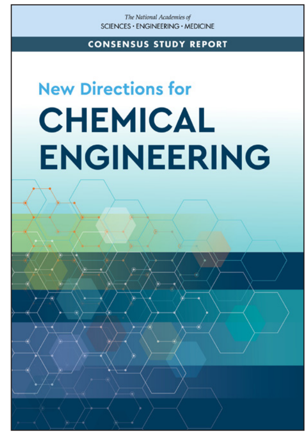
Consensus Study Report

FEBRUARY 2022

HIGHLIGHTS



New Directions for Chemical Engineering

Chemical transformations are at the heart of the technologies that have enabled modern society. Without synthetic fertilizers made with chemical engineering processes, for example, an increase in agricultural productivity to feed more of the world would not have been possible. Without the invention of Ziegler-Natta catalysts, polyolefins would not exist, and the myriad benefits of plastics would not have been realized. Without the invention of tough, stable polymers such as Teflon® and Kevlar®, the commercial and medical devices made from those polymers would not have emerged. And without several generations of chemical engineers, there would have been no oil and gas production to provide energy to the world and no pharmaceutical industry to discover and produce the medicines, therapeutics, and vaccines needed for a long and healthy life.

Chemical engineering traces its academic legacy back to the late 1880s. As the pace of technological change keeps increasing, the challenges facing engineers have expanded and become more difficult, from addressing global climate change and reducing raw material usage, to generating and distributing food worldwide while conserving water and other resources, to creating and scaling the manufacturing and distribution of new medicines and therapies. Across these and other applications, chemical engineers have an opportunity to collaborate with multiple disciplines and engage systems-level thinking to tackle a problem.

Addressing these challenges will require new directions for chemical engineering. In 1988, the National Academies set the course for chemical engineering over the past thirty years in the widely regarded *Frontiers in Chemical Engineering: Research Needs and Opportunities,* better known as the "Amundson Report." This new report presents a vision for the ways in which chemical engineering research, innovation, and education can be better applied to the challenges of the 21st century. It identifies key opportunities for chemical engineers in addressing energy and the energy transition; access to high-quality food, water, and air; advancing health and medicine; transitioning manufacturing toward a circular economy; and developing new materials. The report also makes recommendation for improving chemical engineering education to better prepare the next generation of chemical engineers.

DECARBONIZATION OF ENERGY SYSTEMS

Mitigation of climate change is one of the most pressing problems facing humankind and the planet today. Addressing this problem will require decarbonization of current energy systems. Chemical engineers will enable technological advances at every point in the energy value chain, from sources to end uses, and bring to bear the systems-level thinking necessary to balance the economic and environmental trade-offs necessary to transition to a low-carbon energy system. This work will also require chemical engineers to collaborate with other disciplines, including chemistry, biology, economics, social science, and others. In the energy sector, coordination between academic researchers and industrial practitioners, as well as international collaboration, will be crucial to ensuring that solutions are economically competitive and deployable at scale.

Recommendation: Across the energy value chain, federal research funding should be directed to advancing technologies that shift the energy mix to lower-carbon -intensity sources; developing novel low- or zero-carbon energy technologies; advancing the field of photochemistry; minimizing water use associated with energy systems; and developing cost-effective and secure carbon capture, use, and storage methods.

Recommendation: Researchers in academic and government laboratories and industry practitioners should form interdisciplinary, cross-sector collaborations focused on pilot- and demonstration-scale projects and modeling and analysis for low-carbon energy technologies.

SUSTAINABLE ENGINEERING SOLUTIONS FOR ENVIRONMENTAL SYSTEMS

Chemical engineers have historically played a central role in the energy sector, but their contributions have been more modest in solving problems in the interconnected space of water, food, and air quality. Chemical engineers can bring both molecular- and systems-level thinking to pioneering efforts in this realm. Chemical engineers can support water conservation by both designing higher-efficiency processes and developing methods for using alternative fluids to freshwater. Specific research opportunities range from better understanding of fundamentals of water structure and dynamics to developing membranes and other separation methods.

Global pressures associated with climate change and population growth will require substantial changes in the world's food sources. Specific opportunities for chemical engineers include precision agriculture, non-animal-based food and low-carbon-intensity food production, and reduction or elimination of food waste. A particularly valuable opportunity for collaboration is in pioneering initial demonstrations of "lab-grown" foods on small scales.

