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Perspective

Vision 2050: Reaction Engineering Roadmap

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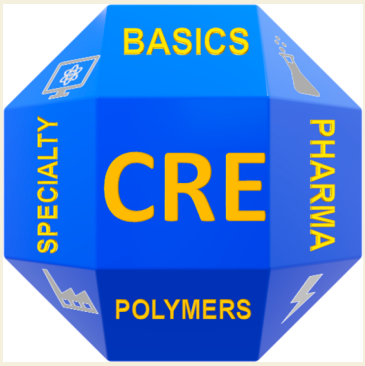
ABSTRACT: This perspective provides the collective opinions of a dozen chemical reaction engineers from academia and industry. In this sequel to the "Vision 2020: Reaction Engineering Roadmap," published in 2001, we provide our opinions about the field of reaction engineering by addressing the current situation, identifying barriers to progress, and recommending research directions in the context of four industry sectors (basic chemicals, specialty chemicals, pharmaceuticals, and polymers) and five technology areas (reactor system selection, design and scale-up, chemical mechanism development and property estimation, catalysis, nonstandard reactor types, and electrochemical systems). Our collective input in this report includes numerous recommendations regarding research needs in the field of reaction engineering in the coming decades, including guidance for prioritizing efforts in workforce development, measurement science, and computational methods. We see important roles for reaction engineers in the plastics circularity challenge, decarbonization of processes, electrification of chemical reactors, conversion of batch processes to continuous processes, and development of intensified, dynamic reaction processes.



KEYWORDS: *reaction engineering, reactor, mechanism, catalysis, electrochemical, decarbonization, circularity*

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■ BACKGROUND

The report titled "Vision 2020: Reaction Engineering Roadmap," published in 2001, "documents the results of a workshop focused on the research needs, technology barriers, and priorities of the chemical industry as they relate to reaction engineering viewed first by industrial use ... and then by technology segment..."[1] Our objective in this perspective is to look back on the past two decades of progress in the field of reaction engineering and offer our perspective on the next two to three decades. We are not the first to editorialize on this and related topics, as many others have provided opinions and advice about the future of reaction engineering as a discipline,[2,3] its application to current and expected challenges,[4−6] and the future of the industries it serves.[7] Figure 1 provides an outline of the body of this editorial commentary, which follows the Vision 2020 document structure except for the additional section on electrochemical systems.

The authors, a team of reaction engineering experts and practitioners from academia and industry, were first challenged to write this perspective during a meeting of the board of directors of the International Symposia on Chemical Reaction Engineering, Inc. While most of this team of authors are former or current members of that board, we recruited additional coauthors to fill expertise gaps, particularly for the pharmaceuticals and electrochemical systems sections. While the authors are concentrated in the United States, three of the authors currently live outside the borders of that country, and all of the authors have international connections through their respective corporate and academic networks. The preparation of this document spanned more than two years and included several dedicated meetings to discuss our perspectives on the various topics. Each of the nine sections was initially written by one to three lead authors. While developing the outline and finalizing the manuscript, we invited all authors to challenge statements and suggest changes. Our goal was to harmonize to a consensus opinion as much as possible. Given the team approach taken in shaping this work, this editorial perspective has a mosaic quality, as different contributors chose to emphasize distinct aspects of the challenges and opportunities facing the field of reaction engineering. We have chosen to retain much of that diversity of focus and emphasis, as we feel the resulting document is a richer, more representative expression of our collective perspective.

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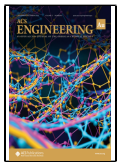

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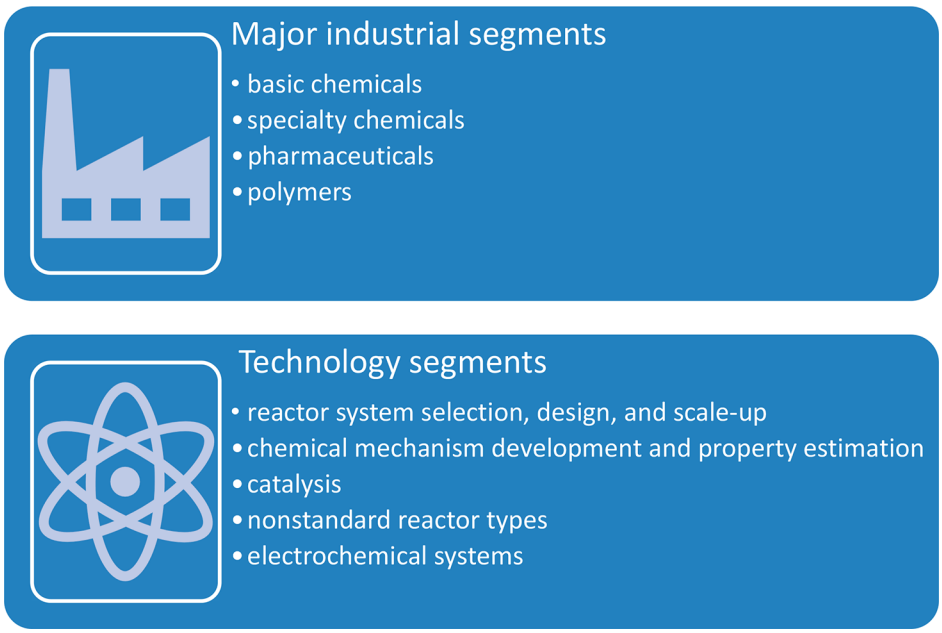

Figure 1. Structure and content of this perspective article.

EXECUTIVE SUMMARY

Many view reaction engineering as a mature field with a fixed set of tools and techniques. However, the central role of reaction engineers connects thermodynamic constraints, transport phenomena, kinetics, and reactor flow patterns as new catalysts, new chemistries, and new reactor concepts emerge from the discovery laboratories. Policy makers and funding agencies must understand and support the vital role of reaction engineering in achieving societal goals. Educators must be vigilant in ensuring that the next generation of leaders in this field is prepared to tackle the challenges to come. Corporate stewards must advocate sensible decision-making informed by the sound practice of reaction engineering fundamentals at the intersection of materials and processes from early stage discovery to commercial-scale implementation.

Based on our collective input in later sections of this report, we summarize here our recommendations regarding the key themes and the highest priority cross-cutting research needs in the field of reaction engineering in the coming decades.

The drive to decarbonize the chemical industry motivates the search for alternative reaction system designs that utilize electricity rather than fossil fuels for energy, especially for the largest energy consumers, such as ammonia, ethylene, propylene, and methanol. Fundamentally sound reaction mechanism development, property estimation, and scale-up methodologies for electrochemical reaction systems will increase their probability of adoption in manufacturing. Many industrial sectors show interest in electrochemical transformations, indicating a need to broaden the range of raw materials and products targeted in academic and government research programs. We recommend shifting away from CO_2 conversion to thermodynamically viable raw materials and broadening the targets to a wider array of industrially relevant product molecules. We encourage development of alternative electrification reactors, including Joule (resistive), microwave, inductive, and plasma reactors, with attention given to energy efficiency and enabling industrially relevant process capacities at acceptable capital costs.

Similarly, the drive for plastics circularity provides numerous opportunities for reaction engineers to partner with polymer chemists and materials scientists to design new molecules and better reactor systems to make them as well as to design reaction process technology to convert waste polymers into raw materials.

Reaction engineers should be intimately engaged in the development of catalyst and electrocatalyst materials to enable higher rates, selectivities, and catalyst lifetimes in economically viable reactor systems. Reaction engineers must remain engaged with laboratory tool developers to ensure issues with mixing, mass transfer, heat transfer, and contacting (flow) patterns do not negatively affect data quality.

Advancing the application of dynamic catalyst, reactor, and process models should reduce waste and improve process efficiencies. These models should accompany efforts to operate systems (on scales from the catalytic site to the integrated process) dynamically when such operation enhances the system performance.

For specialty and pharmaceutical reaction systems, the shift away from batch operations requires identification and demonstration of continuous reactor systems early in the process development timeline for new products and processes. Creative approaches to designing continuous reactor systems that are modular, flexible, and easier to clean might accelerate this transition.

For all types of reactor systems at all scales, further advances in measurement science will enable better models, improved process safety, and better optimized operations. Reaction engineers should partner with analytical chemists to motivate and implement these advancements. Artificial intelligence (AI) could be instrumental in analytical data interpretation, organization, and use.

Continued development of computational chemistry methods for predicting reaction networks and pathways, reaction rate parameters, thermophysical properties, and structure−property relationships should accelerate the decision-making and development timelines for many reaction systems. More broadly, as computer power continues to grow, reaction

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engineers should grow their ability to include increasing levels of complexity in multiscale models. At the same time, reaction engineers should prudently incorporate machine learning into data analysis and hybrid models for workflows from early stage molecular simulations to reactor scale-up and optimization models.

Workforce development is more crucial than ever to prepare future engineers for the energy transition. We suggest modifications of the undergraduate and graduate curricula by developing new courses and incorporating relevant examples in courses.

Finally, the effective education of future reaction engineers (and, more broadly, chemical engineers) is at risk in many chemical engineering departments because research funding is directed at specific technological targets rather than at the application of chemical engineering skills. As a result, many chemical engineers receive doctoral degrees for work where they develop and apply very few core chemical engineering skills during their thesis research. We challenge the academic community to ensure that reaction engineering principles are taught and applied in any research involving reactions, from metabolic engineering to electrochemical synthesis. We challenge the industrial community to promote good reaction engineering practice by funding academic research that hones those skills and actively engaging with the academic community on a regular basis through a variety of mechanisms. Industry should proactively seek opportunities to share the important reaction engineering challenges faced by society that require the development of better materials and processes.

INTRODUCTION

Chemical reaction engineering (CRE) as a discipline continues to evolve. In academic instruction, the topic is often presented in two broad categories: (1) reaction kinetics and (2) reactor design and analysis (Figure 2). The latter category incorporates thermodynamic constraints, transport phenomena, and the flow pattern with reaction kinetics for a holistic understanding of the performance of a reaction system. Any system involving a chemical transformation is thus an appropriate subject for reaction engineering analysis. Given the breadth of relevance of reaction engineering across a wide range of industries and research, a perspective on this topic must selectively narrow the scope. In this article, our omission or limited discussion of many topics is not intended to minimize the importance of those issues. For example, we have chosen not to emphasize many topics that are often associated with process intensification, including modularization, reactive separations, and many other multifunctional or hybrid process intensification methodologies and unit operations.

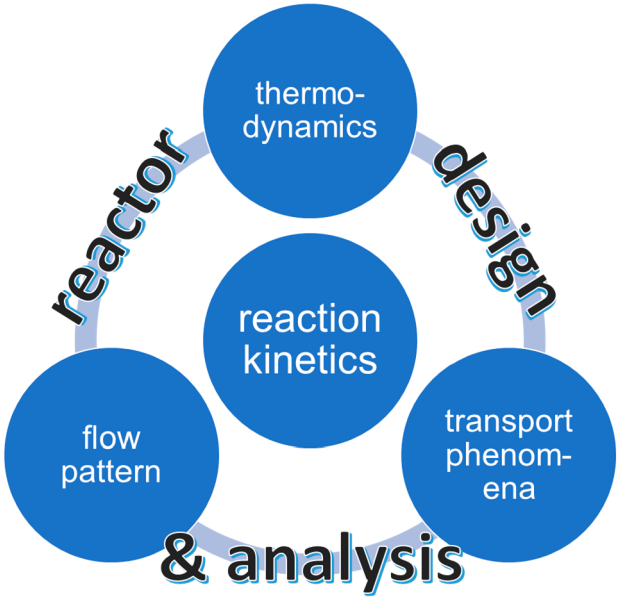

Figure 2. CRE involves the design and analysis of reactors and reaction systems through knowledge and manipulation of the reaction kinetics, flow patterns, and transport phenomena constrained by thermodynamics.

The evolution of CRE is depicted graphically in Figure 3. Web of Science has indexed over 6000 articles since 1958 with "reaction engineering" as a search criterion under the *All field* filter.[8] *Chemical Engineering Science* published 1653 articles, followed by *Macromolecular Reaction Engineering* (710 articles), *Bulletin of Chemical Reaction Engineering& Catalysis* (359), *Industrial and Engineering Chemistry* (357), and *Chemical Engineering Journal* (324). To gauge how the field has changed over the years, we created a bibliometric map of the 100 most frequent keywords with the VOSViewer open software.[9] The largest nodes represent over 1000 articles, while the smallest nodes correspond to 54 articles. Fischer−Tropsch synthesis (top left in Figure 3), developed in the 1920s, has attracted a great deal of interest together with methane, syngas, and hydrogenation. Water treatment and biomass/catalysis are two other areas that have emerged as hot topics in reaction engineering (orange nodes). On the other hand, research in polymer reaction engineering was more prevalent in the 1980s (blue nodes in Figure 3). The green nodes in the figure are topics that were popular historically and continue to attract research investment: modeling, kinetics, catalysis, and nanoparticles (NP).

The title and structure of the rest of this article follow the Vision 2020 report, with one notable addition: a section on electrochemical systems, a field that has blossomed in the past two decades, growing from a niche topic to a significant fraction of the published research in the field of chemical reaction engineering. The growth of interest in electrochemical systems has been driven by three factors: the recent and predicted increasing abundance of renewable electricity at decreasing costs; the ambition of many societies, governments, and corporations around the world to decarbonize; and the proliferation of mobile devices from laptops to smartphones, such that most people around the world carry a small electrochemical device throughout their day in the form of a lithium-ion battery. The body of this document includes two major sections, the first having four subsections and the second with five subsections as shown in Figure 1. In each section, we open with a summary of our highest priority recommended research avenues associated with that segment. We follow with three additional subsections describing in greater detail the current situation, current barriers to progress, and research needs.

