materials

*Traditional practices bolded

ines solutions based on combinations of components and outcomes and identifies solutions that are not evident when single components are examined separately. The water supply portfolio includes water conservation, stormwater capture, water reclamation and reuse, and possibly desalination, coupled with traditional surface and ground water, with the specific sources selected and combined to perform adequately over a range of conditions (Crosson et al. 2021). Management of the portfolio involves deciding what infrastructure is needed to enable the use of a sufficient range of water supplies over a range of conditions (e.g., water excess or drought). A similar approach is developing to manage stormwater. Traditional infrastructure is coupled with engineered natural systems (i.e., "green" infrastructure) and land-use planning to allow for the controlled flooding of areas that can be returned to service quickly, at the least cost and causing the least disruption of service.

The materials and energy needed to operate water service delivery infrastructure are also contained within the human water cycle. For instance, while wastewater treatment generally requires net energy input, the energy contained in the influent wastewater stream greatly exceeds the energy needed for treatment (Pikaar et al. 2022). Sustaining human life on the resource-constrained world we inhabit requires reduced net resource consumption and reduced emissions of substances such as greenhouse gases. Recognizing both the opportunity and the need, water professionals are increasingly focusing on reducing net resource use for water service provision and recovering resources from the human water cycle. Technologies supporting broader water service resource recovery are not as well developed as those that facilitate water reclamation, but engineers are making a significant effort to develop and integrate them into water service provision systems (Pikaar et al. 2020; Ren et al. 2020).

Table 1 illustrates technologies and practices being incorporated into higher-performing urban water service delivery systems, while figure 1 illustrates an integrated urban system. Similar transformations are occurring in the industrial sector. Aquifer storage avoids the negative impacts of new surface reservoir construction, reduces evaporation, and facilitates water distribution in urban areas. Treatment to fit-for-purpose quality standards for non-potable uses reduces energy and other resource requirements. Separation of used water at the point of generation facilitates reduction in energy and resources needed for water reclamation from greywater and increased capture of chemical energy-rich organics (e.g., blackwater) and nutrients (e.g., yellowater, urine) (Hilton et al. 2021). The use of historical practices such as hydropower and biogas is increasing, along with recovery and use of organic matter and nutrients in biosolids. Engineers are developing and implementing new approaches, especially for phosphorus, and the heat content of used water is being recovered. Research and demonstration are ongoing to recover inorganics and specific organics.

Centralized treatment systems have traditionally been used because of the limited capabilities of the treatment technologies available and economies of scale. New treatment technologies, such as membranes, have enabled use of smaller-scale, distributed treatment systems that, in turn, have enabled more localized water reclamation and reuse. Natural treatment technologies such as wetlands and bio-retention systems are also advancing and increasingly being incorporated into distributed systems. Water service delivery systems are becoming more geographically distributed, resulting in increased water use efficiency, reduced energy consumption, and increased resource recovery.

While significant advances in membrane technologies continue at an accelerating rate, other technologies

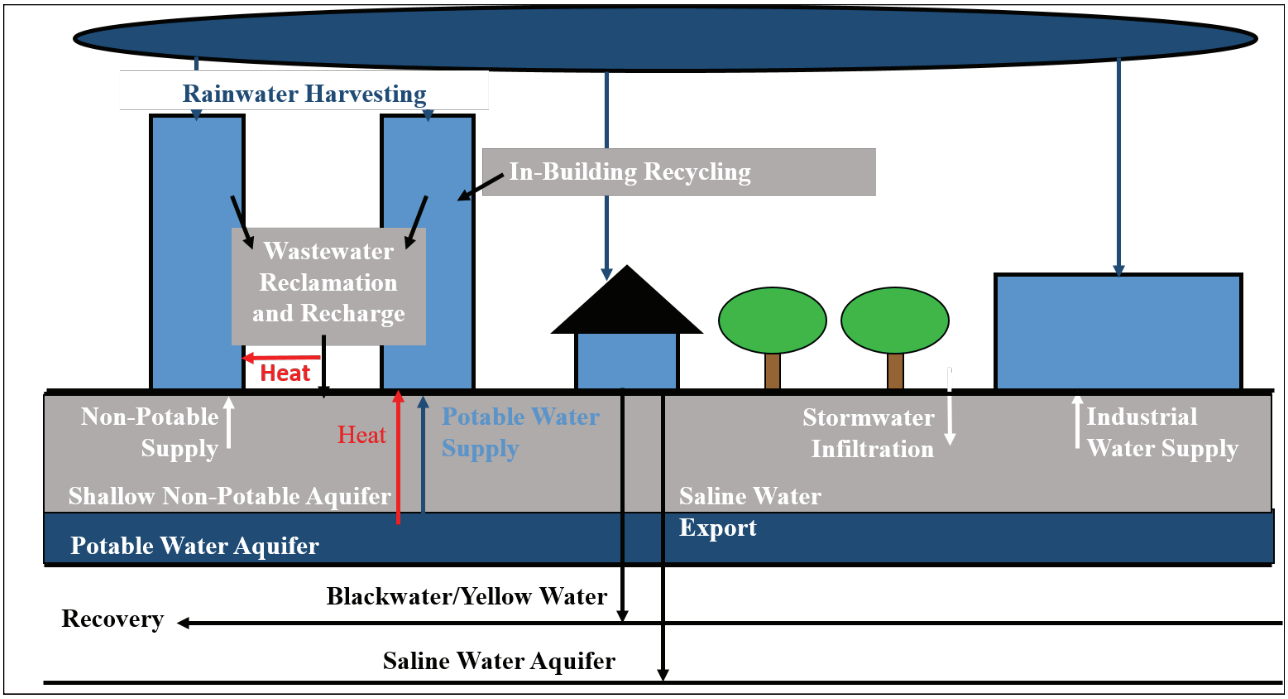

FIGURE 1 Example of an integrated urban water service provision system.

are also instrumental to this transition (Zodrow et al. 2017). Anaerobic technologies are advancing to both increase biogas production and convert organic matter into higher valued products. Advances in biological used water treatment technologies are facilitating dramatic reductions in energy requirements and allowing for more compact systems. They are also reducing the use of resources like carbon and other chemicals for nutrient removal and recovery. Biological technologies are increasingly being used for drinking water treatment and advanced water reclamation, and managing biological activity within water conveyance systems is an emerging practice. Electro-chemical technologies are emerging as interesting options, both for centralized treatment systems and, especially, for distributed treatment systems. A significant investment is being made in membrane and electro-chemical technology development through the federally funded National Alliance for Water Innovation[5] and the Department of Energy's Advanced Materials & Manufacturing Technologies Office.[6]

Future Outlook and Challenges

The One Water and resource recovery paradigms are transforming water service delivery to meet water supply needs, further reducing environmental impacts, and positioning the water sector to provide a resilient and sustainable foundation for the circular economy. Engineers are deeply involved in and essential to this transformation. Unfortunately, effective and sustainable water service provision is not uniformly implemented, with a large proportion of the human population lacking even quite basic systems, as indicated by insufficient progress toward meeting the sustainable development goals associated with water. Achieving effective and sustainable water service provision is truly a team effort requiring numerous disciplines and professions, including engineers, other technical professions, and the social sciences. The lack of effective institutions and governance structures is often the constraint preventing appropriate water service provision implementation. People often doubt whether some communities can afford such systems. The evidence is clear, however, that the broader economic and health benefits of effective water service provision greatly exceed the cost, generally by a factor of five or more.[7] To put it simply, appropriate water service

[5] www.nawihub.org

[6] https://www.energy.gov/eere/ammto/articles/doe-awards-275-million-16-teams-working-decarbonize-us-water-infrastructure

[7] https://doi.org/10.1787/9789264100817-en

provision is not only affordable but a bargain. Engineers have always been not only essential partners with others but often leaders in addressing institutional and governance issues, leading to the establishment of conditions where effective and sustainable water provision systems can be implemented. Continuing this leadership represents a core responsibility of the engineering profession and a leading challenge to extending the human right to water and sanitation.

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Investment in resilient infrastructure is critical for all communities across the United States, especially small and rural communities.

Equitable Transportation Planning and Decision-Making to Support Small and Rural Community Resilience

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In recent decades, the number of natural disasters causing human and economic losses in the United States has continued to rise (Botzen et al. 2019; Boustan et al. 2017; NRC 2012). In fact, since 1980, the United States has experienced over 300 extreme weather or climate-related events (e.g., tornadoes, hurricanes, fires), resulting in almost $2.5 trillion in direct and indirect costs (NOAA NCEI 2023). In response, there has been much discussion about creating resilient infrastructure, defined in accordance with the National Academies of Science, Engineering, and Medicine as systems with "the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events." We often hear most about

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resilience in terms of transportation, power, water, waste disposal, communication, and security systems, with a focus on urban areas. In fact, Presidential Policy Directive 21 (PPD-21): Critical Infrastructure Security and Resilience established sixteen critical infrastructure sectors that support the security and development of the country and highlight the need for united efforts and policies that strengthen and build resilient, secure, and functioning critical infrastructure (The White House 2013).

Small and rural areas are critical to the functioning of the entire United States.

However, it is the small and rural areas (with populations fewer than 50,000 people [NARC 2023]) that often suffer greater damages due to extreme events, include more vulnerable institutions (e.g., agriculture, power plants, transportation hubs, rail corridors, low-income or older populations), and have traditionally fewer resources available to prepare for or recover from these events (Drakes et al. 2021; Strader and Ashley 2018; Tate et al. 2021). Furthermore, research shows that the small and rural areas most vulnerable to flooding have disproportionately higher populations of Black or African American and Native American residents. Specifically, "nineteen million people live in these hotspots of high flood risk, which are clustered in rural parts of Southern states" (Manuele and Haggerty 2022). This current lack of resilience-related activities is surprising, since small and rural areas are critical to the functioning of the entire United States. Small and rural communities cover 97 percent of the US land area; are home to nearly 20 percent of the US population (America Counts 2017); and provide the majority of the energy, food, and raw materials necessary to support the *entire* US population and economy (Kelly-Reif and Wing 2016). Additionally, these communities often include more underrepresented populations, including lower-income, older, and minority groups (Dobis et al. 2021).

While there have been some recent resilience-based investments in rural communities (Chase 2022, Office of the Governor of Alabama 2022, Searcy 2022), they are still significantly behind their urban counterparts in terms of their ability to recover their infrastructure, economy, and quality of life after natural disasters (Elliott and Pais 2010, Fitzpatrick and Spialek 2020, Xu and Qiang 2021). It has also been well documented that small and rural areas struggle to compete for external grants and other resources to help prepare for and recover from disasters (often due to the fact that their performance measures, by definition, fall below those of their urban competitors) (Seong et al. 2021).

Therefore, it is critical to reconsider how we incorporate resilience in infrastructure planning and decision-making such that it (a) equitably supports how we characterize resilience across small, rural, and urban communities; (b) incorporates local social capital, experience, and ingenuity in preparing for and recovering from resilience; and (c) can be used to impartially support critical projects that help all communities *absorb*, *adapt to*, and *recover from* disruptive extreme weather events.

Small and Rural Community Resilience Planning Requires Different Metrics

Small and rural communities are inherently different than their urban counterparts, which means planning for (and responding to) their resilience must also be different. First, small and rural communities have varying geographic densities. These areas often have denser commercial downtowns (compared to the surrounding areas) or main streets that serve as economic and social hubs of the community surrounded by less dense development. This means that the first stage of rural community resilience needs to focus on supporting connectivity *within* each community around these activity hubs. Residents need to be able to continually access these hubs before, during, and after natural disasters to maintain access to goods, information, resources, and fellow residents.

Second, small and rural communities heavily rely on long-distance travel to urban areas for healthcare and goods/services that are not available locally. Therefore, the second stage of rural community resilience needs to focus on supporting connectivity *between* each community and neighboring urban areas. Again, these long-distance connections need to be preserved at all stages of natural disasters to support evacuations as well as the arrival of resources and recovery support.

Third, it is important to recognize that these connections are often supported by a limited set of key, critical infrastructure that lacks redundancies. Most noticeably,

there can often be only a single highway route connecting homes to the downtown area or to the nearest urban area. Small and rural areas typically also have limited power, water, and communication connections. Additionally, one must also consider that there are often limited supply chain connections that support these communities. If any of this infrastructure is affected by a natural disaster when no redundancies exist, it can potentially leave these communities isolated and subjected to long-term recovery issues. Resilience investments and planning efforts in small and rural communities need to focus on identifying these vulnerable, vital infrastructure connections as well as developing redundancies to ensure access remains throughout the disaster event.

Fourth, small and rural communities have many opportunities to leverage the unique interpersonal and adaptive systems they already have in place. Due to their geographic locations, residents of small and rural communities naturally cultivate their own local social capital, or the knowledge, skills, diversity, and interpersonal relationships that allow them to be adaptable and resilient to everyday challenges (Kendra et al. 2018). These relationships and community-specific systems are typically non-transferrable and developed over time to allow local activity to operate smoothly when faced with minor infrastructure interruptions. While research into how to incorporate technological advances into "smart villages" exists (Cunha et al. 2020; Mohanty et al. 2020), it is important to recognize that these efforts rarely consider how to incorporate the aspects of small communities related to their strong social capital. As such, there are great opportunities to consider how small and rural communities can leverage their baseline resilience system rooted in social capital when developing further resilience plans or investments.

Transportation Planning and Decision-Making Require Resilience-Based Performance Measures

Resilient infrastructure has the capacity to operate at an acceptable level before, during, and after an extreme hazard event. Despite many organizations recognizing the need for more comprehensive resilience planning for transportation infrastructure (NRC 2012), the United States still lacks a standardized planning framework to guide these decisions and prioritize improvements, especially those in small or rural areas (NASEM 2021, Wang 2015, Weilant et al. 2019). Ideally, such a resilience framework would be practical, operational, replicable to multiple transportation assets, and transferable to urban and rural areas (Bruneau and Reinhorn 2019).

While there has been much work on measuring different aspects of resilience related to specific types of infrastructure (e.g., network delays, traffic capacity, energy consistency, or bridge fatigue), they are incredibly specific to each infrastructure type and do not allow for planning decisions to consider or compare different operational or physical infrastructures' losses or potential improvements. Decision-makers still need a comprehensive framework that can equitably accommodate all the components of a transportation system (e.g., bridges, roadways, airports, and operations) (Faturechi and Miller-Hooks 2014; Wang et al. 2020). Perhaps more importantly, there is no consensus on best practices or guidance for incorporating resilience assessment in the transportation planning process where these decisions are made (Gonçalves and Ribeiro 2020; NASEM 2019). There are no unified indicators of resilience that incorporate the interaction between asset exposure and performance (Weilant et al. 2019).

Resilient infrastructure has the capacity to operate at an acceptable level before, during, and after an extreme hazard event.

One common planning technique we can build upon for transportation system resilience assessment is agencies' current efforts to collect asset and performance measure data for management, planning, and decision-making purposes. In most cases, state departments of transportation, regional planning agencies, local metropolitan planning organizations, rural planning organizations, and even city planning boards use quantitative performance measures to describe transportation systems' infrastructure and operations, although qualitative approaches are sometimes used. Performance measures are equitable means of evaluating system operations because they (a) provide common metrics for decision-makers to compare across different locations, (b) can be adapted to appropriately highlight the specific goals

of different locations, and (c) incorporate different targets set by local jurisdictions. Performance measures are used by agencies across the United States to evaluate the successes and deficiencies of their current system as well as whether changes would improve their system or not. For example, the National Cooperative Highway Research Program (NCHRP) Report 551 (2006) reviewed the state of practice on performance measures and organized the revised performance measures into four categories: preservation of assets, mobility and accessibility, operations and maintenance, and safety (NASEM 2006). In the case of transportation, and more explicitly planning, performance measures are fundamental for measuring targets and goals and assessing progress (Litman 2017).

More flexible and community-specific performance measures are still needed so urban and rural areas' local resilience goals can be equitably compared.

It is important to note that performance measures are especially significant to small and rural communities in transportation planning. Funding and project prioritization defined by standard metrics, such as impacted population size, traffic volume, or number of highway miles in a community, will naturally promote urban areas. Allowing flexible performance measures that highlight community-specific impacts, such as impacted populations in poverty, indirect costs associated with loss of agriculture, level of isolation, or social capital, allows rural areas to be competitive in rankings. For example, in previous iterations of Building Resilient Infrastructure and Communities (BRIC) grant funding, "communities in relatively populous and wealthy states won more than 80 percent of those dollars" (Manuele and Haggerty 2022). Today, BRIC funding includes equity-based performance measures to help allocate funding to more rural communities.

It is important to recognize that while various resiliency-based performance measures do exist (Cutter et al. 2010; Cutter et al. 2003; Peacock et al. 2010; Weir et al. 2012), they often rely on county-level, public data sources that typically do not offer enough final spatial granularity to characterize the diversity of activities and systems within rural communities. As such, more flexible and community-specific performance measures are still needed so urban and rural areas' local resilience goals can be equitably compared. Table 1 provides prompts to consider when selecting and characterizing transportation system performance measures.

Past and Current Efforts to Incorporate Performance Measures in Resilience Planning

Performance measures need to be incorporated into resilience programs, and there are many opportunities to expand these efforts. Most current work emphasizes urban applications and focuses on specific hazards or infrastructure systems. As such, it is challenging to compare results to determine resilience priorities, especially in rural communities. Still, they are valuable resources for understanding risk and vulnerability.

Some of the most prominent performance measure-based methods include: (a) FEMA's Hazus Program, which models risk, using damage functions to estimate the financial losses to infrastructure given a specific hazard severity (Neighbors et al. 2013; Papadopoulos et al. 2019); (b) Federal Highway's Vulnerability Assessment Scoring Tool (VAST) measures exposure, sensitivity, and adaptive capacity of transportation infrastructure (Martinez et al. 2018); (c) FHWA also has the Absorptive capacity, Restorative capacity, Equitable access, and Adaptive capacity (AREA) framework and its predecessor, the Vulnerability and Adaptive Framework (VAF), to calculate transportation-specific quantitative and qualitative resilience performance measures (Filosa et al. 2017); (d) the American Society of Mechanical Engineers developed the Risk Analysis and Management for Critical Asset Protection (RAMCAP) process to identify hazards and quantify risks associated with them (ASME-ITI 2009); (e) Composite of Post-Event Well-Being (COPEWELL) is a model of community resilience, which uniquely incorporates local data and community capital into its calculations (Sun et al. 2020; US Census Bureau 2017); and (f) the Interdependent Networked Community Resilience Modeling Environment (IN-CORE), developed as part of the

TABLE 1 Resilience question matrix for identifying transportation system performance measures

Asset categories	Stages of resilience		
	Absorptive capacity	**Adaptive capacity**	**Recovery capacity**
	Impacts before asset loss of capacity	*Impacts during asset loss of capacity*	*Impacts to rebuilt asset post loss of capacity*
Daily passenger traffic operation	How well can the asset maintain typical passenger traffic operations during the disruption, but before the asset fails due to the hazard?	How well can the rest of the system support rerouting passenger traffic operations if this asset fails due to the hazard?	How well can the asset support passenger traffic operations as it is being rebuilt after failing due to the hazard?
Asset pavements & materials	How well can the design of the asset pavement and materials increase the time before it fails due to the hazard?	How well can the design of the asset pavement and materials maintain its structural integrity through failure due to the hazard?	How well can the design of the asset pavement and materials be quickly rebuilt after failing due to the hazard?
Asset bridge structural & geometric design	How well can the roadway layout and structural asset elements increase the time before it fails due to the hazard?	How well can the layout and structural asset elements maintain its structural integrity through failure due to the hazard?	How well can the layout and structural asset elements be quickly rebuilt after failing due to the hazard?
Hydrology & environment	How well can the area surrounding the asset and its own hydrological/ environmental status/design increase the time before it fails due to the hazard?	How well can the area surrounding the asset and its own hydrological/ environmental status/design maintain its structural integrity through failure due to the hazard?	How well can the area surrounding the asset and its own hydrological/environmental status/design be quickly rebuilt after failing due to the hazard?
Community access & equity	How well can the asset support access to the preferred evacuation destinations for all resident groups before the asset fails due to the hazard?	How well can the rest of the system asset support access to the preferred evacuation destinations for all resident groups if this asset fails due to the hazard?	How well can the asset support return of residents of all groups as it is being rebuilt after failing due to the hazard?
Emergency planning preparation	How well prepared is the community leadership for a potential failure of this asset due to the hazard?	How well can the community leadership react if this asset fails due to the hazard?	How well can the community leadership rebuild this asset if it fails due to the hazard?

NIST Center for Risk-Based Community Resilience Planning (CoE) by a team at Colorado State University, is a robust modeling and simulation framework for community resilience that connects community socioeconomic relationships with resilience performance (Chen et al. 2019; Dunne et al. 2012).

In summary, while each application provides excellent insights into measuring resilience for specific infrastructure types, they are neither comprehensive nor able to be compared. Successful resilience decision-making needs to be able to understand the relative benefits and costs across *many* different potential projects in order to select the most cost-effective option. In many cases, planning decisions based on only assessing vulnerabilities for a specific infrastructure can lead to poorly-allocated funding that overemphasizes hardening existing infrastructure or projects that duplicate resilience benefits. Performance measures of benefits include infrastructure life cycle, economic growth, operational system efficiency, and community quality-of-life. These performance measures should also consider impacts at all stages of a hazard event, including preparing for, mitigating, adapting to, and recovering from the event. Quantifying performance measures for vulnerabilities, impacts, benefits, and costs associated with resilience improvement in rural and urban areas is dramatically different. There are many opportunities in rural and urban contexts to both define these measures and develop the relationships to show how infrastructure changes can make systems more resilient.

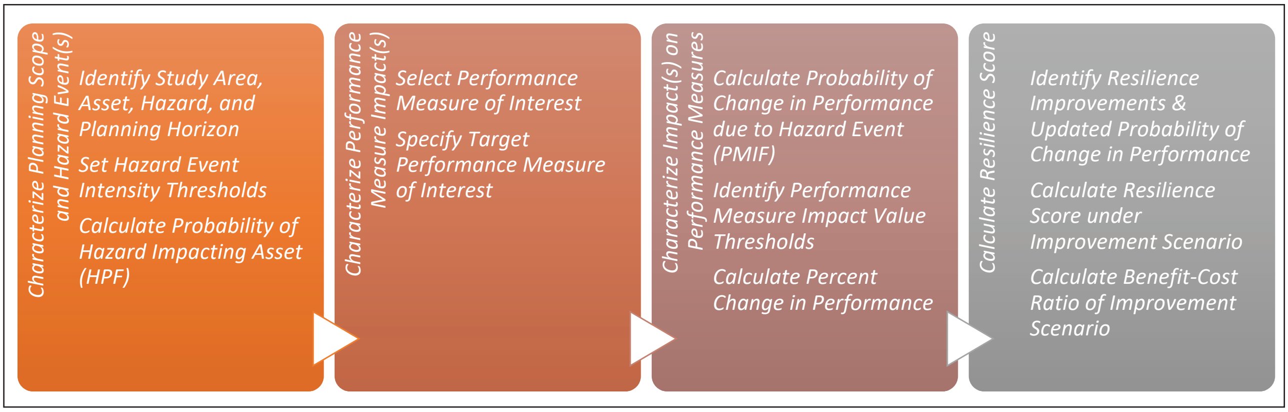

FIGURE 1 Performance-based Resilience Evaluation Process (PREP) framework phases and steps.

Moving Forward with Equitable Transportation System Performance-Based Resilience Planning and Decision-Making

As mentioned previously, there are many efforts to develop procedures that incorporate community-based performance measures into infrastructure resilience evaluation and decision-making. For example, the NIST-funded IN-CORE program is able to consider community infrastructure (e.g., building) damages due to hazard flooding. Another example, specifically focused on transportation-system issues, is the *Performance-based Resilience Evaluation Process* (PREP) framework, developed at Auburn University (Cordero et al. 2023). The PREP framework supports four main objectives necessary for successful implementation: (a) quantify transportation resilience from weather impacts on transportation infrastructure, including impacts on structural, operational, environmental, economic, and community systems; (b) utilize consistent, data-driven, and scalable performance measures to characterize and quantify resilience (and its impacts) across different infrastructure; (c) present a process that is flexible, data-driven, performance-based, adaptable, and scalable; and (d) rooted in existing extreme weather and transportation planning theory. Overall, the PREP framework is practical, operational, and replicable to multiple infrastructure assets in rural and urban areas.

