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Editorial

Lab to Market: Where the Rubber Meets the Road for Sustainable Chemical Technologies

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Global chemical industry sales exceeded 5 trillion U.S. dollars in 2017 and are expected to double by 2030.[1] The chemical industry is among the most energy intensive industrial sectors and has greenhouse gas emissions totaling roughly a third of the greenhouse gas emissions of the transportation sector.[2] Raw materials for the chemical industry along with the energy required for their extraction and further processing are predominantly derived from fossil sources. Without transitioning to more sustainable technologies and raw materials, the required expansion of the global chemicals enterprise will exacerbate sustainability challenges. However, expansion of the industry also presents a significant opportunity to promote *sustainability and a circular economy*. Further, the accelerated increase in global environmental and safety regulations for new and existing chemicals and materials is also driving governmental actions aimed at technologies that are inherently safer and sustainable.[3,4] Despite the COVID-19-induced shrinkage of industrial production in 2020, the global chemical industry could be poised to invest in sustainable chemical manufacturing.[5] New technologies based on renewable sources of energy and raw materials, that are less resource intensive, are urgently needed to minimize harm to the environment and human health.

Sustainable manufacturing of chemicals can be based on plant-based biomass, abundantly available CO_2 and end-of-use waste to promote a circular economy (Figure 1). The future chemical industry can also be powered by renewable sources of power such as solar and wind energy, and renewable hydrogen to eliminate the carbon footprint caused by fossil-based energy sources. Fortunately, plant/waste-based biomass, solar, and wind energies are abundantly available to make this grand vision a reality. Major challenges include the development of new, practically viable technologies to make chemicals and fuels from these emerging feedstocks, finding processes that minimize resource consumption, and mapping a transition for the existing industry to evolve to a new, sustainable configuration.

Fundamentally, biomass resources are physically and chemically different from fossil fuels. While crude oils can be cracked and distilled into various gas and liquid components in an oil refinery and natural gas liquids can be cryogenically separated in gas processing plants, different separation technologies are needed to convert solid and involatile liquid biomass into useful chemicals in biorefineries. Chemically, biomass resources also tend to contain oxygenates, rather than hydrocarbons. Hence, while fossil fuels are transformed into valuable feedstocks largely by selective oxidation of C−H and C═C bonds (generally exothermic processes), transformations of biomass require the exact opposite—to reduce or transform C−O bonds—for which there are very few truly "green" and sustainable methods. This means that the infrastructure and network of processes required for a chemical industry based on biomass processing will be very different from those that exist currently. Mapping pathways to accomplish the transformation with biomass and other emerging feedstocks (CO_2, plastic wastes, etc.) will be challenging. Another challenge will be navigation of the notorious "Valley of Death" between early and late "technology readiness levels" (TRLs) for innovative technologies. Technologies must be demonstrated, economically and environmentally, at appropriate scales to be viable for large-scale commodity level production. These demonstrations will require closer collaboration between the private and public sectors such as governments, academia, and industry to deliver technological solutions. These public−private partnerships will share the greater risks that are invariably associated with transformative technologies.

Despite these challenges, steps in the transition to a sustainable chemical industry are already being taken. Some of these steps have been showcased by the Presidential Green Chemistry Challenge Awards, established by the United States Environmental Protection Agency in 1995 (now known as the Green Chemistry Challenge Awards), that highlight scientific and technical advances in green chemistry. The winning technologies have impacted a broad range of everyday products, including pharmaceuticals, foods, packaging, cosmetics, clothing, and electronics.[6] They are reported to have annually eliminated nearly 360 thousand metric tons of hazardous chemicals, saved 21 billion gallons of water, and cut CO_2 equivalent emissions by approximately 3.5 million metric tons.[7] While these achievements are significant, they only represent proof of viability as there is still ample room to shrink the industry's environmental footprint, such as the billions of metric tons of CO_2 emitted by the chemical industry annually.[1]

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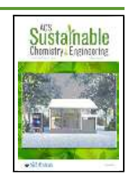