RESEARCH NEEDS, TECHNOLOGY BARRIERS, AND PRIORITIES BY INDUSTRY

Basic Chemicals

Summary. We identified the following top research needs for the basic chemicals industry: (a) continuation and even

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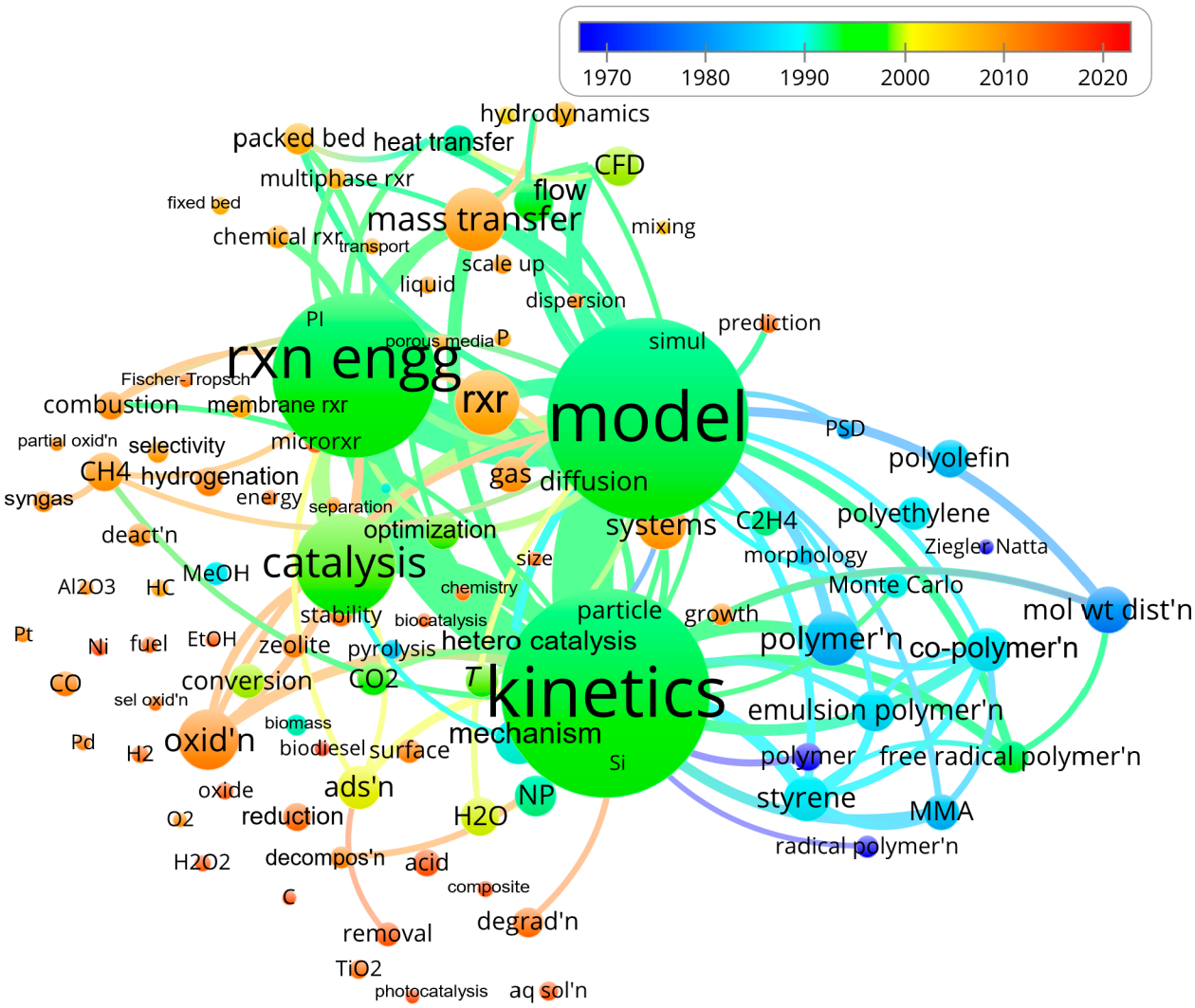

Figure 3. Bibliographic map of the 100 most frequent keywords related to "reaction engineering" indexed in the Web of Science. The size of the node correlates with the number of occurrences of the keyword, and proximity relates to the frequency that they are in the same article. The lines represent cocitations. The color represents time. Kinetics (1068 occurrences), model (1027), reaction engineering (817), and catalysis (478), colored green, appear equally now as they did in the 1970s. Molecular weight distribution (213 occurrences), polymer (117), radical polymerization (90), and Ziegler−Natta (58), colored blue, were cited more frequently in the 1980s. The hotter topics today, in orange, include mass transfer (287), oxidation (269), and CH_4 (166). Based on the color classification, biodiesel (60) is the most recent topic. Abbreviations: ads'n-adsorption, aq sol'n-aqueous solution, C-carbon, deact'n-deactivation, decompos'n-decomposition, degrad'n-degradation, EtOH-ethanol, HC-hydrocarbon, hetero catalysis-heterogeneous catalysis, MeOH-methanol, MMA-methyl methacrylate, mol wt dist'n-molecular weight distribution, oxid'n-oxidation, PI-process intensification, P-pressure, PSD-particle size distribution, radical polymer'n-radical polymerization, red'n-reduction, rxn engg-reaction engineering, rxr-reactor, sel oxid'n-selective oxidation, and T-temperature.

expansion of efforts to find new and better catalysts; (b) improvement and increased application of advanced computational tools for reactor system modeling, optimization, and control; and (c) new and more robust online and in situ process analytical techniques for monitoring compositions, phase fractions for multiphase systems, temperature, and pressure in reactors at the production scale.

Situational Analysis. The basic chemicals segment of the manufacturing industry encompasses commodity or bulk chemicals that are sold based on cost rather than performance. Examples include olefins, methanol, and ammonia, which are produced in large volumes and driven by capital cost constraints and economies of scale considerations. These building block molecules have been produced for decades, during which industry has built new production capacity to support increasing market demand. Industrial reactor technology has matured and remained relatively unchanged in the past 20 years, including workhorse reactors such as fluidized beds, fixed beds, tubular reactors, bubble columns, and stirred tanks. Chemistry and catalyst innovations implemented in known reactor technology drive most technological advances, although improvements in those reactor designs do occur.

The envisioned new unit operations in basic chemicals resulting from process intensification have yielded few transformational reactor technologies or operational strategies that have revolutionized the production of basic chemicals since 2000. While the sustainability-related predictions in the previous forecast[1] were not realized, circularity and decarbonization are receiving significant attention. If current societal and political pressures stay on course, basic chemical processes will shift from fossil fuel energy to electrical energy for process heat, driving motors,[10] and alternative forms of energy transfer.[11] The drive

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for circularity has made life cycle assessments routine for new process technology, shifting the objective function to account for costs and risks previously ignored.[12] The enthusiasm for biobased processes (such as biocatalysis for basic chemicals) has been dampened by economic realities.[13] Biobased feedstocks are more expensive than fossil feedstocks. Furthermore, bioderived feedstock compositions vary more widely, resulting in more difficult hurdles on the path to robust process technology. Biobased feedstocks have variable composition based on type, season, and impurities. This diverse composition necessitates advanced analytical methods for detailed, accurate, and fast composition characterization, purification systems upstream of the reactors, and resilient catalysts and reactors. For example, high-temperature pyrolysis is often selected for its inherent resilience compared to more selective, low-temperature catalytic processes. These complex materials drive a crucial need for real feedstock handling to enable commercialization. Supply chain integration is yet another risk. A few technologies like bioethanol[14] and 1,4-butanediol[15] have been and will be developed, but traditional thermal chemistry methods have continued to dominate. Bioprocessing knowledge and techniques may enable biorenewable and biodegradable products. Exploration of electrochemical processes is in its infancy.[16,17]

The basic chemicals industry segment has been pursuing improvements in digitalization, with continual advances in computer hardware, computer modeling technology, and data science, enabling increasing levels of automation including model-based control and sophisticated approaches for reactor and process optimization[18] as well as application of highly automated high-throughput laboratory capabilities.[19] Adoption has been slower than forecast but is progressing, although few industrial applications of dynamic models and complex model-based control strategies exist. Computational fluid dynamics and computational particle fluid dynamics simulators continue to grow in sophistication but still require experimental validation.[20,21] Computational chemistry continues to gain a foothold but is still not commonly identifying new routes or catalysts a priori. Computational chemistry continues to be interpretive and has not reduced the need for laboratory measurements.[22] Reactor design and optimization efforts are increasingly relying on highly integrated experimental and modeling efforts.[5] Efforts to couple fundamental reactor and kinetic models with machine learning are in the early stages of development. The drive to lower costs is increasing attention on reliability. Numerous factors contribute to unplanned outages, including inability to predict equipment mechanical failure, fouling troubles almost as numerous as the number of different processes, and issues related to solids handling.

The high safety standards in basic chemical operations remain unchanged but with actions and outcomes that are increasingly effective. In the past two decades, the frequency and scope of occupational injuries and illnesses has decreased 2-fold[a] because of continuous improvement in awareness, training, and safety work processes.

Barriers. The most important barrier in basic chemicals is capital, which is expensive, scarce, and driven by cost competition. The U.S. chemical industry spends about $30 billion/year on capital.[23] Using the total market capitalization of about $800 billion[24] as a proxy for the total asset value for the U.S. chemical industry, the replacement rate of those assets is less than 4%/year. Thus, it takes more than 25 years to completely refresh the assets, and many production plants have lifetimes much longer than that. Capital scarcity coupled with the large investment risk required to develop and implement new process technology limits the number of new process and reactor technologies. Safety and environmental concerns also limit the rate of change.

Despite advances in data science and computational power for physics-based models, data quality (reproducibility and systematic error) often limits the quality of models.[25] These quality issues derive from multiple sources: inadequate staffing of support personnel to maintain equipment and calibrations, lack of maintenance and calibration discipline, and unstable analyzers and transducers. Furthermore, the cost structure in basic chemicals also limits the number of analyzers, resulting in limited knowledge of process performance, especially under nonsteady-state conditions.

Research Needs. We recommend continuation and expansion of efforts to find better catalysts to enable breakthroughs for new process technology.[26,27] Some representative "holy grail" examples of the many opportunities for catalyst breakthroughs include conversion of methane directly to methanol and ethylene, direct oxidation of propylene to propylene oxide, partial oxidation of alkanes to valuable intermediates such as acrylic acid and ethylene oxide, direct amination of benzene to aniline, and isocyanates from routes that do not require phosgene.

We recommend a strategic approach to identify opportunities to electrify some reaction processes. This strategy should pay careful attention to process economics and should focus on the largest energy-consuming reactions, such as ethylene production, where replacement of natural gas combustion with a renewable energy source is a public goal for many ethylene producers.[28] For exothermic reactions that generate energy, the motivation for electrification is less. Furthermore, converting the carbon source for any of these large-scale processes to carbon dioxide is an inefficient use of renewable energy compared to alternatives.[29,30]

We recommend further development of computational tools and methods and their integration into process development workflows and process optimization and control of reaction processes. These tools include those designed for a wide range of problem types: differential-algebraic equations with parameter estimation; computational fluid dynamics; computational particle fluid dynamics; advanced process control schemes; real-time process optimization methods; and process systems engineering methods to optimize processing schedules, maintenance planning, turnaround schedules, and reactor system operations.

To achieve higher-quality data and enable better reactor models, we recommend new and more robust online and in situ process analytical techniques for monitoring compositions, phase fractions for multiphase flows, temperature, and pressure in reactors at all scales, from the laboratory to production.

Finally, we recommend educational modifications for better-prepared industrial reaction engineers: (1) Add solids processing and statistics as core undergraduate curriculum components and incorporate data analytics techniques into existing courses. (2) Introduce life cycle assessments in the senior level process design course while continuing to emphasize the significance of capital cost in technoeconomic analysis. (3) Include more electrochemical systems in case studies for coursework and in thermodynamics and transport phenomena courses. (4) Continue to elevate safety training by embedding safety concepts and principles in the academic curriculum, including in unit operations laboratory and chemistry laboratory

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courses and, potentially, a process safety course in the curriculum. At a minimum, introduce students to process safety concepts by including Chemical Safety Board videos (https://www.csb.gov/videos/) or process safety courses from the AIChE Center for Process Safety (https://www.aiche.org/ccps/education/safety-and-chemical-engineering-education-sache-certificate-program) in the reaction engineering course.

Specialty Chemicals

Summary. We identified the following top research needs for the specialty chemicals industry: electrification, computational chemistry, and process intensification. Electrification of specialty chemical manufacturing includes both transitions to electrified chemical processes and electrochemical synthesis. Computational chemistry is increasingly accepted as a surrogate for experimentation and used instead of in vivo testing. This motivates the need to standardize methods accepted by policy makers. Process intensification to reduce capital and operating costs and a transition to continuous manufacturing motivate research into flexible and modular continuous reactor designs.

Situational Analysis. Batch processing remains the most prevalent choice of reactor technology in the specialty chemicals industry.[31] This is partly due to momentum since manufacturing choices are often determined by the most effective technology as determined by the previous experiences of the manufacturer. Repurposing existing capital for new products and block-operating underused assets also pushes process development and reaction engineers into batch assets.

Historically, many specialty chemical manufacturers in the USA owned and operated their manufacturing assets; however, many are moving to lower-cost contract manufacturers in developing markets such as Central America, South America, and Southeast Asia. Contract manufacturers who serve the specialty chemicals markets typically operate batch processes due to the flexibility they offer to manufacture a wide variety of molecules for numerous customers.

The molecular weight of specialty molecules continues to increase, especially for agricultural chemicals, contributing to an increase in chemical complexity, such as the number of chiral centers, and manufacturing processes are becoming more intricate for controlling these chemical features. The industry has increasingly adopted real-time in-process analytical techniques to improve control strategies. The Internet of Things has created an opportunity to further increase real-time process monitoring.

As anticipated in 2000, computational cost has continued decreasing, and much larger problems can be solved computationally.[1,32] Computational toxicology is increasingly accepted by regulators as a surrogate for in vivo testing.[33,34] While machine learning and artificial intelligence have started displacing more fundamental modeling techniques for optimization or troubleshooting of commercial reactors, reactor design is still focused on fundamentals.

Specialty chemicals manufacturers are increasingly focused on improving sustainability of existing processes and developing new chemistries using the principles of green chemistry.[35−37] Electrochemical transformations are emerging as an alternative to traditional transition-metal catalysis.[38] The use of electrochemical reactors is also enabled by an increased interest in electrification to create green energy alternatives to fossil fuels.[39] We observe a trend to replace high-boiling, and often reactive, solvents such as dimethyl sulfoxide and dimethyl formamide with safer alternatives, such as methyl isobutyl carbinol and 2-ethylhexanol.[40−42] Process intensification remains a focus of the United States Department of Energy,[43] and the primary technologies of interest are reactor-separator units, such as reactive distillation and reactive crystallization, which can shift equilibrium to favor products and improve product purity and enantiomeric ratios.

