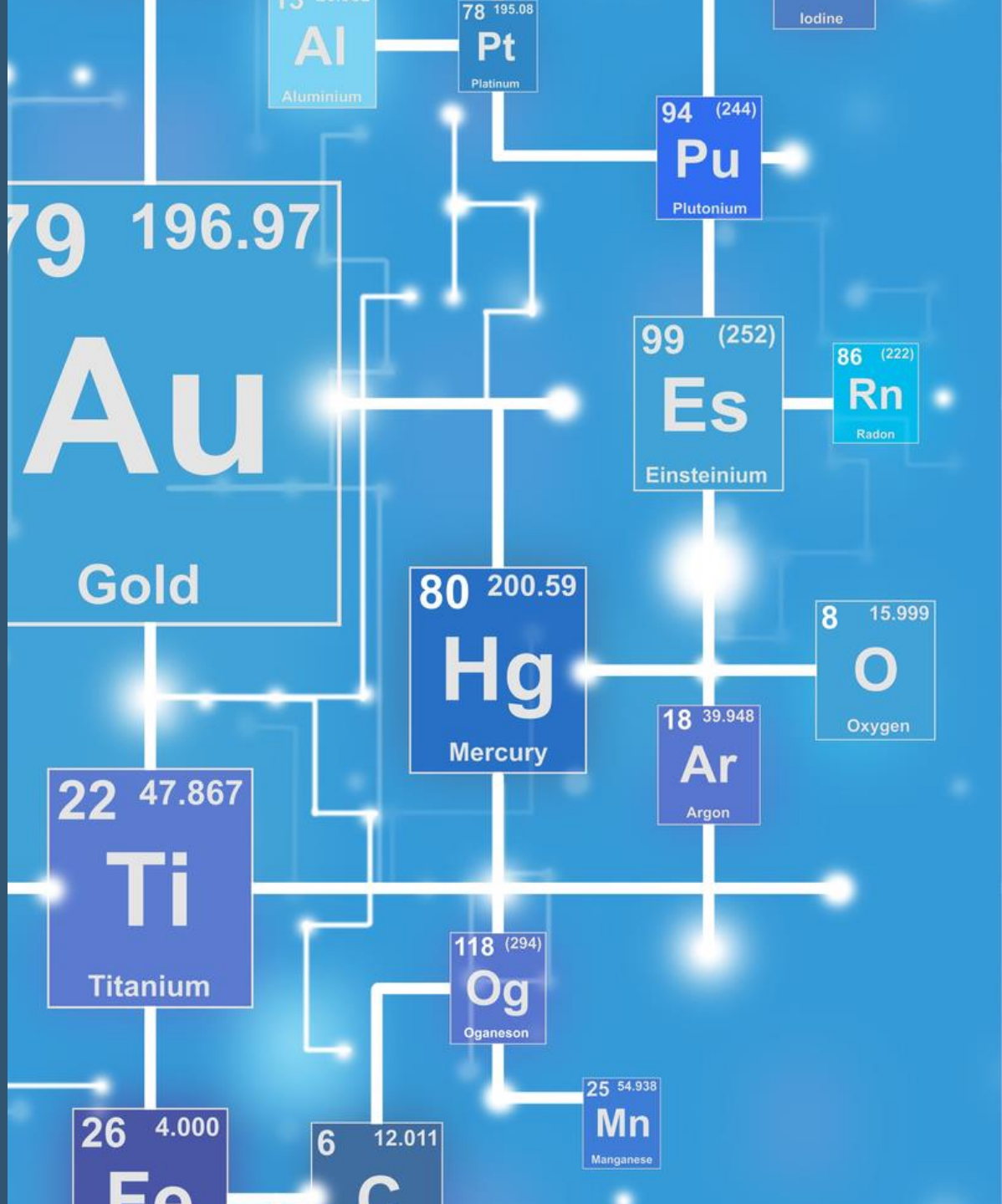
NATIONAL ACADEMIES *Sciences Engineering Medicine*

The Importance of Chemical Research to the U.S. Economy

December 8, 2023

Cathy Tway, Vice Chair



Report Information

Study Committee:

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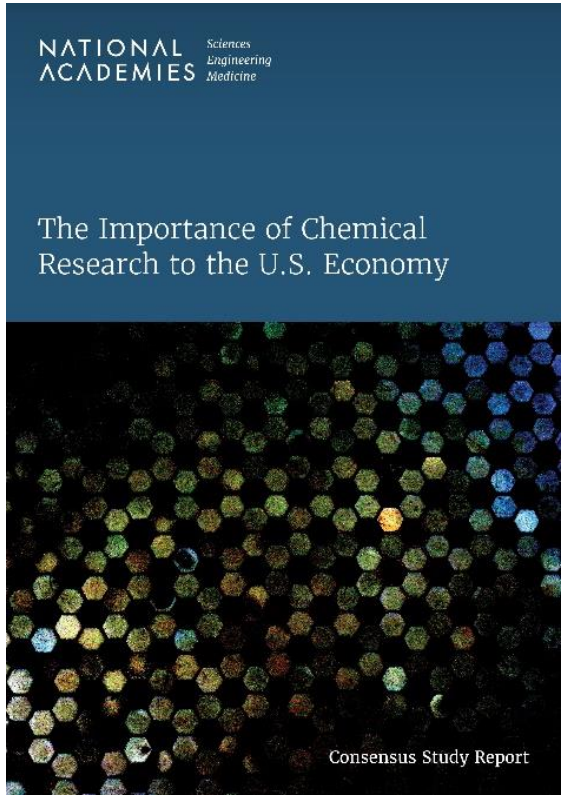
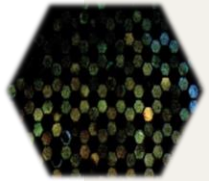


Sponsors:

- National Science Foundation – Division of Chemistry
- Department of Energy – Office of Science
- Department of Energy – Fossil Energy and Carbon Management
- National Institute of Standards and Technology
- American Chemical Society

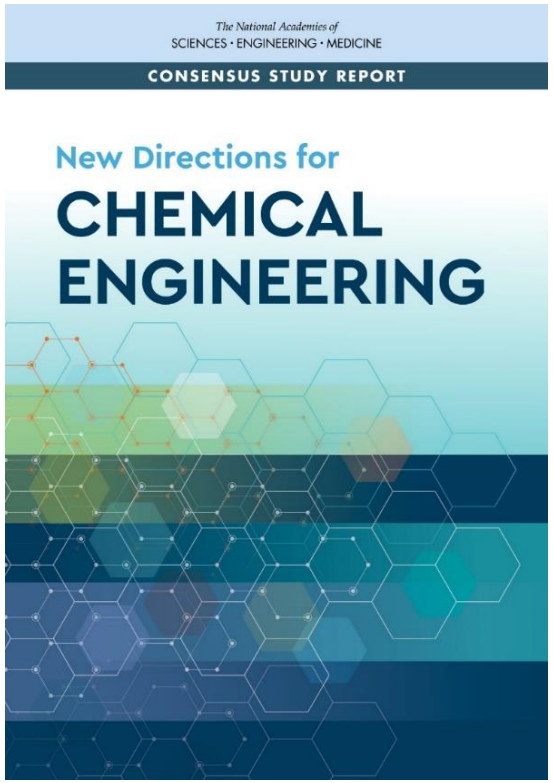
Committee's Charge



Statement of Task:

- Consider strategies to sustain and enhance the economic activity driven by fundamental research investments in the chemical sciences.
  - Examine and define the role of the chemical industry in the U.S. economy.
  - Assess how investments in long-term fundamental research in the chemical sciences have contributed to such goals as national security, environmental sustainability, thriving manufacturing industries, and energy-technology development.
  - Explore strategies for targeted research investments in the chemical sciences by both the public and private sectors to stimulate economic growth and to ensure the United States plays an international leadership role in the field.
  - Discuss options for research investments that would enhance the chemical economy while also advancing environmentally sustainable practices and/or integrating a diverse chemical economy workforce.

