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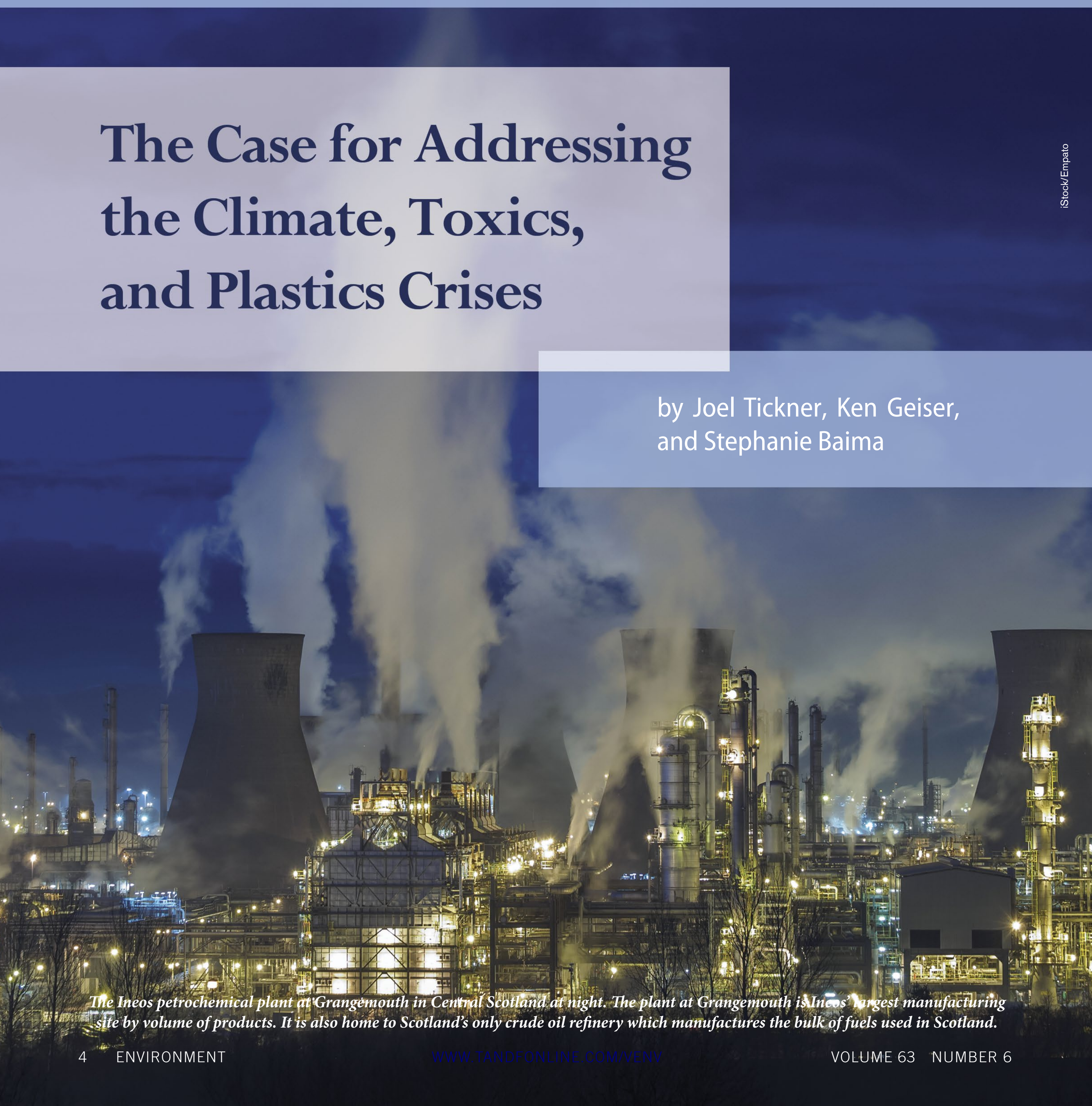
Transitioning the Chemical Industry

The Case for Addressing the Climate, Toxics, and Plastics Crises

by Joel Tickner, Ken Geiser, and Stephanie Baima



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The Ineos petrochemical plant at Grangemouth in Central Scotland at night. The plant at Grangemouth is Ineos' largest manufacturing site by volume of products. It is also home to Scotland's only crude oil refinery which manufactures the bulk of fuels used in Scotland.