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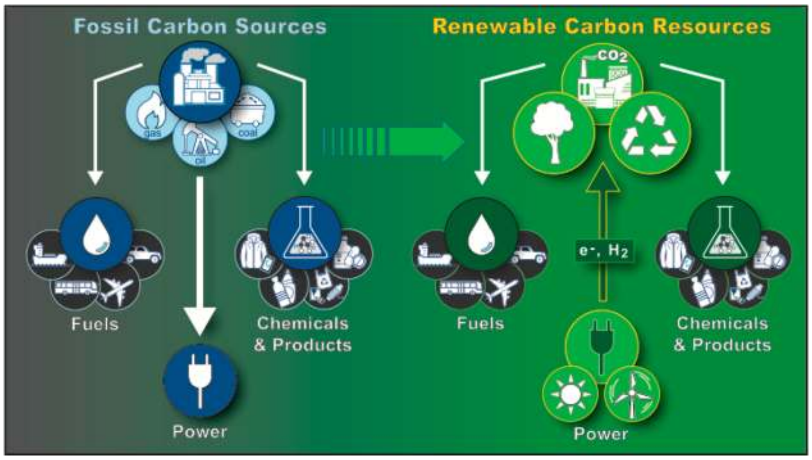

Figure 1. Transition to the grand vision: Distributed biorefineries where chemicals and fuels are made from renewable carbon sources powered by renewable energy.

Since measuring progress is critical in maintaining momentum in transitioning to sustainable chemical manufacturing, it is significant that many major chemical manufacturers now routinely track performance using sustainability metrics. The ACS Green Chemistry Institute reported a survey on how quantitative sustainability metrics are used in chemical manufacturing as well as future needs to translate promising green chemistry ideas into industrial technologies.[8] Major chemical and product manufacturers such as Dow,[9] BASF,[10] DuPont,[11] and Procter & Gamble[12] have used metrics and tools developed within their organizations to reduce the environmental footprints of their existing products and processes. The extent of these reductions may be seen in the annual sustainability reports posted at the company websites.

Beyond the evidence of major manufacturers measuring their sustainability performance, another reason to be optimistic is growth in sales for renewable chemicals. The global market size was $65 billion in 2019[13] and is projected to grow 10% annually and top $126 billion by 2026. While the market size is still a small fraction of the overall chemical industry output, it is significant enough to attract further investment.

All of these advances are driven by innovation. *ACS Sustainable Chemistry & Engineering* (*ACS SCE*) plans to publish a Virtual Special Issue (VSI) later this year titled *Industrial Sustainability*, featuring successful lab-to-market transitions of sustainable chemical technologies. As part of the VSI or otherwise, we invite case studies, which could be normal *ACS SCE* manuscripts such as research articles, features, or perspectives. Contributions are also invited that would be 1000−2000 word manuscripts to describe how barriers to commercialization were overcome in moving sustainable chemistry and engineering innovations from lab scale to commercialization. Manuscripts should identify various techno-economic barrier(s), successful practices for overcoming these barrier(s), and a description of how the experience might benefit other commercialization activities. The content should preferably address the following aspects: (a) brief description of the lab-scale innovation with appropriate literature and patent references, (b) technoeconomic, LCA, and risk/benefit analysis behind the business decision to commercialize, (c) key R&D studies and their scales that helped advance the TRL of the concept toward eventual commercialization, (d) partnerships across the product value chain that were critical to successful commercialization, (e) time from concept to commercialization, (f) estimate of the overall investment for a manufacturing plant of a given capacity, and (g) lessons learned from practices in other sectors or businesses. While all of this content is welcome, it is not necessary that every manuscript address all of these aspects. Figures that show the various production scales and key partners at each scale (producers of feedstock, energy, catalyst, chemical precursors, products, etc.) as well as quantitative sustainability analysis showing beneficial economic and environmental profiles would be appropriate. Manuscripts that are judged to be commercial promotions without generalizable findings are discouraged.

Please note that the foregoing guidelines are meant as suggestions. Authors are encouraged to add other aspects as appropriate. If you wish to specifically contribute to the VSI in preparation, please email us at your early convenience. We look forward to receiving manuscripts in the important area of translational sustainable chemistry and engineering.

We are aware that many of the challenges in bridging the gap between lab to market have not been addressed adequately in this limited space. Our editors will be revisiting this issue of global significance in future editorials.

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