Chemical Engineering Report Information
Committee Chair: Eric Kaler



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EMD Electronics

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- **GREGG T. BECKHAM**, National Renewable Energy Laboratory
- **DIMITRIS I. COLLIAS**, The Procter & Gamble Co.
- **JUAN J. DE PABLO**, University of Chicago
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- **ENRIQUE IGLESIA**, University of California, Berkeley
- **SANGTAE KIM**, Purdue University
- **SAMIR MITRAGOTRI**, Harvard University
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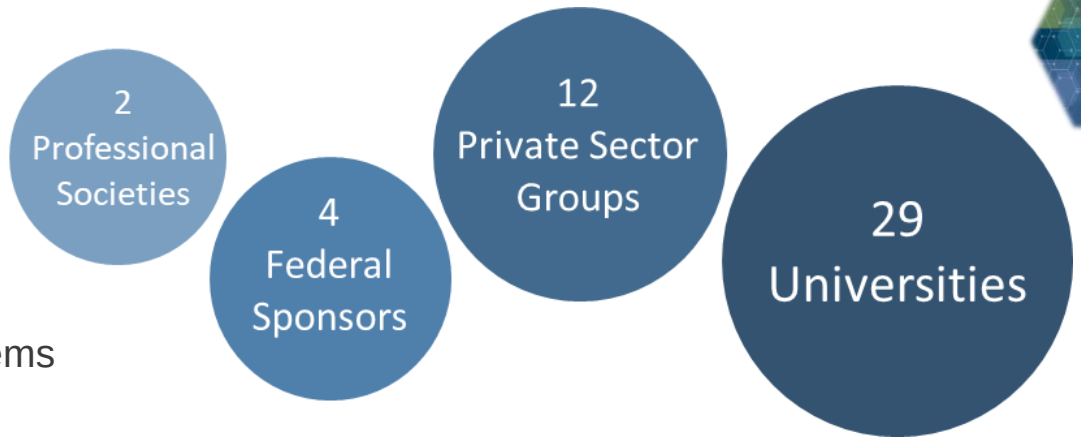
Sponsors and Contributors



DOE Biological and Environmental Research
DOE Office of Fossil Energy and Carbon Management
DOE Advanced Manufacturing Office
NSF Chemical, Bioengineering, Environmental, and Transport Systems

The American Chemical Society
The American Institute of Chemical Engineers

Colorado School of Mines
Georgia Institute of Technology
Johns Hopkins University
Louisiana State University
Massachusetts Institute of Technology
North Carolina State University
Northwestern University
The Pennsylvania State University
Princeton University
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The American Chemistry Council

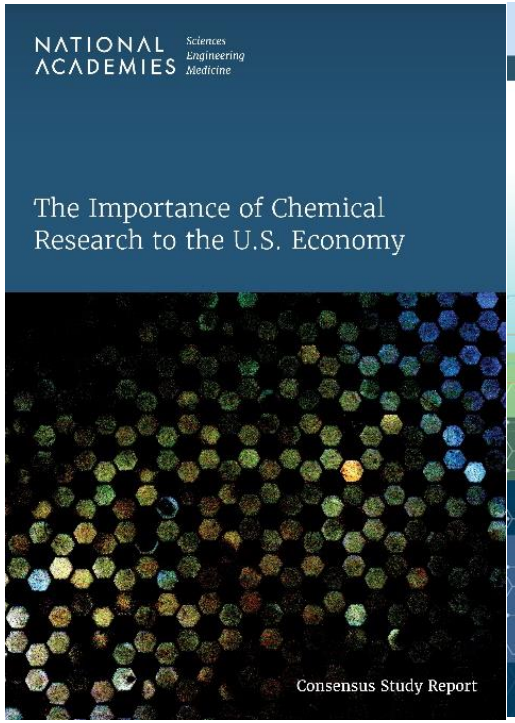
Arkema
Bristol-Myers Squibb Company
The Dow Chemical Company
DuPont de Nemours, Inc.
Eastman Chemical Company
Evonik Industries
Exxon Mobil Corporation
Honeywell International, Inc.
PPG Industries, Inc.
The Procter and Gamble Company
Shell Global

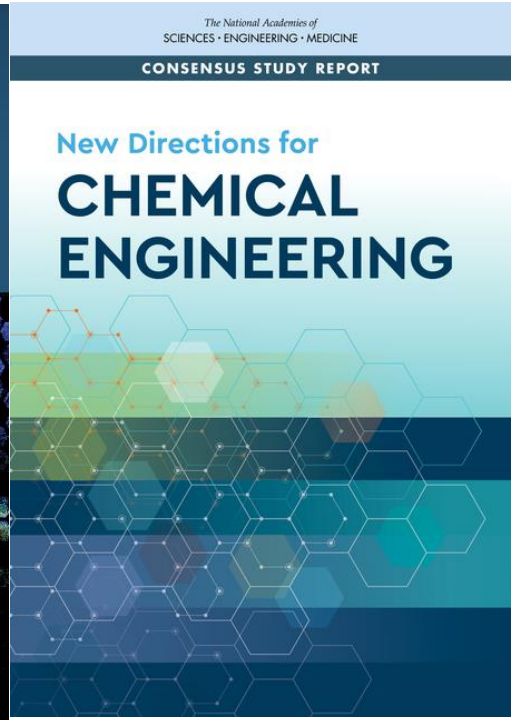
Statement of Task

- Describe major advances and changes in chemical engineering over the past three decades, including the importance and contributions of the field to society; technical progress and major achievements; principal changes in the practice of R&D; and economic and societal factors that have impacted the field.
- Address the future of chemical engineering over the next 10 to 30 years and offer guidance to the chemical engineering community:
  - Identify challenges and opportunities that chemical engineering faces now and may face in the next 10-30 years, including broader impacts.
  - Identify a set of existing and new areas that offer promising intellectual and investment opportunities, as well as areas that have major scientific gaps.
  - Identify aspects of undergraduate and graduate chemical engineering education that will require changes.
  - Consider recent trends in chemical engineering in the United States relative to international research.

Two Related Yet Independent Studies

- **Balancing U.S. competitiveness and collaboration in the global chemical economy**
- **A changing landscape within the chemical enterprise**
- **Emerging processes and technologies**
- **A focus on sustainability**

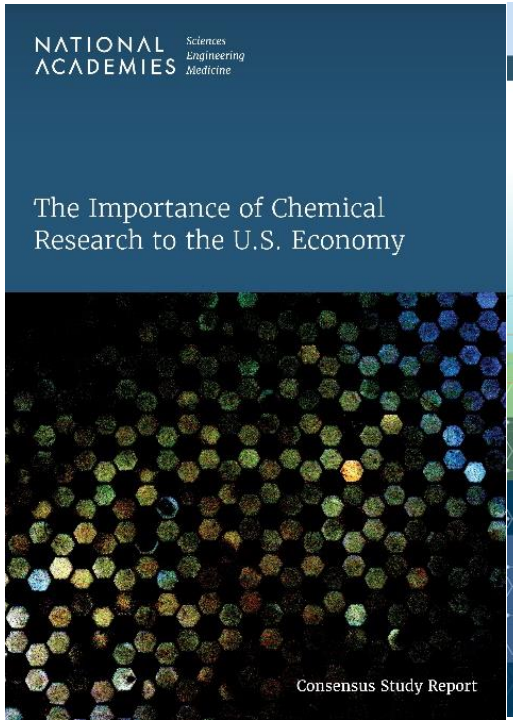


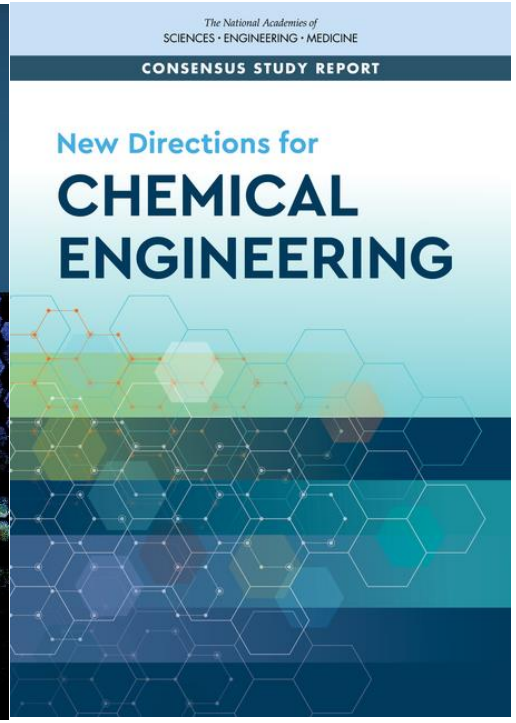


- **Approached challenges and opportunities, new and existing areas and scientific gaps collectively**
- **What is the role of chemical engineering in addressing the key challenges facing society**
  - Energy and the energy transition
  - Food, water, and air
  - Health and medicine
  - Manufacturing and the circular economy
  - Materials
  - Tools