On January 27, 2021, President Biden issued a sweeping set of Executive Orders establishing a comprehensive approach to addressing the climate crisis, with a goal of leading "a clean energy revolution that achieves a carbon pollution-free power sector by 2035 and puts the United States on an irreversible path to a net-zero carbon economy by 2050." What these new promises and most of the current decarbonization discourse miss is that fossil fuels are not only used for energy but are also the fundamental building blocks of the chemicals and materials that support our economy and are embedded in more than 96% of manufactured goods.[1]

Today's energy production system is tightly integrated, and little is wasted. Fossil fuels and refinery by-products not used for energy production become the feedstocks for commodity chemicals and a broad range of downstream products, including plastics. While the production of "petrochemicals" from oil, gas, and coal has helped build modern advanced economies, "Better Living through Chemistry" has come at a cost. The chemical industry is the third-largest industrial source of the greenhouse gasses responsible for climate change. Many of its products are hazardous; improper disposal of its wastes harms communities and ecosystems worldwide; and plastic pollution threatens the health and functioning of the oceans.

As government policymakers, corporate investors, and global nongovernmental organizations look to solve these crises, the industry remains mired in the status quo. Inextricably tied to fossil fuels and operating at massive scale, it is unable to react to change or innovate with agility, and it is subject to fossil fuel price fluctuations and availability. These vulnerabilities will continue to impact the industry's growth, as investors and regulators increasingly press for action on climate change, recycling, toxics, and plastics pollution.

Current chemical industry strategies to address the climate and plastics crises focus primarily on feedstock substitution and improved recycling, without fundamentally changing the production model or chemical products created by the industry. Such tinkering at the margins will help but cannot solve these existential sustainability challenges. Similar to the energy sector, we must then ask whether a thoughtful transition strategy (a "roadmap") is needed to guide the industry into a future where it contributes to the global standard of living and a sustainable economy without compromising planetary and human health. Looking to history is instructive because the industry wasn't always as ossified as it is today. Its first decades were marked by rapid industrialization, innovation, and growth.

In this article, we examine the current state of the chemical industry and its history in order to derive lessons from its rapid growth and understand how it must change course to ensure its future viability.* Our focus is fossil fuel-based organic chemistry, which constitutes around 90% of global sales, and primarily the U.S. chemical industry, though we draw lessons from developments in other regions.[2] We close by making the case for why the industry urgently needs to reinvent itself.

Foundations and Growth of the Modern Petrochemical Industry

The modern chemical industry grew up in the 1940s and 1950s, dominated by the United States, Germany, the United Kingdom, and Japan. The world wars drove rapid expansion. Chemistry discoveries in government, industrial and academic research labs, and collaborations between them created the molecular foundations for the growing industry. The need for synthetic dyes and ammonia for munitions in World War I and synthetic rubber in World War II caused governments to invest heavily in research and development and manufacturing capacity and guaranteed a market for products. The U.S. government's Rubber Reserve Program, known as the "chemical equivalent of the Manhattan project," involved 20 private companies and $670 million ($12 billion today) of government investment. In 3 years, the industry moved from barely producing synthetic rubber to outputting 1.4 billion pounds annually.[3] The World War II effort saw oil companies expand into petrochemicals to supply the butadiene for synthetic rubber, toluene for TNT (trinitrotoluene), high-octane aviation fuel, and polymer replacements for strategic materials like aluminum and brass.[4]

Major private-sector investments were matched with strategic government interventions, such as the confiscation and distribution of German patents after World War II and funding for pipelines, highways, and ports—all critical infrastructure for the industry's growth. Oil and gas subsidies and tax policies in place since the 1920s supported the fossil fuel energy production needed to create low-cost feedstocks for petrochemical products. After the war, the massive plant capacity for rubber production and aviation fuel was transferred to private companies, laying the foundations for the rapid growth of petrochemicals.[5] While promising organic chemistries and derivatives of fossil fuel production were discovered earlier, large volumes of petroleum feedstocks enabled the industry to grow exponentially in the United States, Europe, and Japan.[6] Massive investments by major chemical producers in the United Sates led to the rapid construction of new facilities (in just 16 years approximately 70 facilities—representing 85% of petrochemical capacity at the time—were built in Texas).[7] Technologies developed for petroleum refining and polymerization spawned entirely new sectors, such as agrochemicals, consumer products, and pharmaceuticals.

