Chemical Industry

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An Industry in Transition: The Chemical Industry and the Megatrends Driving Its Forthcoming Transformation

*Mario Pagliaro**

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Dedicated to Professor Giulio Deganello on the occasion of his 80th birthday

***Abstract:** Significant product and process innovation is taking place in the chemical industry. Rather than making bold predictions, this Essay emphasizes that this change, due to impact both main segments of the industry, is driven by societal megatrends concerning the environment, health, and energy which permeate societies on a global scale.*

1. The Chemical Industry

The chemical industry is the industrial backbone of all industrialized countries and economies.[1] It is a huge and growing industry whose raw materials are petroleum, natural gas, and (to a minor extent) coal. A few figures can be given to underline its relevance. In 2017, the world's top 50 chemical companies recorded a total of $851 billion in revenues (+12.2% increase from 2016) and $108.6 billion in profits.[2] No company among the top 50 lost money, and only 13 of the firms reported a decrease in profits. The world's largest chemical company, based in Germany, had $69.2 billion in revenues, and the 50th company, based in Switzerland, recorded $6.5 billion in revenues.[2]

Books[1] and business analyses[3] are routinely devoted to the chemical industry. Production of petrochemicals takes place at large, strongly interconnected ("verbund") production sites owned by petrochemical companies having privileged access to oil and natural gas (methane) used as feedstock. These conditions intrinsically lead to a market oligopoly in which the barriers to market entrance are the huge capital costs to be faced by any potential competitor. Accordingly, a recent scenario study by Jenner and Neumann on the future of the industry clearly identified its three main competitive advantages: 1) economies of scale and synergies, 2) intellectual property protection, and 3) straightforward access to feedstock, especially oil and gas.[4]

[*] Dr. M. Pagliaro
Istituto per lo Studio dei Materiali Nanostrutturati, CNR
Palermo (Italy)
E-mail: mario.pagliaro@cnr.it
Homepage: http://www.qualitas1998.net

The ORCID identification number(s) for the author(s) of this article can be found under:
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Epitomized by the introduction of polypropylene in 1958 in Italy,[5] between the early 1950s and the late 1970s, the petrochemical industry launched countless new chemicals and polymers. What happened in the subsequent years, starting from the early 1980s, was summarized by Plotkin in 2005: "chemical companies realized that their plants could operate for decades without fear of being made obsolete by plants using new higher-selectivity catalysts as it had been the case in the 1960s and in the 1970s… any new process would have to decrease production costs by 25 percent to 35 percent to create 'shutdown economics' over existing plants".[6]

As a result, between 1980 and 2010 the growth of chemical companies focused on expanding production though existing technology in Southeast Asia and in the oil-rich Middle East to provide chemicals and polymers to the booming Chinese and Asian economies, with revenues and profits originating "from best-selling chemicals that are decades old. Polyvinyl chloride (PVC) was invented in 1913, polyethylene in 1936, and polypropylene in 1954".[3] According to Lehr and Auch, innovation in the chemical industry has "merely focused on exploration and exploitation of innovation in a given framework",[7] namely in which incremental innovation takes place within an established framework.

Why then should chemical conglomerates focusing on economies of scale, privileged access to raw materials, and synergies switch to decentralized production based on clean chemical technology, if their huge revenues (and profits) are basically assured by the aforementioned material conditions?

Driven by societal and technology megatrends, two main factors, we argue in this Essay, might reshape the industry in the course of the next two decades (2020–2040), namely 1) the global demand for better, lighter, more durable, healthier, and greener functional products by the industry's largest customers and 2) the uptake of decentralized production based on clean chemical technology.

2. Megatrends Driving Innovation

Management consultants Jenner and Neumann suggest that by 2025 chemical manufacturers might become "general purpose production industrial foundation businesses… just like the telco infrastructure providers that provide the basic infrastructure for today's hyper-connected world, while other tech giants reap the biggest profits".[4] Change in chemical industry's processes and products will result neither from "voluntary" action nor from "responsible care" for the environment, but rather it is and will be mostly customer-driven. On the one hand, the industry's largest customers in automotive, construction, food, textile, detergents, coatings and cosmetic/personal care industries demand better, lighter, more durable, healthier and greener functional products and materials. On the other, significant pricing pressure due to widespread generics production, new regulations demanding higher quality globally, and diminishing supplies of old and widely used medications "that reap little if any profit for manufacturers"[8] require profound changes in pharmaceutical manufacturing,[9] and thus in the production of active pharmaceutical ingredients (APIs) taking place at fine chemical companies.