Two Related Yet Independent Studies

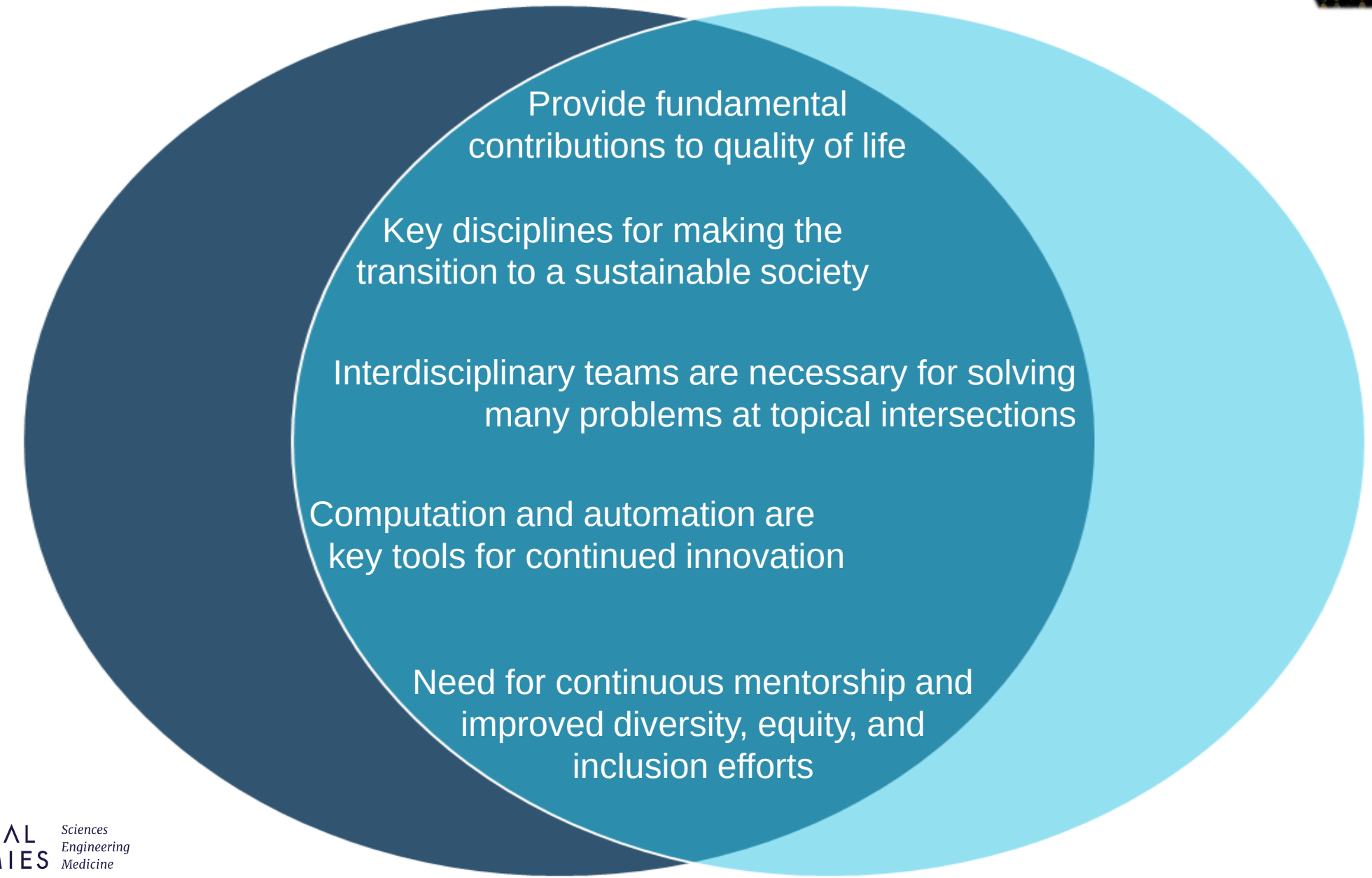
- Independent economic analysis performed by Vertex Evaluation and Research to understand the impact of the chemical economy on the U.S. economy
- 51 different speakers from industry, academia, government, and venture capital
- Call for input to the chemistry community
- Call for input from government agencies
- Review of the relevant academic literature and reports





- The committee met 42 times to gather information, deliberate, and write
  - 27 meetings had a session open to the public and included over 60 guest speakers (see report Appendix D)
- Town hall-style session at the 2019 AIChE meeting and participated in a meeting of the AIChE Virtual Local Section
- Broadly distributed questionnaire for input on the future of the discipline (summarized in report Appendix C)

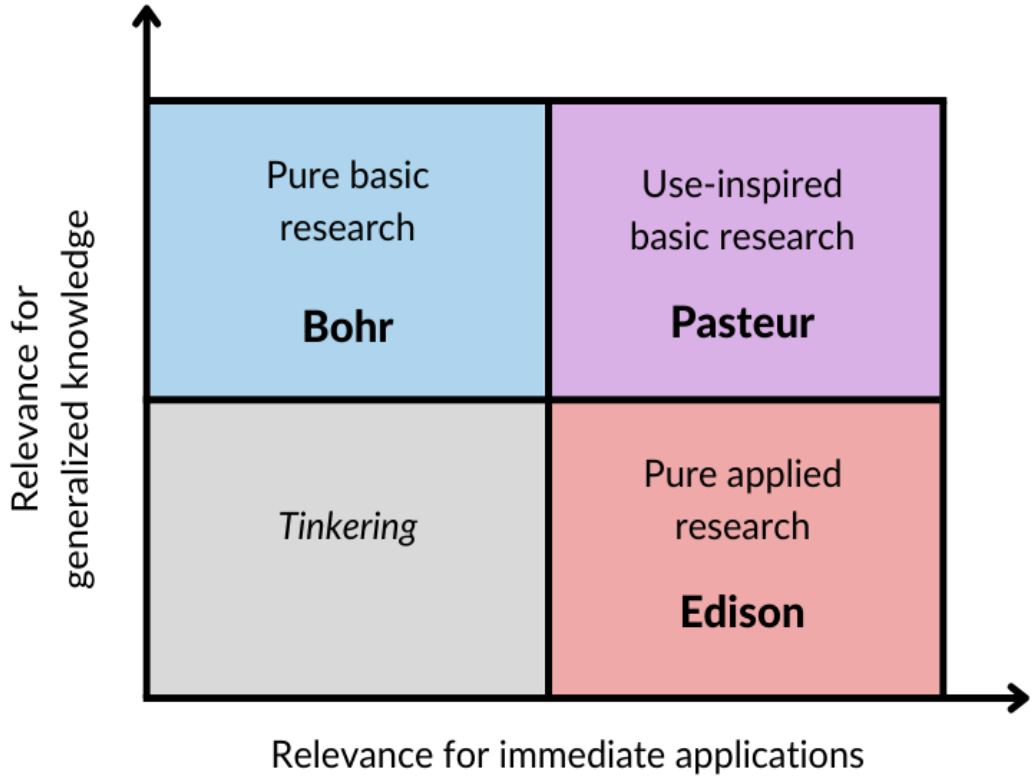
Common Central Themes



Important Definitions in the Report

- **Chemical Economy** - *The chemical economy includes all parts of any value chain that rely on chemical knowledge and transformation processes for advancement and growth.*