PREP provides a comparable measure of resilience based on community-defined levels of performance. While community-defined performance measure-based planning is useful in regions of all sizes (because it takes into account the unique needs, strengths, and challenges of each community), it is especially useful to implement this approach in small/rural areas to highlight the social capital and notably more diverse needs of these remote and smaller resident populations. Specifically, PREP's calculated resilience is a unitless, comparable, and scalable factor, defined as *the expected percent change in performance measure from target value (percent)*. This value is calculated based on (a) probabilities of experiencing a hazard event (i.e., threats), (b) probabilities that an infrastructure will experience changes in performance based on that hazard event (i.e., vulnerabilities), and (c) the actual changes in performance (i.e., losses).

The PREP framework includes 4 main steps, as seen in figure 1, which can be implemented by any small, rural, or urban area to describe any type of infrastructure. The first step has the user define the planning scope of the resilience analysis (e.g., study area, infrastructure asset of interest, hazard event[s] of concern, planning horizon), as well as the characteristics of the hazard event. The second step has the user define how they are evaluating the performance of their infrastructure, including setting target performance levels before the analysis begins. The third step has the user quantify the relationship between the hazard events and infrastructure performance. The fourth step brings together the probabilities of experiencing a hazard event intensity and the probabilities of changes in performance due to these hazard events to calculate a weighted change in performance measure, or the normalized measure of resilience. Users can then evaluate and compare the benefit-cost relationships or net-savings analysis for multiple potential improvements based on how the resilience scores change.

PREP has been used in support of a variety of federally- and regionally-funded research projects focused on airport resilience to extreme weather, com-

munity resilience to coastal flooding events, and pavement lifecycle resilience to flooding and heat. Each project was able to compare resilience across small and large geographies in a fair and equitable manner.

When we create resilient infrastructure, it also means we are creating resilient economies, resilient operational systems, and a resilient quality of life. This investment is critical for all communities across the United States, and especially for small and rural communities that are currently *more vulnerable* to natural hazards (due to lack of access to resources and having more high-risk institutions, like agriculture) and *less likely* to be prepared for them. Therefore, as we move forward to decide where to invest in resilient infrastructure, we must use decision-making tools, like PREP, that equitably recognize the needs, experiences, social capital, and projected benefits of all communities, regardless of size, or their ability to *absorb*, *adapt to*, and *recover from* disruptive extreme weather events. The most cost-effective and equitable way to ensure all of our US infrastructure systems are resilient to natural hazards is through a comprehensive and collaborative approach.

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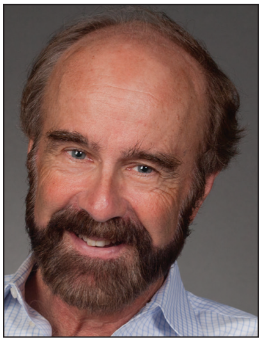
Engineers are crucial to the understanding and integration of natural and industrial cycles.

Engineering Natural and Industrial Systems for Integrated Designs

Benedict Schwegler



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To most engineers, the concept of "industrial cycles" is almost intuitive. Industrial systems and the power cycles with which they operate are fundamental to engineering design and system operation. The engines that create and utilize power for the world's industrial enterprises are all based on thermodynamic cycles that form the basis of engineering education and practice. Indeed, the names of these cycles, like the Diesel cycle (diesel engines), the Otto cycle (most gasoline automobile engines), and the Rankine cycle (solar thermal heat pumps), have become almost commonplace. The oldest of these, the Carnot cycle, is the basis for every measure of thermal engine efficiency. These concepts have been extended to the design of manufacturing equipment and even supply and disposal cycles for industries both large and small.

"Natural cycles," on the other hand, have been, until now, less intuitive for many engineers. The fact that natural cycles are many orders of magnitude more complex than typical human engineering designs has contributed to the apparent paucity of "simple" intuitive explanations. Considering that nature has a head start of several hundreds of millions of years to initiate and improve natural cycles, it would be amazing indeed if they had evolved to less complexity rather than greater. Nonetheless, in the last few decades there has been a resurgence in interest in understanding, imitating, and creating new types of industrial cycles either based on or inspired by natural systems. An important conceptual breakthrough in our understanding of

natural cycles has been the development of the idea of ecosystem "functions" based on their thermodynamic behavior, as first articulated by the ecologist Raymond Lindeman (1942).

Subsequently, the appreciation of natural or ecosystem functions has been augmented by evaluations of their economic values. This approach has led to a hugely productive outpouring of scientific, engineering, and economic research toward an understanding of how these ideas can be used to improve sustainability outcomes. Typically, the economic value of ecosystem functions is evaluated in terms of the "services" that are provided by the functions, a term first coined by biologists Paul Erlich and Anne Erlich (1981). In a practical sense, this is the same method used by engineers to evaluate the social, safety, or health benefits of industrial cycles or individual infrastructure elements like waste treatment plants, transit safety systems, or water supply. In their seminal article, economist Robert Costanza and his colleagues (1997) calculated the total value of the earth's ecosystem services at about US$(2007)46 trillion/year and in the updated version in 2014 that value (still normalized to 2007 US$) was calculated at US$145 trillion/year (Costanza et al. 2014).

To emphasize the economic benefits of those natural ecosystem functions, the services are typically grouped into four areas: *provisioning*, as in agriculture; *regulating*, as in pollination or nutrient cycling; *supporting*, as in the development of soil fertility; and *cultural*, as in appreciation of nature – or more to the point, direct health benefits like improved hospital outcomes when patients have access to natural ambiance.

Despite all the excellent work done so far, the *interactions* between natural and industrial systems have been less well understood than the individual cycles. Nonetheless, a lot of progress has been made in the last century in understanding those interactions, and it is useful to review typical highlights and successes before discussing future opportunities. These successes have been driven by two self-propagating, major changes in our current civilization: urbanization since the mid-nineteenth century and the expansion of consumer products in the twentieth century. Four of the most important examples are:

1. Water supply and wastewater treatment in the nineteenth century are two of the most impactful achievements of civil engineering. What was new and significant in the nineteenth century was the direct link to public health, most notably the elimination of cholera (Hardy 1993). Further demonstrating the link between natural and industrial cycles, the treatment of wastewater stimulated the evolution of natural microbial communities to remove biological oxygen demand from wastewater. One such process practiced today is known as activated sludge treatment.

Not only are engineers at the center of the design and operation of virtually all industrial cycles, but they also contribute to the understanding and integration of natural cycles.

2. The twentieth-century "green revolution" of agriculture, especially the industrial production of nitrogen fertilizers, fundamentally altered the modern food supply system. The green revolution produced vastly greater quantities of food per hectare and vastly greater quantities per labor hour of the agricultural worker. Together with transportation, this virtually eliminated the cycle of famines that had always been part of human history. The global nitrogen cycle is driven by biological nitrogen fixation by diazotrophic bacteria, the most well-known of which are found in the root nodules of legumes. The conversion of atmospheric nitrogen to nitrate or ammonia is an essential first step for virtually all biosynthesis, particularly amino acids and proteins. The industrial Haber–Bosch process duplicated the ecosystem function (but not the process) of converting atmospheric nitrogen to ammonia nitrogen, thereby virtually eliminating this critical capacity limitation.
3. The development of synthetic fibers since the end of World War II has been a world-changing event. For all of human history up until that point, only two types of fibers existed, both of biological origin: cellulosic (cotton-like) and protein-based (woollike). However, as of 2022 more than 61% of all fibers manufactured in the world were synthetic. In principle, all the synthetic fibers today could be made from bio-

logical sources, in essence duplicating an ecosystem function. The fact that they are made from petroleum illustrates one important interaction between natural and industrial systems – the end-of-life part of the industrial polymer fiber cycle is most definitely not as well integrated into the comparable degradation functions as the cellulose and protein precursors (Muthu 2020). This failure to consider the end-of-life part of the cycle is a major contributor to the enormous quantity of plastic and particulate waste in the environment today.

The idea that ecosystem functions are the infrastructure of our planet explicitly places engineers at the key intersection of research, invention, and policy.

4. The development, use, and subsequent elimination of chlorofluorocarbon (CFC) refrigerants and propellants is one of the best examples of discovering and reacting to the unexpected and detrimental interactions between natural and industrial cycles. CFCs are a wholly invented industrial product with virtually no biological analogs, and no natural function to replace. However, as is now widely known, the final fate of these molecules in the stratosphere resulted in the Antarctic ozone "hole" and a harmful increase in ultra-violet radiation (UV-B) with direct negative consequences for human and ecosystem health. The fact that this threat was recognized and eliminated is cause for optimism that the interactions between natural and industrial cycles can be understood and harmful interactions mitigated.

Many of these industrial cycles were controversial at the time they were developed but are now such a basic part of our industrial systems that few recall the controversies. The main point of this introduction is to demonstrate how intimately natural and industrial systems are connected and how the grand challenges of providing sustainability, health, and quality of life depend on understanding those relationships and applying them to the engineering design of coupled natural and industrial systems.

The Engineering Value Proposition

Not only are engineers at the center of the design and operation of virtually all industrial cycles, but they also contribute to the understanding and integration of natural cycles. Two of the most self-evident features of natural systems are their size and complexity, particularly at the organism and ecosystem scales. However, the earliest and currently most successful examples of integrating natural and industrial cycles occur at the organism level. For example, the fermentation of mead in the Neolithic era is the distant ancestor of the genetic engineering of microorganisms to produce vaccines. The first did not require engineering, but the second would not have been possible without the skills of the engineer. However, as our understanding of these interacting cycles improves, we see that the deeper we go—past the complexity of multicellular organisms to the cell and to the level of biochemistry—the more the similarities between natural and industrial cycles become evident. Analyzing and understanding functional relationships of biochemical processes (in essence a type of "deconstruction") is important fundamental research. However, the reverse processes of "construction," invention, and recombination are where the talent of the engineer is critical.

Given this background, it should be clear that engineers contribute to integrating natural and industrial cycles in many ways, but four especially stand out:

Context – Engineers can and do think of natural cycles as "infrastructure of the planet" and understand that natural cycles and industrial cycles are intimately connected. The idea that ecosystem functions are the infrastructure of our planet explicitly places engineers at the key intersection of research, invention, and policy. It is a concept that makes the *role* of the engineer intuitive, even if the scale, details, and complexity of interactions are daunting. The infrastructure-of-the-planet context also carries the implication that it must be maintained, and that it is critical for the health, well-being, safety, and quality of the lives that depend on it.

Tools – The tools of engineering can contribute to understanding the functions of natural systems and how

to use and maintain them. Principal among these tools are the foundational tools of mathematics, mass and energy balances, and structural and materials analysis, as well as secondary tools like design, modeling, simulation, and decision support. Taken together, these tools have sustainability as one of their major goals and underscore the value of engineering as a self-evident aspect of integrating natural and industrial systems.

Scale – Engineers are critical for the integration of the flows of natural and industrial systems (material flows, energy flows, and transformations between industrial and natural systems). Often, the volume and scale of both natural and industrial cycles are difficult to grasp for untrained and inexperienced stakeholders. Global climate change is so vast that it is difficult to comprehend, even for professionals. But one small example is clarifying: the Deepwater Horizon oil spill in the Gulf of Mexico in 2010 lasted 89 days, killed 11 people, and spilled 4.9 million barrels of oil into the Gulf. This disaster is usually ranked as one of the worst environmental disasters in history. The scale of it is remarkable—most especially because the entire episode released not even 25 percent of the US daily consumption of oil in 2022!

Integration – We are on the verge of a tremendous transformation in industrial systems, resulting in engineers developing "synthetic" natural systems that will become the basis of the next generation of industrial systems. The integration likely to occur in the next decade will be the result of a deeper understanding of the fundamental biochemistry and specific enzymes required to produce most of today's synthetic products at a scale that integrates the natural cycle of enzyme evolution with the global scale of industrial production cycles.

Why Engineers and Engineering Disciplines?

Engineering could not be nearly as impactful were it not for the work of the related physical and mathematical sciences, as well as the humanities, medicine, and law. Engineering and engineers take the work of these other disciplines to create practical solutions that answer specific needs. That said, it takes time—and in some cases, a lot of time—to turn basic science into engineering design. It took nearly two generations after Isaac Newton wrote *Principia Mathematica* for the first engineering paper to be written. That is not to say that the builders of the medieval churches of Europe and the pyramids were not capable of greatness, since they obviously were. What is different is that after Newton, quantitative predictions of forces, reactions, structures, and continuous motion became possible, whereas before, they were not.

The complex task of turning scientific knowledge and human needs into physical designs that will improve the quality of life is the real goal of the engineering profession.

Fortunately, engineering does exist, and the complex task of turning scientific knowledge and human needs into physical designs that will improve the quality of life is the real goal of the engineering profession. This is particularly true as we address ever more difficult challenges in integrating natural systems with industrial systems.

The Future of Integrated Natural and Industrial Systems

The consumer economy as we know it today is almost entirely the creation of the mid-twentieth century, during and immediately following World War II. This transformation, including the revolution in chemistry and chemical engineering education and practice that enabled it, was catalyzed by a relatively small group of engineers and, surprisingly, one single company, the Scientific Design Company, eponymously named by the founding scientists (Spitz 2019). This happened with incredible speed because the industrialization and factory production of the nineteenth century, which in large part automated the production of previously artisanal products, were paired with the development of entirely new materials and engineering technology from the petrochemical industry. Until this point, the chemical industry used wood, coal, and alcohol as raw materials; and, after this point, it used petroleum.

I believe we are at a similar inflection point today in the production of commodity raw materials for consumer

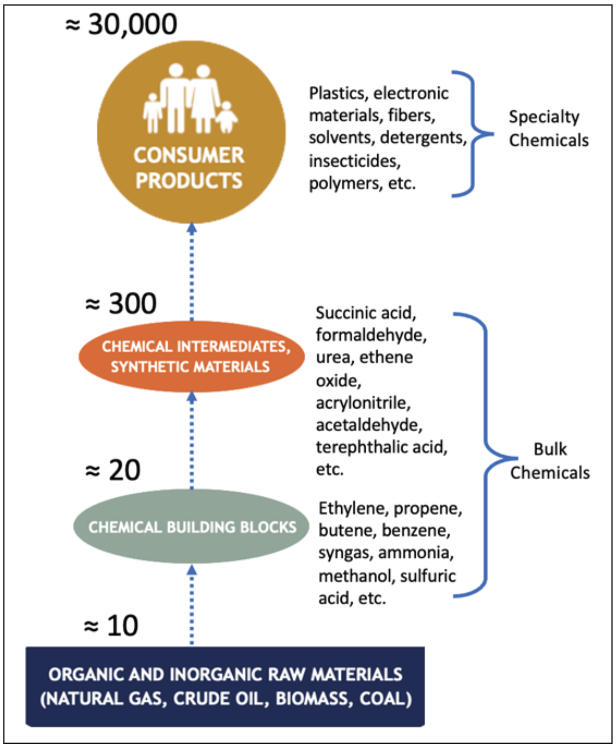

FIGURE 1. The chemical industry scale and value chain.

products. Natural systems (like fermentation) have shown the versatility, specificity, and economic viability to produce vaccines; pharmaceuticals; vitamins; and large-scale quantities of ethanol, polyols, amino acids, and polysaccharides. However, most of these processes are still not economically viable approaches for commodity chemicals compared to the petrochemical processes that feed the consumer products industry.

Fortunately, engineers have learned a great deal from the study of natural processes. New understandings of membrane associated protein complexes and individual soluble enzymes have given us a deeper sense of how nature has evolved a biological conversion machine of astonishing precision. Nature, at the cellular scale, builds and converts molecules literally atom by atom and electron by electron! The goal of cell-free synthesis is to accomplish this same feat in an engineered and controlled system.

The energy flow that enables this "machine" also occurs at the molecular and atomic scales. In particular, the role of energy carriers, sometimes called enzyme cofactors (or coenzymes), appears to be a critical part of the puzzle. These carriers enable the electron-by-electron synthesis that characterizes biological processes. Principal among the energy carriers are the roles of nicotinamide adenine dinucleotide (NAD[H]), adenosine triphosphate (ATP), and adenosine diphosphate (ADP). These energy carriers cycle between an oxidized state (NAD or ADP) and a reduced state (NADH or ATP) during metabolism but are not consumed during the metabolic synthesis reactions. One of the most important keys to cell-free synthesis is the number of cycles the energy carriers can support before they degrade. This is a subject of much interest today, and at least one group of scientists believes they have a method to allow NAD to be recycled indefinitely.

This knowledge has brought us to the point where, today, the development of cell-free synthesis pathways, coupled with the existing genetic engineering technology, appears poised to create a revolution comparable to that of the petrochemical industry in the mid-twentieth century (Carlson et al. 2012).

As shown in figure 1, one important feature of the cell-free approach is the leverage over the complete set of consumer products that is inherent in the production of chemical intermediates. Since the end products are produced from the intermediates, rendering the intermediates carbon neutral gives a leverage of two to three orders of magnitude over the alternative of reducing the carbon footprint of the consumer products themselves.

As good as this approach to cell-free synthesis of intermediates may be in terms of reducing the carbon footprint of consumer products and their intermediates, there is still another opportunity that biochemical engineers are poised to study—an opportunity that may well be one of the most significant integrations of natural and industrial cycles. The great specificity of enzymatic catalysis compared to inorganic catalysis of the petrochemical industry implies that entirely new types of polymers can be engineered to improve the end-of-life decomposition of consumer products (Ahmed et al. 2019; García-Junceda et al. 2015).

Conclusion

Natural systems have formed the basis of human survival since *Homo sapiens* first left Africa. The economic value that these natural systems provide has been calculated using several innovative and detailed techniques—and that value is enormous. These natural systems interact with all human-constructed industrial systems in ways that allow humans to extend and increase the value of those natural functions but also to degrade and destroy others. Engineers now understand that both must be considered to create designs for the future.

Now, for the first time, it seems we can see the possibility of engineering our own natural industrial systems so that their explicit goals are health, well-being, and sustainability.

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Engineers are proving invaluable in the quest to sequester carbon.

Engineering the Sequestration of Carbon


Birol Dindoruk


Silviu Livescu

Birol Dindoruk and Silviu Livescu

Anthropogenic greenhouse gas (GHG) emissions have reached very high levels, causing many observable, long-term climate changes such as rising sea levels, warmer and more acidic oceans, diminishing ice coverage, and increasing global surface temperatures. Furthermore, multidimensional chemical changes are altering the global equilibrium of the earth's systems. Climate change has started to affect natural ecosystems and communities. Consequently, how we manage and allocate natural resources necessitates significant revisions (IEA 2022a; IPCC 2007). Widespread incidents such as heat waves, wildfires, floods, droughts, and cyclones could be a result of climate change. These events pose a significant risk to the entire ecosystem and hamper global socioeconomic progress.

The 2°C temperature target is the international climate policy goal of limiting global warming to less than 2°C by 2100 compared to the pre-industrialization level (IEA 2021). This would lead to CO_2-equivalent emissions of CO_2 concentrations of 450 ppm by 2100, adhering to the most rigorous Representative Concentration Pathway (RCP2.6) established

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by the IPCC (2014) and Calvin and her colleagues (2009). Earlier efforts to decrease GHG emissions have not been sufficient in light of population growth and economic development. Thus, average surface temperature increases between 3.7°C and 4.8°C above pre-industrial levels by 2100 have been predicted (IPCC 2007). This can be attributed to CO_2 emissions that have increased significantly since the Industrial Revolution. Figure 1 shows that the energy generated is almost linear with CO_2 generation. As such, effective adaptation and mitigation strategies have been deemed crucial to meet the 2°C temperature goal and limit global warming. In response, the Paris Agreement was introduced during COP 21 (UN Climate Change Conference) to reinforce the global commitment to address climate change, prompting nations to collaborate and outline actionable plans known as nationally determined contributions (NDCs). To reach the ambitious net-zero target, we need to reduce GHG emissions by 40%–70% by 2050 compared to 2010 levels and aim for neutral to negative emissions by the end of the century (IEA 2021). In planning the execution of these measures, several adaptation and mitigation scenarios have been developed, offering climate projections up until the end of the twenty-first century (IPCC 2014) (figure 2).

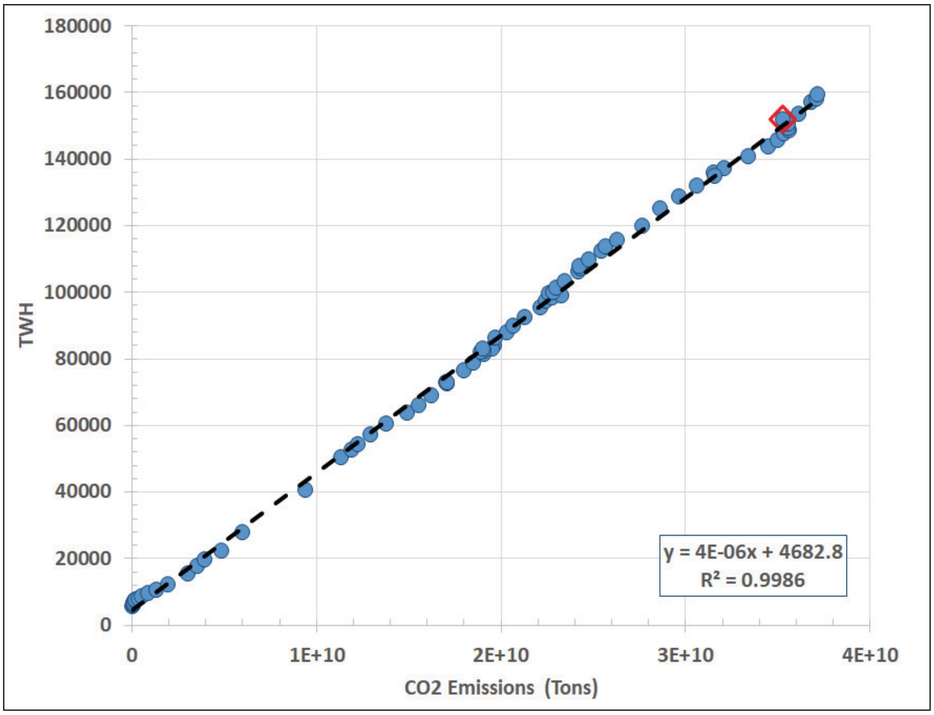

FIGURE 1 Global energy consumption (TWH) versus global CO_2 emissions until the end of 2021 (2020 is marked with a red symbol to show the impact of COVID-19).

CO_2 emissions have increased significantly since the Industrial Revolution and have paralleled the growth in power requirements. Following the linear trend shown in figure 1, if more energy is produced with less CO_2 emissions at scale, we should see an upward trend deviating from this linear fitted line (Dindoruk and Johns 2022).