Continuous manufacturing strategies are increasingly adopted to improve both the productivity and the safety of new processes. Higher heat transfer area per unit volume in continuous tubular reactors compared to stirred tanks not only improves process safety but also enables chemistries historically performed at cryogenic temperatures to operate near room temperature, such as lithiation.[44,45] This in turn increases manufacturing flexibility, significantly decreases the energy intensity of the reactor, and increases the reaction rate compared with incumbent batch reactor technology. Lower chemical inventories in the process contribute to more favorable scenarios from unexpected chemical excursions, such as reactor runaway, and decrease chemical and environmental exposure hazards.

Barriers. Batch processes are often adopted due to the flexibility of the assets; thus, specialty chemical companies bringing products to market find that continuous processes limit their choices when selecting manufacturing partners. Even when the manufacturer owns and operates the assets, the reuse of existing batch assets motivates adoption of batch reactor technology. Batch reactor technology also enables reactors to be block-operated, where the facility produces multiple products in the same reactors, improving the return on capital compared to many small reactors.

The continued trend toward contract manufacturing in developing geographies has made it increasingly difficult to validate reactor models at the industrial scale. Since the owner-operator of the reactor is not the owner of the model, little incentive exists to perform repeated reactor sampling (which is labor-intensive) or install instrumentation for model validation. Furthermore, many manufacturing contracts are written such that the contract manufacturing partner is paid on a per pound of product basis, and reactor sampling is simply out of scope. An additional complication is that contract manufacturing partners are often part of ramp-up strategies, and the technology owner intends to be manufacturing in the leased asset for only a few years. This can delay model validation until manufacturing shifts to the permanent location, by which time validation is often forgotten, overlooked, or no longer considered valuable.

Another barrier to data-driven model development and validation is poor or unreliable instrumentation in the manufacturing environment. Even when quality laboratories are available to analyze the product before release for sale, these laboratories focus on product characterization and often lack analytical tools to quantify reactive intermediates, very dilute concentrations, and other measurements for validating reactor models.

Research Needs. To enable further adoption of continuous processes for specialty chemicals, research should focus on flexible and modular continuous reactor designs that will enable contract manufacturers to invest in them and improve industry adoptions. Enhanced manufacturing flexibility will also contribute to a more robust chemical supply chain.

Research into the electrification of specialty chemical manufacturing, including existing processes and electrochemical transformations, should be encouraged. This would enable carbon-free energy use and decrease the usage rates of transition metals.

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As computational chemistry is adopted as a surrogate for experimentation, standardized methods for validating computational results should be developed and validated. These methods should enable policy makers to make decisions without experimentation.

Pharmaceuticals

Summary. We have identified the top research priorities for the pharmaceutical industry to be as follows: (a) increase development speed and reduce cost; (b) invent more efficient processes; (c) leverage institutional knowledge to accelerate the decision-making process; and (d) develop an operating model and culture of collaboration. The adoption of continuous manufacturing technologies still faces resistance. Developing reaction technologies that safely enable scale-up can shorten synthesis, and flow chemistry can help make it possible. Photochemistry and electrochemistry need development and reactor designs for various scales. The industry desires new and more robust online and in situ analytical techniques. The number of modalities is increasing significantly from mainly small molecules to large molecules (biologics) and medium molecules (peptides, oligonucleotides). Bioreactor and fermenter designs have become more efficient and productive. Computational tools that speed development, including property prediction and rate prediction in various solvents, are needed. The concern that regulatory bodies will not accept model validations limits their use in manufacturing control strategies. Development of efficient and robust manufacturing processes requires cross-functional expertise and collaboration.

Situational Analysis. The pharmaceutical process development pipeline is notoriously complex, intricate, and time-consuming. In 2021, the global industry spent about 238 billion dollars on R&D.[46] A new drug's average clinical development time is about 9 years[47] due to lengthy clinical trials and stringent regulatory approvals. The pharmaceutical industry and regulatory authorities have started to recognize advanced processing technologies, including predictive modeling, continuous manufacturing, automation, and advanced controls and informatics, for their potential economic, environmental, and safety benefits. The Food and Drug Administration (FDA) has recently released continuous manufacturing guidelines.[48]

Batch processing remains the most prevalent, but end-to-end automated capabilities for screening and flow processing have been developed.[49−51] Continuous processing has been adopted for chemistries with safety concerns and scalability issues.[52] For example, continuous processing will continue to be important for reaction engineering safety with azides, which are useful chemistry tools to make a wide variety of structures in an efficient and inexpensive manner, for example, click chemistries and tetrazoles. They are a key synthetic functionality and are useful or necessary for a wide variety of transformations, often emerging as the best synthetic intermediate.[53,54] Synthetic route options are increasing, but large-scale pharmaceutical industry examples are lacking.[55] In-process online deployment of real-time analytical tools remains underused.[56−58]

The number of modalities is increasing significantly. In the past, the focus was on small molecules, but now the focus is on biologics, cell and gene therapy, peptides, oligonucleotides, and antibody drug conjugates. Current solid-phase peptide and oligonucleotide syntheses use large amounts of solvents and have a large environmental footprint.[59,60] The role of reaction engineering in these modalities is very much evolving.

We have seen some advances on dynamic models and their surrogates and complex model-aided control strategies to generate process understanding and what-if analyses and to keep control schemes as simple as possible in the current Good Manufacturing Practice. We see an increasing emphasis on automation and data science in process development and optimization.

In the past twenty years, high-speed reaction/synthesis screening tools have been developed, addressing the Vision 2020 needs, but they are not used consistently or broadly and have limitations. Some contract research organizations have marketed high-speed screening capabilities,[61] but many still run individual experiments. New computer algorithms have been designed by MIT ASKCOS,[62,63] IBM,[64] Synthia,[65] and others[66] for synthesis planning and impurity prediction, but their impact is not being felt—perhaps because models may predict the main reactions but not low-level impurities.

Bioreactors and fermenters are essentially the same geometry today as they were 60 years ago, but they are certainly more efficient and productive. In the last 20 years, the introduction of disposable systems, single-use bioreactors (SUBs), process analytical technology, and robotics represents a step change in efficiency and quality assurance. SUBs, such as the Ambr technology, and accurate scale-down models and systems bring flexibility and enable the design of different expression systems and applications. SUBs reduce sterilization in place and clean in place burdens, ensuring axenic operations and mitigating cumbersome contamination incidents.

Perfusion bioreactors give higher productivity than batch or fed-batch systems.[67,68] In these bioreactors, fresh media is added and spent media is removed simultaneously through ultrafiltration to retain and recycle desired cells back; a cell separation removes dead cells.[69,70] Achieving higher cell mass in the second-to-last scale-up reactor enables a higher seed density for the fed-batch production bioreactor, where products are generated. New federal laws around patent life are expected to shift the balance to more biologics and fewer small molecules. Antibody drug conjugates attach the active small molecule drug (payload) to an antibody that selectively delivers it to a target site in the body. As of May 2021, the FDA had approved ten antibody drug conjugates for cancers, with 80 more evaluated in approximately 150 active clinical trials.[71,72]

Barriers. Continuous manufacturing still faces resistance due to lack of experience, buildup of appropriate infrastructure from lab to plant, equipment availability at scale, a natural propensity to stick with the status quo in a highly regulated environment, capital avoidance, and concerns around patent filing. Furthermore, continuous production trains are typically specific to a single product, not allowing multipurpose production. Drug substance continuous processes have diverse sets of unit operations (reaction, workup, crystallization) with a unique equipment arrangement for each synthetic route. In addition, government regulators are unsure of how to critique packages from continuous processes because there have not been many yet.

Implementation of new reaction technologies is difficult because regulations span multiple global agencies with different levels of experience. Given the short patent life, if the launch is delayed because of new technology approval, each lost day is too costly; therefore, the risk is high.

Electrochemistry and photochemistry[55] designs offer limited options and are not suitable for scale-up.

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The desire for the lowest manufacturing complexity to minimize the number of items to validate has limited the number of analyzers.

There remains no industry-accepted metric of process sustainability. Some pharmaceutical manufacturers prefer kilograms of organic solvents per kilogram of product. The Process Mass Intensity, as proposed by the ACS Pharmaceutical Roundtable, is incomplete because it does not consider the identity of the process chemical but only the mass. A methodology to quantify the environmental footprint of peptide and oligonucleotide synthetic reactions is lacking.

The tendency is to use computer modeling and data science to improve fundamental process understanding and then use less complex process analytical methods and control in the manufacturing plant, primarily because of validation challenges necessary to meet regulations. While a significant effort has been devoted to effective validation protocols,[73,74] model validation at industrial scale remains underutilized because of perceived and anticipated regulatory barriers, internal and external. The concern that regulatory bodies will not accept model validity limits the models to those containing scale-independent parameters. We perceive a lack of harmonization in accepting mathematical models for commercial processes, with the FDA being more visionary than some international regulatory bodies.[75,76]

A barrier to advancing bioreactors and fermenters is that they are not typically part of the chemical engineering curriculum. Furthermore, these systems are typically limited by low gas−liquid mass transfer rates or low concentrations of the reaction products. High capital and operating costs result, with the cost of multiple separation steps often dominating the overall process economic cost.

Research Needs. Technology opportunities exist for continuous reactions, extractions, crystallization, isolation, and drying. New reaction technologies that safely enable the scale-up of previously forbidden chemistries can shorten the route of synthesis. This becomes even more important as the size, complexity, and number of chiral centers of pharmaceutical targets increase. Safe reaction engineering options are needed for hazardous gas−liquid reactions such as high-pressure hydrogenations and aerobic oxidations, hazardous chemistries such as Grignard formations, hazardous reagents such as phosgene and hydrazine, and scalable photochemistry and electrochemistry. Continuous flow may result in shorter conjugation reaction times by enabling higher temperatures and lower shear mixing of the linker-payload with the antibody scaffold, resulting in less hydrolysis of the linker, less aggregation of the antibodies, higher yields, and higher drug antibody ratios.[77] New equipment strategies will streamline utilization of new discoveries at the manufacturing scale. New and more robust online and in situ process analytical techniques are desired for monitoring unreacted starting materials and key byproducts at <0.1% levels in real time.

Enzyme catalysis can improve chiral purity of small molecules and fragment assembly of peptides and oligonucleotides by convergent rather than linear approaches, but technologies are needed for evolving better, more selective enzymes to enable new reactions and higher efficiencies. An alternative to solid-phase synthesis of peptides and oligonucleotides is to develop liquid-phase synthesis options via soluble hubs, membrane separations of reaction byproducts, templating, and enzymatic ligation.

Further development of computational tools and methods and their integration into both process development workflows and process optimization and control applications are needed. Advanced process control schemes and process systems engineering methods are desirable. Computational techniques to predict reaction rates in different solvents and properties will shorten development timelines.

The successful adaptation of enabling technologies relies on a highly multidisciplinary and dynamic environment and cross-functional expertise. Facilitation of cross-disciplinary collaboration among chemical engineers, chemists, biochemists, materials scientists, and pharmaceutical scientists is critical. Increased industry-academia collaborations, as well as pre-competitive collaborations among pharmaceutical companies, will continue to drive greater scientific understanding and leveraging of collective resources to develop new tools and capabilities and to familiarize regulators with new designs and approaches. Companies proactively investing in technologies and the development of talent that enable transformations will be better positioned for a sustainable future. Future chemical engineers should be trained in other disciplines, such as automation and data science. Pharmaceutical processing could be added to the undergraduate curriculum.

Polymers

Summary. We have identified the top research priorities for the polymer industry to be as follows: (a) polymers designed for ease of chemical recyclability (polymers assembled from cost-efficient monomers or building blocks and disassembled efficiently without excessive energy input); (b) compounded polymer products designed for ease of mechanical recycling; (c) novel chemistries to produce monomers and corresponding polymers making capture and sequestration of CO_2 inexpensive; (d) computational chemistry tools to facilitate structure−property predictions for novel sustainable polymers; (e) electrification of reactors and processes to make polymers; and (f) scalable and intensified reactor technology to convert mixed plastic waste to liquids (pyrolysis oil, also known as pyoil) or synthesis gas to displace fossil-based raw materials from the polymer value chain.

Situational Analysis. In 2019, about 460 million metric tons (MMT) of plastics were produced globally,[78] a rate that will double in 15−18 years if the market continues to grow by 4 to 5%. By 2015, the world had produced more than 8 billion metric tons of plastic since 1950, and only 9% of the waste plastics had been recycled.[79] This situation is unsustainable. The polymer industry faces twin challenges of global magnitude: (1) plastics recycling and (2) decarbonization of polymer production processes. The challenges are further compounded by the fact that certain modes of energy-intensive chemical recycling could increase the carbon footprint more than landfilling. The regulatory pressures are expected to intensify in the next two decades. Evolving customer preferences may hasten this transition. The current portfolio of polymers (polymer pyramid) dominated by polyolefins strikes a fine balance between cost and properties but is not suitable for recycling, as depolymerization is highly endothermic. Consequently, some polymer scientists are developing new classes of polymers to satisfy the core needs of the market segments while being easy to assemble and disassemble.[80−82] Also, novel decontamination technologies are being and will be developed to clean up mixed plastic waste for chemical recycling.[83] At least some of these technologies will involve novel reactive chemistries. Specifically, novel technol-

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ogies need to address the removal of heteroatoms (halogens, N, S, O, and metals) from the mixed plastic waste feedstock in a cost-efficient fashion. Mechanical recycling of plastics will continue to play an important role in enabling a circular value chain but will be challenged by the need for large quantities of high-purity, clean feedstock streams. Furthermore, mechanical recycling degrades polymer properties and leads to "downcycling."[84] Novel chemistries that can mitigate downcycling could enable a circular plastics value chain.

The polymer industry needs to develop new materials that support the energy transition and are recyclable. Ever-increasing sizes of windmills, large battery modules for electric vehicles, and weatherable materials for solar panels will accelerate the development of new classes of materials to meet market needs. Materials that can meet these unique requirements and are recyclable will see increased application.