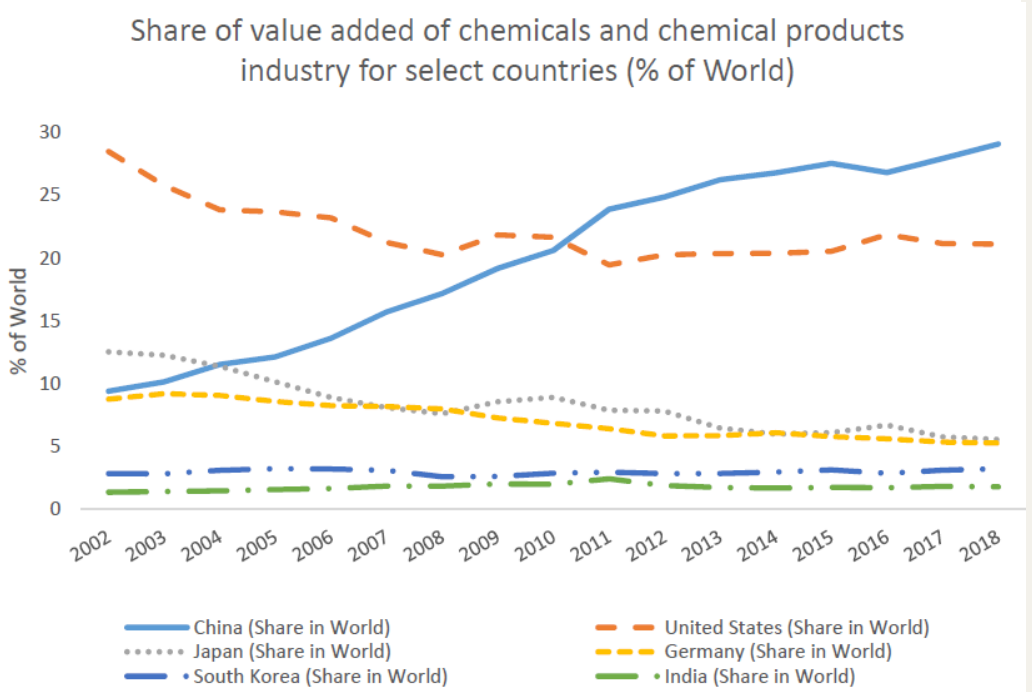
- **Fundamental Chemical Research** - *Fundamental chemical research is basic and applied research that is made available to any interested scientific audience, and which explores the structure and reactivity of atoms, molecules, and materials*.



Aleahmad, 2009

Understanding the Economic Impacts of Chemistry

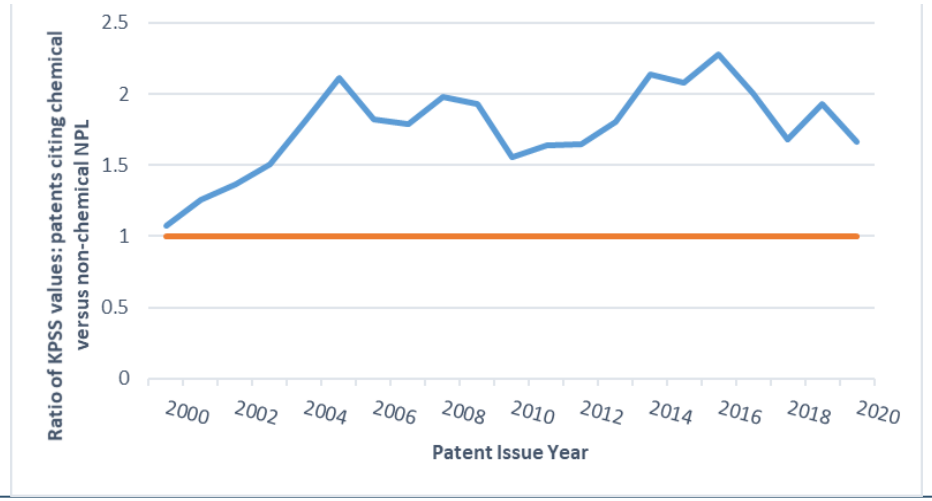
- The United States Chemical Industry's final sales in 2020 were **$457B** (2022, **$614B**), and the industry was responsible for employing **529,000 workers** (2022, **555,000 workers**)
- When considering industries that are dependent on chemistry, the chemical enterprise was responsible for approximately **$5.2T of U.S. GDP in 2020, approximately 25% of GDP** (2022, **$6.5T**)



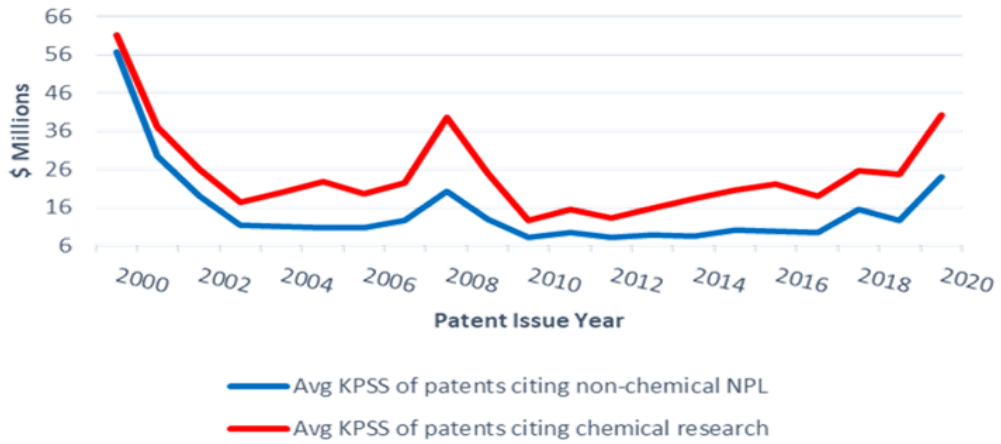
ACC, 2021 & 2023
IHS Markit, 2019

Understanding the Economic Impacts of Chemistry

Chemical patents accounted for 14% of all corporate patents between 2000 and 2020, yet they accounted for 23% of all value



Patents that cite chemical research, are on average more valuable than patents that cite other non-chemistry research



Fleming and Basco, 2021

Understanding the Economic Impacts of Chemistry Conclusion and Recommendations

Challenging to directly link chemical research to economic impact

- Significant time span of impact
- Chemical knowledge deeply integrated into other disciplines
- Lack of data limits assessment
  - patent value estimations
  - widely available licensing terms data
  - government grant data

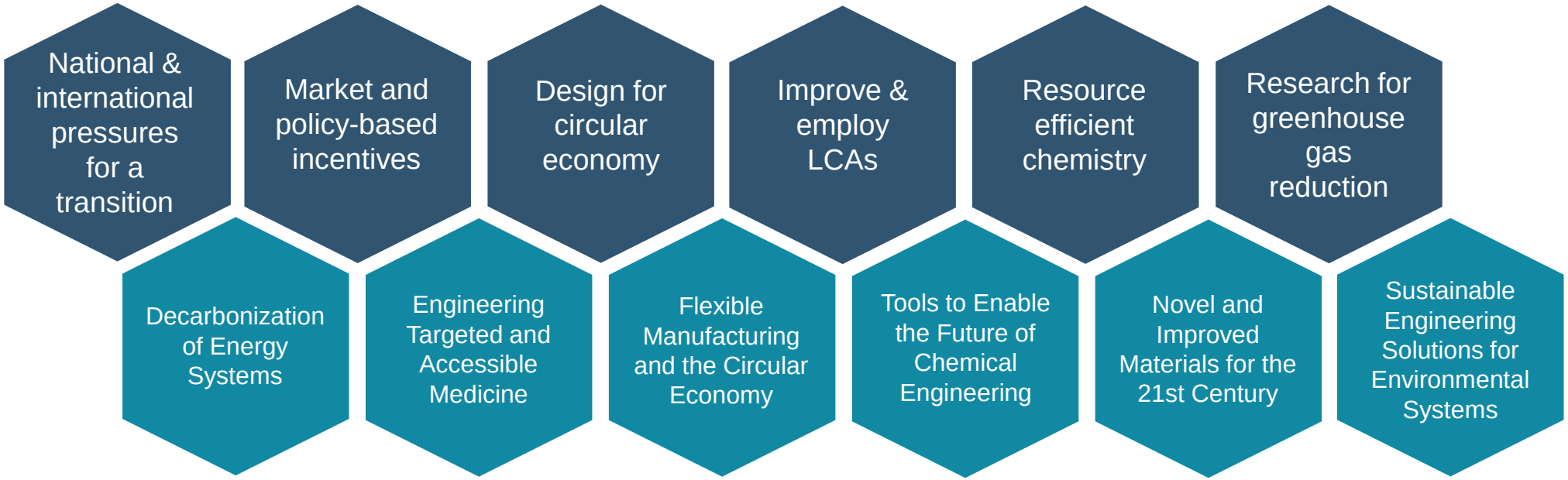
Collaboration between agencies who fund and track data:

- to collect, and make available, the tools and data
- to fund large-scale evidence-building efforts to collect, standardize, use, and interpret these data

Other Possible Analyses:

- An in-depth patent analysis that focuses on one or more top companies in the United States
- An analysis of licensing revenues generated from patents
- Drawing correlations between the number of patents and economic growth