During the past two decades, and especially during recent years, there has been significant momentum in terms of the development of CO_2-production-reducing

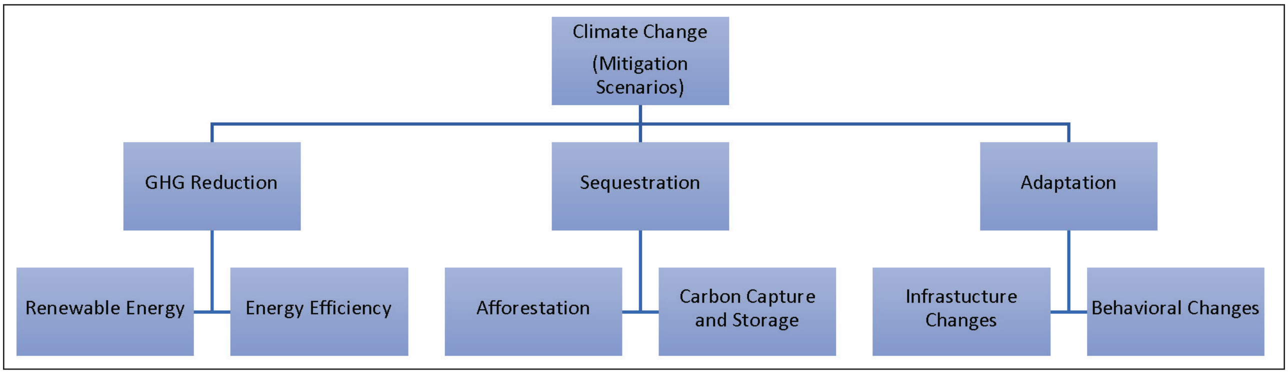

FIGURE 2 Climate change and mitigation scenarios.

technologies. Due to the size and urgency of the problem of CO_2 emissions, many options have been considered. Because of the magnitude of this challenge, one key solution, subsurface storage, is especially important. This is one of the key solutions offered by the oil and gas industry and the hydrocarbon industry. The oil and gas industry is one of the few industries dealing with large-scale systems with high-pressure, high-temperature conditions involving complex fluid behavior, reactivity, rock-fluids, their transport in the subsurface, and geological uncertainties. This capability, combined with the potential to safely store large amounts of CO_2 in saline aquifers and depleted oil and gas reservoirs, makes the aggregate experience gained in the hydrocarbon industry, which focuses on subsurface engineering, essential. Moreover, the hydrocarbon industry has the critical domain expertise to reach and manage deep reservoirs onshore and offshore. These capabilities and know-how put the integrated hydrocarbon industry at the forefront of the endeavor to capture, utilize, and store CO_2 and other GHGs in the subsurface.

From a technological perspective, the oil and gas industry has the tools and expertise to implement and adopt carbon capture, utilization, and storage projects and contribute to a sustainable future.

Consequential technical studies have been proposed to implement carbon capture, utilization, and storage (CCUS) projects. In the context of technological challenges, capacities, and perspectives, we categorize the proposed options into three groups: (1) currently available technologies, (2) near-future technologies, and (3) long-term technologies. Many technologies used in CCUS projects are functions of the energy price and local incentives. Therefore, while focusing on the technical aspects, we also discuss some of the enabling factors. Some of the elements of these technologies are related to source-sink matching. CO_2 source-sink matching means pairing a CO_2 emitter, such as a power plant, with a potential reservoir, considering factors like health, environment, economy, and safety. In addition, direct air capture (DAC) is being highlighted as a remedy for this issue while the costs are still an impediment to widespread use (IEA 2022b, Kuru et al. 2023).

In this article, we examine methods that use CO_2 and other gases to improve the recovery of hydrocarbons and simultaneously store concentrated CO_2 in the subsurface. We also make the case that, from a technological perspective, the oil and gas industry has the tools and expertise to implement and adopt CCUS projects and contribute to a sustainable future. We outline current and future challenges and opportunities, along with the essential role of engineers in securing viable, robust solutions.

CO_2 Mitigation and Sequestration

Overall, increases of atmospheric CO_2 concentrations demand very complex mitigation measures. The first approach is to address the root causes in order to reduce the GHG emissions into the atmosphere. This requires new energy and also contributes to climate change. The main origins of methane are fugitive systems at scale and increases in energy efficiency, regardless of the energy source. Here, while we will not go into the details, mitigation strategies for GHG gasses are not limited to CO_2 emissions. Other GHG gases, such as methane, emissions from hydrocarbon production, and agriculture are also contributors to climate change. Potential future release of methane from natural gas hydrates is also one of the most important byproducts of climate change.

Another general approach for mitigation scenarios is adaptation—including infrastructural and behavioral changes—that also needs to be at a societal scale. Behavioral aspects of the CO_2 equation have latency and require the education of the general public worldwide. The third mitigation approach, sequestration of CO_2, is probably one of the most important aspects of the energy transition. The engineering of CO_2 sequestration itself requires three main domains: (1) separation technologies, (2) transportation and midstream operations, and (3) broader subsurface engineering to identify storage sinks and design efficient systems to safely store CO_2 underground.

The reduction of GHG emissions to net zero is going to take decades (IEA 2022a). Therefore, CO_2 reduc-

tion solutions are needed as soon as possible. There is already a global vision to mitigate, and even reverse, the effects of GHGs. There are many options proposed in the literature when it comes to achieving these goals, and all these options need to be considered. In the coming years, use cases in terms of "where it fits and when it fits" may be more common, as the alignment of various factors—such as sources, sinks, policies, incentives, etc.—may vary according to place and time.

Among the many options for reducing CO_2 emissions discussed by the hydrocarbon industry are:

- Subsurface storage of CO_2 in saline aquifers and depleted hydrocarbon reservoirs
- CO_2 mineralization in reactive rocks
- Bio-domain solutions, etc.

The current focus of the hydrocarbon industry is on subsurface storage, thanks to the existing infrastructure and potential capacity. While mineralization in mafic rocks constitutes an important option, most of the past and present larger-scale implementations are in aquifers and hydrocarbon reservoirs. However, implementation at scale requires expertise in various fields of earth resources engineering, specifically in the discipline of petroleum engineering, which brings up the issue of adjusting the current college curriculum and training subsurface engineers and scientists in the skills needed for CO_2 sequestration.

Effective CO_2 sequestration requires deeper understanding in multiple areas. One of the key factors that requires a mindset change is that both temporal and spatial scales for CO_2 sequestration differ substantially from the problems currently encountered by the oil and gas industry. The post-injection temporal scale and associated assurance and surveillance tasks are different. While the time scale of oil and gas reservoirs is multi-decade, engineering turns into a multi-century containment concern for CO_2 sequestration. Moreover, while the spatial scale might be similar, the large storage capacity needed suggests that untested subsurface volumes will be required, which are more likely to face a wider spectrum of defects and heterogeneities than proven hydrocarbon reservoirs.

In addition, a better understanding of phase behavior at microscale and its impacts on reservoir-scale flow is needed. That understanding can be obtained through theoretical, numerical, and experimental approaches. For example:

- Phase behavior: CO_2 will dissolve and/or mix with other hydrocarbons and the aqueous phase (Ratnakar et al. 2023), and mutually, some of the species existing in the reservoir will dissolve in the CO_2 as well (mutual solubility and phase behavior as dictated by the thermodynamics of phase equilibria). Thermodynamic properties as well as fluid viscosities are integral parts of the coefficients of the equations that define mass balance and flow in porous media. Therefore, those thermodynamic properties that define the phase behavior and interaction of CO_2 with other components present have an impact on the transport and fate of the species as they reside in the porous media.
- CO_2 can interact with some of the minerals as well as man-made components at and near the well.
- Some CO_2 can get adsorbed in porous media, both in the reservoir rocks and in the caprock.
- Couplings of (1), (2), and (3) above within the time and temporal scales of CO_2 sequestration.

The reduction of GHG emissions to net zero is going to take decades. Therefore, CO_2 reduction solutions are needed as soon as possible.

Principal fluids in the reservoir may be combinations of hydrocarbons and water. Even in deep saline aquifers, some small amounts of hydrocarbons might be present, from caprock to the aquifer itself. Capturing the time-dependent behavior of the subsurface system (CO_2, in-situ fluids, porous medium, adjacent formations, wells, etc.) via surveillance requires a full understanding of the physics of these interactions so that inverse modeling of the system can be done. The static microscopic behavior and static parameters such as solubility are coupled with the multiphase, multicomponent flow in porous media, making the problem more complex in time and space (Dindoruk et al. 2021b). In addition, impurities contained in the CO_2 related to CCUS hubs

with multiple emitters using the same transport and storage infrastructure can also play an important role in shared pipelines/injection facilities, especially near the wellbores, as they may accumulate near the wellbore beyond their tolerated concentrations. To be able to screen many potential sink candidates worldwide and implement the projects at high-graded systems for CO_2 sequestration development and utilization/deployment, a successful worldwide CCUS program has to master the following technical components:

- Methodology development, including fast screening (with physics-based and/or statistical models) using easy-to-measure input proxies (i.e., from selected laboratory experiments, etc.), as well as the use of various machine learning and artificial intelligence algorithms.
- Hardware (i.e., sensors) and surveillance, including both reservoirs and wells (Dindoruk et al. 2021a) in order to demonstrate long-term storage and structural and chemical containment.
- Fast numerical techniques, including advanced computational methods looking at the problem in multiple time scales and incorporating 4D seismic and static/dynamic models to efficiently model plume migration and demonstrating containment.

The next generation of engineers should be educated in the CO_2 domain, and all projects should be evaluated in net-zero and/or CO_2 reduction aspects as well as in usual economic terms.

In order to address some of the subsurface aspects of the CO_2 disposal/sequestration processes, we can tap into the experience gained from gas injection processes that are implemented for oil recovery as one of the oldest enhanced oil recovery (EOR)/improved oil recovery (IOR) methods.

CO_2 Capture

The purpose of CO_2 capture is to create a concentrated CO_2 stream that can be transported to a storage site. If the gas stream for the storage site has low CO_2 concentration and/or CO_2 is mixed with significant amounts of other gases, such as N_2, then the storage space will be either wasted and/or other gases will lead to higher pressures for a given amount of CO_2 to be stored. Concentrated CO_2 stream generation is particularly needed for large, centralized sources such as power plants and large industries. CO_2 capture technologies also enable the large-scale production of low-carbon or carbon-free electricity and fuels, as well as smaller-scale or distributed applications. However, the energy required to operate CO_2 capture systems reduces the overall energy efficiency, leading to increased fuel consumption compared to the same type of plant without capture.

CO_2 capture technologies involve the separation of CO_2 from emission sources through the application of the four main capture technologies (NPC 2019). These are absorption, adsorption, the use of membranes, and cryogenic processes (NPC 2019). The choice of the appropriate technology depends on factors such as gas stream volume, CO_2 concentration of gas streams, contaminant concentrations, and purity, which will also impact the cost of capture. Absorption technologies are the most mature and widely used. Examples of locations and projects using absorption technologies include the Terrell Natural Gas Processing Plant in Texas, the Trona Plant in California, the Great Plains Synfuels Project in North Dakota, the Sleipner Project in Norway, the Boundary Dam in Canada, and the Quest CCS Project in Canada. Adsorption and membrane technologies are less mature, and their applications are less widespread.

Research and development efforts are underway to create more efficient and cost-effective sorbents (adsorption technologies) that may require less energy compared to absorption capture with solvents. Similar advances in membrane technologies would reduce the cost of CO_2 capture, especially around gas streams with low CO_2 concentrations. Cryogenic capture technologies are the least mature but have the most potential across several industries. In summary, no single capture technology can be universally applicable at present. Research and development efforts should focus on developing efficient and low-cost capture technologies covering the whole spectrum to enable large scale CCUS developments.

In general, capture facilities that need to separate CO_2 from dilute sources are more expensive, with a larger footprint and higher operating expenses. Overall, separation of CO_2 from the gas streams requires extra energy use and, therefore the costs will go up. As the concentration of CO_2 decreases, the minimum work required for separation increases along with the cost of separation (Wilcox 2012). The minimum thermodynamic work or energy required to capture CO_2 from various coal- or gas-fired power plants is correlated with how dilute the CO_2 in the source is. For example, DAC requires the most thermodynamic work because of the low CO_2 atmospheric concentration (currently 420 ppm). Integrated gasification combined cycle (IGCC) plants, with flue gas CO_2 concentrations ranging from 40 to 60%, require 1/10th to 1/5th of the thermodynamic work required for DAC (Wilcox 2012). Therefore, it is important to see how much CO_2 can be sequestered for a given amount of work (cost). However, CO_2 transportation from source to sink should also be considered. For example, a very high concentration CO_2 source might be so far away from a matching sink that transportation constraints and cost make it prohibitive. As more efficient plants with capture technologies replace older, less efficient plants, the net impacts will align with clean air emission goals for fossil fuel use. Improving the energy requirements for capturing and enhancing energy conversion processes is an important priority for minimizing environmental impacts and costs.

Currently, CO_2 is routinely separated at some large industrial plants (such as gas processing plants), although the primary purpose is to meet process demands rather than storage. While CO_2 capture has been applied to several small power plants, there have been no large-scale applications at power plants, which are the major sources of current and projected CO_2 emissions. There are three main approaches to CO_2 capture: post-combustion, oxy-fuel combustion, and pre-combustion. These methods are applicable to industrial and power plant designs. In post-combustion capture, fuel is burned at the power plant, and no special design is required. At present, commercially available technologies for post combustion capture are centered around chemical absorption technologies. It is the most practiced method due to considerable industrial experience with similar processes. CO_2 is absorbed from the flue gas in a separation tower using a solvent and regenerated by heating in a recovery column at elevated temperatures (higher than 100°C). Post-combustion is advantageous because it can be applied to pre-existing plants, where components can be replaced, developed, and upgraded without fundamental impact on the core of the power plant and its operations. Pre-combustion capture, typically operated with Integrated Gasification Combined Cycles (IGCC), involves gasification and partial oxidization of the fuel to produce CO_2 and hydrogen, which are then separated, commonly using physical absorption processes. Oxyfuel combustion separates oxygen from air using established cryogenic methods and then burns the coal or gas fuel in a mixture of that oxygen, often combined with recycled flue gas to regulate the temperature of combustion (UKCCS 2023).

The creation of an enabling environment will be essential for the ability to execute sequestration projects worldwide.

Many studies have examined the performance and cost of commercial or near-commercial CO_2 capture technologies, as well as those of newer concepts. Current commercial CO_2 capture systems can reduce emissions by 80–90% per kilowatt-hour (kWh) generated, with an increase in the cost of electricity production ranging from 12 to 36 US$ per megawatt-hour (MWh). The overall cost of electricity for fossil fuel plants with CO_2 capturing ranges from 43 to 86 US$ per MWh, and the cost per ton of CO_2 captured or avoided ranges from 11 to 57 US$ (depending on plant type, size, fuel type, and other factors). These costs include CO_2 compression but not additional transport and storage costs. Improvements in CO_2 capturing methods and advanced power systems can significantly reduce capturing costs and energy requirements. It is estimated that improvements to commercial technologies can reduce capturing costs by at least 20–30% over the next decade, with further reductions expected from new technologies currently in development. However, realizing these cost reductions will require the deployment and adoption of commercial technologies as well as continued research and development efforts (IPCC 2005).

CO_2 Transport

Transportation is one of the critical stages of CCUS, connecting emission sources with storage sites. This step is regulated to ensure public safety and is subject to the regulatory framework governing pipelines and shipping. Currently, pipeline transport is already commonly used for long-distance movement of large quantities of CO_2, with a network extending over 2,500 km in the western United States, transporting around 50 million metric tons of CO_2 annually from natural sources to EOR projects (Noothout et al. 2014).

Current regulations specify that the CO_2 stream must be dry and free of hydrogen sulfide to minimize corrosion. However, it is possible to design corrosion-resistant pipelines that can safely handle gas containing water, sulfur oxides, and other contaminants. In general, the captured CO_2 must be as pure as possible. The presence of impurities, such as nitrogen and sulfur oxides, in the captured CO_2 stream can increase the costs of transportation and compression and lead to more uncertain behavior in the geological storage sites. When pipelines pass through populated areas, design considerations, overpressure protection, and leak detection are also crucial. Design considerations, overpressure protection, and leak detection are vital when pipelines pass through populated areas. The challenges faced by CO_2 pipelines are not significantly different from those encountered by hydrocarbon pipelines in similar areas and can be resolved. Alternatively, marine tankers are commonly used for transporting liquefied natural gas and hydrocarbon gases like propane and butane on a large scale. CO_2 can also be transported using the same technology, but on a smaller scale due to limited demand. Liquefied CO_2 shares similarities with liquefied petroleum gases, and the technology can be scaled up to accommodate large CO_2 carriers. A design study estimated the costs associated with the marine transport of 1 million metric tons of CO_2 annually using a 22,000 m^3 marine tanker over a distance of 1,100 km, including liquefaction, loading, and unloading systems. Although liquefied gas can also be transported by rail and road tankers, these options are unlikely to be considered attractive for large-scale CO_2 capture and storage projects (IPCC 2005).

Engineering the Future GHG Challenges

The next generation of engineers should be educated in the CO_2 domain, and all projects should be evaluated in net-zero and/or CO_2 reduction aspects as well as in usual economic terms. In order to achieve those goals, engineering education should include some elements of carbon footprint calculations for every step of project execution. GHGs do not recognize boundaries between countries, and every molecule counts. This is one way of saying there is only one world.

As highlighted earlier, the CO_2 capturing and sequestration processes require interdisciplinary engineering skills in not-so-well-defined systems, such as subsurface. In other words, future CCUS engineers will need to be skilled with tools, techniques, and education that can lead to operating large systems with geological uncertainties. In addition to basic engineering skills, the technical crew should be skilled with surveillance, inverse modeling, and reactive and predictive risk mitigation techniques. Such expertise, coupled with the newer technologies in surveillance and data analytics, will and should cater to the needs of future CCUS engineers. Many new degree programs should consider a more structured approach to this global problem. In doing so, engineering societies as well as educational institutions, coupled with the industries involved in CCUS projects, will be the most important elements for executing these projects around the world. Future GHG challenges will also include nontechnical social and political aspects of the problems. Due to the massive scale and global nature of these challenges, the creation of an enabling environment will be essential for the ability to execute sequestration projects worldwide.

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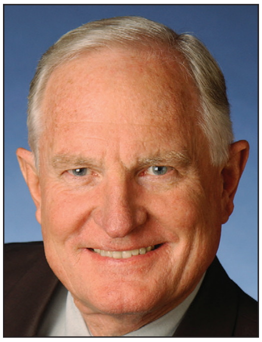
We must reconsider the framework of our K-12 educational system, bringing together high-quality teachers, high standards, and accountability in every classroom.

K-12 Reform: An Endless Discussion, Finally Progress



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Craig R. Barrett

Everyone seems to agree that the economic success of a society is directly tied to the educational attainment of its work force. The ability of workers to add value to their work product directly translates into higher wages, a higher standard of living, and increased economic benefit to society as a whole. This is not a new concept. And yet, even though it has long been common sense, looking back at attempts at US education reform over the past 70 years reveals an endless discussion with little progress. That is finally beginning to change.

After World War II and during the Cold War, when the US economy was the envy of the rest of the world, concern was raised that we were failing our youth with a dysfunctional system. In 1958, shortly after the Soviet Union launched Sputnik, a study funded by the Rockefeller Brothers, *The Pursuit of Excellence: Education and the Future of America*, which discussed the shortcomings of the US K–12 education system, was published (Rockefeller Brothers Fund). The study pointed out the deficiencies of the system, stating that many students were unable to read or write with comprehension and that the great majority of students were unable to do simple, multistep mathematical operations. The report suggested a number of improvements around student expectations, quality of teaching, and curriculum standards necessary to correct these deficiencies. The education system made little effort to implement the suggestions.

In the following decades, several other reports were released that outlined similar recommendations to improve the US education system. *A Nation at Risk* was released by the National Commission on Excellence in Education in 1983, and *Before It's Too Late*, a report on math and science education, was released by the National Commission on Mathematics and Science Teaching for the 21st Century in 2000. In 2005, the National Academies put forward a set of recommendations in *Rising Above the Gathering Storm* and released an updated set of recommendations in 2010 in *Rising Above the Gathering Storm, Revisited* (NASEM 2007 and 2010). Each of these reports, and others released over the past 70 years, failed to make a significant impact on the education system.

Looking at K–12 education today reveals that it has been stagnant despite the many earlier studies. First, consider a recent international test conducted by the Organisation for Economic Co-operation and Development (OECD) that compares student performance in language arts, math, and science.[1] The results are shown in table 1. The mediocre performance of US students is clear in that they are near or below the middle of the pack of the OECD countries. While our absolute scores (pre-pandemic) have improved slightly over the years, those of other countries are improving faster. Table 2 shows the results of the National Assessment of Educational Performance (NAEP) over the last 50 years. NAEP is often referred to as the Nation's Report Card. These data show scores in reading and math in the eighth grade. The results are striking. Reading performance has not changed much since the 1970s, and math performance has improved by only a few points. Comparing tables 1 and 2 reveals that current US math performance is well below the average of our OECD counterparts. Additionally, if you go to American universities and look at the national origins of students majoring in STEM topics you find a large percentage are foreign nationals. Our universities are amongst the best in the world, but the STEM preparation in our K–12 system is weak, and few US students choose this path in post-secondary education. In short, we are doing a poor job preparing our students for the high-tech world of the future.

The many studies on the US education system over the past 70 years have not resulted in effective action by the public education system. In short, there has been

TABLE 1 Global results on the OECD Test for Schools (based on PISA)

	Math	Reading	Science
BASIS Charter Schools	603	637	604
B-S-J- -China*	591	555	590
Singapore	569	549	551
Macao-China	558	525	544
Hong Kong-China	551	524	517
Estonia	523	523	530
Japan	527	504	529
Korea	526	514	519
Canada	512	520	518
Chinese Taipei	531	503	516
Finland	507	520	522
Poland	516	512	511
Ireland	500	518	496
Slovenia	509	495	507
United Kingdom	502	504	505
New Zealand	494	506	508
Sweden	502	506	499
Netherlands	519	485	503
Denmark	509	501	493
Germany	500	498	503
Belgium	508	493	499
Australia	491	503	503
Switzerland	515	484	495
Norway	501	499	490
Czech Republic	499	490	497
United States	478	505	502
France	495	493	493
Portugal	492	492	492
Austria	499	484	490
OECD Average	489	487	489
Latvia	496	479	487
Iceland	495	474	475
Russia	488	479	478
Lithuania	481	476	482

* Beijing-Shanghai-Jiangsu-Guangdong

Note: PISA scores are scaled to fit approximately normal distributions with means around 500 score points and standard deviations around 100 score points.

Source: OECD (2022).

[1] The 2022 OECD Test For Schools was designed to enable international benchmarking against results from the 2018 PISA exam.

TABLE 2 National Assessment of Educational Performance (NAEP) results for eighth graders

	1975	1990	2004	2020	2022
Reading	256	257	259	263	260
Math	266	270	281	282	274

Note: NAEP assessment results are reported as average scores on a 0–500 scale for 8th graders.
Source: Nationsreportcard.gov.

all talk and no action, other than a response by the system that if we would just spend more money, the problem would be solved. That suggestion is often repeated today, even though there is no evidence that spending more money improves anything. In fact, there is evidence to the contrary. Today, the urban school districts in the United States that typically spend more per student than the national average typically achieve the worst results. This fact is borne out by recent reports on school systems in Baltimore, Chicago, and Schenectady, New York, where many schools do not have a single student proficient in math (Illinois State Board of Education 2022; Maryland State Department of Education 2022; New York State Education Department 2022).

In 2008, on the 25th anniversary of the publication of *A Nation at Risk*, Strong American Schools released an analysis of why nothing was changing.[2] That summary still seems accurate: "While the national conversation about education will never be the same, stunningly few of the Commission's recommendations actually have been enacted. Now is not the time for more educational research or reports or commissions. We have enough commonsense ideas, backed by decades of research to significantly improve American schools. The missing ingredient isn't education at all. It's political. Too often state and local leaders have tried to enact reforms of the kind recommended in A NATION AT RISK only to be stymied by organized special interests and political inertia. Without vigorous national leadership to improve education, state and local school systems simply cannot overcome the obstacles to making the big changes necessary to significantly improve our nation's K–12 schools."

Granted, there have been attempts by national leadership to make change. President George W. Bush pushed the No Child Left Behind effort, which focused on closing the reading gap between third-grade students from different socioeconomic backgrounds.[3] The program achieved some success but did not materially alter the overall US K–12 performance. Another effort was that of President Obama to capitalize on the work of 45 state governors who created the Common Core, a more rigorous language arts, math, and science curriculum for K–12.[4] Interestingly, and consistent with the political obstacles to effecting change in K–12, once the Obama Administration picked up the torch on Common Core and began demanding that states adopt the mandated changes in curriculum, the states rebelled. The pushback was loud and clear: K–12 education was controlled at the local level and not by dictates from Washington, DC. So Common Core, originally created under state governor direction, was unwelcome. Some pieces of Common Core were incorporated in some states, but that effort also failed to materially affect the overall K–12 results. One is left to wonder: If 70 years is not long enough to motivate national leadership to solve the problem, how will it ever be solved?