Following a great volume of research in the 1990s and 2000s, a few biorefineries were commercialized to convert biobased feedstocks to fuels, chemicals, and polymers. However, challenges with biofeedstock availability, technical challenges with scale-up, and associated adverse economics have stymied the growth of biobased feedstocks.[85]

Despite significant research in process intensification,[86−89] large-scale deployment of intensified reactors for polymer manufacturing is rare. The industry has not witnessed any megatrend of radical redesign of most common commercial-scale reactors for the synthesis of polymers, particularly polyolefins, over the last two decades. However, considerable advances have been made in commercializing combinations of stirred tanks, slurry loop reactors, and gas-phase reactors to produce a vast array of multimodal polyolefins.[90] Commercialization of multizone gas-phase reactors to produce multimodal polyolefins is a recent development.[91] A variety of multiscale models of multizone gas-phase polyolefin reactors have been developed, and the state of the art is thoroughly summarized by McKenna and co-workers.[92,93] Considerable advances have also been made in developing multiscale models[94,95] and modeling polymer structure−property relationships because of advances in molecular modeling techniques and high-performance computing power that has grown by orders of magnitude.[96] However, significant challenges persist[97] in bridging the gap between quantitative predictions of behaviors of polymers and polymer blends under real-world processing and use conditions attributed to defects, inhomogeneities, and nonequilibrium, among others.

High-throughput experimentation has become common for catalyst discovery, development, and optimization, particularly in polyolefin research. Increasingly sophisticated in situ analytical techniques are being deployed to monitor the progress of the reactions in real time, enabled by advanced sensors and the fusion of hardware and software capabilities for materials characterization.

Development of safer chemistry that seeks to replace hazardous solvents with novel solvents that have lower toxicity and environmental impact continues at a gradual pace.

Barriers. The circular economy demands the emergence of new business models in which large-scale plastic producers, processors, consumers, and vendors who collect and sort waste plastics collaborate to provide solutions. This calls for a complex value chain management structure. The heterogeneity of mixed plastic waste feedstock remains a barrier to the development of scalable reactor technologies to convert it into pyoil and other high-value chemicals. In addition, a large fraction of single-use plastics is composed of multilayered films, which present unique challenges to mechanical and chemical recycling. These multilayered films comprise polymer layers to impart barrier properties. A key technical challenge for reaction chemists and engineers is to help develop monomaterials that have barrier properties against O_2 and water as well as optical and mechanical properties similar to multilayered films. Likely, this would involve use of novel reaction schemes to tailor the molecular architecture of polymers. Reduction of the costs of such materials so that they become competitive against the current generation of multilayered films is expected to be challenging. Mechanical recycling is extremely challenging for multilayered films, leaving capital- and energy-intensive chemical recycling as the only viable option. All of the players in the circular plastic value chain need to work together with regulators to evolve common standards for mixed plastic waste streams that can be used as feedstocks in the refineries and the chemical and polymer industry.

The high capital cost intensity of plastic conversion processes for recycling has stunted the growth of the chemical recycling of plastics. Novel, intensified reactor technologies may play a role in lowering the capital intensity of plastic waste conversion. Furthermore, industry-wide accepted standards for what could be called certified circular products need to be evolved and adopted by regulators to facilitate large-scale investment.

Reactor modeling tools for the unique challenges presented by the conversion of mixed plastic wastes to fuels and chemicals are still in their infancy. Key challenges in the development of such tools are the plastics feedstock and product stream characterization, catalyst deactivation and poisoning in the presence of heteroatoms, and integration of mass- and heat-transfer limitations into reactor models for low Reynolds number hydrodynamics while properly accounting for phase-change dynamics.

Research Needs. Recycling polymers is complicated, as most consumer products and textiles are mixed polymers and contain additives such as stabilizers, pigments, fillers (carbon black, fiberglass), and other compounds required to achieve the required performance qualities of each end-use. Upcycling plastics to value-added chemicals rather than monomers is a promising alternative.[98,99] Mechanical recycling reprocesses plastics into pellets for low-value applications, but contaminants degrade the mechanical properties. Thermal recycling (gasification and pyrolysis) converts the polymer to oils and syngas that are then processed for drop-in fuels and chemicals. Poly(methyl methacrylate) (PMMA − Plexiglas, Lucite, Perspex) is one of the few polymers that thermally degrades to its monomer (methyl methacrylate) at high yield (>90%). Rather than syngas, chemical recycling produces monomer from plastics, but contaminants are a major obstacle to achieving an economic process. New catalytic processes that involve (1) low temperature and selective activation of C-C and C-X; (2) elimination of CO_2 production in C-C activation; (3) mixed plastic waste and blended polymers to liquids and chemical intermediates; (4) removal of heteroatoms from mixed plastic waste; and (5) upcycling of plastics (such as PMMA to methyl methacrylate to methacrylic acid) will be required.

Currently, few modeling tools exist to study the depolymerization of mixed plastic waste. The kinetic models need to address not only the depolymerization of pure polymers but also the interactions between various polymers that result in complex degradation pathways and product yield vectors. While the short- to medium-term need is kinetic models for thermal

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degradation of mixed plastic waste, we expect that catalytic depolymerization will gain more currency once the cost of cleanup of mixed plastic waste to remove catalyst poisons decreases substantially. A second area to enable the circular economy is the development of kinetic models for removal of heteroatoms (S, N, O, halogens, etc.) from mixed plastic waste. A third area of focus is to develop reactor models incorporating kinetics and heat and mass transfer to spur the design of scalable reactor technologies to convert pretreated mixed plastic waste to pyoil or to small molecules that serve as building blocks for polymers and chemicals. A fourth area of focus is to build models to predict the effect of blending of pyoil with naphtha on cracker yield vectors and the effect of blending pyoil with crude fractions on the refinery yield vectors. We expect that computational fluid dynamics models will be able to incorporate larger and more complex reaction networks to enable the development of high-fidelity multiscale models, assuming continued exponential growth in computing power. Advanced models that fuse computational chemistry tools with more conventional multi-scale modeling to connect polymer properties and processability with polymer composition and architecture and further back to reactor operating conditions will remain an area of active research as novel materials are invented. At the same time, effective problem solving requires using the right tool for the task, so researchers should also develop reduced-order multi-scale models, especially for dynamic process control and automation as well as reactor and process optimization.

A key focus area in materials development is the invention of novel materials to support the energy transition. A first focus area would be the development of polymer-based solutions for the lightweighting of large battery packs without sacrificing safety to support electrification of automobiles. Reaction engineers can address the challenges in modeling thermal runaways in large battery packs. A second focus area is the development of polymers and compounded products that can be assembled from building blocks and disassembled with ease for recycling. Polymer reaction engineers can develop novel catalysts, synthesis routes, and separation and purification techniques for such polymeric materials. They should also develop compounded polymer products designed for ease of mechanical recycling, with a focus on simplification of formulations, the use of additives that can withstand thermal cycling, and additives that can help polymers "heal" from degradation induced by environmental and thermal mechanisms. A third research area in support of the wire and cable industry and critical to building infrastructure for the energy transition is the development of recyclable thermoplastics that have excellent insulation characteristics but high thermal conductivity to dissipate heat for applications in long-distance high voltage direct current (HVDC) cables, particularly for offshore wind energy.[100] Polymer scientists and reaction engineers must work closely with electrical engineers to accelerate the development of such materials. Fourth, ion exchange materials for electrochemical devices, membrane separations, and related applications would benefit from further technological advances.

The primary focus area for research in materials processing will remain the same: build better models to connect catalysis and reactor conditions with polymer product properties. The development of predictive models to link catalyst and reaction conditions with polymer structure and hence polymer properties and application-level performance should remain a research area, especially as novel materials are developed to satisfy new applications. A second focus area is the development of material processing techniques to enable use of higher postconsumer recycle (PCR) content in mechanical recycling by preventing or lowering the degradation of polymer properties in repeated heat cycles in extruders. This will also require the redesign of the compounded polymer products to make them more resistant to degradation over multiple heat cycles. Reactive extrusion represents a third focus area, both for synthesis of virgin polymers in intensified reactors and for enabling an alternative approach for chemical recycling of some waste plastic streams. For synthesis of virgin polymers, a combination of conventional stirred tanks or loop reactors followed by reactive extrusion to complete the polymerization needs to be explored as a way to intensify certain classes of polymerization reactions.[89] To use reactive extrusion to enable the chemical recycling of polymers, reaction engineers need to develop simplified kinetic models that can predict the product composition as a function of operating conditions. This problem is complex primarily because of the heterogeneity of the feedstock.[89]

The challenges associated with circularity and the energy transition necessitate a refocusing of the university curricula in polymer reaction engineering to equip students with the right tools. Specifically, greater emphasis needs to be placed on developing a simplified characterization toolkit for highly heterogeneous and "dirty" feedstocks and products, developing kinetic models for depolymerization and incorporating these models into a suitable reactor modeling framework that is designed to deal with mass and heat transfer constraints associated with hydrodynamics at low Reynolds numbers in pyrolysis, hydrogenolysis, and hydrocracking reactors.

RESEARCH NEEDS, TECHNOLOGY BARRIERS, AND PRIORITIES BY TECHNOLOGY SEGMENT

Reactor System Selection, Design, and Scaleup

Summary. We recommend the following top research needs for reactor system selection, design, and scale-up: (a) new and more robust online and in situ process analytical techniques for monitoring reactor compositions, phase fractions for multiphase flows, temperature, and pressure; (b) continuing advances in computational fluid dynamics model accuracy for multiphase flow including systems containing particulates (e.g., fluidized bed reactors); (c) robust and user-friendly nonlinear equation solvers for differential-algebraic equation (DAE) and partial differential equation (PDE) systems packaged with statistically sound parameter estimation capabilities; and (d) innovations enabling laboratory evaluation of reaction processes (with and without heterogeneous catalysts) at high temperatures (>600 °C) at isothermal temperatures and with ideal contacting patterns.

Situational Analysis. Industrial practice varies from completely empirical scale-up with intermediate scales to mitigate risk[101] to model-based scale-up with models based solely on laboratory-scale data.[102] Model-based reactor scale-up requires a knowledge of reaction kinetics, contacting patterns, and relevant transport limitations. This approach is conceptually preferable but not always reliable and cost-effective depending on the reaction system.

Regarding reaction kinetic models, most engineering modeling tools (equation solvers) for reactor scale-up lack statistical rigor and robustness for parameter estimation. As a result, reaction engineers tend to develop kinetic models without statistical feedback that is necessary for data analysis,

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model assessment, and model discrimination. Commercial process modeling tools are more broadly used and more fully developed than reactor and kinetic modeling tools, but those process simulators are not typically designed to facilitate fitting kinetic parameters to laboratory reactor data and they lack the flexibility to account for nonideal contacting patterns, interphase mass transfer, and complex heat transfer scenarios for reactor modeling. To support the development of kinetic models, computational chemistry tools have advanced in the last two decades, but reactor design efforts require accuracy and confidence levels that need measurements to determine kinetic and thermodynamic model parameters, such that computational chemistry calculations at most provide initial guesses for kinetic parameters.[103]

Many industrial reactor designs are based on models derived from laboratory-scale data for reaction kinetics combined with thermochemical and transport property data and correlations to account for the phase behavior and transport steps. Computational methods for predicting these thermochemical and transport property parameters continue to improve, but laboratory measurements are preferred when feasible. In addition, the engineer's ability to predict the contacting pattern in multiphase systems is the primary reason some reactor designs require a pilot plant or large-scale hydrodynamic evaluation equipment.[104] Furthermore, these multiphase systems require correlations for transport phenomena, which affect reactor performance to varying degrees as a function of the process scale.

A common objective to minimize costs is to avoid intermediate scales in the scale-up work process (mini, pilot, demonstration, and pioneer plants). Modeling tools and available knowledge (including thermodynamic and transport property data) enable some model-based design and scale-up of fixed bed and single-phase flow reactors with high accuracy because kinetics, phase equilibria, and transport phenomena can be easily decoupled and measured independently. In contrast, tightly coupled phenomena in other situations prevent parsing the fundamentals at a small scale, making scale-up predictions difficult. A better ability to measure and characterize these phenomena in small-scale equipment, beyond traditional heuristics, may enable building tools to aid step-skipping in scale-up. When eliminating an intermediate scale unit is not possible, modeling tools or analytical capabilities may enable narrowing the scope and simplifying the objectives to accelerate the timeline and reduce costs. However, in many cases, the primary purpose of the pilot plant is to demonstrate the fully integrated process with all separations steps and process recycle streams, not to guide the reactor design process.[101]

Computational fluid dynamics modeling tools for simulation of stirred tanks and fluidized beds still require validation in pilot-scale equipment.[105] Thus, those tools are seldom, if ever, used to bypass scale-up steps, only to reduce the number of experiments by focusing the experimental program on key issues.

For heterogeneous catalytic systems, catalyst deactivation remains a challenge given the long timescales for decay in many systems and the difficulties in achieving reproducible results at any scale. The custom requirements for developing a reliable accelerated aging protocol prevent a universal solution for catalyst deactivation, although narrowing the scope to a single category of catalyst and chemistry may be viable.[106]

Regarding chemical engineering education, some basic lessons and skills of the past are not being advanced or are being degraded and lost as reaction engineering research focuses on application to new areas. For example, most chemical engineering graduates lack sufficient knowledge and skills in statistics and parameter estimation, and few students are given the opportunity to develop models that incorporate reaction kinetics, transport phenomena, thermodynamic constraints, and flow patterns.

Much of the preceding discussion assumes that process economics require that commercial-scale quantities are achieved in large-scale units. In some segments, modularity offers the alternative approach of numbering up.[107] In this scenario, the human resources must be directed away from the reactor toward other priorities associated with engineering and producing many copies of smaller, modular systems such that the capital costs are reduced by the economics of mass production. This latter point is the linchpin of the widespread implementation of modular process technology for the distributed production of large-volume products. The centralized production in most sectors today is a direct consequence of the economy of scale, where capital costs increase with the 0.6 to 0.7 power of the capacity. Thus, modularization is inherently capital-intensive without the counteracting effect of mass production of large numbers of nearly identical units, as practiced in automobile production for more than a century. We recognize the appeal of producing certain reactive and toxic intermediates such as hydrogen peroxide, hydrogen cyanide, vinyl chloride, phosgene, and ethylene oxide on-demand and on-location, but industry has learned to manage the environmental and safety issues associated with the centralized manufacturing of those intermediates. As the world seeks to shift to low-carbon feedstocks, such as waste streams (agricultural waste, forestry waste, plastics, etc.) and biogas in remote locations, unfavorable transportation energy and costs for those feedstocks demand distributed processing in modular units.

