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GUEST EDITORIAL

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The climate is changing. Engineering education needs to change as well

1 | CLIMATE CHANGE IMPACTS ENGINEERING

As atmospheric greenhouse gas concentrations continue to rise and the consequences of climate change become increasingly destructive, engineers, scientists, and the broader population are now aware that climate change is a threat we can no longer avoid. Addressing climate change requires facing two interconnected challenges. The first is to rapidly transition to carbon neutral—or even carbon negative—energy systems while reducing greenhouse gas emissions across all sectors of the economy. The second challenge is to minimize the impacts of climate change, particularly for the most vulnerable populations, by building sustainable and resilient systems. Addressing these challenges will require a fundamental reshaping of engineering education. The next generation of engineers and current practitioners will need new skills to serve society in this environment of uncertainty and rapid change.

Empowering engineers with the skills to address the challenges created by climate change requires adapting both the technological and philosophical frameworks used in engineering education. In particular, engineers will need to (1) understand how climate and sustainability are linked to engineering design; (2) incorporate a wide range of disciplines into engineering solutions; (3) understand the ethics and justice dimensions of engineering; and (4) listen to and collaborate with diverse communities. Developing these skills requires reimagining engineering education and continuing professional development from student to senior practitioner.

2 | ADDRESSING THE TWIN TECHNOLOGICAL CHALLENGES OF CLIMATE MITIGATION AND ADAPTATION

The first technological challenge is to rapidly restructure the energy system and related infrastructure into a system that is sustainable, affordable, reliable, and just. In this context, sustainable means *carbon-neutral or carbon-negative* while minimizing other environmental and human impacts. The urgency of this restructuring was emphasized by the most recent Intergovernmental Panel on Climate Change report, which concluded that only rapid implementation of a low-carbon system could achieve the goal of keeping the change in global average temperatures below 1.5°C (IPCC, 2022). This challenge exists across multiple sectors that impact greenhouse gas production, including fossil fuel-based transportation, agricultural systems reliant on petrochemical fertilizers, long-distance transportation, and energy-intensive manufacturing.

The second technological challenge is to engineer systems resilient to a changing climate. Even if humanity achieves the most optimistic carbon reduction goals, existing greenhouse gas concentrations will lead to decades of change as humanity adjusts to higher sea levels and new local weather patterns. Climate-driven extreme weather events are expected to continue to increase in frequency and intensity (Knutson et al., 2019; Turco et al., 2019). The power system is vulnerable to climate change in multiple ways: droughts have affected hydroelectric production, extreme weather has limited the operation of power plants, and the outdated electrical transmission system in the United States has sparked devastating wildfires. The impact of climate change needs to be considered in the engineering of physical infrastructures, such as water supply and transportation systems. It also needs to be considered in the engineering of systems with physical and human components, such as the healthcare system (Mahmoud et al., 2022). The failure of these systems due to climate change often disproportionately impacts underserved and disadvantaged communities (EPA, 2021).

Meeting these challenges will require engineers to use skills that are currently under-emphasized, or ignored, within their current training. The challenges of climate change are making these skills so foundational to the engineering profession that they cannot be ignored in the context of engineering education.

3 | CHANGING THE ENGINEERING SKILL SET

Responding to climate change will require engineers to have a mix of technical and leadership skills that enable them to work across both disciplinary and cultural boundaries to create just and feasible solutions to the integrated social, technical, and ecological challenges described above. In the context of sustainability and resilience, leadership is defined as the ability to work with and empower others to create technically feasible and morally just solutions, especially when these new solutions require replacing traditional approaches. The following four skills are most readily identifiable as necessary:

3.1 | An understanding of climate, sustainability, and resilience linked to engineering design

Incorporating climate and sustainability into engineering education entails first ensuring that engineers understand the fundamentals of climate science and climate impacts. Engineers will need to consider *climate adaptation* as they consider the impact of climate change on the performance of their systems and design for resiliency in response to increasingly frequent climate events. They will also need to consider long-term *climate mitigation* as part of a larger analysis of the sustainability of their systems. Failure to do so risks the development of engineering efforts that exacerbate or underestimate climate change.