While the many studies on the US education system have not resulted in improvement, they have offered an excellent definition of the problems facing the US education system and a set of suggestions to fix them:

1. No education system can be of higher quality than the quality of its teachers.

In most countries that are high performing in education, teaching is an esteemed profession and teachers typically come from the top tier of university graduates. In

[2] Strong American Schools was a short-lived project of the Rockefeller Philanthropy Advisors supported by the Broad and Gates Foundations in 2007–8 to promote sound education policies for all Americans. Roy Romer, former Colorado governor, was the CEO.

[3] The No Child Left Behind law – the 2002 update of the Elementary and Secondary Education Act – effectively scaled up the federal government's role in holding schools accountable for student outcomes.

[4] The Common Core State Standards Initiative is an educational initiative from 2010 that details what K–12 students throughout the United States should know in English language arts and mathematics at the conclusion of each school year. The initiative was sponsored by the National Governors Association and Council of Chief State School Officers.

the United States it is the opposite. Certainly, there are some great teachers in the United States, but the average teacher quality is below that of our international counterparts. Teachers in our public education system are certified by obtaining an education degree, in pursuit of which they learn the pedagogy of teaching. While they learn how to teach, they are often weak on what to teach. They are typically not content experts, especially in STEM topics. A comparison with US universities is instructive. US universities are amongst the best in the world, especially in STEM. The main qualification to become a university professor is excellence in their field of study or content knowledge. University professors are not required to obtain an education degree. This is the exact opposite of K–12, where an education degree is prioritized above content knowledge. Until we increase the content expertise of our teachers, we are destined to remain mediocre in our K–12 performance.

2. To achieve strong performance in education, you must have high standards.

In general, the United States has low expectations of students. We compare our schools to other nearby schools and are content if we do well compared to our neighbors. We have also consistently lowered standards to ensure increased graduation rates. What we have not done is compare our schools to the best in the world and act accordingly. In essence, the US education system has focused on serving the "lowest common denominator" of students rather than helping *all* students (average performers, gifted, minority, handicapped, etc.), while our international competitors have focused on producing the best students. To use a sports analogy, the United States is focused on competing at the local level while the top-performing countries are focused on winning the Olympics. Recently the system has tried to alleviate this problem by creating magnet schools, public schools with selective admission requirements and focused on accelerated academics such as Thomas Jefferson High School in Alexandria, Virginia, one of the top-rated schools in the United States. While magnet schools have achieved good results, these merit-based schools are currently under attack because their socioeconomic and racial makeup usually does not mirror the general population. In addition, advanced placement (AP) courses, offered by many high schools for high-achieving students, are under attack in several states, also due to the makeup of students taking the AP courses. It appears that many attempts by states to provide higher quality K–12 education are being undermined by a demand for diversity. This seems to be the history of public K–12 education – one step forward, one step back, as special interests and political inertia rule the day.

The urban school districts in the United States that typically spend more per student than the national average typically achieve the worst results.

3. Any high-performing education system needs some internal tension or accountability.

Any organization needs accountability in order to be competitive. This is true in sports, in business, and it is undoubtedly true in education. Accountability here relates to schools, administrators, teachers, and certainly students. In general, we have moved in the opposite direction and insulated all parts of the system from accountability. It is almost impossible to close a poorly performing public school. Teachers achieve tenure after a few years, and it is often difficult to fire a poor performer. Students do not have to demonstrate proficiency and are guaranteed social promotion despite poor grades. The net result is poor performance and zero accountability. Imagine trying to run a business where results are not important, employees are not held accountable for their performance, and the product is not competitive in the marketplace. Again, a comparison to US universities is constructive. University attendance is by choice, not by zip code. Consequently, universities strive to have the best academic reputation possible so that they are attractive to prospective students. There are numerous agencies and methods used to rate universities. On the other hand, K–12, while typically given a letter grade at the state level, is essentially a monopoly where attendance is dictated by zip code. The letter grade is an improvement over the past but hardly a solution to the mediocre performance of our K–12 education system, especially when state standards are low relative to our international peers.

These are the main issues plaguing our K–12 system: below-average-quality teachers, low standards and expectations, and a lack of accountability. While the mainstream K–12 education system has mainly ignored these issues, there is a movement that is finally beginning to change the system and improve results: the movement for charter schools. This movement started out in the 1990s when the first legislation to approve alternative public K–12 education was approved.[5] Public charter schools were initially created to replace failing public schools and to give students an option for a quality education where none existed in the local public schools. Charter schools were exempted from much of the bureaucracy that hampered change in public schools and gave parents and students a choice, an alternative to a failing local school. Since then, charter schools have morphed into much more than a simple alternative to the local public school.

If seventy years is not long enough to motivate national leadership to solve the problem, how will it ever be solved?

First, let's look at teacher quality. In many states charter schools do not have to hire certified teachers as required in public schools. This means that charter schools can focus on content expertise as opposed to pedagogical expertise. For example, charter schools can hire physics majors to teach physics, math majors to teach math, science majors to teach science, history majors to teach history, etc. Frankly, nothing surpasses teacher content expertise in getting students interested in the topic. For decades we have turned off students in math classes because the teacher doesn't like math or doesn't know math and cannot instill any enthusiasm in the students. That all changes when the teacher loves the subject matter and can effectively lead the student down the path of intellectual discovery. In addition to content expertise, charter schools are usually not bound by union agreements that manifest tenure for teachers after a few years of employment. Charters are free to reward good teachers with bonuses and release poor teachers who are negatively impacting student learning. Because charters also receive less state funding per student and their charters are subject to more frequent scrutiny for performance, they are much more sensitive to teacher quality per dollar spent than their public counterparts.

Another thing that charters can do to improve teacher quality is to change the classroom model for the early stages of K–12. With dedicated subject-matter teachers at all grade levels as opposed to a homeroom teacher in the early grades who teaches all subjects, charters can ensure teacher expertise in all subjects at all grade levels and help promote interest in STEM topics at an early age.

With regard to standards, charter schools, like public schools, have to minimally satisfy all state requirements. However, because they need to attract students from the normal public schools, they have to offer something in addition. As mentioned above, charter schools can focus on higher academic standards and specific course areas like the fine arts, STEM, language, classical education, etc. This "something extra" is what sets charter schools apart and leads to higher standards and higher expectations of students compared to normal public schools.

Finally, regarding the issue of accountability, charter schools are required to meet state standards for minimum results. They are also required to have their charters approved periodically. If they do not perform, they are much easier to close than a normal public school.

BASIS Charter Schools, which I chair, operates 37 charter schools in 3 states (Arizona, Texas, and Louisiana) and Washington, DC. BASIS is a prime example of the possibilities charter schools offer. BASIS focuses on high academic achievement. Table 1 shows where BASIS students rank in terms of the international test scores for OECD countries. Their average scores in math, science, and language arts are at the top of the list, beating out every other country. How is it possible that BASIS, which started operations in 1998 with a single fifth-grade class of 58 students and didn't have a high school graduate until 2005, is now probably the best-performing school district in the United States, with 22,000 students currently attending their various schools? They focused on good teachers, high expecta-

[5] The simple and original principle of charter schooling is that charter schools receive enhanced operational autonomy in exchange for being held strictly accountable for the outcomes they promise to achieve. When charter school laws honor this principle, innovative, academically excellent charter schools flourish. In turn, schools that fail to produce strong outcomes close.

tions, and accountability. It is important to note that BASIS, like all charter schools, is open enrollment, which means that students are not admitted on the basis of screening or testing. It is first come, first served, and if applications exceed seats, there is a lottery for attendance. There are many other great charter school operations in the United States (e.g., KIPP, IDEA, Great Hearts, Success Academies), and you can find a full list in the annual *US News and World Report* rankings. Every year more states liberalize their charter laws, more students attend charter schools, and the revolution gains steam. There is political resistance, but results speak loudly.

The result that speaks the loudest is the average performance of charter schools compared to their normal public-school counterparts. A recent nationwide study from Stanford's Center for Research on Education Outcomes, covering over 2 million students in 29 states and a control group in traditional public schools, found charter schools "produce superior student gains despite enrolling a more challenging student population" (Raymond et al. 2023). The nationwide gains for charter students were 6 days in math and 16 days in reading. State-by-state comparisons were even more dramatic. In New York, for example, charter students were 75 days ahead in reading and 73 days in math. Overall, disadvantaged students made the largest gains.

Charter school students are not yet sufficient in number to influence the overall international rankings (see table 1), but the trend is clear. Charter schools are legal in about 90% of states, and today there are over 3,750,000 students in charter schools. Due to the success and popularity of charter schools, public schools have finally recognized that there is competition and parents and students can vote with their feet. For public schools it is either improve or lose students and revenue. For example, in Washington, DC, charter schools now serve about 50% of the students. In Arizona, over 20% of students attend charter schools. In New Orleans, after Hurricane Katrina and the destruction of the entire public school system, the city chose to create a new system based entirely on charter schools. Charter schools have become much more than an alternative to failing public schools. They have become a change agent for the overall K–12 system, something that 70 years of talking about the problem failed to achieve.

Certainly, there is political resistance to charter schools. It is claimed that charter schools are taking taxpayer money away from normal public schools and that this will harm the remaining public-school students. This is the "special interest and political inertia" resistance referenced in the 25th anniversary review of *A Nation at Risk*. The critics seem to think that it is more important to fund failing public schools than have taxpayer dollars follow the child to a charter school where they have the potential to receive a good education. This competition is what is finally bringing improvement to K–12 education. You never see arguments against charter schools based on results; you only see ideological arguments based on resistance to change.

Charter schools, starting from scratch and free from much of the bureaucracy of existing public schools, are embracing the concept of change.

Let me conclude with a few comments about technology and its impact on education. At Intel Corporation, where I worked for 35 years (during which time we invested heavily in improving K–12 education), we had a saying: "Computers aren't magic; teachers are magic." By that we meant that computers and software are tools to help teachers. They are not, in and of themselves, a solution to the K–12 problem. If the teacher knows the material, then computers can be of assistance. But without a quality teacher it is unlikely that the student will succeed at a high level. If it were merely making technology available in the classroom, then the United States, with probably the most computers and software available per student anywhere in the world, would be at the top of the PISA rankings. Certainly there are necessary uses for computers, such as remote learning, where students interface with teachers online, but the recent pandemic demonstrated that the mass use of computers for remote learning is not effective unless the teacher knows how to use the tool. As is the case for any aspect of quality education, the quality teacher is key and is the "magic" that makes the process work. There are quality online K–12 schools, but they are subject to the same

rules as brick-and-mortar schools: good teachers, high standards, and accountability.

In summary, after nearly 70 years of talking about reforming K–12 education it is actually happening. It is not happening as the direct result of studying the problem, making suggestions for improvement, and then actually implementing those suggestions into the system. The K–12 system has rejected most attempts at this sort of reform. Instead, charter schools, starting from scratch and free from much of the bureaucracy of existing public schools, are embracing the concept of change. Charter schools account for only about 7% of the public-school students but are expected to grow rapidly as more states enact liberal charter laws and give parents and students a choice. To anyone who has followed the history of K–12 reform, it is about time.

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There are numerous abundant waste and byproduct materials that could potentially serve as sources for critical materials.

Domestic Wastes and Byproducts: A Resource for Critical Material Supply Chains

Evan J. Granite, Grant Bromhal, Jennifer Wilcox, and Mary Anne Alvin

Evan J. Granite

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Jennifer Wilcox

Mary Anne Alvin

Modern societies generate extraordinary varieties and quantities of wastes and byproducts. By applying principles of circularity and waste minimization, we can take something that would be an environmental hazard and turn it into a resource. A few such wastes that could serve as feedstocks for recovery of metals are coal ash, acid mine drainage, petroleum coke, mine and smelter wastes, asbestos tailings, red mud, produced waters, municipal solid wastes, municipal sewage sludge, e-wastes, garnet waste abrasives, and phosphogypsum waste. The possibility of recovering valuable metals from these abundant wastes is being investigated by the US Department

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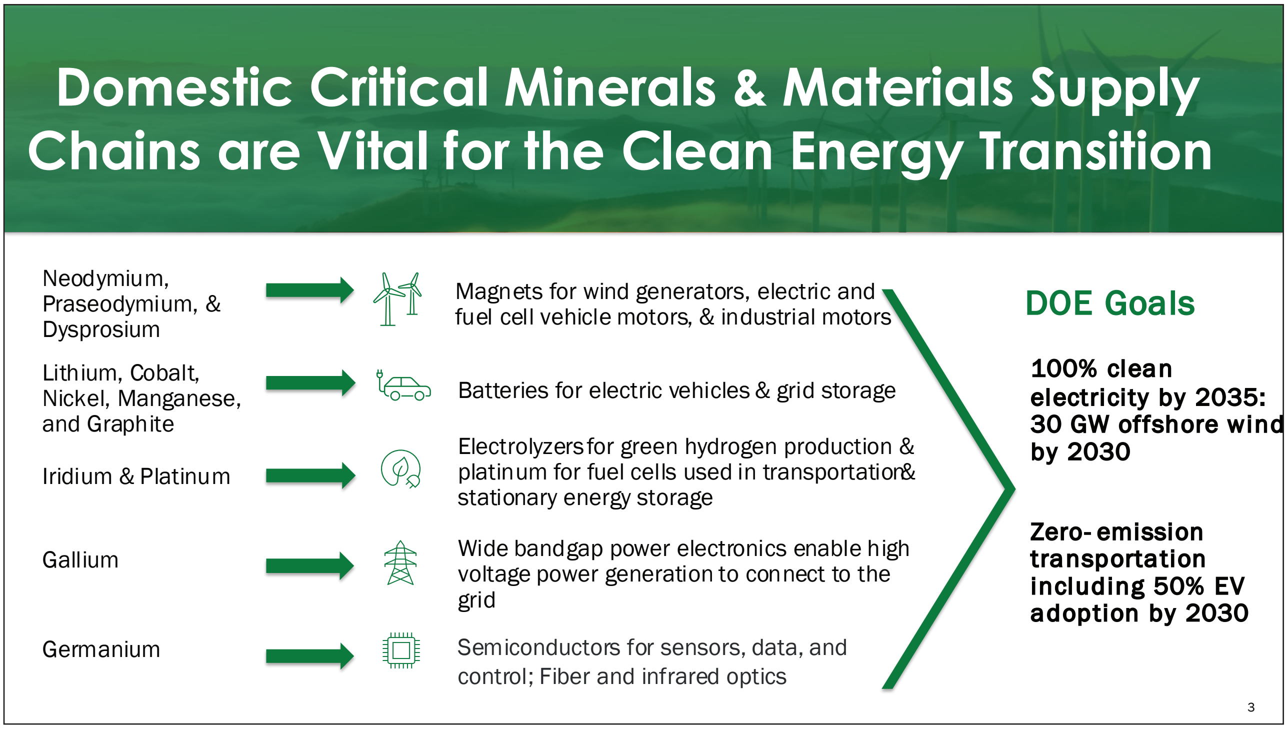

FIGURE 1 The dynamic dozen.

of Energy (DOE). However, to be of greatest value, and to help ensure the materials are used and not discarded, the mineral resources in these feedstocks need to be abundant enough to warrant investing in recovery and reclamation efforts. Metals and materials of interest, dubbed as the "dynamic dozen" for their importance in clean energy and semiconductors, are neodymium, dysprosium, praseodymium, lithium, graphite, cobalt, nickel, manganese, iridium, platinum, gallium, and germanium. A quick exploration of several potential waste feedstocks suggests that the available rare earth element and critical mineral content is ample enough to justify exploration and development activities on a large scale.

Introduction

Critical materials are defined by the Energy Act of 2020 as any nonfuel mineral, element, substance, or material that the secretary of energy determines: (i) has a high risk of supply chain disruption; and (ii) serves an essential function in one or more energy technologies, including technologies that produce, transmit, store, and conserve energy; or are a critical mineral as defined by the secretary of the interior. There are currently fifty materials listed as critical minerals; these are typically metals that are important to the US economy and imported in large quantities. The DOE has developed a subset of twelve of these materials, dubbed as the "dynamic dozen." These materials are neodymium, dysprosium, praseodymium, lithium, cobalt, nickel, manganese, graphite, iridium, platinum, gallium, and germanium, and are crucial for future clean energy and transportation systems such as renewable wind and solar power generation, electric vehicles, and hydrogen fuels, as shown in figure 1.

During the large-scale thermal roasting of ores, combustion of coals, and distillation of petroleum, a happy accident occurs. Elements partition according to their volatility (melting and boiling points of the elements and common compounds), with the highly volatile elements (such as the pollutant elements – halogens, mercury, and sulfur) often going up the stacks with the flue gas, and the less volatile elements concentrating in the solid byproducts such as ashes, flue dusts, slags, and cokes. This phenomenon allows elements of economic importance, such as the dynamic dozen, to concentrate in numerous solid waste materials resulting from large-scale thermal processing such as roasting or combustion. The concentration of these elements in abundant byproducts suggests their use for metal recovery.

The characteristics of wastes and byproducts of interest for recovery of critical materials include being abundant, accessible, preferably currently produced, having opportunities for environmental remediation, being easily extractable, and having multiple potential salable products that can be recovered. A few of these wastes are briefly discussed below.

Wastes and Byproducts from Large-Scale Thermal Processes

Coal Ash

There is approximately 2 billion tons of coal ash residing within over 1,000 impoundments scattered across the United States. The combustion process allows the coal-burning power plants to serve as large-scale concentrators of many critical elements that are present within coal. Preliminary estimates have been made for the quantities of critical elements contained within the stored ash. Table 1 shows the estimated quantities for selected metals of interest. These represent significant potential supplies, at current rates of consumption, as shown in table 2.

Note that extractability of the elements of interest is also an important factor for economic recovery, and some metals may be more easily recovered from the many waste coal impoundments in the United States. It is important to note that *much larger quantities of these metals* will be needed soon to facilitate the clean energy transition.

TABLE 1 Estimated quantities in US legacy coal ash

Critical Metal	Estimated Mass
Nd	172,000 tons
Dy	62,000 tons
Li	288,000 tons
Co	110,000 tons
Ni	252,000 tons
Ir	40 tons
Pt	600 tons
Ga	20,000 tons
Ge	130,000 tons

TABLE 2 Potential supply in US legacy coal ash, at current rates of consumption

Critical Metal	Estimated Mass	Potential Supply (Years)
Nd	172,000 tons	40
Dy	62,000 tons	14
Li	288,000 tons	130
Co	110,000 tons	15
Ni	252,000 tons	1.1
Ir	40 tons	15
Pt	600 tons	15
Ga	20,000 tons	1,100
Ge	30,000 tons	3,900

Petroleum and Refinery Wastes

The United States refines approximately 18 million barrels of petroleum/day. It is known that heavy crudes contain valuable metals such as nickel, vanadium, and molybdenum. The heart of any petroleum refinery are the distillation units, and metals can concentrate within the high boiling fractions, and particularly in the petroleum coke. Estimates are being developed for the quantities of nickel currently produced in domestic cokes. Earlier work by the DOE analyzed abundant Alberta, Canada, oil sand process waste streams to determine the lanthanide element distributions and concentrations and suggested that these byproducts could be a source of titanium, zirconium, and some rare earth elements.

Steel Slag

Approximately 90 million tons of steel is produced every year in the United States. The slags can contain interesting concentrations of critical metals, and the quantities are being determined. Kim (2021) recently examined the potential for steel byproducts as a source for manganese, chromium, niobium, aluminum, titanium, and magnesium.

Metal Smelters

The refining of metal ores is another large-scale thermal process that concentrates valuable metals in the voluminous solid residues (flue dusts). Estimates are being made for the quantities of metals of interest that reside in the many domestic waste sites.

Other Large-Scale Solid Wastes

Mining and Mine Tailings

Mining often produces copious quantities of waste rock. The initial processing of mined ores typically involves

physical separations based upon size, density, magnetic properties, and floatability (froth flotation). The reject streams from each of these processes can leave significant quantities of both the original mined metal, as well as other metals, behind. As domestic high-quality ores have been depleted over time, the cut-off grades for most metals have been reduced, so much so that many mine tailings and waste rocks now contain economically recoverable concentrations of metals. There is extensive literature on these byproducts for copper, zinc, and nickel, and Rio Tinto has made extensive efforts to recover tellurium and copper from mine wastes and tailings. It is also noted that there are over 4 billion tons of coal waste stored in many impoundments across the United States.

As we continue to collect information about these different source materials, we are better able to assess the potential for them to support domestic and worldwide critical mineral needs for the decades to come.

Red Mud

Red mud is a voluminous byproduct of aluminum production. In the Bayer Process, bauxite ore is treated with sodium hydroxide. The stoichiometry of the Bayer Process shows that 1–2 times as much red mud is produced versus alumina. Over 1 million tons of alumina are produced annually in the United States. The alkaline red mud wastes are enriched in rare earths, typically containing 0.1–1 percent rare earths by weight. Both the currently produced and legacy red mud byproducts are attractive sources for rare earths; with perhaps enough to supply annual domestic demand for rare earths, which is 10,000 tons/year. Early work on red mud is being supported by the DOE. The highly alkaline red mud also presents potential opportunities for carbon dioxide sequestration.

Asbestos

Asbestos mine tailings are highly alkaline and contain 25–30% magnesium. Researchers have proposed commercial recovery of magnesium and other valuable metals. The Vermont Asbestos Group Mine (VAG) was operational from the 1930s through 1993 and has left large quantities of legacy waste materials behind. This material could be beneficially treated to recover metals, clean-up the waste, and potentially sequester carbon dioxide.

Municipal Solid Waste

The United States produces approximately 300 million tons of municipal solid waste (MSW) annually; this translates to roughly 1 ton of MSW per person per year. The crude composition of MSW includes yard waste, food, paper, cardboard, plastics, wood, and metals. MSW can contain significant concentrations of metals, with as reported values between 1 and 17 wt%. Unfortunately, these metals are contained within a highly heterogeneous matrix. MSW ash from incinerators will contain even higher concentrations of metals and may represent a better opportunity for economic recovery.

Municipal Sewage Sludge

There is recent excitement in the research community on the elevated ppm levels of platinum group metals such as platinum, palladium, and rhodium being found in some municipal sludges. The origin of these noble metals is believed to be road dusts originating from debris from the 3-way automobile catalysts, with the dusts washing into storm drains from the rain. Some researchers have suggested the possibility of economic recovery of the platinum group metals from municipal sewage sludge.

E-Wastes

Modern society unfortunately disposes large quantities of computers, televisions, phones, and batteries, with much regrettably ending up in landfills. These devices contain most of the target metals needed for the clean energy revolution. Research is being supported by the DOE on the recovery of nickel, graphite, cobalt, manganese, lithium, and some rare earth elements from e-wastes.

Other Nontraditional Sources

Produced Waters

The commercial production of oil and gas also produces enormous quantities of produced waters. A preliminary study of domestic produced waters suggests lithium may

be economically recoverable from a few of these produced waters. The DOE is initiating new research on the recovery of lithium and other valuable metals from produced waters.

Garnet Abrasives and Sands

Garnet is used as industrial abrasives, with approximately 100,000 tons produced annually in the United States. Recent work by Oak Ridge National Lab suggests the spent abrasives have high rare earth concentrations, with as much as 0.1–1% by weight total rare earth, yttrium, and scandium. The more valuable heavy rare earths and scandium are well represented in these wastes.

Acid Mine Drainage

The oxidation of sulfides present in both coals and metal ores produces waste sulfuric acid. The sulfuric acid formed will often beneficially leach valuable metals such as manganese, nickel, and cobalt from the surrounding environment. The DOE is sponsoring pilot-scale research on the recovery of manganese, nickel, cobalt, and rare earths from abundant acid mine drainage solid wastes present in West Virginia, with encouraging early results.