Barriers. One of the largest barriers to implementing new process technology is the cost of the entire development process, including capital investment, which becomes increasingly prohibitive with increasing production process scale and complexity. This is experienced in all segments of industry but especially in the commodity basic chemicals and polymers segments. This capital investment barrier also applies to distributed processing in modular process units, which are constrained by the same economic requirements for return on capital.

With respect to education, the government and industry funding infrastructure for academic research favors the development of new materials and process concepts at the lab scale. Students have limited opportunities to learn and practice the key contributing disciplines to reactor selection, design, and scale-up (including thermodynamic and transport fundamentals and scale-up modeling) on commercially viable scales.

Research Needs. Given the current situation and barriers to successful reactor scale-up, we recommend researchers develop less intrusive, more reliable, and more accurate tools for in situ characterization of lab-, pilot-, and production-scale reactors. With respect to lab-scale measurements, we desire innovations enabling laboratory evaluation of reaction processes (with and without heterogeneous catalysts) at high temperatures (>600 °C) under known temperatures (ideally isothermal) with ideal contacting patterns (differential, well-mixed, or plug flow).

Regarding computational capabilities, continuing advances in computational fluid dynamics model accuracy for multiphase flow, including systems containing powdery catalysts (e.g., fluidized-bed reactors), will eventually enable reaction engineers

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to bypass costly scale-up steps. We also urge software vendors to continue to develop more robust, user-friendly nonlinear equation solvers for DAE and PDE systems packaged with statistically sound parameter estimation capabilities using platforms that enable flexible use of those reaction engineering models from early stage kinetic model development to final reactor model delivery in process simulation software with customized user interfaces including spreadsheets and open-source platforms. More frequent extension of kinetic, reactor, and process models to simulate dynamic (time-dependent) operation at all scales will enable further advances in reactor system performance. Recent enthusiasm for machine learning and artificial intelligence applications shows promise in certain categories such as optimizing process conditions based on historical data or correlating catalyst deactivation data to enable predictions about catalyst longevity. Further research should pursue such avenues while seeking to quantify the uncertainty of predictions from machine learning as a function of the level of extrapolation.

Finally, we recommend several adjustments in the educational offerings from universities: (1) increased requirements for coursework in statistics (undergraduate level) and advanced statistics including parameter estimation (graduate level); (2) more emphasis on reaction engineering concepts for undergraduate and graduate-level chemical engineers, as coursework focused on solving homework and test problems can shift attention from key concepts that do not require a complex mathematical framework; (3) more ties between academic professors and industrial practitioners so professors understand current problems and appropriately prepare students; and (4) exposure to machine learning tools and their limitations.

Chemical Mechanism Development and Property Estimation

Summary. We identified the following top research needs for the area of chemical mechanisms and property estimation: (a) models for realistic feedstocks and catalyst formulations to support the energy and industry transition to circularity and sustainability; (b) development of hybrid models that combine first-principles physics models, data, and expert knowledge (human-in-the-loop) to deliver extrapolative capability, accuracy, and low development time; (c) models for catalyst dynamics; (d) mechanisms and properties for electrification of chemical reactions and reactors; and (e) software, workflows, and tools for automation, smart data collection, reaction network identification, rate expression estimation, and model integration across scales.

Situational Analysis. *Sub-Category: Ab Initio Simulations and Microkinetic Modeling.* With the advent of newer density "functionals" and improvements to include weak intermolecular interactions, such as van der Waals forces, density functional theory (DFT) has become more accurate.[103] Except for a few hybrid functionals, which are computationally expensive, DFT still lacks the necessary accuracy for several reaction systems and catalysts, e.g., oxides. While we understand errors for gas-phase quantum mechanical calculations,[108] we do not generally know these for heterogeneous catalysts.[109] Correlations between parameters result in partial cancellation of errors, and thus, the accuracy of DFT may not be as bad as thought a decade ago. Studies over the past decade on single atoms, clusters, various facets, and defects indicate that the simple representation of the catalyst structure causes much larger errors than DFT.[110] Missing key elementary steps can also lead to poor predictions.[111]

With the immense growth of high-performance computational infrastructure and speed of execution, ab initio simulations followed by microkinetic models (MKMs) for medium-sized molecules are now feasible. MKMs are becoming common due to the creation of software.[112−118] Bayesian methods to assess MKM accuracy and estimate parameters have also been developed.[119,120] MKMs still employ the mean-field theory that assumes a uniform distribution of adsorbates at the nanometer scale because kinetic Monte Carlo (KMC) simulations are expensive.[121] Industry adoption of ab initio models to simulate "catalytic" reaction mechanisms has improved slightly, but it has not caught up to the state of the art in academic research. This is partly because industrial systems involve much more complex molecules, complex catalyst formulations, multicomponent feedstocks including impurities, and other environmental effects, such as solvents, and partly due to the time necessary to develop even simple first-principles models.

First-principles simulations on heterogeneous catalysts in solvents and melts are modeled less often,[122] and novel method development has been prolonged because these calculations are computationally extremely demanding and require advanced training in molecular simulation and statistical mechanics, not typically taught in the chemical engineering curriculum. Most DFT calculations are conducted under vacuum or use an implicit solvent. Such an approach lacks dynamics and reaction temperature effects. Experiments show profound solvent effects in activity and selectivity, but a general theory for understanding these effects and predicting suitable solvents is lacking.

Ab initio modeling of thermochemistry in the gas phase has been advanced to chemical accuracy for small and medium size molecules. Semiempirical methods[123] for estimating thermochemistry (e.g., group additivity) and activation energies (e.g., via the Bronsted-Evan-Polanyi relations) in multiphase systems have been introduced, but their practical implementation is severely limited. These methods have seen tremendous success for homogeneous (gas and liquid) systems. This is partly due to the lack of thermochemistry databases with enormous data sets needed to describe catalyst composition, structure, and promoters. Solvents change the adsorption of reactants, products, and intermediates to varying degrees, and solvents influence the stability of transition states and surface intermediates, complicating the method development.

Subcategory: Reaction Mechanism Development for Large and Complex Reaction Systems. Several new feedstocks have recently emerged for sustainability, including multiple biomass process chemistries, plastic waste, small alkane dehydrogenation to replace naphtha cracking, and electrochemical transformations to reduce CO_2, split H_2O, or fixate N_2. Reaction mechanisms for several biomass transformations have been developed but are limited to a single substrate without accounting for impurities and solvents. These models and knowledge are hard to transfer to other reactions and solvents. Fundamental models for propane dehydrogenation have been introduced but are still limited to single crystals (e.g., Pt, PtSn, and Ga/Al_2O_3[124]) and ideal microporous environments (e.g., Ga/H-MFI[125]). In contrast, real catalysts and feedstocks are much more complex. As a result, although computational work has provided insights, it cannot easily be translated into reactor design and catalyst prediction. In addition, given the abundance

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of solid feedstocks, developing mesoscale particle level models is key to further advance the field.[126]

Electrochemical mechanisms have been extensively exploited for several transformations, and the field has matured over the past decade.[124] Modeling of electrochemical interfaces and electrolyte effects, such as the dependence on pH, is still in the embryonic stage. Fundamental mechanisms and models for solid transformations, such as biomass, food and agricultural waste, plastics, coke formation, and sintering, remain rare.

Advanced discrete-lumped models successfully developed to handle the compositional feedstock complexity in refineries have not been transferred to emerging feedstocks, e.g., bio-oil and plastics recycling and upcycling. Experiment- or data-based mechanism development has been based mainly on batch reactor data. Spatial and temporal temperature gradients during heat-up make extracting fast kinetics inaccurate.

Across all application domains, a few tools have been built for automated, rule-based mechanism generation for heterogeneous catalysis.[127] The rules were based on intuition and logic. First-principles-based rules, learned by machine learning and experimental data, have still not been extended to heterogeneous catalytic reactors beyond work on the retrosynthesis of organic molecules.[128]

Sub-Category: Machine Learning and Automation. Steady-state kinetic experiments are common in academic laboratories. Yet, high-throughput kinetic experimentation with laboratory automation has not been implemented uniformly across academia and is only now emerging.[129] Transient kinetics, using techniques such as the temporal analysis of products (TAP) and the Steady-State Isotopic Transient Kinetic Analysis (SSITKA), have been advanced but remain singular expertise.[130] Machine learning techniques for the design of experiments, the discovery of descriptors, and improving the accuracy of models are becoming popular.[131,132] Still, their use for catalyst discovery and reactor design is not routine yet. The widespread application of these tools is aided by easier access to many open-source libraries of machine learning tools, the vast improvements to the machine learning API (Application Programming Interface), and the high expectations of the community. Their impact on modeling complex chemistry and learning reaction mechanisms has been limited but is expected to grow rapidly.

Integration of process modeling and surface chemistry MKMs remains accessible by a few experts,[133] and widespread adoption in academia is lacking. Process models still rely on empirical, experimental, data-driven kinetics or very simplistic stoichiometric rate laws. Tools such as Aspen Plus have not evolved enough to include complex reactors and complex chemistry. Machine learning surrogate models for integration into Aspen Plus are emerging.

Predicting new materials has advanced over the past twenty years; however, very few new catalysts have been predicted. Most of the advancements revolve around improvements to existing catalysts via alloying or bifunctional activity. The Sabatier volcano concept has dominated model development at this frontier, and predictions are typically based on a single binding energy (and occasionally two). The use of machine learning to advance catalyst discovery is an upcoming avenue with increasing prospects.

Databases of thermochemistry, kinetics, solvent effects, support, and catalyst effects that are critical for chemical mechanism development are not publicly available.[134] Tools to harness literature are lacking,[134,135] but availability of information has increased profoundly and is expected to increase further with automation and high-throughput experiments and calculations. Machine learning and natural language processing have tremendous potential to automate parsing and sorting of the exponentially growing scientific literature, organize the data, and make it accessible.

Barriers. The computational cost of DFT remains high for more complex models to the point of being intractable. The accuracy of DFT is still not well-understood for solid catalysts and complex reaction media. The materials gap remains one of the biggest roadblocks to extrapolating ab initio models for describing real experimental systems. Most models suffer from a lack of key physics such as particle size and shape, promoters, support effects, and heterogeneity of active sites. Only after careful consideration and validation of the assumptions made within ab initio simulations can they meaningfully describe realistic systems. This is a significant barrier preventing the extensive adoption of these methods in industry. The integration of spectroscopic methods with experimental kinetics and simulation is happening but difficult, and much trial-and-error is required to close the experimental-modeling gap. The workforce lacks this troubleshooting ability. Kinetic models lack the ability to describe the dynamics of catalysts, such as reconstruction and sintering, which can severely impact surface chemistry. Software tools that integrate fundamental models and macroscale process models are still lacking, and documentation of software is inadequate, making self-learning hard. The same applies for AI tools for automating experimental and computational workflows. New fundamental concepts for dynamic catalysis, multifunctional materials, and tandem reactions of multifunctional catalysts and blends are lacking. Multiphase effects stemming from solvents and a melt phase, as in the depolymerization of plastics, are hard to include. Fundamental ab initio models describing new key reactors involving electrode−solvent interfaces and plasma−catalyst interfaces are still lacking. Macromolecule chemistry is too complex to simulate using fundamental techniques.

Research Needs. Given these barriers and the current situation, we recommend several research directions. The most important one is to go beyond simplistic models and handle the complexity of real feedstocks and reactors as well as multiphase and multiscale physics arising from solvents, melts, and solids. This complexity vs the current model simplicity limits us to providing insights with only occasional predictions. The integration of (a) much bigger data sets (computational and experimental), (b) physical models (e.g., group additivity concepts but advanced by machine learning where we learn graphs and other descriptors to achieve chemical accuracy), (c) expert knowledge, and finally (d) AI provides an unmatched opportunity to develop hybrid models in a much shorter time with much improved accuracy and better extrapolation capability than AI-only models.

The second direction we recommend is to develop models for electrification and decarbonization of chemical reactors to advance the science and enable successful scale-up. Specifically, the interactions of electric and magnetic fields, electrolytes, and plasmas with catalysts can alter the materials, and conversely, the materials could strongly affect the field around them. Since some of the heating mechanisms do not follow conventional heat transfer principles, engineers must understand and predict the temperature field, the field-induced chemistry, and field-material interactions accurately. Similarly, scientists must capture the catalyst dynamics, how chemistry impacts the catalyst, and how

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the catalyst structure and dynamics affect the chemistry. We also recommend significantly expanding the mechanisms and models for catalyst deactivation and approaches to prevent it. The above hybrid model approach should be suitable here, as well.

Many advances are needed on the computational side. Those analyzing data must quantify errors and reduce them or improve the accuracy of ab initio methods and resulting MKMs, going beyond mean-field MKMs whenever needed. We must improve computational speed and develop methods to bridge length and time scales to simulate realistic systems and enable optimization. Process electrification may require new reactor designs and catalyst formulations; hybrid models can enable innovative designs and optimization. Developing user-friendly software tools with documentation, tutorials, and case studies for integration into software and automation of workflows will assist newcomers to the field. Finally, training the workforce in emerging tools and hybrid models and integrating experiments and models is crucial to succeed in the energy and chemical industry transition.

