The Biofuels Landscape Through the Lens of Industrial Chemistry

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PERSPECTIVE

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Paul A. Willems

Replacing petroleum feedstock with biomass in the production of fuels and value-added chemicals carries considerable appeal. As in industrial chemistry more broadly, high-throughput experimentation has greatly facilitated innovation in small-scale exploration of biomass production and processing. Yet biomass is hard to transport, potentially hindering the integration of manufacturing-scale processes. Moreover, the path from laboratory breakthrough to commercial production remains as tortuous as ever.

A century's worth of innovation in industrial chemistry has afforded the plethora of fertilizers, pharmaceuticals, coatings, fabrics, and packaging materials so integral to modern society. The history of these developments, arising largely from a steady supply of petroleum-based feedstock, offers an enlightening perspective on the challenges and opportunities facing nascent projects to prepare a full range of commodity-scale fuels and chemicals from biomass sources.

As the name implies, industrial chemistry has predominantly been the domain of major corporations, rather than universities or small companies. The road to commercialization is typically a long one, on the order of 10 years from initial invention to broad commercial application. Along the way, a great many innovations fall by the wayside, not so much because the initial idea was flawed but rather because some ancillary aspect prevented economical deployment on a large scale. Issues range from minor impurities or compositional variations in real-world raw materials, which can disrupt the manufacturing process, to market imbalances in byproduct streams, to mismatches of the product properties with marketplace specifications. Only large companies have traditionally had the capacity and capability to weather these scale-up storms.

The process typically goes through several stages: investigation of various unit operations at the lab scale; development of computer models to analyze and scale up the results; construction of an intermediate-scale asset (a so-called pilot or demonstration plant), which integrates the various operations into a fully functioning facility, including recycle streams; a scale up from pilot plant to the first full-scale commercial facility; and finally, replication of that facility into multiple commercial assets. In reality of course, the process is not linear, and multiple iterations through some of these steps are often required. Given the time frames involved in the design, construction, and operation of the various stages, it is not difficult to arrive at the 10-year projection noted above. From a business perspective, initial innovation is relatively easy and cheap; most of the risk resides in the expensive and lengthy scale-up and commercialization process. Therefore, choosing which innovations to take forward becomes a critical question.

Despite industrial chemistry's extensive history, many practitioners in the field will attest that innovation has actually been accelerating over the past 10 years. This has been due in large measure to the advent of high-throughput experimentation (HTE) capacity. The capability to do many small-scale experiments in parallel relatively quickly has opened up vast avenues for investigation. Initially, HTE was used primarily for "needle-in-a-haystack" searches: trial-and-error exploration of multiparameter combinatorial problems such as new catalyst compositions or new product formulations. Attractive leads discovered through this process were then subjected to the conventional development process. As the technology has become more sophisticated, however, applications have emerged to systematically explore process parameters for optimization purposes and even to derive kinetic information. In this regard, HTE is improving not only the initial discovery step in the innovation process but also the rate at which the early commercialization steps can proceed. At the same time, it has become clear that the machines can quite quickly generate more data than humans can process and interpret. The blind application of HTE merely results in data overload.

As the cost of HTE capability has come down, the technology has reintroduced the academic community as well as some small companies to the innovation landscape in industrial chemicals. HTE in effect lowered the barrier to entry into the innovation space. The problem of how to get from the lab to commercial application has not fundamentally changed, however. Most of the cost, time, and risk still reside in the scale-up process; we now just have more good ideas competing at the beginning of the queue.

Another feature of industrial chemistry is the highly integrated nature in which the industrial processes and value chains have evolved. Driven by the need to make the most out of every barrel of petroleum and to create maximum economic value at minimum cost, the industry has evolved manufacturing complexes with shared infrastructure, in which the byproduct of one process becomes the raw material for another. Well-defined and globally accepted product specifications allow for tight integration along the value chain. This standardization has created value for buyers and suppliers alike, though it also tends to create barriers to entry for new products seeking to displace an incumbent one, because they need to meet at least the same specifications and performance expectations while conserving (or ideally lowering) costs.