Recommendation: Federal research funding should be directed to both basic and applied research to advance fundamental understanding of the structure and dynamics of water and develop the advanced separation technologies necessary to remove and recover increasingly challenging contaminants.

Recommendation: To minimize the land, water, and nutrient demands of agriculture and food production, researchers in academic and government laboratories and industry practitioners should form interdisciplinary, cross-sector collaborations focused on the scale-up of innovations in metabolic engineering, bioprocess development, precision agriculture, and lab-grown foods, as well as the development of sustainable technologies for improved food preservation, storage, and packaging.

ENGINEERING TARGETED AND ACCESSIBLE MEDICINE

There are few areas of science and engineering in which the rate of progress has been, and continues to be, more rapid than in advances in biology and biochemistry aimed at treatments and cures for human illness. Specific contributions of chemical engineers include reactor design and separations, and more recently cell engineering, formulations, and other aspects of drug manufacturing. Opportunities to apply quantitative chemical engineering skills to immunology include cancer immunotherapies, vaccine design, and therapeutic treatments for infectious diseases and autoimmune disorders. The development of completely noninvasive methods for drug delivery represents an exciting frontier of devices and materials-based strategies. In addition, the demand for monoclonal antibodies, therapeutic proteins, and mRNA therapeutics will continue to grow.

Recommendation: Federal research investments in biomolecular engineering should be directed to fundamental research to

- **advance personalized medicine and the engineering of biological molecules, including proteins, nucleic acids, and other entities such as viruses and cells;**
- **bridge the interface between materials and devices and health;**
- **improve the use of tools from systems and synthetic biology to understand biological networks and the intersections with data science and computational approaches; and**
- **develop engineering approaches to reduce costs and improve equity and access to health care.**

Recommendation: Researchers in academic and government laboratories and industry practitioners should form interdisciplinary, cross-sector collaborations to develop pilot- and demonstration-scale projects in advanced pharmaceutical manufacturing processes.

FLEXIBLE MANUFACTURING AND THE CIRCULAR ECONOMY

The production and manufacturing of useful materials and molecules enabled by chemical engineers, such as plastic, are now creating problems previously unforeseen that have to be solved at scale. A sustainable future will require a shift to a circular economy in which the end-of-life of products is accounted for, utilizing new developments and advances in green chemistry and engineering. Specific opportunities for chemical engineers include redesigning processes and products to reduce or eliminate pollution, developing new ways to reduce and utilize waste, designing products to be used longer and to be recyclable, and designing processes and products using sustainable feedstocks.

Recommendation: Federal research funding should be directed to both basic and applied research to advance distributed manufacturing and process intensification, as well as the innovative technologies, including improved product designs and recycling processes, necessary to transition to a circular economy.

Recommendation: Researchers in academic and government laboratories and industry practitioners should form interdisciplinary, cross-sector collaborations focused on pilot- and demonstration-scale projects in advanced manufacturing, including scaled-down and scaled-out processes; process intensification; and the transition from fossil-based organic feedstocks and virgin-extracted inorganic feedstocks to new, more sustainable feedstocks for chemical and materials manufacturing.

NOVEL AND IMPROVED MATERIALS FOR THE 21ST CENTURY

Chemical engineers can contribute to materials development across a range of material types and applications. They have a unique role to play in the continued development of polymer science and engineering because of their understanding of chemical synthesis and catalysis, thermodynamics, transport and rheology, and process and systems design. They can play a role in the research and development of complex fluids and soft matter, the science and application of nanoparticles in both industry and biomedicine, and in the development of biomaterials both for regenerative engineering and in understanding and improving target drug delivery both spatially and temporally. Chemical engineering expertise around reactor design, separations, and process intensification is critical to the success and growth of the electronic materials industry.

Recommendation: Federal and industry research investments in materials should be directed to

- **polymer science and engineering, with a focus on life-cycle considerations, multiscale simulation, artificial intelligence, and structure/property processing approaches;**
- **basic research to build new knowledge in complex fluids and soft matter;**
- **nanoparticle synthesis and assembly, with the goal of creating new materials by self-or directed-assembly as well as improvements in the safety and efficacy of nanoparticle therapies; and**
- **discovery and design of new reaction schemes and purification processes, with a steady focus on process intensification, especially for applications in electronic materials.**

TOOLS TO ENABLE THE FUTURE OF CHEMICAL ENGINEERING

Developing tools that synthesize available data in real time and frameworks or models that transform data into information and actionable knowledge could become one of chemical engineers' key contributions to society over the next decades. In addition, the evolution of artificial intelligence will have enormous implications not only for the types of problems chemical engineers will be able to solve, but also for the way in which chemical engineers will solve problems. Chemical engineers are poised to contribute significantly to the development of modeling and simulation tools that will influence education, research, and industry.