The demand for such new products and processes, in turn, is driven by societal megatrends concerning the environment, health, and energy which permeate the global economy. These megatrends translate, for instance, into the recent global adoption of new vehicles running on electricity rather than on the combustion of refined oil, as well as energy-efficient and ecofriendly buildings, and green and less toxic agrochemicals, paints and coatings, textiles, cosmetic and personal care and food products. In the following, we show how these new demands are impacting the chemical industry.

3. Ongoing Changes of Practical Significance

The first driver for change is the ongoing rapid uptake of electric vehicles (EVs).[10] The shift from internal combustion engine vehicles to EVs directly impacts the revenues of petrochemical plants whose profitability is strictly connected to adjacent gasoline and diesel fuel refineries. This connection was proven in the early 1980s by a company that intended to build an oil refinery in Texas "for the sole purpose of making petrochemical feedstocks".[11] This petrochemical company readily learned "to its dismay that a refinery that does not produce gasoline will probably not be profitable".[11] To quote data based only on electric buses, by the end of 2018 approximately 385 000 of the world's estimated three million buses were entirely electric (99 % of them operating in China), leading to a displacement of about 177 000 barrels of diesel fuel per day.[12] Originally limited to China, the adoption of electric buses is now spreading across the world. Furthermore, from new tires to new composite-based frames, automotive companies demand new lightweight and robust materials to make lighter, robust, and better (when compared to conventional internal combustion engine vehicles) electric vehicles.

Mario Pagliaro is a chemistry and energy scholar based at Italy's Research Council. Developed in cooperation with scientists based in 20 countries, his research group's achievements include new catalysts and catalytic processes, protective coatings, cement additives, and sunlight-driven new synthetic routes and natural product extraction processes. He has co-authored close to 250 research papers and 22 books. Ranking among Italy's most cited scholars in materials science and nanotechnology, Dr. Pagliaro has studied and worked in Italy, the Netherlands, Israel, Germany, France, and Canada.

A second important driver for change is the global shift to energy-efficient and ecofriendly buildings. Over two decades (1980–2000) the construction and remodeling of existing buildings typically made use of insulating polymers such as polystyrene and polyurethane to lower heating requirements and costs. In contrast, in today's energy efficient and nearly zero-energy buildings, natural materials based on organic fibers are preferably used to reduce the amount of both fuel and electricity for heating and cooling the building, respectively.[13]

This trend, once again, was due to new societal demand for buildings that are not only energy efficient, but also ecofriendly and healthy (with good indoor air quality, without moisture accumulation, with optimized cleaning requirements etc.).[14] Today's natural insulating materials are advanced composite materials offering excellent multifunctional (thermal and acoustic) insulation performance in any season, prolonged durability under different thermohygric conditions, and lack of flammability.[13]

Along with new insulating materials, the global demand for water-based coatings increased sharply, driving the colorants and coatings industry to shift from organic solvent- to water-based formulations,[15] and, more recently, to introduce the first bio-based binders and coatings.[16] Again, the technical properties of the resulting paints are not only on a par, but often exceed those of conventional systems, providing improved coating performance.