Engineers in all disciplines work on technologies and infrastructure whose use may continue for decades and require prolonged investment over multigenerational periods. *They will need to understand how the functionality and performance of these systems change in a changing climate*. For example, while it remains unclear if saltwater intrusion linked to climate change contributed to the, 2021 Surfside condominium collapse, the event is seen as a warning that civil engineers will need to consider the impact of climate change on structures (Parkinson, 2021). Similarly, mechanical engineers will need to understand how increasing temperatures will limit the thermodynamic efficiencies of power systems (Craig et al., 2018). Aerospace engineers will need to understand how hotter days will affect the ability of aircraft to serve critical aviation needs (Coffel et al., 2017).

Engineers will need to design systems to be more resilient as the frequency and intensity of natural disasters, such as wildfires (Turco et al., 2019), floods (Ghanbari et al., 2019), and heat waves (National Academies of Sciences, Engineering, and Medicine, 2016) increase due to a changing climate. They can identify structural vulnerabilities, devising innovative solutions to lower initial damage during an event, and accelerate recoveries. Identifying vulnerabilities or devising solutions often requires cross-disciplinary collaboration. For instance, addressing the role of saltwater intrusion in the built environment will require knowledge from climate science, hydrology, hydrologic engineering, and geotechnical engineering (Abdelhafez et al., 2022). Efforts to address the resilience of larger-scale systems, such as transportation or healthcare, will require even more integrated knowledge sharing and collaboration.

Engineers will need to consider the sustainability of these systems in the context of climate mitigation and other impacts. A project's environmental externalities may persist for decades, compelling the incorporation of sustainability into design. Current engineering practices to enhance resilience focus mainly on reducing damage to the built environment at a minimal initial cost with limited consideration for sustainability. However, climate change requires consideration of future performance and costs as well and should encompass all direct and indirect social, economic, and environmental costs over the lifecycle of a project or technology. This approach should be applied to *all* technologies, including clean energy technologies. This requires the use of frameworks that allow for making risk-informed decisions. The use of these tools may enable mitigation strategies that make resilient and sustainable infrastructure design and construction practices financially and socially attractive to community decision-makers (Adhikari et al., 2021).

3.2 | An ability to incorporate knowledge from a range of scientific disciplines

A useful example of how engineers will have to work directly with and incorporate knowledge from a range of scientific disciplines is ecology. Climate change is a substantial stressor on ecosystems, and in turn, ecosystems affected by other stressors are also less resilient to climate impacts. These stressors include human-driven environmental problems such as chemical pollution, habitat degradation due to agricultural and population expansion, strains on water delivery systems, and inefficient waste generation and disposal. These stressors act synergistically to exacerbate climate impacts on certain ecosystem services, including those related to food production and soil, air, and water quality. They also worsen climate-related impacts by weakening climate-mitigating services, such as natural carbon sequestration. These environmental problems reflect past and current engineering values and priorities that place both ecosystem and human health at risk. Reimagining engineering solutions requires the ability and willingness to incorporate knowledge from the life sciences and environmental impacts of engineering interventions into engineering decisions.

Climate-sensitive engineering requires an appreciation for the complexity of biological and ecological processes. Biological systems are more multifaceted and unpredictable than the typical human-made systems that engineers encounter during their education. As a result, engineers may underestimate the sensitivity of living systems, and thus, the environmental impacts of common engineering goals and applications. For example, hydraulic fracturing for natural gas can negatively impact fish populations through diverse hydrologic, physical, and chemical changes (Weltman-Fahs & Taylor, 2013). It can be particularly difficult for engineers and biologists alike to anticipate how alterations to the environment scale with increased adoption of a product or method. As climate change continues, predicting environmental impacts will be complicated by concurrent impacts of climate on ecosystems.

Effectively mitigating environmental impacts requires improvements in various research, education, and policy domains. Due to the links between the environment and human well-being, engineers will need to interact not just with life scientists, such as ecologists, biochemists, and wildlife biologists, but also epidemiologists and public health experts. This will require a change in how engineers are educated in biological, ecological, and life sciences, as well as how they develop the skills they need to successfully communicate with and collaborate with different scientific communities.