Sustainability for the Chemical Economy

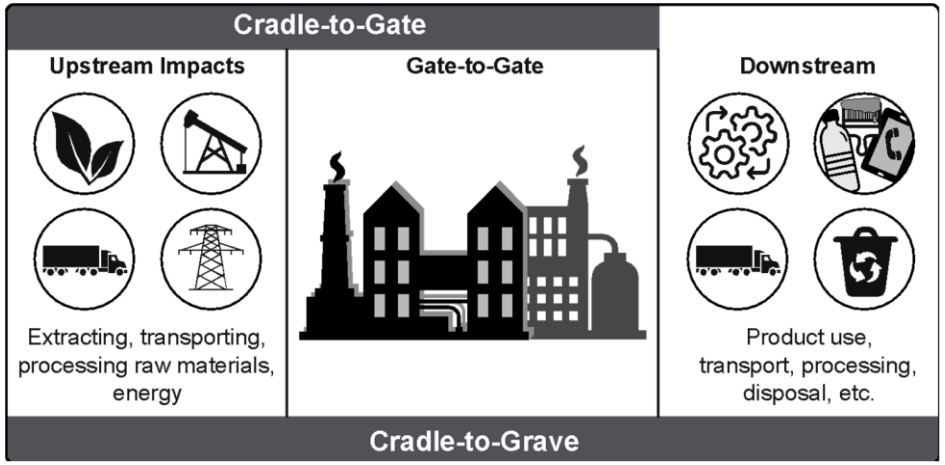


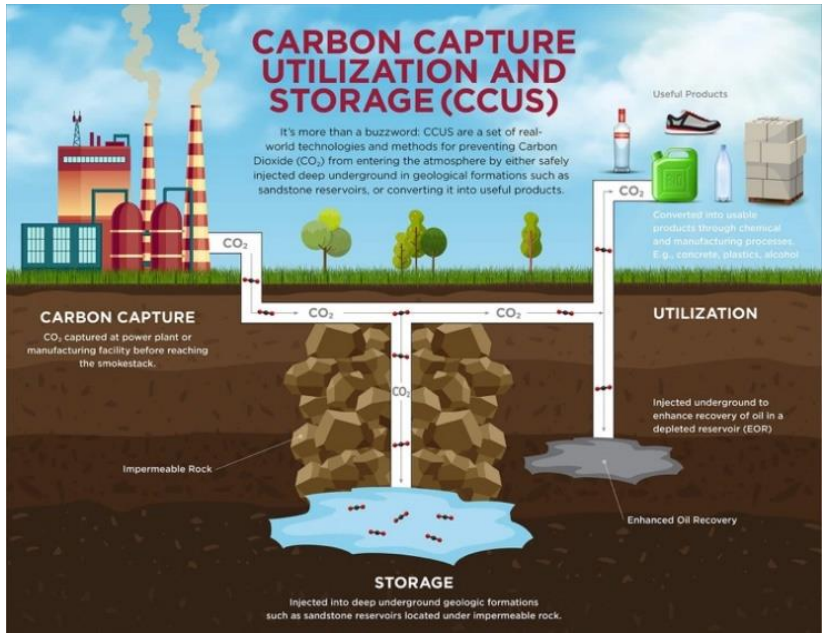
"…further advances in fundamental chemistry are needed to address major problems arising from the use of chemistry…."

Sustainability for the Chemical Economy

Areas that are prime for future chemical innovation:

- better measurements for life-cycle assessments;
- enhancement of recycling technologies and co-design of plastic products for recyclability;
- sustainable syntheses;
- sustainable feedstocks and energy sources;
- carbon capture, utilization, and storage;
- monitoring and improving air quality;
- monitoring and improving water safety; and
- monitoring and improving food safety;

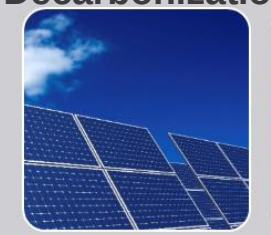




Subramaniam, 2021b; Mah, 2021

Sustainability for the Chemical Economy

Decarbonization of energy systems





Sources
- Advance solar technologies
- Innovations in shale oil and gas production
- Contribute to biofuels production and lignin alternatives

Carriers
- Re-imagine petroleum refineries
- Increase clean hydrogen production
- Increase efficiency of chemical transformations

Storage
- Increase battery lifespans and design for end-of-life disposal
- Design batteries that use earth-abundant elements

Use
- Contribute to advances in electric vehicles, fuel cell engines, and internal combustion engines
- Reduce emissions from cement, steel, and chemical production

Carbon Capture, Use, and Storage
- Design new solvents and sorbent materials
- New approaches to CO_2 conversion

Sustainable engineering solutions for environmental systems

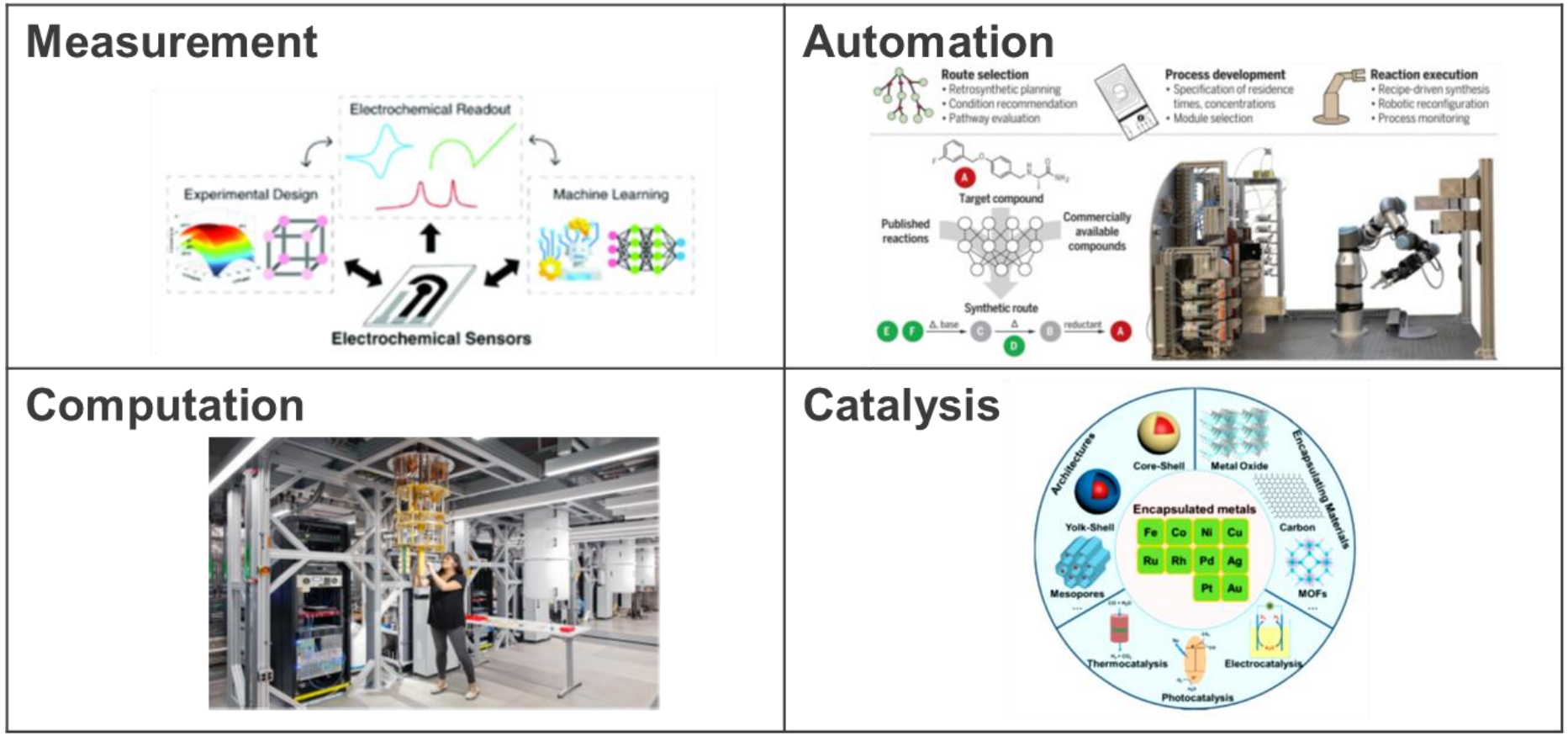


Water
- Advance separation and treatment technologies
- Improve understanding of interfacial layers

Food
- Improve per land area crop yields
- Pioneer ammonia production beyond Haber-Bosch
- Develop applications for agriculture and food processing waste streams