The third important factor that is driving change in chemicals production is the increasing global awareness of the environmental and health problems posed by non-biodegradable plastics as well as from old manufacturing routes starting from oil feedstock. For instance, microscopic plastic beads (microbeads; namely, solid plastic particles less than 5 mm in diameter), widely used by the cosmetic and personal care industries, eventually end up in sea, river, and lake waters where they absorb toxins[17] and are eaten by marine life, eventually making their way up the food chain.[18]

Generally composed of polyethylene, polypropylene, polyethylene terephthalate, polymethyl methacrylate, or nylon, microbeads were eventually banned from cosmetic and personal care products in the United States in 2015.[20] Their production and use was no longer allowed in the U.S. starting in July 2017, thereby creating new and large growth opportunities for bio-based, biodegradable alternatives such as polyhydroxyalkanoates (PHAs) obtained by the fermentation of glycerol (or several other agricultural by-products such as potato, sugar cane, and sugar beet waste). Indeed, one of the world's first companies manufacturing such PHA-based microbeads recorded 364 % growth in fiscal year 2018 alone, with revenues increasing from €11 million in 2017 to €51 million in 2018, and over 20 PHA plants being already licensed for construction in the next four years across the world.[21]

Featuring excellent high-temperature performance and a tunable set of properties set, PHA copolymers have potential as bioplastic substitutes for fossil-fuel-derived plastics in a wide range of applications, including metal replacement in automotive parts (Figure 1). Indeed, PHAs have already penetrated packaging, food service, agriculture and medical product markets, both low-value, high-volume markets such as compost bin liners and low-volume, high-value markets such absorbable surgical films.[22]

A recent significant example showing that frequently conventional routes to petrochemicals are more convenient than alternative routes starting from bioproducts is provided by epichlorohydrin production in China. In 2017 the Chinese government shut down several conventional epichlorohydrin factories due to uncontrolled release of chlorinated wastewater.[23] As a result, production at China-based industrial plants using the much cleaner route[24] to epichlorohydrin starting from bioglycerol soared.[23]

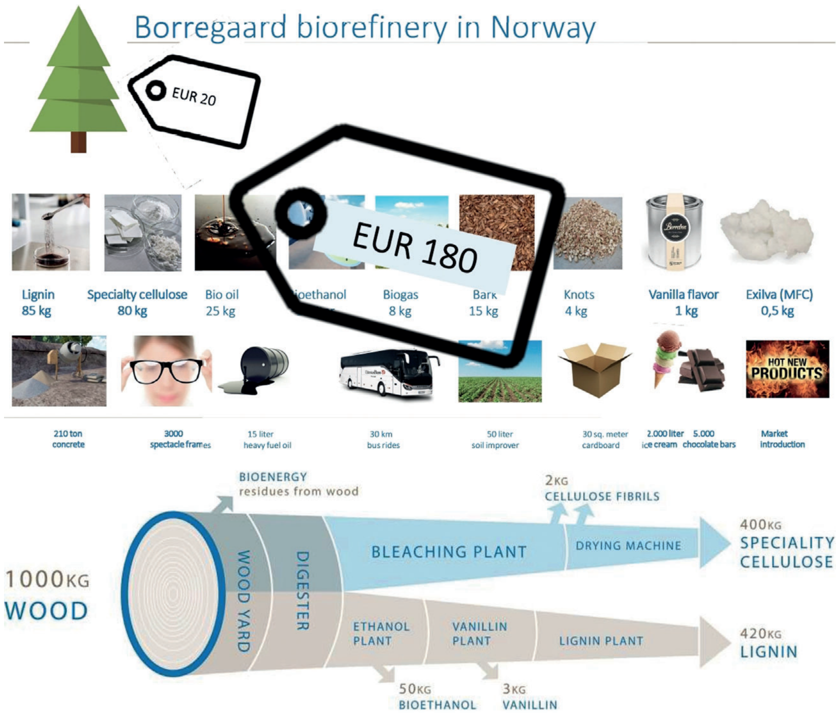

Figure 2. Value added for a leading biorefinery in Norway manufacturing a number of valued chemicals from wood (top) including lignin and speciality cellulose (bottom). Reproduced from Refs. [25,26], with kind permission.

Another example of the achieved economic feasibility of biorefineries is provided by a large pulp and paper company in Norway ($470 million in revenues in 2017) which, having to face rapid decrease in paper demand due to the global adoption of the internet as communication and information medium, turned into a biorefinery. Thanks to complete transformation of cellulose, hemicellulose, and lignin components into highly valued bioproducts, this biorefinery could enhance the economic value of wood tenfold (Figure 2).[25] These products include refined lignin, vanillin, lignosulfonate-based binding and dispersing agents, ethanol, specialty cellulose,[26] and since 2016 also microfibrillated cellulose (MFC, also known as cellulose nanofiber, a multifunctional rheology modifier suitable for water-based formulations with improved properties compared to those from the existing technology).[27] In response to increasing global demand for biosourced chemicals, in 2018 the same company opened a new 100000 t/a lignin plant in Florida.