Catalysis

Summary. Catalysis research over the next several decades will focus increasingly on (a) the use of nontraditional chemical feedstocks such as waste, biomass, shale gas, end-of-life plastics, and CO_2, (b) the development of green and sustainable catalytic paths to establish carbon-neutral processes, such as the use of organic carrier molecules for hydrogen storage and production, (c) the electrification of chemical conversion and production processes, and (d) the establishment of alternative reactor energy inputs, including plasma, microwave, light, ultrasound, and Joule (resistive) heating. The past few decades have witnessed significant advances in the development of in situ methods to determine the catalyst structure. Further developments in spectroscopic methods and advanced characterization tools that can provide detailed atomic structure and track surface intermediates that form under reaction conditions with respect to time are needed to provide more detailed insights into reaction mechanisms, identify deactivation paths, and enable strategies to increase catalytic activity, selectivity, and durability. The close integration of these characterization and spectroscopic tools with kinetic analyses and computational methods will enable advances in understanding the sites and mechanisms that control different catalytic transformations. Key research priorities include the use of theory and experiment to develop structure−property relationships and determine the reaction and process conditions under which these catalysts could be operated. The development of AI/ML (artificial intelligence and machine learning) methods will help extend structure−property relationships and aid in identifying improved catalytic materials. Exploiting emerging research thrusts, such as dynamic catalysis and the influence of the local catalytic environments, will require significant improvements in the spatiotemporal resolution of characterization techniques. In situ and operando techniques will increasingly need to be applied under conditions of relevance to commercial operation, especially for reactions carried out at high pressures and with higher reactant conversions. Computational methods have advanced significantly and provide insights into the kinetics and mechanisms for homogeneous and well-defined heterogeneous catalytic systems. Further advances are required to model more complex, realistic heterogeneous environments. Many of the computational tools used in predicting catalytic performance remain usable only to specialists focused on computational aspects and not experimentalists. Coupling microkinetic models that capture chemical behavior with heat and mass transfer models that describe quantitatively physical processes at the reactor scale or even merely with empirical models often used in reactor sizing would advance the utility of microkinetic tools in facilitating commercial applications. Experimental high-throughput screening methods are being used by industry to accelerate catalyst discovery, but the scaling up of reactors employing these new catalysts remains a major bottleneck in deployment of novel catalyst technology. Lastly, the development and implementation of best practices for the measurement and reporting of catalytic data can help with reproducing catalyst performance data advertised to be exceeding the state of the art.

Situational Analysis. Feedstock substitution has driven catalyst research in bulk and specialty chemicals for decades. One of the first major feedstock substitutions involved the exchange of ethylene and other olefins for acetylene. A second change that has been a major focus over the past 25 years has involved the development of alkane activation processes including the conversion of ethane to ethylene, propane to acrylonitrile and acrylic acid,[136] butane to maleic anhydride, and iso-butane or ethylene to methyl methacrylate and methacrylic acid[137] and catalysts to drive these processes actively and selectively. While catalytic dehydrogenation at the mega-scale is an alternative to reduce cost, it comes with uncertainty in scale-up and requires enormous capital investment and risk.[138] Global emissions and climate change have driven the focus on the development of sustainable options to produce the current portfolio of fuels, chemicals, and polymers. Industry has increasingly explored the possibility of using wastes such as cellulose, saccharides, lignin, and fats and oils as primary feedstocks. As the alkane-alkene substitution has been a slow and only moderately successful process, we expect that the commercialization of new biobased processes will be even slower.

Greater than 7 billion tons of plastic waste together with the exponential increases in plastic production over the next century have focused the demand for catalytic processes that can efficiently convert plastic wastes back into chemicals and fuels.[139] In addition to the mounting plastic waste, we face other environmentally harmful pollutants such as NO_x and wastes such as pharmaceuticals in the water supply.[140] Clean water has become an important concern, and significant efforts have been made toward catalytic water purification paths. Catalysis, photocatalysis, and process intensification with alternative energy sources must be scaled up and implemented widely to mitigate any deleterious effects and to assuage the anxiety of the general population.

While cost is a major constraint in developing alternative processes, two other major contributors are catalyst deactivation and selectivity. Biomass and waste feedstocks are potentially less expensive, but transportation adds costs, particularly for low-density solids. Furthermore, impurities in plastics and other wastes limit their treatment options because of catalyst poisoning.

In addition to solid and liquid wastes, anthropogenic atmospheric CO_2 is considered by some to be the next source of carbon to serve as a feedstock to the chemical industry.[141] Heterogeneous as well as electrocatalytic routes can aid in the reduction of CO_2 to CO, methanol, and ethylene products and their subsequent conversion to chemicals and monomers, albeit at the great expense of energy. Accelerating this chemistry will require a better understanding of the complex interactions of the

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Carbon-Neutral Processes	• Hydrogen production • Hydrogen storage processes • CO_2 removal - selective catalytic reduction • Oxidation of water and alcohols • Solid oxide fuel cells and electrolysis cells • Polymer electrolyte membrane fuel cells
Energy Conversion	• Selective conversion of C1-C3 light alkanes to fuels and chemicals • Biomass conversion
Polymer Upcycling and Coprocessing	• Catalysts and processes for low temperature and selective activation of C-C and C-X activation to form monomers • Catalysts that eliminate CO_2 production in C-C activation • Catalysts to convert mixed plastic waste as well as blended polymer and naphtha streams to valuable liquids and chemical intermediates • Removal of heteroatoms from mixed plastic waste • Catalysts and processes resistant to catalyst deactivation that enable coprocessing and conversion of mixed polymer feedstocks
Environmental Remediation	• Selective NO_x removal • H_2O_2 synthesis
Electrification	• Robust, durable electrocatalysts and electrocatalytic processes • Catalytic mediators to facilitate electrochemical transformations • Capital-efficient electrochemical unit operations for large volume applications
Novel Processing Approaches	• Dynamic cycling • Plasma processing • Photocatalysis
Biocatalysts, Enzymes, Biomimetic Catalysts, and Mixed (Homo, Hetero, and Bio) Catalytic Processes	• Improved selectivity and activity along with control of chirality • Novel synthetic approaches to control specific bond making and breaking reactions • Expanded efforts on catalysts and catalyst design for sustainability
Pharmaceutical and Specialty Chemical Syntheses	• Stereo-selective catalysts • Highly selective catalysts in the presence of substrates with many functional groups
Pharmaceutical and Specialty Chemical Production	• Catalysts that can operate in flow systems • Catalysts that maintain activity and selectivity in the presence of solvents, proton sources, electrolytes, etc. • Electrocatalytic processing
Catalyst Durability and Selectivity with Complex Feedstock Mixtures	• Resistance to poisoning, coking, and sintering • Resistance to feedstock impurities • Stability under harsh conditions of higher temperatures and pressures

Figure 4. Key chemistry research needs for catalysis.

reactants with adsorbed intermediates, promotors, solvents, microporous environments, electrolytes, and the local environments. Achieving this goal will require continued advances in experimental characterization, kinetic analyses, and computational strategies to better characterize the local reaction environment and its role in enhancing catalytic activity and selectivity. AI and ML methods will reduce the computational costs to analyze these systems but will also be applied to identify reaction conditions and process operation to optimize catalyst performance and link catalyst properties with performance.

Barriers. Collaboration between academia and industry together with limited access to the latest analytical advances (operando, spectroscopic, and high-throughput testing) have been and will continue to be barriers in catalysis. Unlike high-energy physics, most catalyst laboratories work in silos, and catalytic performance is rarely substantiated in independent

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laboratories or even within the same research organization. Catalyst companies patent sparsely and publish less on catalyst synthesis techniques, as they prefer to keep the information as a trade secret. Furthermore, they often resist sharing samples with universities because of a lack of confidence in the utility or their limited resources to follow university programs.

The complexity in catalyst synthesis and the challenges associated with the control of catalyst variables limit many companies to simply testing commercially available catalysts rather than developing their own. Catalyst testing often creates significant hurdles toward catalyst development, as it requires detailed accounting of reactor geometry, crushing and sieving, temperature (position), pressure, feed rates, feed composition, residence time, stability over time, cycles (for the cases of batch operation and materials in continuous processes with frequent periodic regeneration, such as in propane dehydrogenation), and analytical techniques to measure composition. Cyclic operation entailing material reduction and oxidation or catalyst deactivation and regeneration imposes several challenges for materials stability and scale-up from the laboratory to industrial scale. Transient kinetic models that capture oxidation−reduction−deactivation dynamics could significantly aid the further optimization of processes requiring periodic regeneration.

Finally, while computational chemistry, microkinetic modeling, and computational fluid dynamics are tackling ever more complex chemistry, catalyst compositions, and reactor hydrodynamics, the increasing level of complexity in these simulations significantly increases the computational costs. As such, these efforts often restrict the application of these methods to engineers dedicated to modeling rather than as a simple tool to help guide the research effort.

Research Needs. We divide the research needs for catalysis into four categories: I. Chemistry: Development of Catalysts and Catalytic Processes, II. Experimental Tools, III. Process Methods, and IV. Modeling Tools.

I. Chemistry − Development of Catalysts and Catalytic Processes. Like the "Catalysis" section in the Vision 2020 report, the full list of "chemistry research needs" is summarized in Figure 4. Some additional details are elaborated below for a few areas in the figure. For other areas, we refer the readers to the corresponding other sections of this paper.

Society requires industry to seek carbon-neutral processes to minimize anthropogenic emissions to the atmosphere.[142] Lignocellulosic waste, end-of-life polymers, and atmospheric CO_2 are carbon neutral sources that could serve as primary feedstocks for basic chemicals. Pyrolysis of the first two components produces an oil that requires further catalytic processing. Gasification produces low-quality syngas and methane that require additional hydrogen to serve as a feedstock to produce methanol, dimethyl ether (then gasoline), Fischer−Tropsch (FTS) hydrocarbons, and ammonia. All of these processes require hydrogen. For many prognosticators, the hydrogen economy is the promise of the future.

We discuss hydrogen production by water electrolysis in the section "Electrochemical Systems." Other options for hydrogen production include the following:

(a) Reverse water gas shift (RWGS): RWGS converts carbon dioxide and hydrogen to carbon monoxide and water and can be catalyzed by Fe. In the case of reacting anthropogenic CO_2, the RWGS reaction requires a source of hydrogen to reform the CO_2 to CO. Catalytic membrane reactors are one option to selectively remove water or CO and thereby drive the equilibrium reaction to produce more CO.

(b) Natural gas and low carbon feedstock pyrolysis: The conversion of natural gas and low carbon feedstocks to H_2 and carbon, yielding carbon materials of high quality, such as carbon nanotubes, offers potential for improved process economics relative to low-value carbon byproducts.

(c) Dry reforming: Another potential hydrogen source involves conversion of methane and other light hydrocarbons with carbon dioxide to syngas.

Adopting hydrogen as a primary energy vector requires a safe means to transport and store it at large scales.[142] Options include ammonia, methanol, liquid organics, and solid hydrides as hydrogen carriers, as described next:

(a) Ammonia as a vector is an obvious choice as it can store up to 0.176 g/g of hydrogen. Ammonia is stable at ambient conditions and produced at enormous scales but consumes 3−5% of the methane produced globally. Electrolysis with ionic liquids (phosphonium salts) has the potential to produce green distributed ammonia.[143] The conversion of ammonia to H_2 requires a highly endothermic, slow cracking step followed by purification of H_2 from ammonia and possibly from N_2, depending on the application.

(b) Methanol synthesis: Methanol can store 0.126 g/g of hydrogen and is safer and easier to transport than ammonia. Potential sustainable feedstocks for methanol include biomass. Carbon deposition, sulfur poisoning, and sintering deactivate Cu-based catalysts. Research on new catalysts is imperative to achieve high activity and stability.[144]

(c) Liquid organic hydrogen carriers (LOHCs): This includes aromatic-saturated systems such as toluene − methyl cyclohexane and dibenzyltoluene − perhydro dibenzyltoluene; in addition, N-heterocycles have shown considerable promise.[145] For example, toluene releases hydrogen when it dehydrogenates to methylcyclohexane and has a storage capacity of 0.061 g/g.[141,146] This closed cycle minimizes CO_2 release compared to ammonia and methanol depending on the hydrogen source. Precious metals catalyze the methyl cyclohexane dehydrogenation, and, since the reaction is endothermic, high temperatures are necessary. Less expensive transition-metal catalysts including bulk oxides and perovskites could improve the economics of the process. Liquid carriers offer tremendous advantages for long-range distribution. However, because essentially all liquid hydrogen carrier conversions are endothermic, the operating window is limited, and the catalyst composition is constrained by the thermal requirements of the process. Catalysts that can incorporate novel strategies for supplying this thermal energy discontinuously (including locally available renewable electricity) in response to the expected intermittent demand for hydrogen will also be critical.

(d) Solid hydride carriers: Three types of solid hydrides have been tested: elemental metals (MgH_2, AlH_3), intermetallic hydrides ($A_xB_yH_z$), and complex metal hydrides (alanates − $NaAlH_4$). Intermetallic hydrides and MgH_2 have a lower enthalpy of dehydrogenation compared to other hydrides and, thus, dehydrogenate at lower

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temperature and require less energy. In any event, heat transfer limitations remain a challenge at the industrial scale.

With the global drive for decarbonization, some people are seeking to convert carbon dioxide to useful materials. One route for CO_2 utilization is gas-phase hydrogenation for methanol production: Carbon Recycling International built a 4 t/day plant in which Cu/Zn catalyzed the hydrogenation of CO_2 to methanol. Industrial scale plants require a more active, stable, and selective catalyst. Zeolites and ordered mesoporous silica-based catalysts are potential candidates for which their hydrophobic/hydrophilic, acid/base, and redox properties can be modified to improve performance.[147] Other direct routes for the conversion of CO_2 to ethylene, aviation fuels, and other products are also being examined. However, a challenge for all CO_2 utilization reactions is the thermodynamic barrier and the resulting high energy cost per unit of CO_2 mitigated. We address electrocatalytic reduction of CO_2 in the section "Electrochemical Systems."

The second major category in Figure 4, energy conversion, offers many opportunities for the reaction engineering of catalytic systems. Natural gas, shale gas, biomass, waste, end-of-life polymers, and other alternative feedstock conversions will be needed to help meet future energy demands.

Activating the C-C paraffin bond in light alkanes to selectively produce fuels and chemicals has been an objective for the basic and specialty chemical industries for decades. n-Butane is one example of a successful substitution. The cost of propane is half that of propylene and remains a potential feedstock for acrylonitrile, acrylic acid, and propylene oxide. However, selectivities are low, so achieving shutdown economics (30% lower investment, 30% lower operating costs) with new process configurations has been out of reach. Adapting commercial fixed bed reactors that are already in place is untenable because the heat of reaction with propane is higher and the selectivities are lower, which translates to a loss in productivity given the same temperature profile. Process intensification promises to improve heat management, but catalysts also need to improve.