Recommendation: Federal and industry research investments should be directed to advancing the use of artificial intelligence, machine learning, and other data science tools; improving modeling and simulation and life-cycle assessment capabilities; and developing novel instruments and sensors.

TRAINING AND FOSTERING THE NEXT GENERATION OF CHEMICAL ENGINEERS

Chemical engineers are in high demand across most professions and job levels, and chemical engineering provides an excellent foundation for many career paths. The undergraduate chemical engineering curriculum has served the discipline well and has evolved slowly in response to scientific discoveries, technological advances, and societal needs. However, several issues have been identified, including a need to help students make connections among the topics covered in the core courses of chemical engineering, a lack of experiential learning opportunities, and a need to bring math into the core chemical engineering curriculum. Another problem is that women and members of historically excluded groups are underrepresented in chemical engineering relative to the general population, even by comparison to chemical and biological sciences and related fields. Diversifying the profession will bring valuable new perspectives and is therefore essential to the field's survival and potential for impact.

Recommendation: Chemical engineering departments should consider revisions to their undergraduate curricula that would

- **help students understand how individual core concepts merge into the practice of chemical engineering,**
- **include earlier and more frequent experiential learning through physical laboratories and virtual simulations, and**
- **bring mathematics and statistics into the core curriculum in a more structured manner, by either complementing or replacing some of the education that currently occurs outside the core curriculum.**

Recommendation: To provide graduate students with experiential learning opportunities, universities, industry, funding agencies, and the American Institute of Chemical Engineers should coordinate to revise graduate training programs and funding structures to provide opportunities for and remove barriers to systematic placement of graduate students in internships.

Recommendation: To increase recruitment and retention of women and Black, Indigenous, and People of Color (BIPOC) individuals in undergraduate programs, chemical engineering departments should emphasize opportunities for chemical engineers to make positive societal impacts, and should build effective mentoring and support structures for students who are members of such historically excluded groups. To provide more opportunities for BIPOC students, departments should consider redesigning their undergraduate curricula to allow students from 2-year colleges and those who change their major to chemical engineering to complete their degree without extending their time to degree, and provide the support structures necessary to ensure the retention and success of transfer students.

Recommendation: To increase the recruitment of students from historically disadvantaged communities into graduate programs, chemical engineering departments should consider revising their admissions criteria to remove barriers faced by, for example, students who attended less prestigious universities or did not participate in undergraduate research. To provide more opportunities for women and Black, Indigenous, and People of Color (BIPOC) individuals, departments should welcome students with degrees in related disciplines and consider additions to their graduate curricula that present the core components of the undergraduate curriculum tailored for postgraduate scientists and engineers.

INTERNATIONAL LEADERSHIP

America's scholarly leadership in chemical engineering in both the quantity of research, as measured by numbers of publications, and the quality of research, as measured by citation impact, has decreased significantly in the past 15 years and lost ground to international competitors, particularly from China. The United States is in a leadership position in some areas of chemical engineering technology, but lags in many niches compared to various other countries. The increase in research output from China is a result of large investments in technology areas, many of which are either central to or highly relevant to chemical engineering. Similar levels of investment in the U.S. research enterprise are imperative. At the same time, U.S. chemical engineering will be strengthened through increased coordination and collaboration across disciplines, sectors, and political boundaries.

THE COMMITTEE ON CHEMICAL ENGINEERING IN THE 21ST CENTURY: CHALLENGES AND OPPORTUNITIES

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For More Information . . . This Consensus Study Report Highlights was prepared by the National Academies of Sciences, Engineering, and Medicine based on the Consensus Study Report New Directions for Chemical Engineering (2022). The study was sponsored by US Department of Energy and the National Science Foundation. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any organization or agency that provided support for the project. Copies of the Consensus Study Report are available from the National Academies Press, (800) 624-6242; http://www.nap.edu or via the Board on Chemical Science and Technology web page at https://www.nationalacademies.org/bcst/board-on-chemical-sciences-and-technology

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