A similar expansion is in progress for the France-based petrochemical company which started the production of polyamide 11 (tradename: Rilsan PA11) via polymerization of 11-aminoundecanoic acid (Figure 3) obtained from castor

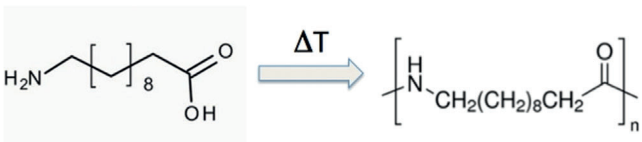

Figure 3. Polymerization of 11-aminoundecanoic acid to form polyamide 11.

oil over 70 years ago. The company is currently building a large plant in China which will increase its production capacity by 50%.[28] Used in demanding applications such as gasoline transfer lines, hydraulic and pneumatic hoses, cable sheathing, medical equipment, and electronic device components, thanks to its lightness, excellent resistance to chemicals, wide range of working temperatures (from −60°C to +130°C),[29] polyamide 11 is also used to produce a polyamide 11 block copolymer with polyether segments (Pebax RNew)[30] which, featuring superior energy return, lightweight, sturdiness, and flexibility, is used for making high-performance running shoes and ski boots.

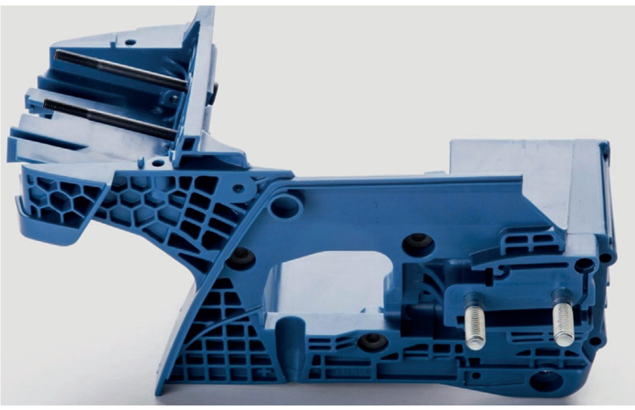

Figure 1. Lightweight polyhydroxyalkanoate copolymers can successfully replace metal in numerous automotive parts. Reproduced from Ref. [19], with kind permission.

A fourth factor impacting sales of petrochemical products is the dramatic growth of the natural products industry driven by the consumer requests for healthy food, cosmetics, nutritional supplements, fragrance and personal care products that are free of chemical contaminants. For example, food companies are increasingly required to replace synthetic antioxidant additives such as BHA (butylated hydroxyanisole), BHT (butylated hydroxytoluene), PG (propyl gallate), and TBHQ (*tert*-butyl hydroquinone) used to stabilize fat in baked and fried products, vegetable oils, and margarine with natural biophenols[31] and to substitute synthetic red dyes with natural reds such as betanin[32] and lycopene[33] extracts.

4. New Technology, New Raw Materials

In 2018, despite low oil prices and a lack of political support, the total volume of biopolymer production grew by 4% to reach 7.5 million tonnes, about 2% of the 375 million tonne production volume of petrochemical plastics.[34] According to the same market analysts, the production of bio-based polymers will continue to grow at an annual rate of about 4% until 2023.