By the 1950s, the chemical industry had become a major engine of economic growth. Strong patent protections and a prevailing antitrust atmosphere led to the rise of new engineering firms, staffed by chemical engineers who helped perfect chemical processing.[8] Collaboration and licensing brought new innovations from the lab to commercialization and scale. As "the industry of industry," chemicals were closely connected to most other industrial sectors, leading to a great diversity of products and applications: novel fibers for textiles, new polymers for housewares, state-of-the-art solvents, films, and coatings. Advancements in transportation, communications, and construction technologies and a rising middle class eager for manufactured products created a large demand for new chemicals and polymers. Rapidly, these revolutionary materials began to replace wood, metal, and ceramics in products like bottles, dishware, and toys.[9]

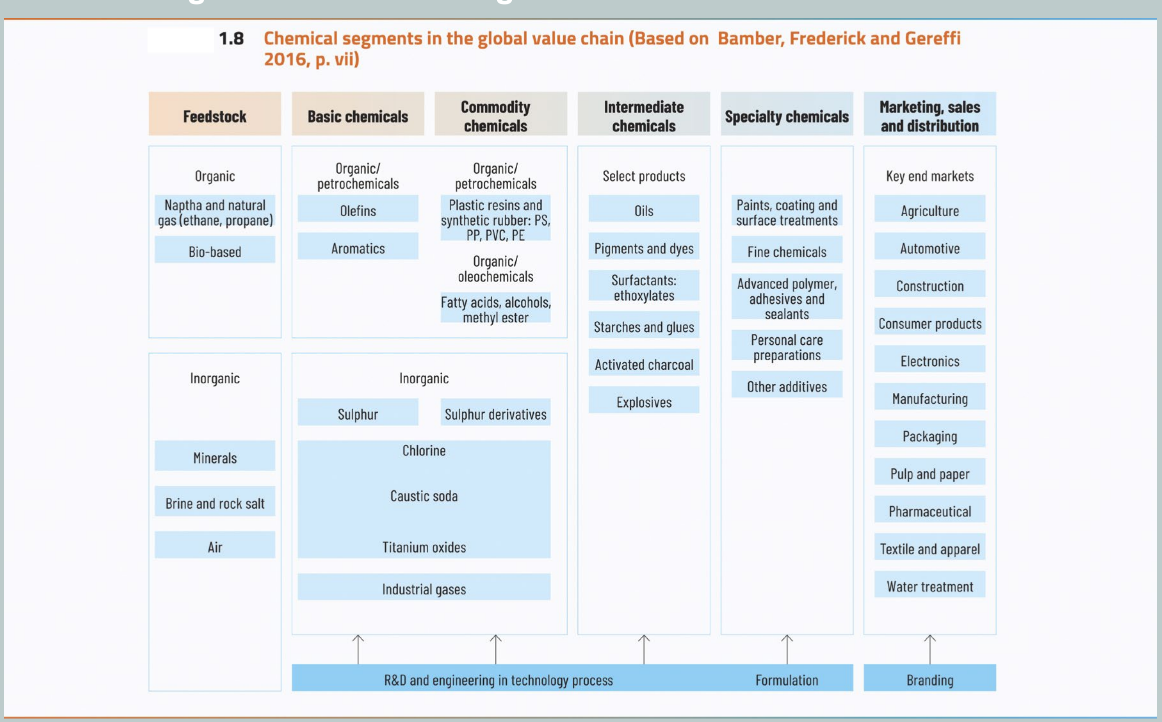
American firms, already fully invested in oil and gas as feedstocks, took the lead in petrochemical production after World War II. Shifting European firms from coal to petroleum, a more versatile feedstock for chemical production, took more time.[10] However, Germany's well-connected academic and industrial sectors, organized around profit sharing and cartels, permitted large prewar firms to continue dominating even after being broken up structurally.[11] The transition from coal to oil and rapid growth were fueled by co-development with petroleum companies, government-supported infrastructure development, the evolution of highly efficient integrated processes, and a focus on internationalization and exports.[12] Japan's petrochemical sector, based on petroleum from its inception, grew quickly after the war due to the dominance of integrated industrial conglomerates, close ties to its domestic market, and government protectionism.[13]