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So where do the emerging efforts in the industrialization of biofuels and biomass-derived chemicals stand in this context? Lignocellulosic biomass is one of the most widely available raw materials on Earth, and its conversion to liquid transportation fuels, basic chemicals, and specialty materials is a thriving international research theme. If we are successful in making the conversion of biomass to value-added products an economical proposition, then it will be an important contributor in the fight against global warming. It will also potentially satisfy other political objectives: increasing the security of energy supplies and supporting rural communities and agriculture in general. The issue here is not whether the task is technically feasible, but whether it can be done economically and sustainably.

Some believe that biomass-based production pathways will gradually substitute for petroleum-based routes, and that a similar industry will arise from a different raw material—hence the concept of biorefineries. Yet biomass is quite different from petroleum. Biomass is a bulky solid with relatively high water content. The range over which it can be economically transported to a manufacturing facility is on the order of 40 to 80 km. This supply constraint limits the scale of processing facilities, in contrast to petroleum-based manufacturing, whose scale is currently limited purely by our technical ingenuity. Scale factors in turn limit how many products can be economically produced in the biorefinery, because their range and quantity are limited by the size of the raw material supply. It is therefore unlikely that we will see manufacturing complexes arise with the same degree of integration seen in refining and petrochemical processing. It is also unlikely that the existing petrochemical complexes will be retrofitted to process biomass, because they are for the most part distant from the raw material supply. The inherently local nature of biomass will probably result in distributed processing plants spread across the country rather than in megacenters. A long-term symbiotic relationship will have to exist between the processing plant and the surrounding farming community, as they are effectively locked in together.

Tight product specifications are also likely to stand in the way of the market penetration of new biomass-based chemicals and polymers. The polymer segment is likely to be especially difficult, because products are generally sold on the basis of their processing and performance characteristics, which will be difficult to match unless the biomass-based material is chemically identical to the incumbent petroleum-based product. In this respect, the barrier to entry for lignocellulosic fuels is lower than for bulk and fine chemicals. Because gasoline and diesel are already mixtures of varying composition, new components can be integrated, and in the long run we might be able to produce biofuels at large scale that comprise hydrocarbons similar to those in petroleum-based fuels. Even in the fuel sector, however, questions remain over which biomass crops to grow; how to maximize agricultural productivity and sustainability; how to harvest, store, and transport the raw material efficiently; and how to transition from annual crops to perennials.

Once the biomass arrives at the manufacturing site to be processed into biofuels, we are in territory similar that of contemporary industrial chemistry. What can we learn from the world of industrial chemistry that might be relevant to biofuels? The biofuels innovation landscape is crowded with multiple academic and government labs, as well as venture capital–backed small companies. This situation is due to the relatively low barriers to entry enabled by biological HTE and data accumulation techniques similar to the chemical ones noted earlier. It is relatively easy to come up with an innovation that might be of importance in future conversion processes. However, the road from initial innovation to full commercial deployment remains as long and arduous in the biofuels case as in the industrial chemistry case. As time goes by, a gradual transition in lead roles from start-up companies to a few major corporations therefore seems likely.

There are also many competing technologies in the biofuels arena: (thermo)chemical conversion processes, biochemical strategies based on a huge (and growing) range of microorganisms and enzyme packages, and various different molecular product targets (each with associated pros and cons). Time will be necessary to determine which of these approaches ultimately proves superior. Because no one organization has the capacity to seriously invest in all the possibilities, each prospective commercialization effort carries a substantial risk that the chosen pathway might become technically obsolete. This in turn magnifies the risk profile of the scale-up process. A typical industrial chemistry asset needs at least a 20-year useful economic life in order to produce an attractive return on investment. A $500 million asset that becomes technically obsolete in 5 years is bad news from an investor's perspective. Meanwhile, regulators and legislators are pushing for faster and larger-scale implementation and are providing (temporary?) financial incentives to help push the process along. Taken all together, these factors produce a rather intimidating landscape in which to make prudent investment decisions. Only time will tell how things settle out in the end.

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