3.3 | A knowledge of ethics and justice as applied to engineering

The ethical challenges associated with climate change go beyond recognizing climate change as undesirable. Engineers will be required to take rapid action at global and local scales to reduce greenhouse gas production and create sustainable and resilient systems. Without an ethical framework in place, engineers risk creating solutions whose benefits and costs are distributed unevenly or even unethically. This raises questions around the basic tenets of justice: Who is *recognized* as a stakeholder in the design of engineering systems? Do diverse stakeholders have the ability to effectively *engage* in system design? Once designed and deployed, are the benefits and impacts of the system equitably *distributed*? Environmental justice seeks to ensure that no population bears a disproportionate share of the negative environmental consequences from resource extraction, hazardous waste, and other land uses, past injustices are remediated, and thriving futures are created (Schlosberg, 2009). Energy equity relates to inequities impacting disadvantaged communities that are overburdened by pollution from energy facilities, experience underinvestment in clean energy, and lack access to energy-efficient housing and transportation (Sovacool & Dworkin, 2015). Engineers should have the ethics education necessary to understand and apply these concepts.

Teaching ethics is an ongoing challenge in engineering education that goes beyond climate (National Academy of Engineering, 2017; Reynante, 2022). Ethics in engineering often focuses on microethics, including day-to-day decision-making and client relations. However, engineers must also consider macroethics, which refers to broader concerns around professional responsibility, values, and societal concerns (Karwat et al., 2015). Climate change impacts both. At the macroethical level, climate change influences the professional responsibility of the engineering profession as a whole and the career decisions of individual engineers. At the microethical level, climate change may influence decisions about community input and balancing benefits and impacts across communities.

The conceptual frameworks of environmental justice and energy equity can be applied to both existing and emerging energy technologies. For example, while nuclear power plants reduce greenhouse gas emissions, three-quarters of all uranium production comes from mines in or near Indigenous communities. Mines are often left unremediated after production ends, poisoning the land and people while impacting traditional ways of life (Verma & Djokic, 2021). The impacts of resource mining are also seen in the energy transition: demand for cobalt for batteries has similar repercussions (Sovacool, 2021). Driven by ideals of justice and macroethical ideas, engineers can, for example, advocate for technology and knowledge transfer to countries in need, increased data transparency, and prohibitions on the import of unethically or illegally sourced goods and resources (Karwat, 2022).

Achieving just and equitable solutions will require engineers to avoid narrowly-defined "optimal" solutions that can cause disproportionate harm to individual communities. It also requires engineers to obtain both input and consent from affected populations. Implementing sustainable solutions requires that engineers understand environmental justice and energy equity well enough to incorporate these concepts during the development and deployment phase in a way that addresses the entire life cycle of systems.

3.4 | Representation of, and the ability to work with, diverse communities

Low-income and non-White communities are disproportionately affected by climate change and its impacts (EPA, 2021). This raises two fundamental challenges to engineering education. The first is a *representation of affected groups within the engineering profession*. The underrepresentation of low-income students and Black, American Indian, Native Alaskan, and Latino communities within undergraduate engineering education is well-documented (National Center for Science and Engineering Statistics, 2021). Asian Americans' "model minority" status obscures the fact that groups, such as Hmong Americans, are under-represented in STEM (National Public Radio, 2021). These historically excluded groups are affected by a culture within STEM that constructs a "hostile obstacle course" for entry and retention (Berhe et al., 2022), and by post-graduation professional barriers, such as engineering licensing (Dempsey, 2018). Underrepresentation in engineering denies these communities the knowledge to respond to climate change and limits the ability of the engineering workforce to identify critical problems.

The second issue is *the ability of engineers of all backgrounds to work with underrepresented communities*. Engineers and scientists who ignore embedded community knowledge or are unable to relate their recommendations to the experience of local communities risk both being scientifically incorrect and having their findings ignored (Wynne, 1989). In climate change research, this has led to the adoption of practices that incorporate the experience and knowledge of local communities (Norström et al., 2020). This approach requires a level of cultural competency that is not always developed in engineering curricula.