Biomass is another feedstock option. Hydrogenolysis, which enables the selective activation of C-C bonds along with the elimination of water, can be carried out over metal catalysts that can activate C-OH bonds and carry out the subsequent hydrogenation reactions or by bifunctional acid and metal catalysts that perform dehydration and hydrogenation, respectively. Ethanol from biomass is produced at an enormous scale, but overall yield is low due to the inherently inefficient fermentation process. Furthermore, the energy density is much lower than gasoline, diesel, and jet fuel. 2,5-Dimethyl furan produced from lignocellulosic glucose and fructose has a 40% higher energy density versus ethanol and a research octane number of 119. Process questions to be addressed include developing a one-pot reactor (rather than a two-phase system) and a high-yield catalyst that is simple to produce. Biomass is an unlikely substitute for petroleum fuels because of its limited availability: an order of magnitude more biomass would be required to replace petroleum.[148]

Polymer upcycling and coprocessing such as electrification conversions are discussed in the "Polymer" and "Electrochemical Systems" sections.

II. Experimental Tools. In situ and operando characterization of catalysts under more realistic reaction conditions on commercial catalyst formulations remains one of the most urgent needs from the standpoint of advancing catalysis research. In terms of a molecular-level understanding of catalytic phenomena, the spatiotemporal resolution of characterization techniques must be advanced significantly. An understanding of the density, composition, and structure of active sites and how active site properties vary with time on stream is critical to improving reactor performance and rationally designing improved catalysts. Recent trends in catalysis research emphasizing the importance of coordination environments beyond the binding site[149,150] exact even greater demands on catalyst characterization and seem to require tomographic characterization at unprecedentedly small length scales. Active site nuclearity may evolve at sub-turnover timescales, requiring high time resolution and a combination of theory and experiment to fully elucidate active site identity.[151] The rapid emergence and growth of dynamic catalysis as a subfield amplifies this need for catalyst characterization at ever shorter timescales.[152] Most in situ/operando characterization tools also tend to provide physicochemical information that is averaged over the entire distribution of sites, and tools that can enable deciphering of the distribution in site speciation are urgently needed. The more broadscale use of theory-guided workflows to analyze complex X-ray absorption spectroscopy data represents just such an example of obtaining more detailed characterization than would otherwise be possible[153,154] merely through experimentation alone. These workflows are agnostic to the identity of the active metal and support used and, hence, can be extended to other supported metal catalyst systems of industrial relevance.

A second important need is to extend the application of these in situ and operando characterization tools to (a) catalyst formulations employed in industry and (b) harsh conditions often encountered in commercial processes. For example, scanning transmission X-ray microscopy (STXM) measurements are increasingly being used to map metal distribution under FCC (Fluid Catalytic Cracking) conditions, allowing for insights to be gained into heterogeneities in dealumination processes occurring in multicomponent catalysts containing binders.[155] Extending these types of in situ characterization studies to other commercial processes could lead to novel strategies for extending the catalyst lifetime. In this context, we envision that the use of techniques such as X-ray photoelectron spectroscopy (XPS) at conditions close to those encountered during catalytic reactions will find increasing use in the catalysis and reaction engineering community.[156,157] In summary, the spatiotemporal resolution of characterization techniques will need to be advanced to keep pace with advancements in concepts in dynamic catalysis and elucidating catalytic sites and their environments, both of which are gaining widespread traction in the catalysis and reaction engineering research community. The characterization of active sites and reaction intermediates in the liquid phase remains especially challenging, and the discovery of electrocatalysts for key oxidation and reduction reactions will rely on the advancement of techniques that can be applied efficaciously in the liquid phase.

A third need as regards experimental tools relates to the spatial resolution of concentrations (and hence rates). Most kinetic studies published in the literature report data only at low conversions; in cases where high conversion data are reported, concentrations are typically reported only at the reactor outlet. This approach can lead to the development of kinetic models that have limited fidelity owing to the limitation of being tested against only a limited amount of data. Spatially resolved concentration data measured under integral conditions can help

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more rigorously test proposed kinetic models and aid in identifying and isolating features that appear upon the depletion of certain reactant species. We envision that spatially resolved measurements using both mass spectrometry[158] and gas chromatography[159] that are now available will find increasing use over the next few decades. We note that operando characterization techniques such as high-energy X-ray diffraction can now be employed in a spatially resolved fashion,[160] opening new avenues into the investigation of catalyst properties at high conversions that may be more representative of industrial conditions. We surmise that the increasing availability and decreasing cost of spatially resolved techniques will help make them more common in the evaluation and design of heterogeneous catalysts.

III. Processing Methods. High-throughput screening remains somewhat of a niche processing method to identify optimal catalyst compositions. Banks of shaker tubes have been around for liquid−solid systems for decades, and commercial systems with dozens of parallel microreactors are available for gas−solid systems.[161] These screening approaches accelerate catalyst discovery by 2 orders of magnitude. However, the impediment to successfully commercializing new chemistry and processes remains designing and scaling up reactors that meet the financial objectives.

Microreactors quantify reaction rates based on feedstock composition, pressure, and temperature and even assess catalyst stability. However, scaling up catalyst manufacturing and reactor vessels introduces unknown and unsubstantiated factors that impact selectivity, conversion, and stability. Monitoring each step during commercial catalyst synthesis requires a close collaboration between the plant and laboratory but would necessarily increase the cost if each step were to be analyzed systematically as for catalyst screening.

Achieving hydrodynamic similarity between lab-scale catalyst screening and commercial-scale manufacturing reduces uncertainty in the expected catalyst performance. Hydrodynamic similarity in the process is possible for simple reactor configurations like packed beds and multitubular fixed bed reactors. As feedstocks become more heterogeneous, reactor configurations will adapt to include multiple feed injections, dynamic cycling of catalyst and feeds, and alternative energy sources: plasma, microwave, ultrasound, induction, or electrical heating. Matching hydrodynamic similarity will remain the overriding objective in scaling up a first-of-a-kind reactor. To explain any deviation between actual commercial yield and expectation requires multiple catalyst sampling locations to diagnose and quantify the differences.

High-throughput screening would accelerate identifying optimal catalyst compositions for electrochemical systems, membrane reactors, gas−liquid−solid reactors, and ionic liquids, but investing the time to build is a major deterrent. Neural network analyses could also expedite optimizing the catalyst composition but only when combined with high-throughput testing. Neural nets applied to pilot plants and commercial plants would help identify the optimal process conditions to maximize selectivity (or revenues) and minimize deactivation. However, convincing plant management to explore a wide range of conditions is always challenging, as their first responsibility is to produce safely and meet the financial targets. First-of-a-kind plants measure pressure, temperature, and composition in dozens of regions in the plant, which are ideal to develop a data set to combine with modeling tools (like Artificial Neural Networks, ANNs) to analyze catalyst performance to optimize the reactor and process conditions. Because the data are collected at a frequency of 1 Hz or better, data collected while starting up or shutting down would be ideal to train the ANN models.

IV. Modeling Tools. Many of the research needs for modeling catalytic processes were described in some detail in the earlier section on "Chemical Mechanism Development and Property Estimation." We recommend the following research directions for modeling catalytic systems:

(1) ab initio methods and models that can more rigorously treat the active sites and more complex local environments, which include the catalyst−support interactions, complex microporous and mesoporous environments, solvent effects, promoters, and electrolyte;
(2) modeling tools that can simulate the detailed intrinsic catalytic kinetics and mass and heat transfer effects as well as elucidate and optimize the catalyst, solvent, and reaction conditions;
(3) more detailed integration of detailed microscopic kinetic models with CFD (computational fluid dynamics) simulations to simulate reactor performance;
(4) models that can simulate and optimize the catalyst together with the reactor;
(5) integration of modeling and experimental data for AI and ML efforts; and
(6) development of models that follow catalyst performance together with catalyst deactivation and life.

Nonstandard Reactor Types

Summary. Since 2000, development of nonstandard reactor types has flourished with the continuing development of thermally coupled reactors,[162] unsteady-state processing,[163−166] membrane reactors,[167−169] and microreactors. The growth of process intensification as a dedicated field in chemical engineering over the past two decades[170] has driven the development of nonstandard reactor designs that support waste and risk minimization, modularity, process flexibility, and sustainability.

Situational Analysis. Microreactors and membrane reactors have emerged as potential means of process intensification via thermal or mass-integration of multiple reaction and separation processes.[171,172] In addition to providing greater efficiencies and waste reduction, these compact designs offer modular chemical processing.[173,174] First described by Stankiewicz and Moulijn,[175] sufficient reduction in component size with accompanying rate enhancements could transform the chemical industry by replacing the traditional sprawling chemical plant with a compact, modular production facility with minimal environmental impact. Likewise, autonomous modular chemical processes would enable the on-site utilization or upgrading of otherwise "stranded" or distributed resources.[176]

Process safety has emerged as a significant driving force for process intensification. One of the three key methods of process hazard reduction is to reduce the reactor volume and thus the potential energy release from reactor failure. One of the first microreactor studies under the DuPont-MIT alliance aimed to provide on-demand production of hazardous reactive intermediates;[177] since then, microreactors, minireactors, and flow reactors have been developed for on-demand production of reactive intermediates, parallelization of hazardous chemistries, and reduction in reaction volume by providing continuous alternatives to conventional batchwise processing.[178]

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Most recently, efforts to develop distributed, modular chemical processing have driven interest in electrification of[179] the chemical industry to enable decarbonization. Chemical reactors typically require operating ranges from 100 to 1000 °C, traditionally achieved either directly or indirectly (via additional steam utility infrastructure or furnaces) through combustion of fuels.[179] As of 2018, natural gas accounted for approximately 60% of the fuels used for process heat in the United States. Electricity accounted for just 13%.[180] This not only limits the modularity but results in significant greenhouse gas (GHG) emissions, estimated at 6% of global GHG emissions.[180,181] Electrical heating of chemical reactors (termed "power-to-chemicals") promises to drive chemical processes from renewable and distributed electrical resources. Current efforts have been aimed at direct resistive electrical heating or indirect heating via application of microwave and radio frequency electrical fields.

Barriers. *Membrane Reactors.* Multiple barriers remain to realizing industrially practical membrane reactors, including (i) thermal or chemical compatibility of the membrane with reaction chemistry and conditions, (ii) membrane material costs and manufacturability, and (iii) sufficient permselectivity and permeability to enjoy the advantages of a membrane reactor. All of these barriers present materials science and processing challenges. While a wealth of polymer-based membranes exists, many of which can exceed the traditional "Robeson Upper Boundary" in terms of flux and selectivity, they are, at best, limited to operating temperatures below 200 °C; additionally, the high costs associated with either the materials themselves or their manufacturability to form practical hollow fibers limit all but a few from industrial application. While inorganic membranes can operate at 200−500 °C (for palladium-based metal membranes) or 400−1000 °C (for solid-oxide ceramics-based membranes) with very high permselectivities, they suffer from chemical incompatibility with reaction chemistries[182] and materials and manufacturing costs. Regardless of the membrane material selected, the membrane reactor design is only advantageous when permeation rates are at least comparable to those of the catalytic reaction; this poses a significant requirement on achievable membrane permeability to make the membrane reactor design competitive with a traditional two-step reactor-separator process.

Micro- and Mesoscale Reactors. Micro- and mesoscale reactor designs have focused on identifying a universal architecture that can be affordably mass-produced and scaled-out to fit multiple continuous processes (e.g., Ehrfeld Mikrotechnik) to make them economically competitive with traditional reactors. However, most recent successful implementations of mesoscale reactors have been limited to fine chemicals and pharmaceuticals manufacture, where a traditional large-scale batchwise process is replaced with a mesoscale continuous process, with the primary advantage of reducing both the physical and hazard footprint of the process.[183] These mesoscale reactors are primarily custom-built, as opposed to standardized designs originally envisioned for broadly enabling micro- and minireactors across the chemical industry. Additionally, their implementation requires the development of compatible units for integrated plants.

Additional barriers for implementation of micro- and mesoscale reactors include the following: an increased number of potential points of mechanical failure (such as leaks) compared to simpler traditional reactors, a greater sensitivity to fouling because of the smaller characteristic dimensions, a greater level of instrumentation and automation required for numbered-up systems (many parallel units), a greater level of rigor required for the hydrodynamic distribution of feed materials across the parallel units, and higher costs for replacing deactivated heterogeneous catalysts.

Joule (Resistive), Plasma, and Microwave Reactors. Nonstandard reactors that rely on electrical power sources are gaining momentum, though they are limited by a different set of engineering challenges. Resistive heating in lieu of the combustion of fossil fuels, potentially a low-hanging fruit, is an attractive route to decarbonization. Retrofitting existing production-scale unit operations is plausible, especially for applications below 150 °C, which represent 60% of process heat from chemical manufacturing overall and more than 50% of the process heat needed for the ethanol, inorganic, and basic organic categories. Future capabilities to achieve electrically heated temperatures up to 300 °C would also enable electrification of an additional 15% of process heat from chemical manufacturing.[180] Laboratory-scale plasma and microwave reactors have also received attention in recent years for both catalytic and noncatalytic reactions. However, the current infrastructure lacks enough renewable electricity available to drive these reactors at manufacturing scales and where chemicals are produced geographically today. Chemical process safety of high-power electrical hazards that also represent ignition sources demands an interdisciplinary approach to conventional reactor design. Variable renewable electricity is another barrier with these reactors, as chemical processes most ideally run at steady-state and cannot simply be turned on and off like a light switch. The question of whether to disconnect from the grid will likely play a critical role in how they are designed to operate, as will the economics of electricity usage and the capital costs of designing these nonstandard reactors at production scales.[184,185]

Structured Reactors for Process Intensification. Structured reactors, although already in practice, are limited in industrial applications such as electrification. Modular, scalable, and structured electrochemical reactors with sufficient electrode contact area continue to limit their implementation in industry processes. Likewise, the electrode stability/lifetime, electrolyte design, and electrical safety considerations remain barriers.[184,185] Large-scale heating coils for electrical heating that are also structured, flexible, and modular are lacking, as well as structured catalyst designed in beds that are easily rechargeable and with the desired heat transfer characteristics.[184,185] Other types of emerging structured reactors that have already shown potential for industrial implementation include vortex reactors for natural gas conversion,[186] cyclones for geometric heating efficiency,[187] and nature-inspired structured chemical reactors, such as redesigned conventional reactors (for example, fluidized beds based on biomimicking nature[188]).