Phosphogypsum Waste

Rare earths are often found in nature as the phosphate monazite. Phosphogypsum wastes are byproducts of phosphoric acid or fertilizer production. Much of the original rare earth elements originally present with the phosphate rocks are concentrated in the phosphogypsum. DOE-supported research is currently examining the potential of these wastes for recovery of the rare earths.

Novel Sources

Outer Space

There are several recent start-up companies examining the possibilities of recovering valuable metals from the Moon, Mars, meteorites, and asteroids. NASA is part of intergovernmental efforts led by the DOE on "Space Mining."

Ocean and Ocean Floor

The oceans contain vast stores of many metals; unfortunately, the concentrations are typically low. For example, lithium is present in seawater at concentrations of 1 ppm. Coproduction of metals and potable or usable water could improve the economics of metal recovery. Seabed minerals present on the remote ocean floors are also being considered for future exploration. On April 28, 2023, the DOE announced potential funding for exploration of critical mineral extraction from macroalgae in the ocean. This Advanced Research Projects Agency-Energy (ARPA-E) effort seeks to study macroalgae as a potential source of critical rare earth elements.

Future work is needed on determining the optimum waste materials for recovery of critical materials, the development of improved separation techniques, the characterization of these typically heterogeneous materials, and the identification of the best products when multiple possibilities exist.

Locations and Quantities

These wastes are present broadly across the United States and North America. The figure below shows locations where many of them are prevalent in substantial quantities. For these types of wastes, a "hub and spoke" model of production and processing is a typical approach when there are several potential sources in a region, where minerals can be recovered and concentrated at the sources (spokes) and brought to a central plant (hub) for further processing. As we continue to collect information about these different source materials, we are better able to assess the potential for them to support domestic and worldwide critical mineral needs for the decades to come. Metal mining and refining byproducts, municipal solid waste, and asbestos dumps represent valuable stores of critical materials. Some locations of wastes and

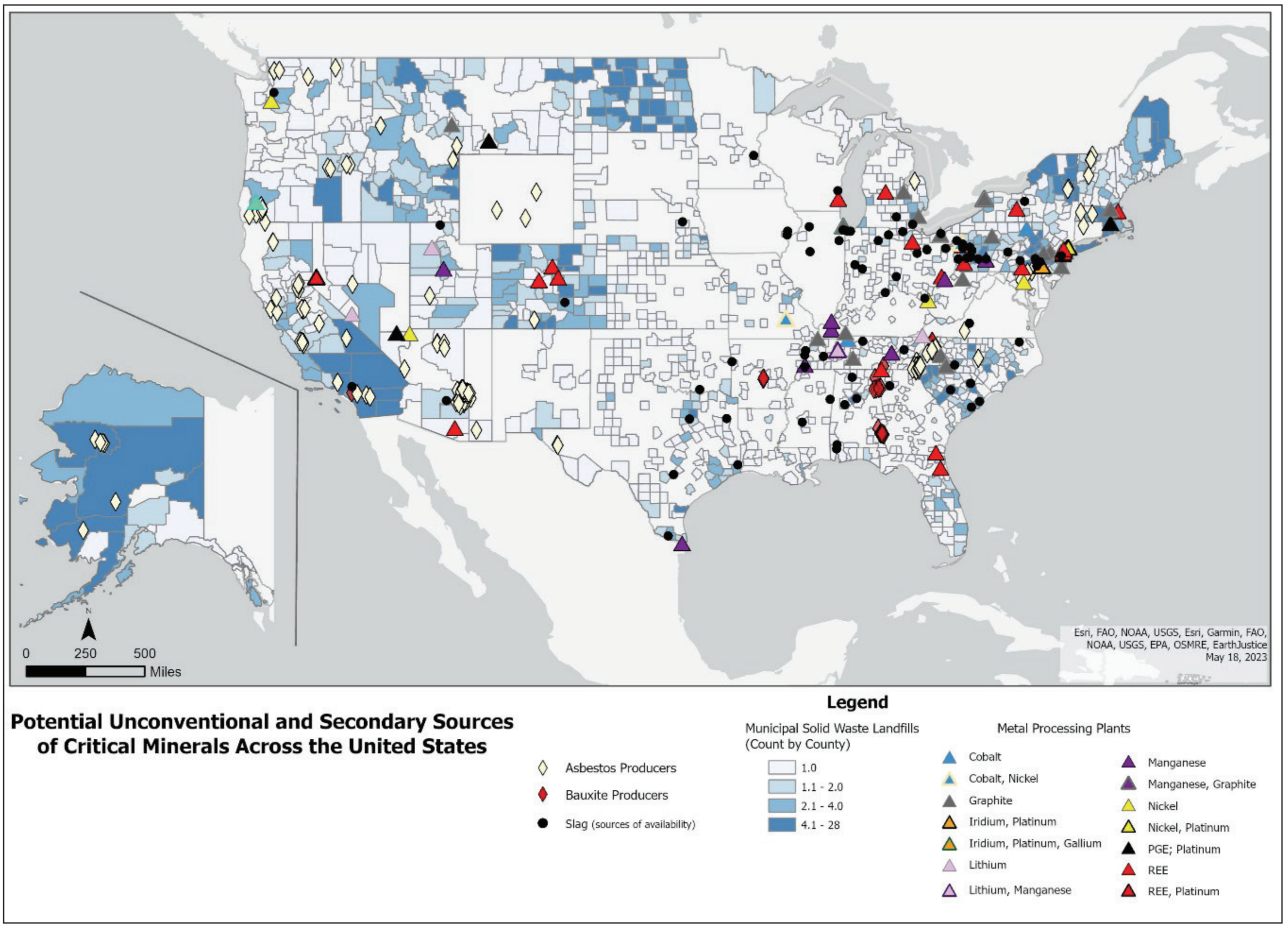

FIGURE 2 Location of select wastes and byproducts.

byproducts, along with elements present within these sites, are shown in figure 2.

The voluminous byproducts of fossil energy production and utilization are a potential resource for critical materials. The locations of petroleum refineries, coal mines, coal-fired power plants, and coal ash ponds are shown in figure 3.

Private Sector

The private sector has made significant efforts in recent years to obtain critical materials from waste materials. Numerous companies such as Alcoa, Redwood Materials, Ascend Elements, Nth Cycle, Cirba Solutions, Aqua Metals, ElementUS, Rio Tinto, and many others are targeting recovery of critical materials from abundant wastes and byproducts, using both traditional physical, thermal, and chemical separations, as well as novel separation technologies such as electrochemical and plasma methods. The DOE is spurring innovation and technology development through research efforts and funding opportunities, in collaboration with the private sector, academia, and various local and federal government agencies.

Conclusion

There are numerous abundant waste and byproduct materials that could potentially serve as sources for critical materials. These opportunities are currently being explored by the DOE, as well as the private sector, to enhance domestic security and clean up the environment. Other nontraditional and novel sources of critical materials such as produced waters for lithium recovery also merit further research. Challenges for recovery of the critical materials include the modest and often variable concentrations; ease of extraction; and development of multiple recoverable products. Future work is needed on determining the optimum waste materials for recovery of critical materials, the development of

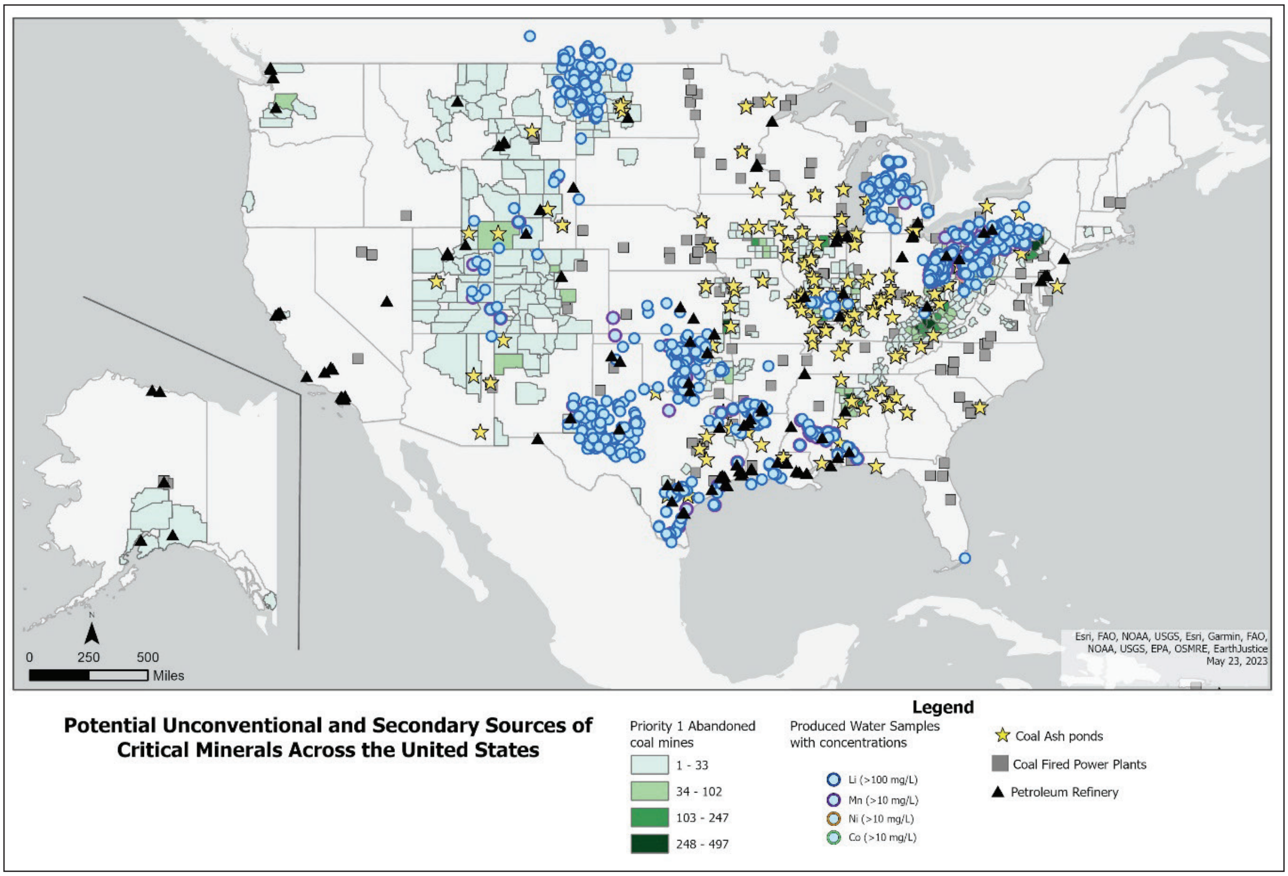

FIGURE 3 Locations of oil refineries, coal mines, ash ponds, and coal-fired power plants.

improved separation techniques, the characterization of these typically heterogeneous materials, and the identification of the best products when multiple possibilities exist. The timely and safe permitting of resource recovery from waste materials is an additional challenge that needs to be addressed.

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An Interview with . . .

Kevin O’Mara, dean, The School of Business, Campbell University, and Mike Minter, Head Football Coach, Campbell University

Kevin O’Mara

Mike Minter

RON LATANISION (RML): Good morning, Mike and Kevin. We’re delighted you could both join us for this conversation. When the dean of engineering at Campbell University, Jenna Carpenter, mentioned the history of you folks, it seemed like a wonderful opportunity to learn about how you’ve used your engineering background, if at all, in practicing what you’re doing today, because Mike, as coach of a football team, and Kevin, as dean of a business school, you’re doing things that would not necessarily be expected of a chemical engineer or mechanical engineer. So, we’re interested. That’s the perspective of this call.

Kevin, let me start with you. Tell us a little about your background and how you made the transition from industrial engineering to become dean of the School of Business at Campbell.

DR. O’MARA: I became an engineer because of my parents. I’m the fourth of four brothers and my parents

This interview was conducted on May 15, 2023, by Ron Latanision, editor in chief of *The Bridge*, and Cameron Fletcher, former managing editor. It has been edited for length and clarity.

went through the Depression. I heard it a hundred times: engineers always have a job. My oldest brother is a mechanical engineer, my second oldest brother is a civil engineer, and my other brother actually played football and got a scholarship. I think the school probably didn't have an engineering school, so he's an accountant. I was heavily influenced to go into engineering.

Upon graduation, I had this unique background in both engineering and business that organizations valued.

I went to the University of Texas. At the time, in the mechanical engineering department and the business school, they had an engineering program that was analogous to a typical industrial engineering degree program. I always liked the business side of things, so this was a wonderful marriage between the two. Upon graduation, I had this unique background in both engineering and business that organizations valued. Fortunately, due mostly to the engineering training, I had a lot of job opportunities. The engineering side of companies wanted me to converse with the business side, while the business side thought I could be helpful in bridging the business and engineering sides of their firm. It could not have worked out better.

I wound up working at an oil company in Houston. I worked in the reservoir engineering and production side of the company, with my responsibilities focusing on the financial analysis of potential projects and the profitable mix of the output. I did my MBA, and that opened up the doors for getting a PhD in business.

CAMERON FLETCHER (CHF): And you preferred to leave the private sector for academia?

DR. O'MARA: Yes. I always wanted to start my own business since I was a kid. I thought, 'Well, 90 percent of businesses fail, so my fallback was going to be the old adage, "Those that can't, teach." I could become a professor if my business never made it off the ground.' When I started teaching, I enjoyed it. Before I knew it, I was in it 10 years. It was a bit too late to move over to the entrepreneur side.

RML: The interesting point in what you've just said, Kevin, is that, as engineers, the systems we build serve a social purpose. There is a need to manage them and there is a need to get them into the marketplace. So your interest in engineering from a management and business point of view is quite important.

You know, just one little sidebar, I have a granddaughter who's just finished her freshman year at Penn State. She's a National Honor Society student and I thought she would go into some field of science or engineering, but she decided she wanted to study business. She told me, 'I can see how important business is, but I also understand that technology's important, so I'm looking to get a minor in some field like biomaterials or bioengineering.' I thought, 'This kid has it right. That's an important combination.' So I applaud what you've done.

DR. O'MARA: MBA programs actually got their start after World War II. A good deal of the Allies' success was due to their ability to bring resources to the battlefield more efficiently and quickly than the Germans through utilizing what became known as operations research. This engineering-focused approach became valued by corporations after the war. However, engineers did not always have the managerial skills as they were promoted. So, many, if not most, of the MBA programs in the 1950s and '60s were designed for engineers to learn management skills. They obviously had all the technical skills, but at some point, you get into management and you're not doing engineering anymore; you're managing people.

RML: Absolutely. Coach Minter, could you give us a similar account? I understand you have a BS in mechanical engineering from Nebraska. Have you practiced mechanical engineering, or did you go directly from your career as an All-American at Oklahoma to playing professional football? And then how did you become a football coach?

MR. MINTER: The way I decided to study engineering was in high school when I talked to my guidance counselor. She asked me what I wanted to do in college. I said, 'I'm really good at math, so anything that has to do with that.' She rattled off a list of jobs, or things I could study, and I asked her, 'Which one makes the most money?' She said, 'Engineers make a lot of money.' I said, 'That's what I want to do. I want to be an engineer.'

She told me that there are many engineering disciplines. So I asked, 'Which one makes the most money?'

She said that the mechanical engineer does. So I said, 'Okay, I'm going to be a mechanical engineer.'

Engineering taught me process—how to think. I think one of the most important things for people to do today is to sit down and think about what they believe. How do they process information to come to their conclusions? That's what it did for me. It did it on the football field when I was a player. I was able to look at plays and remember them based on a system. I built systems for myself as a player. That's the way I was successful in college and the way I was successful in the National Football League.

Once I got done playing, I went into business. I built my own entrepreneur business, just like the dean. I had about 300 employees. It was a multifaceted business deal. We were in the oil business, real estate development, and the consulting business. We would go into Fortune 50 companies and help them with business work and organizational development. But I got bored.

CHF: You were doing a lot, but you got bored. Wow.

MR. MINTER: Yes, because my passion is to unlock the greatness in people. In business, you just create deals. It's not really about dealing with people and unlocking their greatness. So when I got a call from one of my buddies who wanted me to come coach at the high school where he was the athletic director, I took the job. After three years and three state championships, I knew this is what I needed to be doing. I need to be helping young men figure out life. High school was easy. I wanted to challenge myself. I wanted to take the worst team in college football.

I got a call from Campbell University, and they were the worst team in college football. That's how I became the Head Coach at Campbell University.

DR. O'MARA: Glad we could oblige. And we're no longer the worst team!

RML: It must be inspirational for kids in your locker room to hear what you have to say. Not only from the point of view of athletics, but from the point of view of your business experience. I think that's a pretty powerful message, coach.

Does your engineering experience affect the way you interact with your athletes? Does it help you motivate them?

MR. MINTER: I think in terms of academics and being a student athlete, they have a head coach who understands. They can't come in and say, 'This is so hard. I can't get it done,' when their head coach was an engineer. They've got to buckle down—it's really about discipline.

I show them that, at the end of the day, whatever you set your mind to, you can accomplish it. Your set limit beliefs are what stop you. So I let the students know that they have no excuses to have bad grades.

The other thing I think helps is the systems I've built in my 10 years as Head Coach at Campbell University to try to simplify how people see things. That includes coaches, along with the players. My mind works that way. If you were to come to my organization and look at it, you would think I was at an engineering firm.

CHF: As a former teacher, I can tell that you've found your calling. What a role model you are for all those student athletes. Do you use your engineering background in terms of the plays on the field and the team and how they interact?

MR. MINTER: I'm always talking about the dimensions of the football field. I tell the kids, 'If you get to this spot, you can make any play on this field.' I teach them that the football field was designed in a certain way not just because people wanted hash marks and numbers and yard markers. Those things are there to show you how far you have to go to get to a certain spot.

Engineering taught me how to look at plays and remember them based on a system. I built systems for myself as a player.

I tell them that that's really important to understand. It eliminates a lot of the stuff that doesn't matter. I also tell them that if they can count to four, they can play football, because football is really about one to four people. A lot of people think it's about 11, but it's not.

I break the game down into sections for them, and they understand, okay, these two people right here are the most important to making this play work—or to stopping this play. Again, there are a lot of math and dimensions in how we look at the game.

RML: That's all wonderful. Dean O'Mara, does your engineering background inform your activities in the School of Business in any way?

DR. O'MARA: Every day. Mike has put his finger on a lot of important things. He talked about process. I always think what I got the most out of engineering training was systems thinking. Systems thinking makes you consider how all parts of an organization, or implications of a decision, impact each other and impact potentially important components. These are not things in isolation. If you turn up the torque on something, it's going to put some pressure somewhere else. It's the same thing in an organization. If you change something, it's not going to have an effect only on that area. It's also going to have an effect on other things.

If you could find a way to encourage people to take engineering fundamentals, it would help them greatly in their fields.

The idea of third derivative thinking—that it's not just what's on the surface of a decision, but it's what else happens because of this that may be more important. You understand that type of thinking from engineering schools, which was tremendously important to me.

Mike talked about there being no excuses to get bad grades. In engineering courses, you used to get a lot of good-natured ribbing if you raised your hand and were wrong and it was obvious why you were wrong. So it taught you to be prepared for classes. You were prepared down to the details. That approach has been a long-term benefit for me.

Obviously, the logic that underpins a lot of engineering, to understand that and be comfortable with that, that's always been helpful. Like Mike said, he grew up being good with numbers. Proficiency with numbers really comes in handy in meetings. You can run through the numbers probably quicker than most people can. I've never complained about having the engineering training, other than the fact that you might have studied a little bit more on Friday night or Saturday than your friends in other majors. Other than that, it was great.

RML: You both have just reminded me of an experience I had when I was teaching at MIT. At one point, I was leading a precollege education initiative at MIT, trying to engage young, precollege people, in studying science, math, technology and so on. I realized that one of the important elements of this was to make sure that kids study—that they put down their cell phones and they spent a good amount of time studying what they were supposed to be learning.

Along the way, I met a fellow who played with the Boston Bruins: Andy Brickley. I also knew the dean of science at MIT, a fellow named Bob Birgeneau. It turned out that the dean of science played hockey when he was in high school or college. He was a goalie. I got in touch with these two guys and I said, 'You know, Bob and Andy, there's an issue with kids studying and spending time out of the classroom preparing.' I said, 'Maybe you guys could send a message.'

We agreed on the following: Bob put on his goalie mask and protection gear, and he got in the goal at the Boston Garden. Andy was on the ice. He came skating down the ice, took a shot at Bob from somewhere up, just before the blue line. It was pretty theatric. Bob caught the puck in his glove and he flipped off his mask and he said, 'Hi. I'm Bob Birgeneau, dean of science at MIT and this is the way I practice something I like, hockey. But you'll have to practice by studying.'

I thought that was a wonderful message. It was recorded and distributed to high schools in Massachusetts. It just captures what you guys have been saying. You've got to study. You've got to practice. You really have to put an effort into this. I think that's a powerful message from both of you. I appreciate hearing that.

DR. O'MARA: To follow up on what you said there: if you could find a way to encourage people to take engineering fundamentals, it would help them greatly in their fields. We have a Pro Golf Management program here where they train you to become a golf professional. Not a player on the tour, but to work in country clubs and teach.

I dropped in their class a couple years ago and looked at the board and they're doing all this spin stuff to determine where the ball's going to land and why it's going to go off in a certain direction. It was all engineering. It's all physics. They just didn't know it. They were eating it up. But if their next class was a physics class, they would be bored to tears. They loved it because it benefited what they really wanted to get better in.

RML: It sounds like that would really engage their mindset. That's a great story. Cameron, I want to turn back to Mike for a moment. There's something you may not know about Mike. He played in the Super Bowl against the Patriots, but what you probably didn't know is he played in that game with a broken foot. Isn't that right, Mike?

MR. MINTER: Yes, that's correct.

RML: The Patriots won that Super Bowl. I have to be honest, Mike. I remember watching that game. I didn't know that you had a broken foot while you were playing. Did you know your foot was broken during the game?

MR. MINTER: As soon as it happened, I knew I had broken it. It's very similar to when anybody does something wrong: they know right away that something is wrong. I came to the sideline after the series was over. I sat on the bench, and I told the trainer, 'I broke my foot.'

He was like, 'What? No way.' I said, 'Yeah, I broke my foot. So don't take my shoe off. Just tie it up tighter and then wrap tape around it, around my shoe, and I'll be fine, and I'll finish this game.' That's how it went.

CHF: And which team were you playing on? For how long and in what position?

MR. MINTER: I'm a safety, so I was in the secondary. I broke it at the beginning of the third quarter. I played really the whole second half with a broken foot.

RML: This guy, just for a reference, Cameron, he's not only a safety, but he also played for the Carolina Panthers. He has all their records, don't you, Mike? You have a number of them anyway.

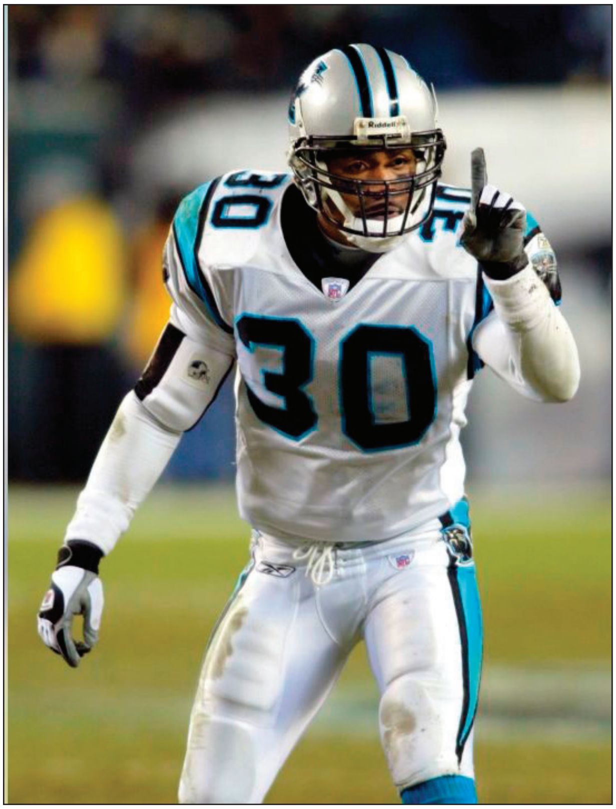
MR. MINTER: Yeah, I had all of them when I retired. That was about, what, 15, 20 years ago? That's amazing how fast time flies.