The challenges that these gaps may create can be illustrated by examining environmental justice problems not related to climate change. During the Flint Water Crisis, as many as 100,000 residents of a majority Black city were exposed to high levels of lead in their drinking water. This led to exposure symptoms, such as digestive problems, renal issues, anemia, and possible long-term mental health issues, which may be exacerbated by the stresses of poverty and other environmental factors (Maloney et al., 2018). Members of the Flint community identified these symptoms as consistent with lead poisoning. Their findings were ignored due to their lack of academic credentials. The community then formed an alliance with academic water-quality experts that attracted national attention to the lead poisoning, but that unraveled due to a lack of shared understanding between researchers and the community. If the engineers had discarded the "deficit" model, built on the idea that a lack of knowledge in the community required scientists to speak for them, in favor of an engaged partnership model, these issues might have been avoided (Lambrinidou, 2018).

The response of the Diné (Navajo) to climate change shows that approaches wherein disadvantaged groups combine their own experience and values with scientific information are viable. The Navajo Nation is acting to both build a sustainable energy economy (HighCountryNews, 2021) and to prepare its lands and people for the impact of climate change (Navajo Nation Climate Change Program, 2021). Training engineers to empower leadership in communities that are impacted by climate change will require engineers to re-examine their understanding of leadership and community.

4 | REACHING THE ENTIRE ENGINEERING PROFESSION, FROM STUDENTS TO SENIOR PRACTITIONERS

The climate crisis is immediate and cannot wait for a new generation of engineers to be trained. *The skills described above are needed immediately across the engineering profession*. Currently, practicing engineers are making design decisions that will last for decades in a changing climate. Failure to consider climate impact and resiliency in these systems will exacerbate the climate crisis while creating systems doomed to rapid obsolescence. Acquiring the skills needed to do this requires current and future engineers to be *lifetime learners, as envisioned in the engineering licensing process*. If the skills described above are mastered only by early-career engineers, who often lack both the experience and the authority to set priorities, then the opportunity to limit climate change while creating resilient systems will be missed.

This creates new challenges for engineering educators. The need to broadly teach sustainability and resilience to undergraduate and graduate students requires faculty to develop an understanding of how these topics fit with their individual areas of technical expertise. Faculty should also consider the development of educational programs relevant to engineers at all levels in private industry. These programs should recognize industrial learning incentives and goals. Finally, truly effective teaching of the technical and leadership skills required to meet the challenges of climate change requires the practice of these skills to be integrated into project-based learning across the curriculum.

These skills are meaningful in contexts beyond climate change and align with student outcomes defined by the Accreditation Board for Engineering and Technology (ABET). In particular, engineers are expected to graduate with "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" combined with "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, 2020). Engineering graduates and practitioners who are unable to explicitly understand how their solutions both impact the climate and must function in a changing climate meet neither of these criteria.

Similarly, the expectation that engineers graduate with "an ability to communicate effectively with a range of audiences" (ABET, 2020) should consider cultural contexts. It can also incorporate the idea that communication is not one way and that engineers should develop the skills to listen to communities affected by their actions.

Fully implementing these outcomes requires not only innovation in engineering education but forward-looking interpretation, or possible expansion, of ABET accreditation requirements. Advocates for greater diversity, equity, and inclusion have pointed out that accreditors play a critical role in pushing for the training of engineers with a greater range of skills. (Gallimore, 2021). A combination of faculty innovation, funding for the development of a new curriculum relevant to practitioners, and forward-looking accreditation requirements offer the best opportunity for preparing engineers for what the growing climate crisis brings.

5 | FINAL THOUGHTS: THE URGENCY OF CHANGE

Both engineers and the systems that they designed have lasted for decades. Joe Sutter, who led the design of the Boeing 747, began his engineering education at the University of Washington in 1939. The first 747 entered service in 1970 (Sutter, 2006). After multiple updates, the final 747 will be delivered in 2022 (Aviation Week Network, 2022), and is likely to remain in service until the 2040s, continuing to contribute to greenhouse gas emissions while operating in conditions substantially impacted by climate change. Similarly, engineers beginning their education in 2022 will practice into the 2060s or beyond, and the impact of their decisions will be seen well into the 22nd century. Unless sustainability and resilience are considered in engineering designs *today*, engineered systems will continue to have negative climate impacts for decades while requiring expensive modifications to achieve resiliency. This, in turn, requires climate and sustainability to be incorporated into engineering education and professional development *today*. Otherwise, engineers may continue to design long-lasting systems without the skills needed to create sustainable and resilient systems. Transforming engineering education to give engineers the tools they need to meet these challenges is now an urgent requirement for both engineers and the society they serve.

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