About one quarter of the current total output of bioplastics (7.5 million tonnes) is biodegradable.[34] The remainder is not biodegradable but still renewable, as it is obtained from renewable biomass and not from oil. For example, since 2010 Brazil's largest chemical company has manufactured polyethylene from bioethanol made from sugarcane via fermentation at a 200000 tonnes per year plant located within the Triunfo Petrochemical Complex (Figure 4). Currently, over 150 brands worldwide have already adopted "green plastic" in packaging, adopting the "I'm Green" label, for the most diverse segments, such as food, personal hygiene, and durable goods.[35]

In early 2018, the same company started to supply a shoe manufacturer based in San Francisco with ethylene vinyl acetate (EVA) produced from sugarcane-based ethanol.[36] As renewable chemicals companies grow in size and financial strength thanks to revenues from fine chemical and specialty polymer sales, they will be increasingly able to target commodity-type polymers starting from immensely abundant lignocellulosic biomass (731 million tonnes of rice straw alone),[37] rather than from vegetable oils or crops.

Figure 4. Braskem's 200 kt/year green ethylene plant at the Triunfo Petrochemical Complex, Brazil. Photo courtesy of Braskem S.A.

When sugars (monosaccharides) are available at low cost from lignocellulosic biomass rather than from agricultural crops, renewable chemicals companies will start, for example, to manufacture monoethylene glycol (MEG) and make inroads on the $25 billion MEG market. Currently, at the MOnoSAccharide Industrial Cracker operating as a pilot plant in Denmark, sugars are "cracked" rather than hydrocarbons.[38]

"We are not interested in shipping bottled water across oceans and continents," recently commented the founder of a PHA-based water bottle company in the U.S., adding that "as the company expands we will set up multiple manufacturing and packing facilities across the US…to localize production and minimize transportation".[39] This recent statement from the chief operating officer of a bioplastics company shows how new chemical production based on advanced catalysis technologies—such as nanocatalysis, biocatalysis and, soon, single-atom catalysis, operating under mild conditions (and thus requiring low capital and operative expenditure) and starting from readily available biomass raw materials—intrinsically leads to decentralized production, located close to customers. A common feature of all new catalytic technologies is that they are ideally conducted heterogeneously and under flow, namely in continuous processes over solid catalysts in a continuous flow reactor (a unit that processes many reactor volumes without interruption), affording very limited waste and by-products or none at all.

Besides dramatically lowering production costs, thus making the production of APIs for inexpensive drugs economically feasible,[9] this change supports the production of chemicals in flexible tonne-scale production plants similar to Taiichi Ohno's lean production of goods (including vehicles).[40] Numerous companies across the fine chemical, specialty, and pharmaceutical sectors are conducting manufacturing "campaigns" on the scale of several hundred or thousand tonnes per month based on these new technologies and are meeting the demanding requirements of regulatory agencies. This clearly shows that new production technology is eventually being accepted and taken up.[41]

5. Outlook and Conclusions

Selected recent examples in this Essay show that significant product and process innovation is taking place in the chemical industry. Rather than making bold predictions, this Essay emphasizes that this change is driven by societal megatrends concerning the environment, health, and energy which permeate society on a global scale.

From the world's two most populous countries, China and India, through affluent societies in North America and western Europe, and finally Russia and Latin America countries, societies no longer tolerate environmental pollution. This directly translates into increasing social scrutiny on chemical productions, as is evident, for example, from the recent massive factory closures in China.[42] Tightening limits on emission levels translates into increasing petrochemical production costs. Similarly, we argue, the concomitant shift from internal combustion engine vehicles to electric vehicles and from fossil-fuel-derived energy to renewable energy from sun,[43] wind, and water directly impacts the revenues of the petrochemical industry, whose overall profitability needs the concomitant fuel production of nearby oil refineries,[11] creating room for renewable chemicals productions. Remarkably, publicly funded work is already in progress in western Europe aimed at removing the existing policy and standardization hurdles currently creating disadvantageous conditions for the biobased chemical industry.[44]

The use of biomass instead of oil as the chemical industry's new raw material has a fundamental economic foundation. The end of cheap (i.e., readily extracted) oil combined with global wealth and population dynamics[45] suggests that the transition to a renewable chemicals industry is needed as much as the transition to renewable energy.

Conflict of interest

The author declares no conflict of interest.

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Essays

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M. Pagliaro* ■■■■–■■■■

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Change is good: Significant product and process innovation is taking place in the chemical industry. This Essay emphasizes how these changes are driven by global societal megatrends concerning the environment, health, and energy.