Research Needs. Catalytic micro- and mesoscale reactors remain hindered by the ability to regenerate or replace spent or deactivated catalyst; the latter is exacerbated by the fact that the catalyst is typically washcoated, not packed, into individual channels. This is an economically infeasible situation, since catalyst replacement implies that the entire reactor must be replaced. Developing methods for easy catalyst replacement is essential. Microfixed beds are one such possibility.

The manufacturing costs associated with modular micro- and mesoscale reactor designs continues to limit implementation in high-volume and low-margin industries, despite significant improvements in manufacturability of metal microchannel designs.[189] In the cases of low-volume, high-margin industries

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(such as pharmaceuticals and fine chemicals), mesoscale flow reactors (homogeneous catalytic or noncatalytic) have seen recent success;[190] however, there remain significant challenges for multiphase reactors and reactions with solids handling.[191]

Additive manufacturing, also known as three-dimensional (3D) printing, can standardize the environment and assist with modular reactors. However, grafting features over multiple length scales has yet to be accomplished. Furthermore, while 3D printing has advanced for some materials, such as polymers, hard and multifunctional materials that can accomplish heat transfer, mass transfer, separations, and chemical reactions are still missing by-and-large. Additionally, the cost of additive manufacturing is still a concern. The cost is expected to decrease with massive production.

The operating conditions influence the composition of plasma-generated species and their lifetime. Reactor configuration, including electrode design, feed ratios, mixing, phase behaviors, residence time, applied voltage, waveforms, pressure, and temperature, must be optimized for each chemical reaction, not to mention the added complexities of introducing a heterogeneous catalyst. For instance, catalytic surface reaction mechanisms are more complex than conventional thermal catalysis and still need a thorough investigation. The design of plasma reactors is truly a multivariate optimization problem best understood by computational experts who collaborate with experimentalists. Our current state of knowledge on the reaction kinetics and mechanisms is limited, primarily because only a handful of laboratory-scale reactors have been designed to quantitatively study plasma chemical reactions,[192−194] making it rather difficult to validate theoretical/computational models. There remains a basic need to integrate plasma reactors with existing and new spectroscopic techniques for deconvolution of the kinetics.[195−197]

Process intensification by structured reactors ultimately demands computational efforts in parallel with experimental designs to adequately evaluate their gradients and contacting patterns while numbering up. Additional research is needed on pressure losses, materials including electrodes and electrical heating components, rechargeable configurations when catalyst is needed, and the development of first-principles contacting pattern models.

In addition to the "nonstandard" reactor designs discussed above, we also see the potential to achieve significant process intensification via "nonstandard" or unsteady-state modes of operation. Unsteady-state processing has been studied since the 1990s[165,166,198] to improve overall heat- and mass-transfer rates in multiphase reactors,[199,200] burn low concentration organics by trapping the heat inside the reactor, and isolate and exploit hot-spots in catalytic processes[201] via switching feed flow rates and direction.[164,202] More recently, efforts have focused upon introducing oscillations in feed composition[203] to directly manipulate reaction chemistry with the goal of achieving significantly greater product yields than what can be achieved by traditional steady-state continuous processes or traditional batchwise processes. Electrification enables transient operation at high frequencies not exploited in the past and may enable enhanced performance unattainable by steady-state operation.[184,204]

Electrochemical Systems

Summary. Decreasing the use of fossil fuels and the shift to renewable energy make electrochemical reaction processes candidates to replace conventional thermochemical reaction processes. Many expect the cost of electric power to become competitive with that of fossil fuels. One proposed application of renewable electricity involves the production of hydrogen from water electrolysis, an intermediate step to other useful products from "Power to X" (P2X) systems. In the literature, power to gas (P2G) was the first P2X concept proposed, then power to liquids (P2L) or power to fuel (P2F), followed by power to chemicals (P2C).[205] In these systems, hydrogen would be converted to synthetic natural gas, liquid fuels, and chemicals by reaction with carbon dioxide and nitrogen.[206] Because of the downstream process conditions, process economics favor water electrolyzers that work at a high pressure to generate high-pressure hydrogen.

Hydrogen, which has a high energy density, can also be supplied directly to fuel cells. A significant reduction in the production cost of fuel cells and the recycling of electrolytes and metals are required for widespread adoption and sustainability. Beyond hydrogen production and fuel cells, electrochemical production of specialty and potentially basic chemicals is emerging.[207] Outstanding issues of designing electrolytes, devices, scaling out, and cost remain. Chemical reaction engineers can establish electrochemical reactor design and optimization methods and lead the development of novel electrocatalysts to achieve the drastic cost reductions required for economic viability. However, suitable workforce development is necessary.

Situational Analysis. *Hydrogen Production.* Due to decreasing fossil fuel reserves and the demand for CO_2 emission reduction, the shift from fossil fuel energy to renewable energy is continuously encouraged by governments and nongovernmental organizations. Batteries, chemical energy, and water pumping are, depending on the scale, practical for storing electric energy generated unsteadily from renewable energy sources for power supply leveling. For chemical energy storage, hydrogen, ammonia, methane, and some other chemicals have been considered, but hydrogen is the most popular. Already today, water electrolysis can efficiently convert power into hydrogen.[208,142] However, water electrolysis costs more than five times than hydrogen derived from steam methane reforming. Catalyst breakthroughs, government regulations, and government incentives are required to make electrolysis competitive.

Electrolysis at high pressure is the most efficient way to produce high-pressure hydrogen electrochemically, as less energy is required to pressurize liquid than to pressurize gas.[209] Unfortunately, oxygen produced simultaneously with hydrogen by the electrolysis of water is rarely used effectively. Some prefer routes that oxidize bioethanol or something else to produce valuable chemicals rather than oxidize water to oxygen.

Utilization of Hydrogen and Methanol. Fuel cells can convert hydrogen energy into electricity with a high efficiency. Solid oxide fuel cells (SOFCs) are preferable on a large scale, as SOFCs can work at high temperatures where waste heat can be utilized. Solid oxide fuel cells are made of layers of ceramics, constituting the anode, cathode, and electrolyte of the system. They operate from 500 to 1000 °C, and the challenge is to increase the system efficiency at lower temperatures with advanced materials to reach higher electrochemical activity. Polymer electrolyte membrane fuel cells (PEMFCs) are beneficial on a small scale, such as residential use, and for applications like vehicles that require frequent startup and shutdown, as PEMFCs can operate below 100 °C.[210]

Fuel cells are expensive; chemical reaction engineers can play an important role in optimizing their design and operating

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conditions. The high capital costs for fuel cells (and galvanic cells) are a consequence of those reactors being governed by surface reactions rather than volumetric reactions. Consequently, electrochemical cells are scaled as stacks of multiple identical cells, with the electrical connections usually in series, while the process fluid flows are parallel. Optimizing these stacks of tens to hundreds of parallel cells is a reaction engineering challenge as these systems perform best with uniform fluid flow and electrical current distributions. Heat management in these stacks is also a critical issue for larger scale processes, where the ambient losses that dominate laboratory systems are not sufficient to maintain the desired reaction temperature. While the coolant can be circulated between cells for heat transfer, the resulting current losses diminish the efficiency of the stack relative to an individual cell. Finally, electrocatalyst deactivation will require replacing cells on some basis, a cost that could dwarf the cost of replacing heterogeneous catalysts in thermochemical reactors because of the greater mechanical complexity of electrochemical systems.

As an example, direct methanol fuel cells (DMFCs) utilize Pt and Ru electrocatalysts to oxidize methanol and water to produce protons (H^+), electrons, and CO_2 at the anode. The protons that form travel across a Nafion membrane to the cathode, where they react with oxygen and electrons generated at the anode to form water. The energy output from PEM cells is higher than that for batteries. They are compact, are simple to build with low power loss, and facilitate immediate recharging. Barriers to commercialization of DMFCs include slow kinetics, methanol toxicity, durability, stability (susceptible to CO poisoning), heat management, water management, and cost. Supports, such as titania−carbon nanofibers, minimize the poisoning while enhancing activity. Replacing Pt with metal oxides could reduce costs while improving stability.[211]

Emerging applications for hydrogen use include the removal of heteroatoms from biomass and plastic waste and hydrogenolysis and hydrocracking of plastic waste.

Electrochemical Production of Chemicals. Some chemicals, including chlorine, adiponitrile, maltol, fenoprofen, and *m*-hydroxybenzyl alcohol, have been or are produced in electrochemical reactors.[212−214] If generated from fossil fuel, electric power is three times more costly than heat from fossil fuel combustion. This disadvantage of electrochemistry would disappear if the electric energy generated from renewable sources results in the lower electricity costs forecasted by some. Given more favorable electricity costs, oxidation of alcohol, Kolbe electrolysis of carboxylic acids, acylation, azidomethoxylation, and other electrochemical reactions are expected to become economically attractive.

The electroreduction of carbon dioxide, such as to CO, formic acid, ethylene, or ethanol,[215] is a very popular topic in current laboratory research. Although the synthesis of products from carbon dioxide requires a lot of energy (for example, about ten times as much energy is required to make ethylene from carbon dioxide rather than ethane), highly selective electrochemical reactions might offset a portion of the energy cost by reduction in the costs associated with separation. However, while many funding agencies are currently emphasizing development of CO_2 conversion processes, we expect implementation of these at a significant scale to be uneconomical and an inefficient usage of renewable electricity compared to other CO_2 mitigation alternatives.[29,30]

Catalyst development is the most important means of reducing the production cost of fuel cells. Further, the economic cost of some electrochemical processes is negatively affected by the cost of replacing electrolyte that is chemically degraded or lost during separations. Product separations can also adversely affect the electrochemical process economics. For batteries, such as lithium-ion batteries and redox flow batteries, the development of porous electrodes and electrolyte solutions or solid electrolytes is the most important. Materials synthesis process studies guided by chemical reaction engineers can contribute to these developments.

Barriers. Reaction engineers are gaining experience in electrochemical systems. Most reaction engineering work in electrochemistry occurred in and after 2000, including 97% of all academic papers studying fuel cells, 90% of all papers on electrolyzers, nearly 100% of all papers on lithium-ion batteries, and 92% of all papers describing electrochemical reaction processes.

The factors that govern the reaction rate of electrochemical reactions differ from those of ordinary chemical reactions. Unlike the thermochemical reaction rate, which is a function solely of temperature and concentrations, the electrochemical reaction rate also depends on the interfacial potential difference. The transport of ions, which are the reactants in electrochemical reactions, is mainly driven by potential gradients rather than concentration gradients. The interfacial potential difference and electrostatic drift are less familiar to chemical engineers.

A fuel cell is a complex system involving, in addition to electrochemical reactions, mass and energy transport by diffusion, advection, conduction in porous media, evaporation and condensation of water, multiphase flow, deformation of porous materials, sorption of water to polymers, chemical and mechanical degradation of polymers, and permeation of gases and electro-osmosis of water through polymer membranes. This complexity creates a high learning barrier. In addition, electrochemical processing faces a large initial investment in building new manufacturing and evaluation facilities.

Porous gas diffusion electrodes are required in hydrogen fuel cells because the reactant is gas. However, the most common electrolyte is a solution and the most common electrode is a metal plate. Theories that describe the performance of gas diffusion electrodes are not sufficient and would benefit from a systematic chemical reaction engineering approach. More generally, porous materials are often used in batteries and fuel cells. It takes a long time to measure many of the transport properties required for the design of these reactors.

Research Needs. The opportunities for reaction engineers in electrochemical systems are abundant. One area entails reaction engineering principles and methods to describe electrochemical reaction processes, including the interfacial potential difference and electrostatic drift and better processes for designing fuel cells. We expect measurement and database archival of the reaction rate constants and transport properties.

Processing landfill gas and biogas provides other opportunities for solid oxide fuel cells. Decomposition of the ceramics and accumulation of fuel impurities are also major obstacles.

In 2040, Japan hopes to reach a volumetric stack power density for PEMFCs of 9 kW/L, which is double the power density demonstrated as of 2023. Europe is more aggressive and targets 2024 to reach 9.3 kW/L.[216] Heat management, managing water concentrations on the anode and cathode, permeability, and electrical conduction are among the properties to optimize to reach these targets. Durability and cost are the overriding factors that limit the scale-up of PEMFCs. Metal

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corrosion poisons catalysts, and coating the surface is one approach to reduce its impact.

To date, most electrochemical systems research and development is at a very small scale, with little attention being paid to the challenges of cell scaleup. Reaction engineers should play a leading role in developing robust optimized systems that deliver the needed efficiencies at the production scale.

For battery and cell materials, components, and production processes, reaction engineers can establish materials and process informatics and models, including modeling the degradation of battery and cell components. They could guide the optimization of electrode (catalyst layer) production, especially for PEMFCs for product evaluation.

We also recommend the development of ab initio simulations and molecular dynamics simulations for these systems, particularly for the estimation of transport properties where measurements are not feasible. We expect AI to enable prediction over a wide range of operating conditions based on a small quantity of measured data.

Finally, we recommend feasibility studies of electrooxidation and electroreduction for producing valuable chemicals, especially for high value, low volume specialty chemicals and pharmaceuticals. Those processes require robust, durable electrocatalysts and electrocatalytic processes, including both homogeneous and heterogeneous catalyst materials. Improved reduction paths are required as well as mediator design for oxidation and reduction systems.[217] We encourage the pursuit of increased energy and capital efficiency by "pairing" two processes so that both electrodes become working electrodes, making valuable products. For example, in linear paired reactions, the same substrate is converted to the same product at both electrodes, enabling theoretical electrochemical yields of up to 200%.[218] Any electrochemical process development should include technoeconomic analyses coupled with device design and optimization. For electrochemical chemical production, industry requires capital-efficient electrochemical unit operations for large volume applications.

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Notes

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ADDITIONAL NOTE

[a]From https://www.bls.gov/web/osh/table-1-industry-rates-national.htm#soii_n17_as_t1.f.1 (2021 data) and https://www.bls.gov/iif/nonfatal-injuries-and-illnesses-tables/soii-summary-historical/ostb1129.pdf (2001 data), incidence rates of nonfatal occupational injuries and illnesses by industry, and (selected) case types: C = chemical manufacturing: 2.0 rate of total recordable cases in 2021; chemicals and allied products: 4.0 rate of total recordable cases in 2001.

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