RML: That's amazing. Was that 15 years ago? When was that Super Bowl? I've forgotten what year it was.

MR. MINTER: The Super Bowl was 2004. So that was 20 years ago.

RML: Wow. It seems like it was just yesterday. I love sports. I've always loved sports.

DR. O'MARA: Let me tell a quick story. You talk about how Mike is a leader of people and young men. In the second or third week I was here at Campbell, I came into the building and there's a person standing in the hallway, kind of looking around like they're a little bit lost. And so I said, 'What can I do for you?' He said, 'I'm looking after my boys here.'



Coach Minter

So I thought it was his sons or something like that. I said, 'Well, alright, is there anything I can do for you?' He says, 'Oh, no.'

Then I found out later that that was Mike. That he was there at 8:00 in the morning to make sure his students, his players, were taking their classes at 8:00 o'clock. He walks the walk.

RML: That's a terrific story. I mentioned earlier on that Jenna Carpenter actually connected with us and suggested that we reach out to you folks. I'm delighted that she did. But do you interact with Jenna on a regular basis? What kind of interaction do you have with her and the School of Engineering?

DR. O'MARA: I meet with her quite often. At least once or twice a month. We have a Dean's Council meeting. She's not that far away on campus. They have a great program over there. Extremely hands-on. Much more than the program I went through. She runs an excellent program.

Coach Minter in action.

MR. MINTER: So, anytime a player comes in and says they want to do engineering, I meet with them and their parents for about an hour. My job is to talk them out of it, right? And the reason why I do that is because you'd better be committed to make this happen. This is not something that you just kind of like, 'Oh yeah, this sounds good to me. Let me try it.' You have to be 100 percent committed. So I spend a lot of time doing that to find out—are they really committed, or is this something coming from somewhere else?

Once I do that, and I find out that the kid is really about the study, the process, preparing for the things that they need to prepare for, and playing football at that time, that's pretty much everything that I give when it comes to preparing the kid for going into that school. If you get through that hour interview with me, you are ready. I don't concern myself with the kid after that.

CHF: That is a little amusing considering your own motivations for going into engineering.

MR. MINTER: Right. I really understand the commitment that it takes to do both. If somebody could sit back and do that hour interview with me, before I decided I'd do it, I probably wouldn't've done engineering.

CHF: But no regrets that you did.

MR. MINTER: No, absolutely not. Again, if you look back with all the understanding that I have now of what it gave me and how I used it to get ahead of a lot of people on the football field, no, I wouldn't trade that for the world.

CHF: How long did you practice engineering when you were running your company and being an entrepreneur? How long were you a professional football player? How many years for each of those?

MR. MINTER: We interact with Jenna if we have players coming in from high school who want to go into engineering. The Engineering School would come over and spend some time trying to let them know what to expect.

RML: I know the School of Engineering at Campbell is relatively new. I think it was formed in 2015, or thereabouts. Jenna is also president of the American Society for Engineering Education. I've had some interaction with them over the years. I recognize her name. I did not know until we heard from her that she had gone on to Campbell.

I knew of her background prior to Campbell. I've forgotten where she was teaching. Louisiana Tech, I think, or somewhere in the South, before she joined the faculty at Campbell, but she's an outstanding person. I'm not surprised that she gave us this recommendation. I admire her.

CHF: Mike, do you offer any kind of mentoring to team players who are interested in engineering or actually studying engineering?

MR. MINTER: I've never practiced engineering. Never. I went straight from college to the National Football League. There was no break in between. Then, once I got done playing for 10 years, that's when I went straight into business. I have never gotten a chance to practice engineering at all.

CHF: I thought engineering was involved in your entrepreneurial work, your business.

MR. MINTER: Well, it was because from a standpoint of—I had a construction business and a development business, okay? So, yes, I'm going to use those skills that I learned from there, but I also had the ability to hire great people who had the expertise. I spent a lot of time learning from all my employees that I hired over the years and sat down with them.

They were kind of tickled because all they know me as is an NFL football player, right? So they don't know me as the engineer. When I used to go into these meetings and sit down, they were talking about building roads and going underground. We had an underground construction business too. We used to lay pipes under the ground. We would also do cabling underground. So we had the boring machine and I wanted to talk about the rotation and how long it would take to pull something 500 yards. They were really tickled about the fact that this NFL dude wanted to sit in here and talk about these things.

RML: Let me ask a more, maybe, futuristic question. I know that Campbell University was founded right around the time MIT was founded, around 1887. MIT was founded maybe 25 years earlier, right around the time of the Civil War. Kevin, as dean of the Business School, where do you see the Business School now and in, let's say, five years in the future? What is your vision of where the school is going?

DR. O'MARA: I've been there about five years, six years now, and what we're hoping to do is to reach out more into the business community than many business schools do. So we're doing a lot of programmatic initiatives where we focus on training, particularly in niche businesses. We have a Trust and Wealth Management Program here. It's the only one in the country. We're going to put a Risk Management Institute together. We have a Sales Analytics Program that we're putting in place.

So the idea is to have a more engaging experience in a business school, rather than just the more classic lecture type. It has been very helpful and very successful, knock on wood. We see the need for getting students more engaged, more involved, in the day-to-day operations through projects and competitions and things along those lines. That's where I'm hoping to take the school. Something that the industry and the business community look at and say, 'There's a school that people come out of here, not only trained, but with some hands-on experience.'

RML: Right. That's important, I think. Did I understand correctly? Did you mention a risk management element to the Business School?

DR. O'MARA: We just got approved for our Risk Management Institute. We just hired the person who was the deputy commissioner of insurance in North Carolina. She was actually a professor here and then went to take that job for five years. We're going to open that up and we think this gives a real unique niche. I didn't realize just how big that industry is. It's actually bigger than the banking industry. It doesn't have the same profile as the banking industry within most business schools. We think we can create a niche, especially given where we live here in North Carolina, with the state legislature and the insurance commission right here in Raleigh.

RML: That sounds to me to be a really important direction to go in, in the following sense. I think about risk management in three different ways. One is that there's always a technological risk with a new engineering system. Will this product actually perform in service? Can it be scaled up to get into the marketplace? Those are technical risks.

We're hoping to reach out more to the business community than many business schools do.

There are also financial risks. You need to find investors. And then, finally, there is a social risk. Does it really serve a social purpose? Is it useful in a societal way? I think that that Risk Management Institute sounds like not only an important new direction, but it could become a really, really important niche for the

school. I think that's a wonderful idea.

DR. O'MARA: Thank you. Think of driverless cars. What's holding them back a little bit, beyond the technology, is who's at risk if they have an accident? Is it the manufacturer? Is it the owner? The parts manufacturer?

RML: That's very good. Is this a program that is just now beginning?

DR. O'MARA: Yes. We just got approved about two months ago at the Board of Trustees meeting. We are actively seeking funding right now.

RML: How many faculty do you have in the school and how many students?

My passion is to unlock the greatness in people.

DR. O'MARA: At the Business School we have about 20 faculty. We have about 650 undergrads. Another 150, 200 grad students. We have three grad programs. One is the Master of Trust and Wealth Management Program. Again, it's the only one in the country. We have a master's in accounting program, and we have an MBA program. All are in-seat and online. For undergrad, we have nine majors.

RML: Great. Nine business majors. That sounds like quite an effort. Do you have administrative deans along with yourself, who manage the school, or how are you organized?

DR. O'MARA: We have two associate deans, then we have the director of the MBA program, a graduate program, an assistant recruiting person for the grad programs, our own career services person, our own alumni person, and then another person who works with the faculty. There's about seven of them.

RML: Let me ask the same question of Mike. Mike, in terms of the football program, both in terms of the athletic performance, but also in terms of their, let's say, the evolution of the young men who are part of your team, what do you see in five years for the program?

MR. MINTER: It's a great question. We, with the football program, have been growing so fast. When I got the job, we were non-scholarship. Even though we were Division I, we were non-scholarship. The first course of action for me was to get us to be scholarship. Then we moved up into scholarship. This was in 2018. Then COVID hit. Now we are going into the Coastal Athletic Association (CAA). The CAA is a Football Championship Subdivision conference and, at our level, it's the equivalent of the Southeastern Conference of the Football Bowl Subdivision. We just moved up into that conference.

The program has been growing tremendously in that sense, as far as the notoriety and the footprint. We have kids from all over the United States. The last two years we've been number one in recruiting, for two years in a row. People are starting to understand who Campbell Football is. Five years from now you will see us competing for National Championships. That's what you're going to see. That's the path that we're on. We're happy to be there.

As far as the graduation rate, we are at 87 percent. At first, I thought that was bad. I was like, 'That's not very good,' and they said, 'No, do you realize that the national average is about 40-something percent?' I said, 'What are we doing?' I thought 87 was bad.

So, we're tops in the country when it comes to graduating our guys. This is something that I'm proud of. We have six guys right now who are very, very big in the banking industry because of the master's degree in Trust and Wealth Management that they got. We have another young man who's doing an internship. They are all located in Texas right now. These guys are all football players. We're going to do a story this off-season—I should say, this season—about how we have not only put six guys in the National Football League, but we also put six guys in the 'National Banking League.'

RML: I admire very much what you've just said. I think you've got the attitude and welfare of your players front and center. Both from the point of view of athletics and from the point of view of academics. I think that's really important. That's the way you build respect, not only among your team, but also among your peers and colleagues at the university.

DR. O'MARA: They're going to get a lot more respect on November 4th after they beat UNC. Isn't that right, Mike?

MR. MINTER: That's going to take a lot of prayer.

DR. O'MARA: We're a Christian university. We can handle that.

MR. MINTER: Yeah.

RML: You know, you mentioned the fact that you're a Christian university. I have a very good friend, actually a friend of our family, who is a former Moravian minister who lives in Winston-Salem, which might be pretty close to your location.

DR. O'MARA: Yes.

MR. MINTER: Sometime when we get an opportunity to come to Winston-Salem we're going to make a stop at the university. I hope you folks will be willing to see us.

DR. O'MARA: I'd love that.

RML: Well, this has been a real treat. As I mentioned a couple times, I really do like sports and I do like engineering and I do think it's important for engineers to fully consider the societal implications of what we do. We've talked about all of those things this morning and I'm really grateful to both of you for the time you've given us.

NAE News and Notes

NAE Newsmakers

Charles F. Bolden Jr., founder & CEO emeritus, the Charles F. Bolden Group LLC, is a winner of the AAAS inaugural **Mani L. Bhaumik Breakthrough of the Year Award** for his work on the James Webb Space Telescope. He shares the award with John Mather (NAS), senior project scientist of the JWST since 1995; and Bill Ochs, JWST project manager from 2011 through the telescope's launch. The award honors them for supporting vast swaths of the JWST community over decades and for their persistence amid multiple setbacks to ensure the mission's completion.

Vinton G. Cerf, VP and Chief Internet Evangelist, Google Inc., was awarded the **Medal of Informatics**. The honor comes "in recognition of his achievements that contributed to serving humanity and his distinguished role in the development and spread of global Internet policy and standards." He is praised for his contributions to the development of the Protocol of Data Transfer Control.

Charles T Driscoll, Jr., Distinguished Professor and University Professor, Syracuse University, has been selected to receive the **2023 Athalie Richardson Irvine Clarke Prize for Outstanding Achievement in Water Science and Technology** from the National Water Research Institute. The prize is one of the most prestigious in water science. Dr. Driscoll will receive the award and give a lecture in Irvine, California, on October 21.

James Dyson, chairman and founder, Dyson Technology, received the **Public Service Star** (Distinguished Friends of Singapore) award on July 4. The award recognizes senior executives for their outstanding contributions to the economic growth of Singapore.

Juan J. de Pablo (NAS), Liew Family Professor in Molecular Engineering, University of Chicago, and Alon Chen of the Weizmann Institute of Sciences, received the inaugural **Bennett Family Award for Collaboration in the Science of Wellness**. The annual award is designed to recognize experts doing collaborative research that merges science and wellness for the advancement of human health and well-being globally. It is a joint initiative between wellness advocate and Bennett Family Foundation President Bija Bennett and the Global Wellness Summit, an annual international symposium for leaders shaping the wellness industry's future. Drs. de Pablo and Chen were chosen for "groundbreaking developments with their work that can change life as we know if for the better."

Norman A. Fleck, professor of engineering, Cambridge University, and **Huajian Gao**, Distinguished University Professor, Nanyang Technological University, have each won a **George Irwin Gold Medal** from the International Conference on Fracture. Dr. Fleck received the medal for "seminal contributions to the deformation and failure of solids and structures." Dr. Gao was honored for "leadership and major contributions on the mechanics of engineering and biological materials." The medals were presented in June at ICF 15 in Atlanta.

Robert M. McMeeking, Tony Evans Professor of Structural Materials & professor of mechanical engineering, University of California, Santa Barbara, was inducted an **ICF Honorary Fellow** for "advancements in theoretical and computational mechanics for enhancing the understanding of the performance of materials."

Paula T. Hammond (NAM/NAS), Institute Professor and head, Department of Chemical Engineering, Massachusetts Institute of Technology, has been named the recipient of the **2023–2024 James R. Killian Jr. Faculty Achievement Award**. Professor Hammond is honored for her work designing novel polymers and nanomaterials, which have extensive applications in fields including medicine and energy.

Paul C. Kocher, president and chief scientist, Cryptography Research Inc., received the RSA Conference **2023 Award for Excellence in the Field of Mathematics** in April. The award acknowledges the outstanding contributions of individuals and/or organizations whose work helps to continue the fight against cybercrime. Mr. Kocher is a champion for innovation and research across the cybersecurity industry.

R. Vijay Kumar, professor and Nemirovsky Family Dean, University of Pennsylvania, has been named a **fellow of the National Academy of Inventors**.

Fei-Fei Li, Sequoia Capital Professor, Stanford University, and co-director, Stanford Institute of Human-Centered AI, has been awarded the **WTF Innovators Award** for numerous impactful contributions to the field of AI, with her work spanning across the domains of computer vision, machine learning, and cognitive and computational neuroscience. The award recognizes excellence at the precipice of societal change.

Chen-Ching Liu, American Electric Power Professor and director, Power and Energy Center, Virginia Tech, has been named a **foreign fellow of the Chinese Society for Electrical Engineering**.

Karen Lozano, Julia Beecherl Endowed Professor, University of Texas, Rio Grande Valley, has been recognized by the Carnegie Corporation of New York as a **Great Immigrant, Great American**. Every Fourth of July, Carnegie celebrates society-enriching contributions made by immigrants to America. Professor Lozano has made a name for herself locally and nationally for her work with nanofiber research and her mentorship to students from underserved populations.

Rafael L. Bras, provost & executive vice president for academic affairs, **Marilyn A. Brown**, Regents' Professor, School of Public Policy, and **Susan S. Margulies** (NAM), professor of biomedical engineering, all at the Georgia Institute of Technology, have been **elected to the American Academy of Arts and Sciences**, one of the nation's oldest and most prestigious honorary societies and a leading center for independent policy research. Dr. Margulies is currently serving as assistant director of the NSF's Directorate of Engineering.

Linsey C. Marr, Charles P. Lunsford Professor, Virginia Polytechnic Institute and State University, has been selected for a **Distinguished Scientist Award** by the Southeastern Universities Research Association (SURA) for her transdisciplinary research on aerosol transmission. She was recognized by SURA for exemplifying its mission "to advance collaborative research and strengthen the scientific capabilities of its members and the nation."

James G. Maser, senior vice president, Aerojet Rocketdyne, has been selected as a **2023 Honorary Fellow of the American Institute of Aeronautics and Astronautics**.

Thuc-Quyen Nguyen, professor and director of the Centre for Polymers and Organic Solids, University of California, Santa Barbara, has been awarded the **Wilhelm Exner Medal 2023** for her valuable contributions directly impacting the future economy through the development of organic solar cells. The award honors researchers who have directly influenced businesses and industries through their scientific achievements and contributions. The award ceremony took place in Vienna, Austria. Professor Nguyen is the first Vietnamese-origin person to be nominated and receive this prestigious award.

Oyekunle Olukotun, Cadence Design Professor, Stanford University, is the recipient of the **ACM-IEEE CS Eckert-Mauchly Award** for contributions and leadership in the development of parallel systems, especially multicore and multithreaded processors. He was formally recognized during an awards luncheon on June 20th at the International Symposium on Computer Architecture (ISCA 2023).

Mark T. Peters, executive vice president, National Laboratory Management & Operations, Battelle Memorial Institute, was presented the **2023 Henry DeWolf Smyth Award** by the American Nuclear Society and the Nuclear Energy Institute at the Nuclear Energy Assembly in Washington, DC, on May 17. The award recognizes an individual for outstanding service in developing and guiding the peaceful uses of nuclear energy.

Mark R. Prausnitz, Regents' Professor, Regents' Entrepreneur, and the J. Erskine Love Jr. Chair in Chemical and Biomolecular Engineering at the Georgia Institute of Technology, has been selected by the American Institute of Chemical Engineers to deliver the **2023 John M. Prausnitz AIChE Institute Lecture**. The 75th annual lecturer and son of the lecture's namesake, Professor Prausnitz, will describe his research during his presentation entitled "Translation of Biomedical Microtechnologies from the Lab to the Clinic" on November 8 at the 2023 AIChE Annual Meeting in Orlando, Florida.

Junuthala N. Reddy, Distinguished Professor, Regents' Professor, and O'Donnell Foundation Chair IV, Texas A&M University-College Station, is the recipient of the **2023 Leonardo da Vinci Award**. The award is the highest honor that the European Academy of Sciences bestows. Dr. Reddy, who is internationally renowned and highly cited for his research in the fields of applied and computational mechanics, is being honored for his original and continuing contributions to research and educational activities related to composite materials and structures. The award will be presented at the Annual Sympo-

sium of the Academy in October in Madrid, Spain.

Jonathan M. Rothberg, chairman, 4Catalyzer; **Deepika B. Singh**, founder and chief executive officer, R&D Investment Holdings LLC; **Krishna P. Singh**, president & chief executive officer, Holtec International, and professor, Institute for Advanced Discovery & Innovation, University of South Florida; and **Gary K. Starkweather** (deceased), architect, Microsoft Corporation have been **inducted into the Florida Inventors Hall of Fame**.

Margo I. Seltzer, Canada 150 Research Chair & Cheriton Family Chair, University of British Columbia, has been named the **2023–2024 ACM Athena Lecturer**. The award celebrates women researchers who have made fundamental contributions to computer science. Professor Seltzer is recognized for foundational research in file and storage systems, pioneering research in data provenance, impactful software contributions in Berkeley DB, and tireless dedication to service and mentoring.

On March 3rd, **Gwynne E Shotwell**, president and chief operating officer, SpaceX, accepted the **2023 Washington Award** of the Western Society of Engineers. She received the award for her leading role spearheading private enterprise space exploration. It was also noted that through leadership in both corporate and external STEM programs, Ms. Shotwell has helped raise more than $1.8 million for STEM programs reaching thousands of students nationwide. In addition, in 2021 Ms. Shotwell was selected an **Honorary Fellow of the Royal Aeronautical Society** for her successful engineering management of the SpaceX business ensuring that its concepts are designed, manufactured, and deployed profitably.

S.V. Sreenivasan, Joe C. Walter Endowed Chair in Engineering, University of Texas at Austin, and **Rex W. Tillerson**, retired chairman and chief executive officer, Exxon Mobil Corporation, received **UTA's Presidential Citation Award**. They were recognized for setting inspirational standards of excellence and for having given back to the University in truly exceptional ways.

The Virginia Tech College of Engineering has elected to its **Academy of Engineering Excellence William J. Dally**, chief scientist and senior vice president of research, Nvidia, and **Essex E. Finney**, retired associate administrator, Agricultural Research, US Department of Agriculture.

The following NAE members were **elected to membership in the National Academy of Sciences** at the NAS Annual Meeting in April: **Dan Boneh**, Chaired Professorship, Computer Science Department, Stanford University; **Gang Chen**, Carl Richard Soderberg Professor of Power Engineering, Massachusetts Institute of Technology; **Jack J. Dongarra**, Emeritus Professor, Innovative Computing Laboratory, The University of Tennessee, Knoxville; **Jennifer H. Elisseeff** (NAM), professor, Johns Hopkins University; **Geoffrey E. Hinton**, Distinguished Researcher, Google Inc.; **Jeffrey A. Hubbell** (NAM), Eugene Bell Professor in Tissue Engineering, University of Chicago; **Dina Katabi**, Thuan & Nicole Pham Professor, MIT; **Daphne Koller**, CEO and founder, Insitro Inc.; **Dan Shechtman**, professor, Technion-Israel Institute of Technology; and **Gregory Stephanopoulos**, Willard Henry Dow Professor of Biotechnology and Chemical Engineering, MIT.

Celebration of Life: William A. Wulf

The NAE will host a Celebration of Life honoring **William A. Wulf** on Sunday, October 1, 2023, from 4:00–5:30 pm in the Fred Kavli Auditorium in the NAS Building in Washington, DC. The event will take place during the NAE Annual Meeting at the National Academies in Washington, DC.

Among his many professional and personal achievements, Bill is remembered and revered for his service as NAE president from 1996–2007. With his vision, statesmanship, and optimism, he expanded the NAE's programmatic contributions and restored the relevance and stature of the NAE as a nationally important organization. Bill led the expansion of NAE initiatives to include diversity and inclusion and effectively argued for their value in strengthening the engineering profession.

Bill was a wonderful human being whose presence brought positivity wherever he went.

The Wulf Celebration of Life is open to the public. To register to attend in person, visit the NAE website at www.nae.edu and click on Annual Meeting. For those unable to attend in person, the event will be livestreamed on the NAE website.

2023 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education

Azad M. Madni, university professor and holder of the Northrop Grumman Foundation Fred O'Green Chair in Engineering in the University of Southern California's (USC) Viterbi School of Engineering, executive director of USC's Systems Architecting and Engineering Program, founding director of the Distributed Autonomy and Intelligent Systems Laboratory, and faculty affiliate of the USC Ginsburg Institute for Biomedical Therapeutics, was awarded the 2023 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education on May 2. The ceremony with students, alumni, faculty, friends, and NAE members took place at USC's Epstein Engineering Plaza, University Park Campus.

From left: Dean Yannis Yortsos; Dianne Chong, NAE Gordon Prize Committee; Gordon Prize recipient Professor Azad Madni; USC Provost Andrew Guzman; and NAE President John Anderson.

The prize was awarded "for creating and disseminating a transdisciplinary systems engineering education paradigm based on entrepreneurial leadership, innovation, convergence, social awareness, and diverse thinking and backgrounds."

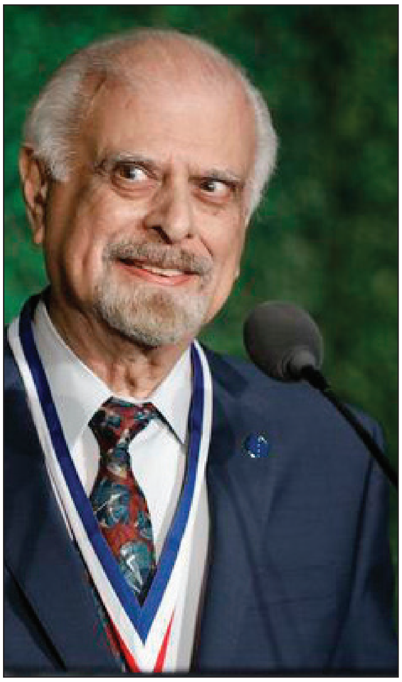
NAE president **John L. Anderson**, USC provost and senior vice president for academic affairs Andrew T. Guzman, Dean **Yannis C. Yortsos**, and the 2023 immediate past chair of the Gordon Prize committee, **Dianne Chong** (retired vice president of Materials, Manufacturing Structure & Support, Boeing Research and Technology) presented the award on behalf of the National Academy of Engineering. The public lecture took place on the same day in front of family, friends, and colleagues at USC's Ronald Tutor Hall.