Air
- Reduce emissions of pollutants
- Advance mitigation technologies
- Contribute to fundamental understanding of aerosols

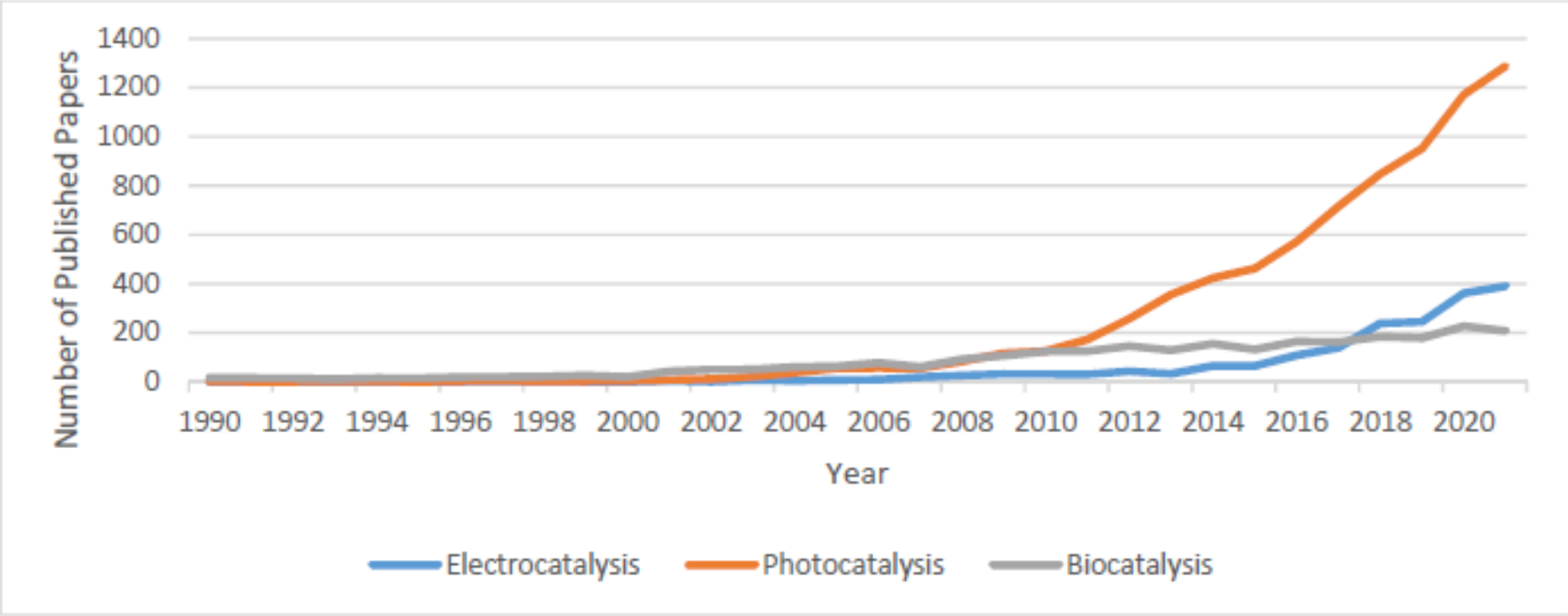
Emerging/Transitioning Areas in Chemical Sciences



Data Science is an indispensable tool for the chemical sciences research community, and will help to increase the pace and efficiency of innovation

Puthongkham et al., 2021; Coley et al., 2019; https://www.flickr.com/photos/ibm_research_zurich/51098680334/; Gao et al., 2020

Emerging/Transitioning Areas in Chemical Sciences-Catalysis



Subfields of catalysis that have experienced a recent resurgence in research due to their potential in addressing basic chemistry questions, and for their use in critical applications:

- Heterogeneous catalysis
- Homogeneous catalysis
- Biocatalysis
- Electrocatalysis
- Photocatalysis
- Theoretical/modelling of catalysis

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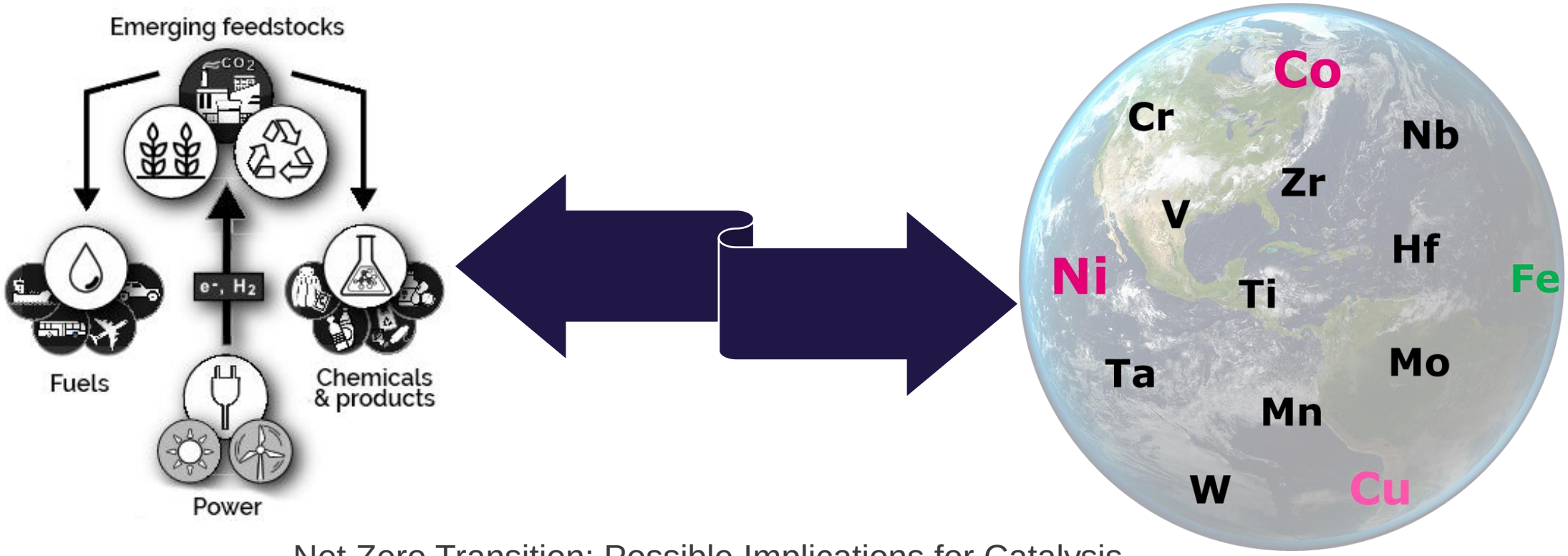
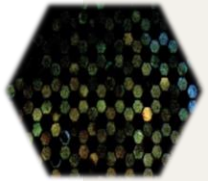
Data from Scopus;

Emerging/Transitioning Areas in Chemical Sciences - Catalysis



Net Zero Transition: Possible Implications for Catalysis
ACS Catal. 2023, 13, 12, 7917−7928

Subramaniam, 2021a; Bullock, 2020; iea, 2021; DOE, 2023



Challenging the Underlying Assumptions of Chemical Research

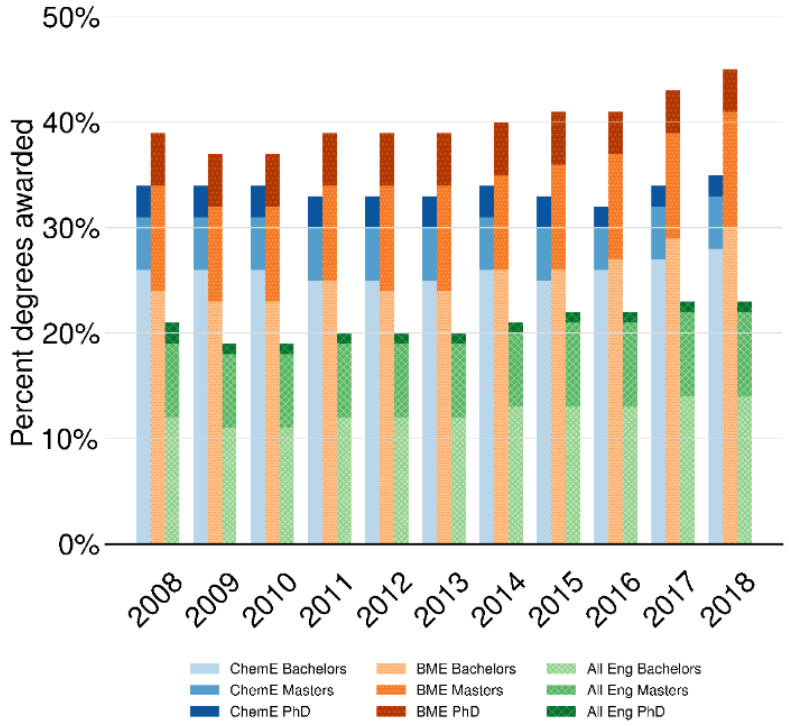
- **Conclusion:** As the world moves deeper into its current energy transition, an increasing focus on circularity and new technologies will significantly alter the operations and processes of current industries, creating new opportunities and challenges that will benefit from fundamental chemistry and chemical engineering advances.