Bernard M. Gordon Prize Acceptance Remarks by Azad M. Madni

President Folt, soon to be Provost Andrew Guzman, Dean Yortsos, President Anderson, colleagues, family, and friends, a good evening to you all. Receiving the NAE Bernard Gordon Prize is the crowning achievement of my academic career. It is truly an honor not just for me but also for all my students, fellow faculty members, and colleagues who have been part of my journey as an engineering educator. Many of them are here today.

I would like to thank the Gordon Prize Award committee for selecting me for this prestigious honor, and **Bernie Gordon** and the NAE for creating this very special award to recognize excellence in engineering education. I also thank **Norm Augustine** and **John Slaughter** for their enthusiastic support and guidance as I embarked on my journey of transforming systems engineering education.

I would be remiss if I didn't mention the most important figure in my journey, my father. He instilled in me the importance of education from a tender age. I have indelibly etched memories of my father routinely engaging with my teachers in elementary school not so much to



Azad Madni

inquire how I was faring in my classes but to learn about their teaching methods. That memory stayed with me and is perhaps the main reason for my fascination with education and educational paradigms.

Much of what I have accomplished as an engineering educator would not have been possible without the steadfast support of my wife, Carla, a fellow engineer, research collaborator, and, above all, my soulmate.

My personal educational perspective is shaped in part by a couple of astute observations. The first is Winston Churchill's famous refrain, "I am always ready to learn, although I do not always like being taught." The second is from Albert Camus, a French philosopher, who famously opined when asked about lecturing students, "Some people talk in their sleep. Lecturers talk while other people sleep." I took these to heart and have carefully avoided the perils of traditional lecturing.

With these considerations in mind, I approached engineering education in general and teaching in particular as a joint venture between learners and instructors, with the instructor in the role of storyteller, facilitator, and guide, and with learners engaging in active learning through story-driven role play, student-led discussions, and peer-to-peer interactions.

My research had shown that storytelling principles from the entertainment arts could be combined with principles from the learning sciences to make the acquired knowledge more connected and therefore more useful. This approach works, is easily disseminated, and, importantly, is exceedingly popular in our student and employer communities.

These experiences led me to formally define the field of transdisciplinary systems engineering and the creation of TRASEE™, a new educational paradigm that reflects transdisciplinary systems engineering principles. TRASEE exploits storytelling in conjunction with the principles of the learning sciences to make learning both effective and enjoyable.

My wife, Carla, and I have designated the entirety of the $250,000 Gordon Prize money to be retained by the NAE to create the Azad M. and Carla Madni Fund for Transdisciplinary Systems Engineering. This fund is intended to support the NAE's robust efforts through a wide variety of activities such as lectures, forums, and research with a focus on transdisciplinary systems engineering.

In closing, I'm reminded of the late NAE President **Chuck Vest**'s declaration, "This is the most exciting time for science and engineering in human history." With respect to systems engineering and systems engineering education, I will say, "This is the most historic era for systems engineering and systems engineering education in recent memory."

My sincere thanks to the NAE and Viterbi team for planning this wonderful event and to Dean Yortsos for making it all happen. Thank you all for attending! I will cherish the memories from tonight. It is said, "Life is a series of meetings and partings—meetings to create memories and partings to preserve them." After tonight, my family and I will have a lot of memories to treasure and preserve. Thank you all once again for being here to celebrate this evening!

2023 Japan-America Frontiers of Engineering Held in Tokyo

The 2023 Japan-America Frontiers of Engineering Symposium (JAFOE) was held in Tokyo at Waseda University's Research Innovation Center on July 17–20. NAE partners with the Engineering Academy of Japan (EAJ) to carry out JAFOE symposia, which started in 2000. The symposium organizing committee was cochaired by NAE member Dr. **Christopher Schuh**, dean of the Robert R. McCormick School

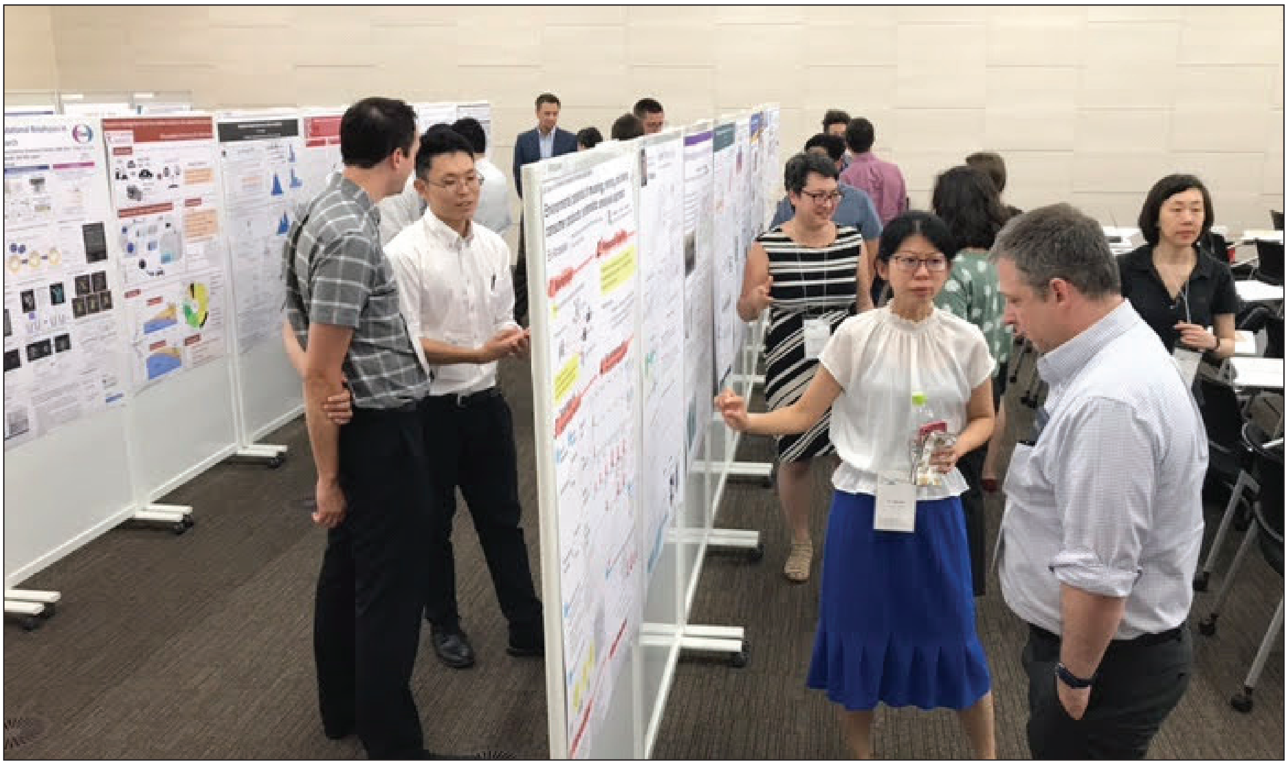
of Engineering and Applied Science at Northwestern University, and Dr. Chiharu Tokoro, professor in the Department of Science and Engineering at Waseda University.

The 2023 JAFOE symposium brought together approximately sixty early-career engineers from US and Japanese universities, companies, and government labs, where leading-edge developments in four engineering topics—materials by design, computational approaches to infectious diseases, mobility exoskeletons, and circular economy—were discussed.

The “Materials by Design” session covered recent advances that enable custom tailoring of materials for optimal performance and effectiveness. Modern tools such as first-principles calculations, thermodynamic modeling, machine learning, and high-throughput experimental methods are converging to change the way new materials are developed and industrialized. Rather than creating new materials as the end goal, it is becoming commonplace to connect through the entire product design lifecycle to ensure the best material is used, accounting for factors such as performance, cost, and sustainability. The speakers in this session discussed the molecular design and chemical synthesis of nanographene, how carbon nanomaterials are engineered to interact with biological systems in medical and agricultural applications, applying first-principles calculations to understand the behavior of ceramics within a materials informatics framework, and alloy development for additive manufacturing in the aerospace industry.

Now more than ever, we are aware of the global impact of infectious diseases. In the last few years, there has been a rise in innovative computational approaches such as physics-based simulations and data analysis by machine learning that have improved our understanding of the nature, spread, and treatment of infectious diseases. Because these approaches have become more pervasive at every step from pathogen transmission to treatment, it is important to examine both their capabilities and inherent limitations. The talks in this session covered ultra-fast drug discovery for hundreds of pathogens, computational approaches to drug discovery for infectious diseases, the utilization of engineering principles in epidemiological forecasting and analysis, and computational models to help guide health decision-making.

Millions of people suffer from mobility deficits caused by lost mechanical effort provided by the human neuromotor system, often stemming from factors such as aging, weakened muscles, or stroke. Presenters in the session titled “The Arduous and Exciting Path to the Development of Successful Mobility Exoskeletons” described the potential these technologies have if they can be translated from the laboratory to the lives of those who need them. Doing so requires optimizing diverse objectives involving clinical knowledge, engineering expertise, human factors, aesthetics,



and monetary costs. Talks covered research on and commercialization challenges for a wearable robot especially designed for children with cerebral palsy, novel personalization methods to enhance the performance of rehabilitation robots, the challenges of commercializing consumer exoskeletons, and the human and societal effects of a digital cyborg society.

The final session was on circular economy, or the concept of reconfiguring the current system of how we extract, produce, transport, consume, and discard into a more sustainable system through efficient resource use and resource recovery. The first two talks covered the quantitative contribution of the circular economy through lithium-ion battery recycling and assessment technologies for carbon neutrality. This was followed by talks on life cycle systems modeling for woody biomass utilization and policy gaps for achieving the net-zero greenhouse gas emissions target in the United States.

Abstracts of the papers and presentation slides where permission has been granted can be accessed in the list of sessions for the 2023 JAFOE at www.naefrontiers.org.

A video message from EAJ president Yoshimitsu Kobayashi opened the meeting, followed by welcome messages from NAE executive officer Alton Romig, EAJ deputy president Koichi Hishida, director of the Japan Science and Technology Agency's Department of International Affairs Osamu Kobayashi, and the symposium co-chairs, Chiharu Tokoro and Chris Schuh. In addition to the technical sessions, poster sessions preceded by flash poster talks were held over two days. These served as an icebreaker and an opportunity for all participants to share information about their research and technical work. The posters were displayed throughout the meeting, which facilitated further discussion and exchange during the coffee breaks.

Frontiers of Engineering symposia typically include a dinner speech by a senior-level engineer. The dinner speaker at the JAFOE meeting was Keio University president and JAFOE alumnus Kohei Itoh, who is known as a pioneer in quantum computing in Japan. Kohei was involved with the program as a speaker in 2005, and an organizer in 2007 and 2008. He spoke about his career in research on quantum computing, showing some of the slides that he utilized in his 2005 presentation. He also noted that he is still in contact with a number of US attendees from those meetings.

On the second afternoon, the group visited the AI Research

Center, the largest public AI research center in Japan, which is part of the National Institute of Advanced Industrial Science and Technology. Participants visited three research areas: autonomous mobile robots, digital technology for human-centered cyber-physical systems, and robotic biology. This was followed by a presentation by NAE international member **Chieko Asakawa**, executive director of Miraikan, the National Museum of Emerging Science and Innovation. She described her work developing technologies for the visually impaired, including a navigation suitcase that utilizes AI. The day concluded with a multi-course dinner at the hotel that ended with a few competitive games of *jan ken pon*—or rock, paper, scissors—with prizes awarded to winners.

Funding for the meeting was provided by The Grainger Foundation and the National Science Foundation. The next JAFOE meeting will be held in 2025 in the United States.

In addition to the Grainger Foundation Frontiers of Engineering US-based symposia, NAE has other bilateral Frontiers of Engineering programs with Germany, China, and the European Union. The FOE meetings bring together outstanding engineers from industry, academia, and government at a relatively early point in their careers since participants are generally within twelve years of receipt of an advanced degree. Frontiers provides an opportunity for them to learn about developments, techniques, and approaches at the forefront of fields other than their own, something that has become increasingly important as engineering has become more interdisciplinary. The meeting also facilitates the establishment of contacts and collaboration among the next generation of engineering leaders. For more information about this activity, go to www.naefrontiers.org or contact Janet Hunziker at jhunziker@nae.edu.

Simil Raghavan Recognized by the Society of Women Engineers

As a senior program officer for the National Academy of Engineering, Simil Raghavan, PhD, directs the Inclusive, Diverse, and Equitable Engineering for All (IDEEA) initiative, a collection of programs that seeks to educate, inspire, and provide opportunities for marginalized students and their caregivers to discover and engage with engineering. Simil was chosen by the Society for Women Engineers to appear in the special feature “Women Engineers You Should Know” in the spring issue of their magazine.

Dr. Raghavan grew up on the Pine Ridge Indian Reservation, an Oglala Lakota Indian reservation in South Dakota and Nebraska. There, she spent much of her childhood learning about farming and life on the prairie. An excellent student who excelled in math and science, she had never been exposed to engineering during grade school and set off to college expecting to study to become a teacher. At Oral Roberts University in Oklahoma, she was able to explore various majors and career options, and she discovered engineering as a pathway that combined many of her passions.

She graduated with bachelor’s degrees in mechanical engineering and Spanish and was inspired to improve STEM education, particularly for underrepresented populations. She went on to receive her PhD in biomedical engineering/auditory neuroscience from Johns Hopkins University.

While pursuing her own PhD, she felt this step was crucial for young women to remain connected to a community and to reinforce their interests in engineering.

At the NAE, one of the hallmark programs Dr. Raghavan manages is EngineerGirl, now in its twenty-first year. When the program began in 2000, only 9 percent of the US engineering workforce identified as women. In 2022, that had risen to 16 percent. The EngineerGirl program focuses especially on middle-school girls to encourage students at this important stage of their education to consider STEM and have awareness of engineering career paths.

The article featuring Dr. Raghavan and fourteen other women engineers is found at https://magazine.swe.org/weysk-23/.

University of Central Florida Hosts NAE Regional Meeting and Symposium on Digital Twins

By NAE members Carolina Cruz-Neira and Deborah Nightingale

In April 2023, the University of Central Florida in Orlando, Florida, hosted the NAE Regional Meeting and Symposium on Digital Twins. The emerging discipline of digital twins is progressing rapidly, reshaping the foundations of engineering, driving the future of work, and demanding new paradigms for innovation and competitiveness. Furthermore, digital twins is also becoming a strong initiative in Central Florida as an evolution from being recognized as the modeling, simulation, and training (MS&T) capital of the world. Central Florida is one of the fastest growing economies in the nation and has become a hub where government, academic institutions, and industry come together to innovate in space, energy, health care, education, entertainment, national security, transportation, and many other sectors. The region, anchored by one of the largest universities in the United States, the University of Central Florida, and strengthened by many more academic institutions, has over 50,000 higher education students within a 100-mile radius. The NAE regional meeting was an excellent forum to bring together a diverse and talented group of engineers from academia, industry, and government to highlight their research and practical work and to engage in discussions about the vision for a future where digital twins will play a prominent role.

Opening remarks were made by Michael Georgiopoulos, dean of the College of Engineering and Computer Science at UCF, on the critical application of digital twins in industry and government. This was followed by a presentation by **John Anderson**, president of the NAE, on the future of engineering and the critical role that the NAE plays.

The technical sessions at the 2023 Digital Twin Symposium had a good balance among academic and industry presenters and covered the following topics:

"Digital Twins for Magical Experiences," Michael Tschanz, director, Engineering Technology and Analysis, Disney Parks, Experiences, and Products, discussed the important role that digital twin models are playing in Disney operations to adjust park configurations in real time.

"Digital Twins & Digital Transformation," Douglas Juul, Missiles and Fire Control at Lockheed Martin Corporation, presented Lockheed Martin's strategy and applications in employing digital twins in their advanced product offerings.

Presentations on current academic research related to digital twins were facilitated by Dirk Reiners, associate professor, Computer Science, University of Central Florida:

"Medical Digital Twins," Reinhard Laubenbacher, professor of systems medicine and director of the Laboratory for Systems Medicine, Department of Medicine, University of Florida, presented a number of case studies where digital twins are being applied in healthcare.

"Six Human-Centered Artificial Intelligence Grand Challenges," Ozlem Garibay, assistant professor, Industrial Engineering, University of Central Florida, presented her research in human and social issues and their impact on AI.

"Digital Twin as a Force for Innovation," Grace Bochenek, director, School of Modeling, Simulation and Training, University of Central Florida, former US Secretary of Energy, former director of the National Energy Lab, provided an overview of the broad base of potential strategic applications for digital twin modeling.

The meeting also included a tour of UCF's Digital Twins laboratories across the School of Modeling, Simulation, and Training and the College of Engineering and Computer Science. Attendees experienced hands-on exposure to cutting-edge applications and research.

We thank the sponsors of the NAE Regional Meeting and Symposium on Digital Twins: The Knights Digital Twin Strategic Investment Program at UCF, the Office of Research at UCF, the National Academy of Engineering, and all the faculty, staff, and students that generously made this event a success.

Unlocking Data in Genomics: NAE Regional Meeting Hosted by the University of California-San Diego

The Southern California Regional NAE Symposium titled "Unlocking Data in Genomics" was held on February 16, 2023, at the Jacobs School of Engineering, University of California, San Diego. The symposium, co-hosted by the Jacobs School of Engineering and Illumina, an applied genomics technology company, brought together more than 120 experts, researchers, and professionals in the field of genomics to explore the latest advancements, challenges, and opportunities at the intersection of data science, technology, and healthcare. The event was structured with a series of informative sessions, insightful presentations, and dynamic Q&A discussions that collectively illuminated the cutting-edge developments in genomics.

Albert P. Pisano, dean of the Jacobs School of Engineering, along with **John L. Anderson**, president of the NAE, inaugurated the symposium with welcoming remarks and both addressed the significance of genomics research in transforming healthcare and the broader scientific landscape. Dr. Anderson even underscored the essential nature of collaboration with a bold call to action to bring together the "big thinkers" in innovation and engineering.

Delving into the intricate relationship between genomics and data management with his presentation on "Data Challenges in Genomics" was Rami Mehio, head of Global Software and Informatics at Illumina. He highlighted data management, data silos, and geographic/technical constraints in data sharing as the key challenges society faces while emphasizing the value of genomics in discovering insights into human health.

Mark Ham, principal engineer in Bioinformatics at Illumina, took the stage to elucidate the role of cutting-edge technologies in advancing genomics research and solving some of Mehio's proposed challenges. Ham explored the applications of lithography, optics, SIM (Structured Illumination Microscopy), FPGA (Field-Programmable Gate Array), CPU (Central Processing Unit), signal processing, and artificial intelligence in the realm of genomics. His presentation showcased how these innovations are driving breakthroughs in data acquisition, processing, and analysis.

Diving further into the realm of technology at the core of the solutions was Patrick Mercier, associate professor of electrical and computer engineering and codirector of the Center for Wearable-Sensors. Mercier provided insights into the world of wearable sensor technology and its implications for genomics. His presentation shed light on the potential of wearable devices to capture real-time physiological data, enabling personalized healthcare and enhancing the understanding of genetic interactions with environmental factors.

Several more Illumina and UC San Diego experts in genomics and technology came together to discuss the topic further, including Illumina's Kyle Farh, a Distinguished Scientist, AI Product Development, in his discussion on improving clinical diagnostics with AI.

The first session wrapped up with an engaging lightning-round panel, moderated by Dean Albert Pisano, providing attendees with rapid-fire insights from experts across the various disciplines. Speakers shared their perspectives on pressing questions, fostering diverse viewpoints and igniting thought-provoking discussions with questions from the audience.

In the second session of the day, the focus shifted toward "Federated Data Sharing," with Pam Chang, senior director of product development at Illumina, discussing how the aggregation and querying of genomic data across different institutions are accelerating biological insights.

Chang's presentation emphasized the importance of collaborative data sharing in advancing genomics research.

Kevin Patrick, a professor at UC San Diego Health, shared insights into the realm of digital health innovation within the UC San Diego Health system. He showcased how digital tools and technologies are transforming patient care, enhancing medical research, and promoting healthier lifestyles.

Closing out the presentations were co-directors of the Center for Nano-Immunology, and professors at UC San Diego, Nicole Steinmetz and Liangfang Zhang. They explored how nanotechnology is intersecting with immunology to create innovative solutions for diagnosing and treating diseases, including cancer. Their insights illuminated the potential of nano-based interventions in personalized medicine.

The Unlocking Data in Genomics Symposium provided a panoramic view of the dynamic convergence of data science, technology, and genomics and the intersections between them. It served as a platform for cross-disciplinary learning, idea exchange, and the fostering of new partnerships.

Memorial Tributes Transitions to Digital

We, the NAE Memorial Tributes team,[1] are excited to announce an important development in our beloved publication, *Memorial Tributes*. *Memorial Tributes* provides an enduring record of the many contributions of deceased NAE members to engineering for the benefit of humankind. In order to allow the tributes to reach the widest possible audience, reflect twenty-first century publication practices, and increase the speed with which completed tributes can be published, *Memorial Tributes* will be transitioning to a digital offering only.

Monthly posting of tributes will provide faster publication of those that have completed the editorial process. We also look forward to reducing our environmental footprint while ensuring that the content remains readily available to all our members as well as the public.

Starting in September, you will be able to access the latest tributes online, where you can read, download, and share them with ease. We will continue to link the tributes to the member profiles of the respective deceased member and NAE member authors. This will allow you to easily access, share, and commemorate the legacies of our esteemed colleagues and contributors, fostering a stronger sense of community and remembrance.

Even as *Memorial Tributes* shifts to digital publication, families and authors will receive a printed version of their loved one's tribute. We understand the importance of preserving these memories in a tangible form, and this gesture is our way of honoring the contributions and legacies of our esteemed colleagues and cherished members. The essence and quality of the tributes will remain intact, and we are committed to providing you with captivating and inspiring content in this digital era.

Thank you for your ongoing support and understanding as we embrace this transformation. We look forward to sharing the digital version of *Memorial Tributes* with you and hope you will find it as engaging and enriching as ever. We look forward to continuing to work with you as you, the NAE members, continue to support the publication of tributes by writing commemorative pieces for your colleagues or identifying other authors with whom we can work.

If you have any questions or concerns regarding this transition, please feel free to reach out to us. We value your feedback and are here to address any inquiries you may have.

[1] The NAE Memorial Tributes team members are Michaela Curran, Penelope Gibbs, Kyle Gipson, Kim Middleton, and NAE member Julia Phillips.

EngineerGirl Announces 2023 Writing Contest Winners

This year's competition asked students in Grades 3 through 12 to write an essay on how female and/or non-white engineers have contributed to or can enhance engineering's greatest achievements. Specifically, this year's contest asked students to choose one of the greatest engineering achievements of the twentieth century and explore how these innovations developed in the last century compare to new technologies being developed today. Over 700 submissions were received, and prizes were awarded to students based on grade level.

"Congratulations to all 2023 EngineerGirl Writing Contest winners for their captivating stories and essays that truly demonstrate how diverse perspectives enhance the work we do as engineers," said NAE President **John L. Anderson**. "These students not only showcased how diversity has greatly contributed to technological innovations in the twentieth century but also showcased how their diverse perspectives will shape the future of engineering."

Shriya Madhavan, a fifth grade student at STEM School Highlands Ranch in Highlands Ranch, Colorado, placed first among students from grades 3 to 5 for her essay, "Hedy Lamarr - The Visionary Inventor and Mother of Wi-Fi." Seventh grader Benjamin Wu from Narrows View Intermediate in University Place, Washington, won first place among entries from grades 6 to 8 for his essay, "Diversity and Inclusion in Engineering: The Impact of Dr. Patricia Bath's Legacy." Among students from grades 9 to 12, Tami Shogbola, a student at Cheltenham Ladies' College in Cheltenham, England, United Kingdom, placed first for her essay titled "The Luxury of Water: To Be or Not To Be."