- **Recommendation:** Changes in energy sources complemented by the technology and processes offered by chemical companies will lead to entire industries being created, transformed, and terminated. A group of experts from chemistry and other impacted disciplines, who represent the chemical economy and academic research, should be convened to assess the implications of these industrial shifts and understand their impacts on current chemical research paradigms.

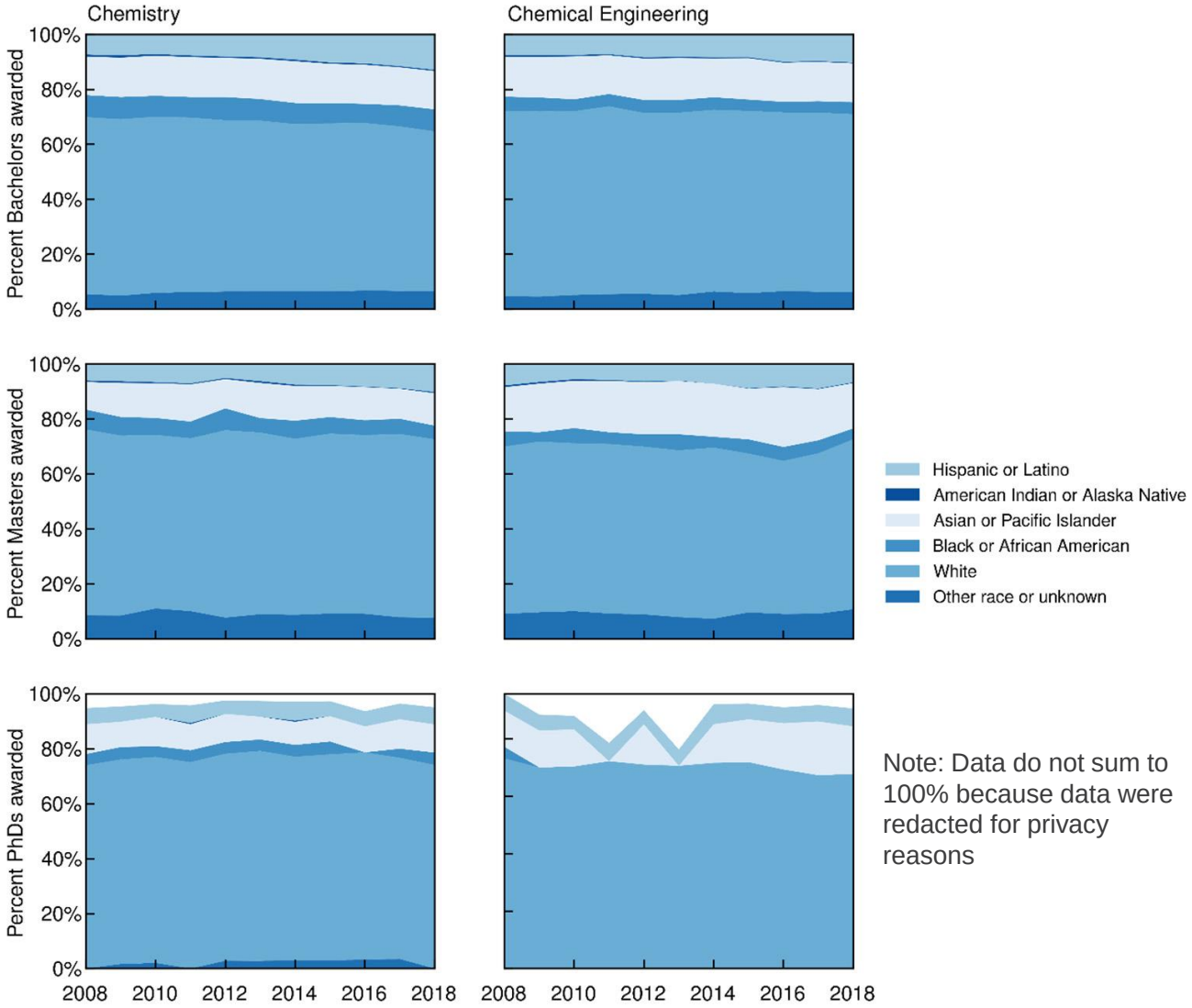
Preparing and Empowering the Next Generation Chemical Workforce

"The complex solutions to these challenges will benefit from a diverse and well-trained workforce with a deep knowledge of the chemical sciences and the ability to use cross-disciplinary tools and technologies."

The Future Chemical Workforce – Diversity, Equity, and Inclusion



Percentage of chemical engineering degrees awarded to women remains relatively unchanged over past decade



Note: Data do not sum to 100% because data were redacted for privacy reasons

National Center for Science and Engineering Statistics, https://ncsesdata.nsf.gov/sere/2018/.

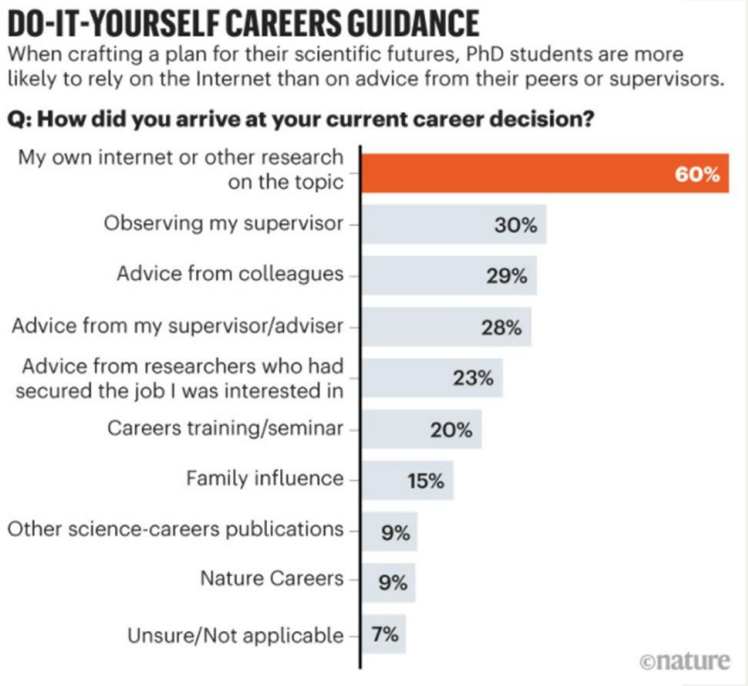
The Future Chemical Workforce – Mentorship and Professional Development

Undergraduates

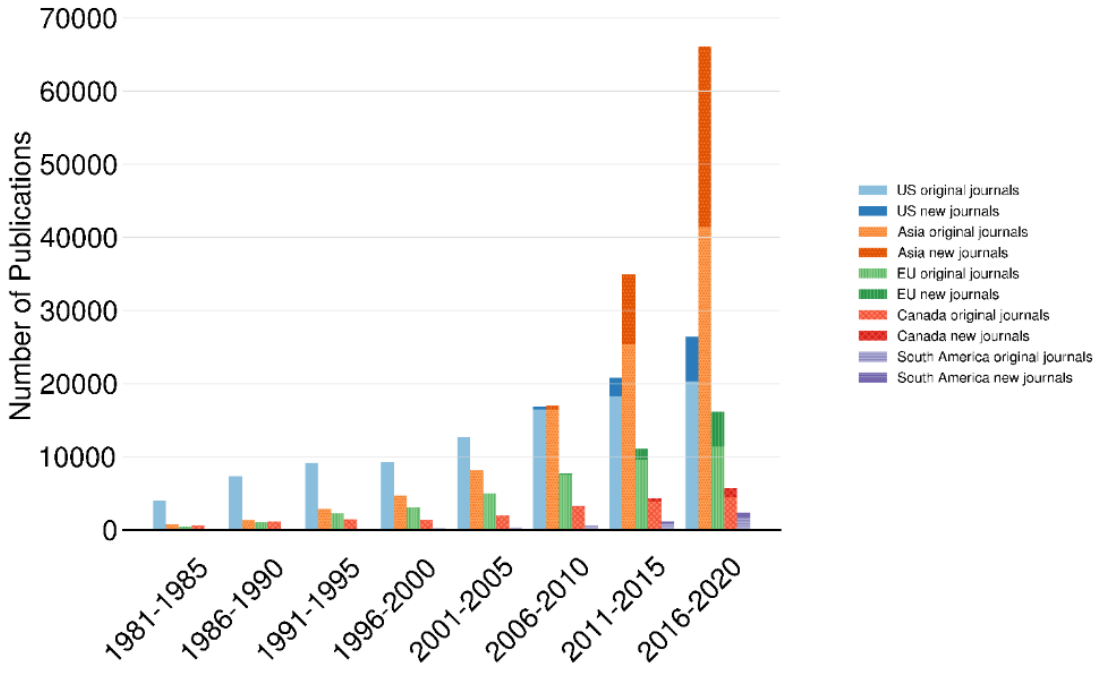
- **Curriculum Revisions**
  - Connections across the core
  - Experiential learning
  - Math and statistics into the core
- **Attract more women and BIPOC students**
  - Opportunities for societal impact
  - Effective mentoring and support structures
  - Recruit and support transfer students

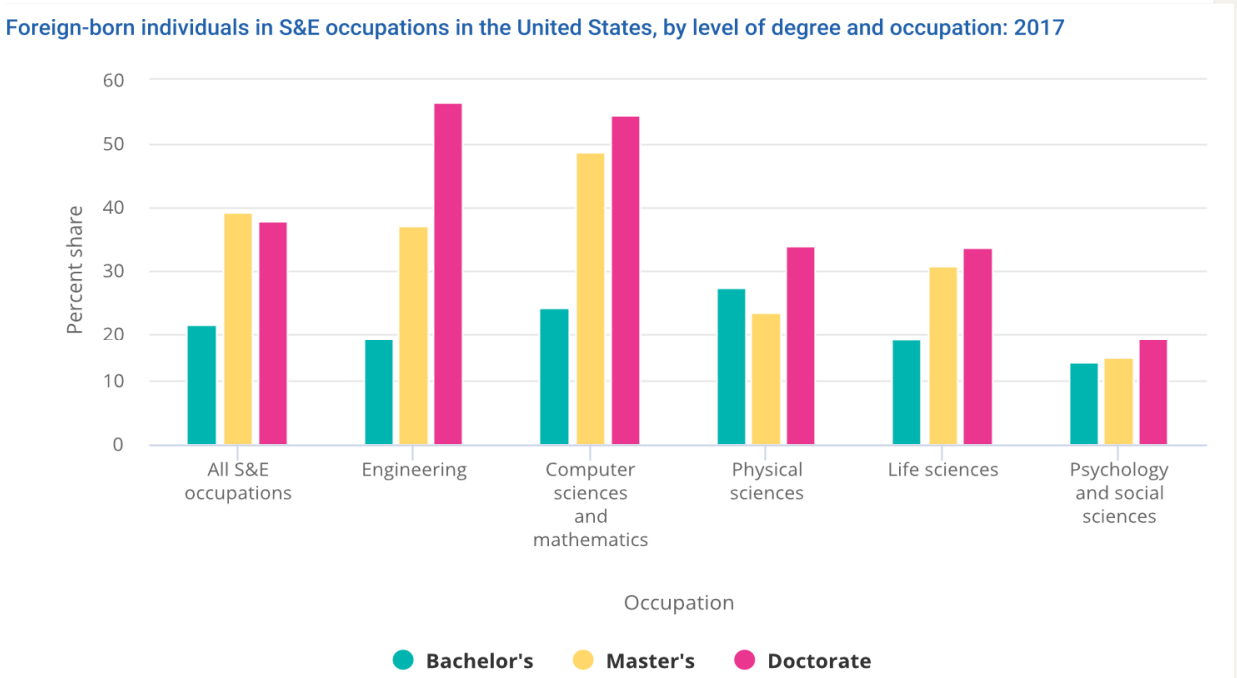
Graduate Students

- **Experiential Learning through Internships**
  - Training revisions
  - Changes to funding structures
  - Coordination among universities, industry, funding agencies, and AIChE
- **Attract more women and BIPOC students**
  - Revise admissions criteria to remove barriers
  - Welcome students from related disciplines



The Future Chemical Workforce – International Leadership and Collaboration





- U.S. leadership has decreased in the past 15 years
- Growth in research output from Asia largely driven by China and reflects large investments in R&D
- Research investments should support international collaborations with the goal of connecting U.S. research to points of strength in other countries

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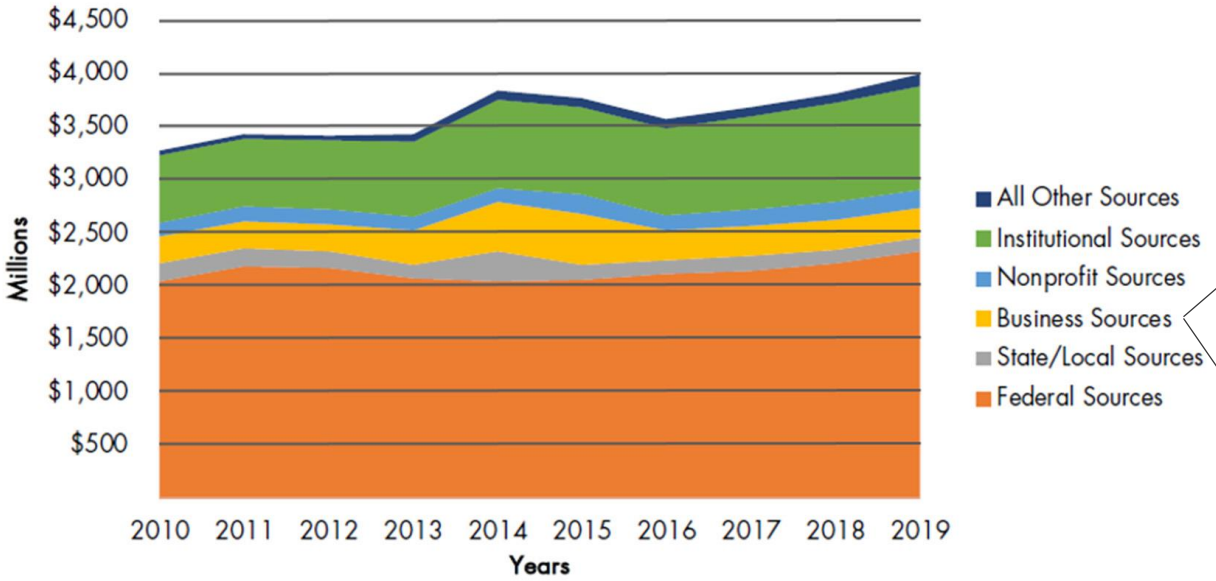
Scopus, NSB,2019

Funding Chemical Research



- Avg 2-3% of sales reinvested in innovation
- In 2019, 91% self-funded R&D
  46% of aerospace self-funded R&D

"Because our industrial strategy centers on technology, **we want to invest in research**, development, advanced manufacturing. Sixty years ago, our government spent more than twice as much on research as a percentage of our economy as we do now – investments that, in turn, catalyzed private-sector innovation. It's how we won the space race, invented the semiconductor, built the internet. **We used to rank first in the world in R&D as a proportion of our GDP – now we're ninth.**"

-Secretary Antony J. Blinken, Speech at The George Washington University, Washington, DC, on May 26, 2022

Fleming and Basco, 2021; ACC, 2021

Conclusions

- Chemical research is important to the U.S. economy
- Chemistry's contributions are greater than assessed because of interdependency
- Chemical research is important for advancing sustainable technologies
  - A changing economy highlights the importance of challenging assumptions of chemical research
  - Chemical data and analysis will continue to grow in importance for chemical research
- Increasing global competition must be balanced with collaboration to create the diverse, equitable, and inclusive workforce needed to support the chemical enterprise
- Broad sponsorship and funding is important to maintaining and advancing the chemical economy

AIChE

Both Reports