Awards for contest winners are $500 for first place, $250 for second place, and $100 for third place. Students awarded an honorable mention receive an EngineerGirl sweatshirt, and all winners receive a certificate.

Surveys of contest participants indicate that forty percent of girls say they are more likely to consider an engineering career after writing their essay. EngineerGirl is part of the NAE's ongoing effort to increase the diversity of the engineering workforce. All the winners and their essays are posted at https://www.engineergirl.org/150807/2023-Contest-Winners.

New NAE Staff

Kyle Gipson

KYLE GIPSON joined the NAE Outreach and Communications team on June 20 as editor. He will oversee all NAE editorial projects, including *The Bridge*, *Memorial Tributes*, reports, studies, marketing materials, and more. Kyle has honed his editorial expertise through his six years in scholarly book publishing at some of the nation's most renowned university presses, including Johns Hopkins University Press and the MIT Press, as well as trade publishers. His ability to edit in a manner that (1) allows authors to communicate their messages as directly and clearly as possible to readers, (2) aligns with the author's vision and voice, and (3) conforms to set standards for style, content, and format will be a great asset to NAE. Kyle earned an MA in English from Harvard University and a BA in sociology from Bard College.

Kyle says that working with experts across the sciences, humanities, and social sciences has strengthened his ability to effectively communicate their ideas to a variety of audiences. "This has allowed me to become adept at distilling complex ideas into clear and concise language, and to tailor that language to different readerships. By working with experts in various disciplines, I've also fine-tuned the ability to quickly familiarize myself with specialized fields of study." You can reach him at kgipson@nae.edu or 202-334-2915.

Sydney Green

SYDNEY GREEN joined the NAE team on July 10 as a senior program assistant working with the IDEEA and PEER programs. Sydney is native to the DC area and graduated from Morgan State University with a degree in psychology in May 2022. She describes herself as motivated, determined, team-oriented, optimistic, friendly, and fun-filled. She loves to laugh, travel, explore new places, binge-watch Netflix, do word-search puzzles, journal, and listen to music. Sydney looks forward to spreading positive energy, interacting with people, having an excellent impact with creative ideas and solutions, and working on future NAE endeavors. She can be reached at sgreen@nae.edu or 202-334-2676.

Ariana Madrid

ARIANA MADRID started as an undergraduate intern with the IDEEA Program on July 26. She is a first-generation college student at Rochester University, studying for a bachelor of science in information systems programming. Ariana will be helping to support content creation and posting for *EngineerGirl*, applying her perspective on how to best reach diverse girls. She has a passion for working with technology in a variety of ways, such as programming, esports, connecting

with people, learning new skills, and bringing her imagination to life, and hopes to someday become a software developer to create influential games that, like Mario, inspire a new generation of kids. You can reach Ariana at amadrid@nae.edu.

Melissa Moore-Esquivel

MELISSA MOORE-ESQUIVEL joined the Program Office on June 5 as the NAE programs coordinator. In this dynamic role, Melissa will organize and coordinate the overall administrative aspects of the NAE's diverse programs and projects, including interdivisional and international collaborations. She will serve as a staff resource and mentor and will assist the director and the activities of the Forum on Complex Unifiable Systems (FOCUS) program as well as the Council Committee on Programs.

Melissa joins the NAE after seven years with the Smithsonian Institution's Office of Advancement, providing administrative, operational, and customer support as their advancement associate. While at the Smithsonian, Melissa served on the Smithsonian Advancement Academy Diversity & Inclusion Workgroup and the Smithsonian Asian Pacific American Alliance Committee. From 2021–22, Melissa was the Guam Society of America Inc.'s secretary, working in tandem with the Society's Communications Committee. She is an active member of the Guam Society of America Inc. and the Scottish-American Women's Society. Melissa graduated from Towson University in 2012 with a BA in history and early modern European studies. For fun, Melissa enjoys hula dancing, rock climbing, Sailor Moon nostalgia, and period dramas. Melissa can be reached at mmooreesquivel@nae.edu or 202-334-2949.

Hayda Wallen

HAYDA WALLEN joins us in the role of council administrator. Her expertise in administrative management and international relations will undoubtedly contribute significantly to the Academy's mission. Hayda's professional journey also includes roles as the administrative coordinator at the Environment & Sustainability Institute (The Earth Commons) at Georgetown University and as the Security Cooperation Specialist at the Embassy of Trinidad and Tobago, where she coordinated the security portfolio of the CARICOM Caucus of Ambassadors for over twelve years. She also served as program manager for the Inter-American Committee against Terrorism at the Organization of American States. Hayda holds a master's degree in hemispheric security and defense (with distinction) from the Inter-American Defense College, along with master's and bachelor's degrees from the University of the West Indies.

Hayda is an avid reader who enjoys exploring the genres of historical fiction, fantasy, and Greek mythology. Some of her favorite books include *Game of Thrones*, *Wheel of Time*, and *Pride and Prejudice*. The proud mother of a daughter who is currently attending middle school, Hayda has a passion for travel and cooking, often combining these interests whenever possible. You may reach out to Hayda at hwallen@nae.edu or 202-334-2367.

Legacy Gift Highlights Dedication to International Partnerships in Engineering

Donor Story

Virginia Bugliarello – wife of legendary civil, bio, and social policy engineer Dr. **George Bugliarello** (NAE ’87) – has made a vitally impactful pledge through a combination of outright and bequest gifts in honor of her late husband to establish the *George and Virginia Bugliarello Endowed Fund*. This fund will empower the newly named *George and Virginia Bugliarello NAE International Secretary* to execute their work at the NAE supporting programs that promote and foster relations with international partners in a more robust fashion than ever before.

This incredibly generous gift is special because of the history and connection it shares with the Bugliarello family. Born in 1927 in Trieste, Italy – before earning his master’s degree and PhD at the University of Minnesota and the Massachusetts Institute of Technology, respectively – George knew firsthand what it meant to the NAE’s immigrant and international members to have an academy that welcomes, values, and serves them.

George served as international secretary on the NAE Council from 2003 to 2011 with his trademark collegiality, leadership, and kindness, but that was only the capstone of his service to the NAE’s international membership and the international community at large. In addition to his work within the Academies connecting with international members and serving on committees fostering scientific cooperation between the United States and nations such as Japan, Iran, and Russia, George consulted with UNESCO and took on assignments as a specialist with the US State Department working towards economic development in Venezuela and Central Africa.

George and Virginia Bugliarello

Listed above are only a handful of highlights from a career dedicated to bettering our world through engineering, a mission George began closer to home while president of the Polytechnic Institute of New York (now the Polytechnic Institute of NYU). From the start of his term in 1973, George led a revitalization of the institution’s flagship campus in Brooklyn, which culminated in the development of the Metropolitan Technology Center in the area surrounding campus. At its height, MetroTech brought 22,000 corporate workers to Brooklyn, and its effect in kickstarting the borough’s revitalization earned George the New York City Mayor’s Award for Excellence in Science and Technology.

While a partner in all her husband’s philanthropic and humanitarian endeavors, Virginia took on her own efforts to give back to their local community as well. For 40 years, she served as a public librarian in their hometown of Port Washington, NY, providing generations an enriching public space to grow and learn.

With the support of the NAE and other leading organizations, Virginia and George spent the rest of their lives together spreading their community development work globally. With Virginia’s gift, future NAE international secretaries now have the resources to follow in George’s footsteps to collaborate with leading engineers around the world and bring forth positive change and progress. This gift also qualifies Virginia

for membership in the Abraham Lincoln Society of the National Academies of Sciences, Engineering, and Medicine. The Abraham Lincoln Society acknowledges and honors members and friends whose lifetime giving is $1M or more. We are profoundly grateful for Virginia's support of the NAE and its global outreach work as overseen now by the *George and Virginia Bugliarello NAE International Secretary*.

Calendar of Meetings and Events

September 29–30	NAE Council meeting
October 1–2	**National Academy of Engineering Annual Meeting**
October 15–18	EU-US Frontiers of Engineering Nokia Bell Labs, Murray Hill, NJ
October 24–25	TQA Workshop: Occupational Noise Exposure Risks and Controls by invitation only

All meetings are held in National Academies facilities in Washington, DC, unless otherwise noted.

In Memoriam

Lewis M. Branscomb, 96, professor emeritus, University of California, San Diego, died May 31, 2023. He was elected in 1974 for leadership in advancing national and international science and technology.

J. Fred Bucy, 92, independent consultant, and retired president and CEO, Texas Instruments Inc., died May 20, 2021. Mr. Bucy was elected in 1974 for contributions to semiconductor design and to the development of seismic oil survey devices.

Reg Davies, 86, consultant (retired), Particle Science and Technology, died October 22, 2022. He was elected in 1999 for the development of particle technology in the United States for business application and contributions to higher education.

Robert C. Dean Jr., 94, professor of engineering emeritus, Thayer School of Engineering, Dartmouth College, died January 7, 2023. Professor Dean was elected in 1977 for contributions to theory and reduction to practice in the field of mechanical design of fluid machinery.

Judson C. French, 98, director emeritus, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, died February 2, 2021. Mr. French was elected in 1990 for outstanding contributions to and leadership in developing unique measurements for electronic components, systems, and semiconductors.

John B. Goodenough, 100, Virginia H. Cockrell Centennial Chair in Engineering, University of Texas at Austin, died June 25, 2023. Dr. Goodenough was elected in 1996 for designing materials for electronic components and expositor of the relationships between properties, structures, and chemistry.

Arthur C. Gossard, 87, professor of materials and electrical and computer engineering, University of California, Santa Barbara, died June 26, 2022. He was elected in 1987 for contributions to the study of the physics of ultra-thin semiconducting layers through molecular beam epitaxy, leading to new physics and new devices.

Donald L. Hammond, 93, retired director, Hewlett-Packard Company, died April 8, 2021. Dr. Hammond was elected in 1987 for technical and managerial contributions to electronic instrumentation and measurement.

Michael Hatzakis, 95, retired director, Institute of Microelectronics, died February 3, 2023. Dr. Hatzakis was elected in 1989 for innovation and leadership in materials and technology for submicrometer device fabrication.

U. Fred Kocks, 93, Distinguished Professor – Affiliate, Jacobs School of Engineering, University of California, San Diego, died May 6, 2023. Dr. Kocks was elected

in 1999 for advancements in the theory of strength, kinetics of plasticity of metals, and texture analysis.

Robert J. Madix, 84, senior research fellow, Harvard University, died May 25, 2023. Dr. Madix was elected in 2022 for development of quantitative models for predicting catalytic selectivity through fundamental understanding of reaction mechanism and kinetics.

Robert Malpas, 95, Eurotunnel PLC (retired), died June 18, 2023. Sir Robert was elected an international member for substantial contributions to the industrial engineering community and to its relations with academe in England, Europe, and the United States.

Perry L. McCarty, 91, Silas H. Palmer Professor Emeritus, Stanford University, died June 4, 2023. He was elected in 1977 for contributions to the environmental engineering profession through education, research, and service to government and industry.

William James McCroskey, 86, retired senior research scientist, US Army Aviation and Missile Command, died May 26, 2023. He was elected in 1996 for experimental and numerical studies of unsteady aerodynamics for rotary wing aircraft.

Sanjoy K. Mitter, 89, professor of electrical engineering, Massachusetts Institute of Technology, died June 26, 2023. He was elected in 1988 for outstanding contributions to the theory and applications of automatic control and nonlinear filtering.

Albert Narath, 90, retired president, Energy and Environment Sector, Lockheed Martin Corporation, died May 2, 2023. Dr. Narath was elected in 1987 for effective leadership of research and development in the weapons, energy, and government communications systems.

George P. Peterson, 88, independent consultant, died May 7, 2018. Mr. Peterson was elected in 1985 for instituting advanced manufacturing systems leading to significant improvement in aerospace productivity, including pioneering of composite materials and processing for structural applications.

Henry Petroski, 81, Aleksandar S. Vesic Professor of Civil Engineering and professor of history, Duke University, died June 14, 2023. Dr. Petroski was elected in 1997 for books, articles, and lectures on engineering and the profession that have reached and influenced a wide range of audiences.

Henry H. Rachford Jr., 97, senior principal software developer, GL Industrial Services Inc., died October 31, 2022. Dr. Rachford was elected in 2000 for contributions in the numerical solution of partial differential equations to solve petroleum reservoir and pipeline hydraulics problems.

Paul E. Rubbert, 83, retired Boeing Technical Fellow, Boeing Commercial Airplanes, died December 23, 2020. Dr. Rubbert was elected in 1993 for contributions to the development of computational fluid dynamics as an effective tool for aerodynamic design.

Hsieh W. Shen, 90, professor of civil engineering emeritus, University of California, Berkeley, died December 2, 2021. Dr. Shen was elected in 1993 for development of flow control and release plans of reservoirs to restore and enhance the ecological environment of rivers.

Shivaji Sircar, 75, distinguished research fellow, Lehigh University, died February 13, 2020. Dr. Sircar was elected in 2004 for contributions to the fundamental science and technology of adsorption separations and their applications in process industries.

Walter M. Wonham, 88, university professor emeritus, University of Toronto, died May 14, 2023. Professor Wonham was elected an international member in 2005 for work on the geometric theory of linear systems and for bridging the gap between control theory and computer science.

Dante C. Youla, 95, presidential fellow and professor of electrical and computer engineering emeritus, New York University, died August 31, 2021. Professor Youla was elected in 1982 for contributions to broadband matching in microwave networks and to optimal controllers for multivariable feedback systems.

Invisible Bridges

Creative Intolerance*

Guru Madhavan is the Norman R. Augustine Senior Scholar and senior director of programs at the National Academy of Engineering.

There is an allegory found in ancient Sanskrit texts of a swan that is often interpreted as a metaphor for spiritual progress. As the story goes, the graceful bird could separate nectar from a swamp, just as an enlightened sage separates the true self from the embodied self. I like to think of this "supreme swan" in the context of engineering. Could enlightened engineering help us discern the moral implications of our manufactured environments?

Engineering has long focused on the worldly—the "art of the possible"—rather than the nectar: the possibilities of art. Aiming to render what was once inconceivable into the inevitable, engineering has taken the practical attainment of prosaic goals as its highest calling. Engineers enable high-carbon habits, just as we promise to ease the emissions themselves. We entertain fanciful romances with data and algorithms that can lead us to grievous traps: unwanted, unintended, and unattended. In this world, the swan cannot separate the waters. The individual engineer must contend with what it means to be a good practitioner while straddling commerce and community; revenues and responsibility; safety and sustenance.

The Venice Biennale Architettura 2023 looks at some of these dichotomies with fresh eyes. It's not aimed at engineering; it's about architecture, the artsy cousin. But in this iteration, Lesley Lokko, the biennale's first Black curator, shifts the typically Eurocentric pavilions to a collaborative experiment centered on Africa and its diaspora. Called *The Laboratory of the Future*, the collection is a vast material meditation on stories of decolonization and decarbonization. "The vision of a modern, diverse, and inclusive society is seductive and persuasive, but as long as it remains an image, it is a mirage," Lokko notes.

In society at large, equitable civics is frequently desired but rarely designed. What would it take for engineering to contribute to equity and related ideals? How could we shift from our narrow focus on touchpads and touchless transactions toward touchy subjects and their tradeoffs? For starters, we might ask why engineering doesn't have a biennale. Since 1895, Venice has presented art for the public to weigh in on; the focus on architecture started in 1980. People are invited to contemplate not just what architecture is (and how much it costs) but what it does—for the mind, the markets, and mother nature. The biennale attempts to have open-ended conversation with viewers, inviting compliments and criticism.

Some of the work is deliberately constructed to provoke. In the section "Dangerous Liaisons," GRANDEZA STUDIO, a collective of artists and architects based in Spain and Australia, present their allegorical project *Pilbara Interregnum*. The interlinked multimedia installation uses the Pilbara, a pillaged region in the north of Western Australia, as a staging ground to unearth the forces behind relentless resource "expulsions, explosions, and exploitation." One segment spotlights the hood of a car bearing a maquette that seems to portray an extractive battlefield: the supply chains for key minerals that are often hidden behind the fanfare of the vehicle. Exploring these vast technological regimes and the ideologies that power them, the studio points to the disconnect between technology and responsibility.

This provocation raises overt questions about the engineering worldview that the profession is only beginning to grapple with. For many years, engineers have implicitly reckoned with these questions when choosing

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Inspired by the name of this quarterly, this column reflects on the practices and uses of engineering and its influences as a cultural enterprise.

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* This essay also appears in the summer 2023 issue of *Issues in Science and Technology*.

FIGURE 1 GRANDEZA STUDIO, *Pilbara Interregnum*. Photo by Clelia Cadamuro, courtesy GRANDEZA STUDIO.

FIGURE 2 Kéré Architecture, *Gando Primary School Library*. Copyright Kéré Architecture.

between jobs with software companies, defense contractors, and municipal waste treatment facilities. When questions of ethics and motivations are not considered critically, and perhaps publicly, individual engineers may get the sense that the grace of the enlightened swan is not for them.

This biennale also ponders the meaning of earth itself—as a building material and as a way for communities to leverage ancient knowledge and local resources to shape their own futures. Architect Diébédo Francis Kéré from Burkina Faso is among those featured in the section "Force Majeure."

Kéré grew up in a modest village east of Ouagadougou, where he sat through lessons in a small heat-locked classroom rigged from cement blocks. That suffocating structure shaped Kéré's future and his Pritzker Prize-winning projects. He vowed to ensure a child's right to a comfortable classroom. Kéré's first plan—a primary school—was engineered by and for the approximately 2,500 people in his village of Gando, from concept to completion. Three rectangular classrooms line up like a granary, oriented east-west to limit severe heat. An elevated sheet roof over the ceiling provides shade and natural cooling. This technology was allied with bricks handmade and laid by local people. The completed project galvanized Gando,

laying the foundation for literacy and ownership of public space. As Kéré put it: "If they build it themselves—like the school in Gando—and feel like they own it, they will take care of it."

In Kéré's vision, architecture is far more than a structure: it is a means of extending community through time. "Things are broken, and no one takes care to fix it," he observes. "You have the feeling it's owned by the government—but who is the government?" We tend to neglect that engineering itself has a governing—and a governance—role in civic life. Kéré's work suggests that the function of the school is not only to care for the students but to encourage the community to care for its creation—and thus, to care for itself.

This communal sensibility can be found in the earliest examples of engineering. In present-day Pakistan, the ruins of Mohenjo-daro reveal a metal-age metropolis of 40,000 inhabitants built around 2500 BCE. Constructed on silt, the builders used wide, strategically laid foundations to anchor the city, with linked streets for wheeled transport. Almost every house had a bathroom and water-flushed latrine, located street-side to efficiently discharge effluents via tapered terracotta tubes into the catchments or drains. A grid of wells supplied fresh water transported by sloped shafts made of baked bricks. We know little about who these people were and why their civilization collapsed, but what remains clear is their commitment to civic infrastructure, which many parts of "modern" India lack today, millennia later.

In this context, Kéré's work is a reminder that good engineering is necessarily a product of scarcity and social engagement, and it doesn't need to be fancy or frivolous. More recently, Kéré has worked on a community-built library in Gando. This elliptical building with a eucalyptus façade has become a conduit between the primary school and its extension, shielding the playground from dusty winds. The ceiling, embedded with sliced terracotta pots made in the community, provides round light openings. The slanted rays produce a dynamic pattern of lights and shadows, and the "stack effect" from the overhanging metal roof and polycarbonate sheet ventilates the inner space, together enriching the library's spatial sense.

Engaging with these provocations has spurred me to offer my own: How might we challenge the idea of what engineering is and could be if we shifted our attention from Silicon Valley to the Indus Valley? Today's vision of engineering is one based in mass production, not only of goods and software, but also of consumers. Could we turn these skills toward mass-producing responsible citizens and communities?

Therein lies a touchy subject: Are we doing the right kinds of engineering? How should we invite the public in to discuss it at our own biennale? What might they discover? And how willing are we engineers to be provoked to reconsider the foundations of our unquestioned beliefs? To return to the allegory of the swan: we cannot learn to distinguish between what we can and cannot tolerate if we never examine the swamp in which we survive.

Sir Mortimer Wheeler, who organized detailed excavations of Mohenjo-daro in the 1940s, argued that in modern society, tolerance and passivity—not necessity—"scribbled" our sceneries with humanmade pillars, cables, and villas. He encouraged "creative intolerance," by which he didn't mean being artistic narrow-mindedness, but refusing to accept "dumb obediences" of thought that blunt critical judgment toward complex civic problems. Instead of carefully understanding our problems, "we talk ourselves first into confusion and then into coma," Wheeler said. The idea of creative intolerance, so evident in the installations of the Venice Biennale, is one way for engineering to seek something like enlightenment.


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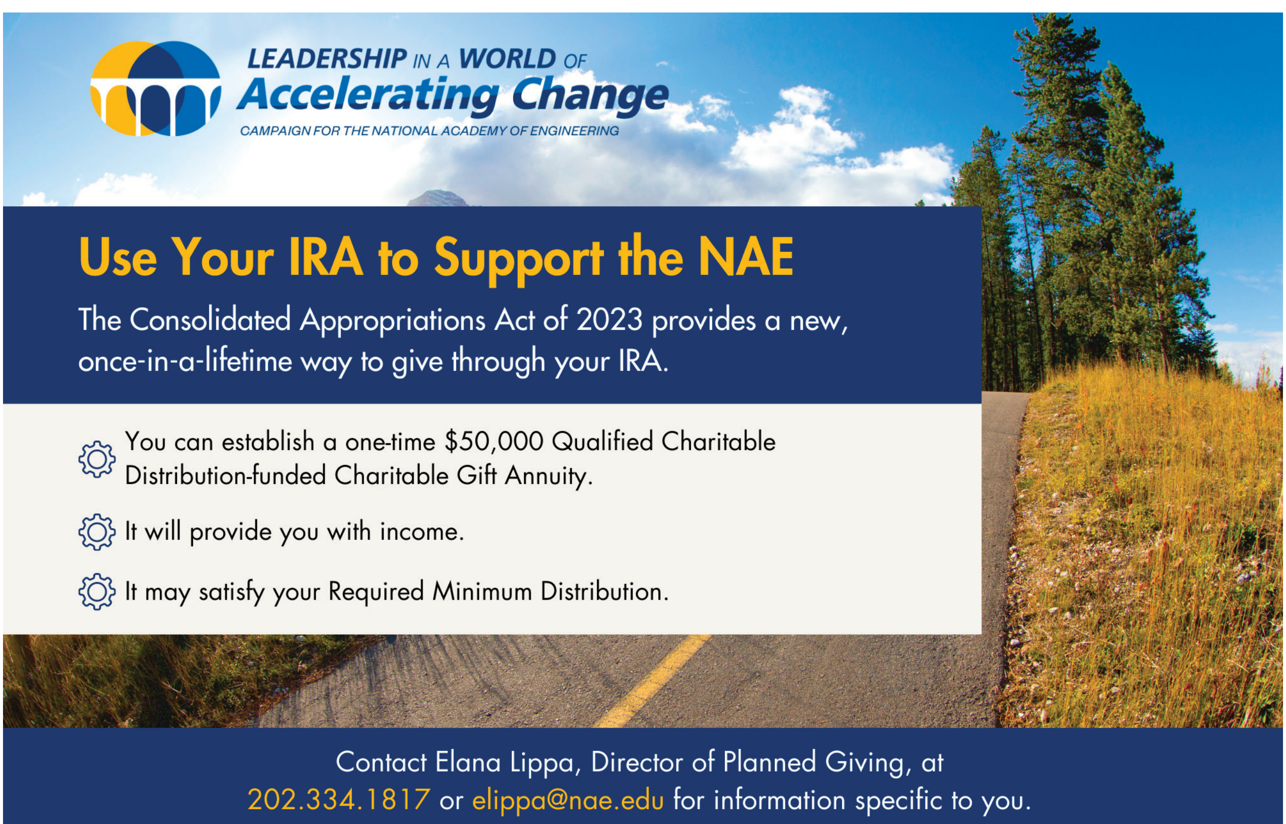
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