The Modern Chemical Industry: A Behemoth Tied to Fossil Fuels

By the late 1960s the chemical industry was considered a mature industry, exemplified by a 1961 *Fortune Magazine* article entitled "Chemicals: The Ball Is Over."[14] As the massive infrastructure in the United States and Europe began to age, excess capacity limited new investments, and price cutting ate into margins and spurred defensive competition. Having adopted a paradigm of large-scale, capital-intensive, and highly integrated manufacturing infrastructure, the industry's technological development locked onto a set path with a small number of platform chemicals becoming dominant ingredients for downstream products and chemistries. As a result, nearly every major commodity plastic on the market today was developed before 1960, and the industry's technological structure looks much the same today as it did then.[15]

The global chemical industry is one of the world's largest manufacturing industries, representing US$4 trillion of sales in 2019.[16] Its products are categorized as basic (bulk or commodity), specialty, agricultural, pharmaceutical, and consumer chemicals. Basic chemicals comprise about two-thirds of global chemical production and consumption, and just seven petrochemicals (methanol; olefins—ethylene, propylene, and butadiene; and aromatics—benzene, toluene, and xylene) constitute the platform that serves more than 90% of downstream organic chemical production, including tens of thousands of chemical products.[17] With an inexpensive supply of basic carbon backbones, the industry focused on perfecting the chemistry and

Figure 1. Chemical Segments in the Global Value Chain



Source: UNEP Global Chemicals Outlook II 2019, p. 30 (based on Bamber, Frederick, and Gereffi 2016, p. vii).

engineering to functionalize them. The vertical integration of energy production and chemical manufacturing has only grown. Many of today's top chemical companies are recognizable oil and gas names, including multinational giants ExxonMobil, Chevron, and Shell, state-owned Chinese Sinopec, and state-owned Saudi Arabian SABIC.

The profitable production of the low-value basic commodity chemicals and materials that dominate the market is only possible through economies of scale. Oil and natural gas account for 99% of chemical feedstocks, and the remainder comes from biomass and coal.[18] Refinery infrastructure is often huge, with many U.S. oil refineries having a production capacity greater than 75,000 barrels per day.[19] The production of many key chemicals, materials, and especially their basic precursors, requires massive and expensive processing facilities. For example, Shell's ethylene cracker plant, being built outside Pittsburgh to take advantage of natural gas liquids from fracked natural gas, is expected to produce 1.6 million tons of polyethylene annually and cost $6–10 billion to build.[20] Many operations require extremely high temperatures and pressures, yielding high operating costs. Margins for producing commodity chemicals are often variable and low—even falling below zero.[21] This operational scale carries risks of overcapacity, as market conditions can change significantly, and production must run at as close to full capacity as possible for optimal cost efficiency. High throughput requirements have led to production rigidities, a focus on cost reduction strategies, and slow responsiveness to economic or supply chain events.

A highly integrated global industry brings significant interdependencies and long supply chains, often spanning multiple countries or continents. One country or major supplier curtailing production or experiencing a disruption can create shockwaves. For example, Chinese environmental restrictions on a precursor to the widely used preservative benzisothiazolinone caused supply-chain disruptions in 2018 that were felt in downstream manufacturing in pharmaceuticals and consumer products.[22] In 2021, U.S. petrochemical capacity was severely impacted by unusually cold temperatures in Texas. The resulting outages caused shortages of chemicals and downstream products that rippled through connected markets, from consumer chemicals to automobiles.

Research and development investments and new discoveries in commodity chemicals have steadily declined in recent decades.[23] Only one new commodity polymer has gained market prominence in the past 30 years, as the industry has focused primarily on process efficiencies and expanding applications.[24] From 2018 to 2019, research and development spending by 29 of the top 50 chemical companies in the United States decreased by 5.1%, despite a 2.9% increase in capital expenditures.[25] Research and development spending on commodity chemicals, at 2–3% of revenues, lags behind research and development spending on specialty chemicals (4–8%) and on pharmaceuticals (10–25%).[26,27] Additionally, government–industry technology collaborations have waned over time and research dollars have declined or focused on less risky iterations of existing chemistry, rather than on new breakthroughs. Even the collaborations that marked efforts to scale bio-based fuels and chemicals in the early 2000s focused primarily on drop-in replacements for fuels and existing commodity chemicals.[28]

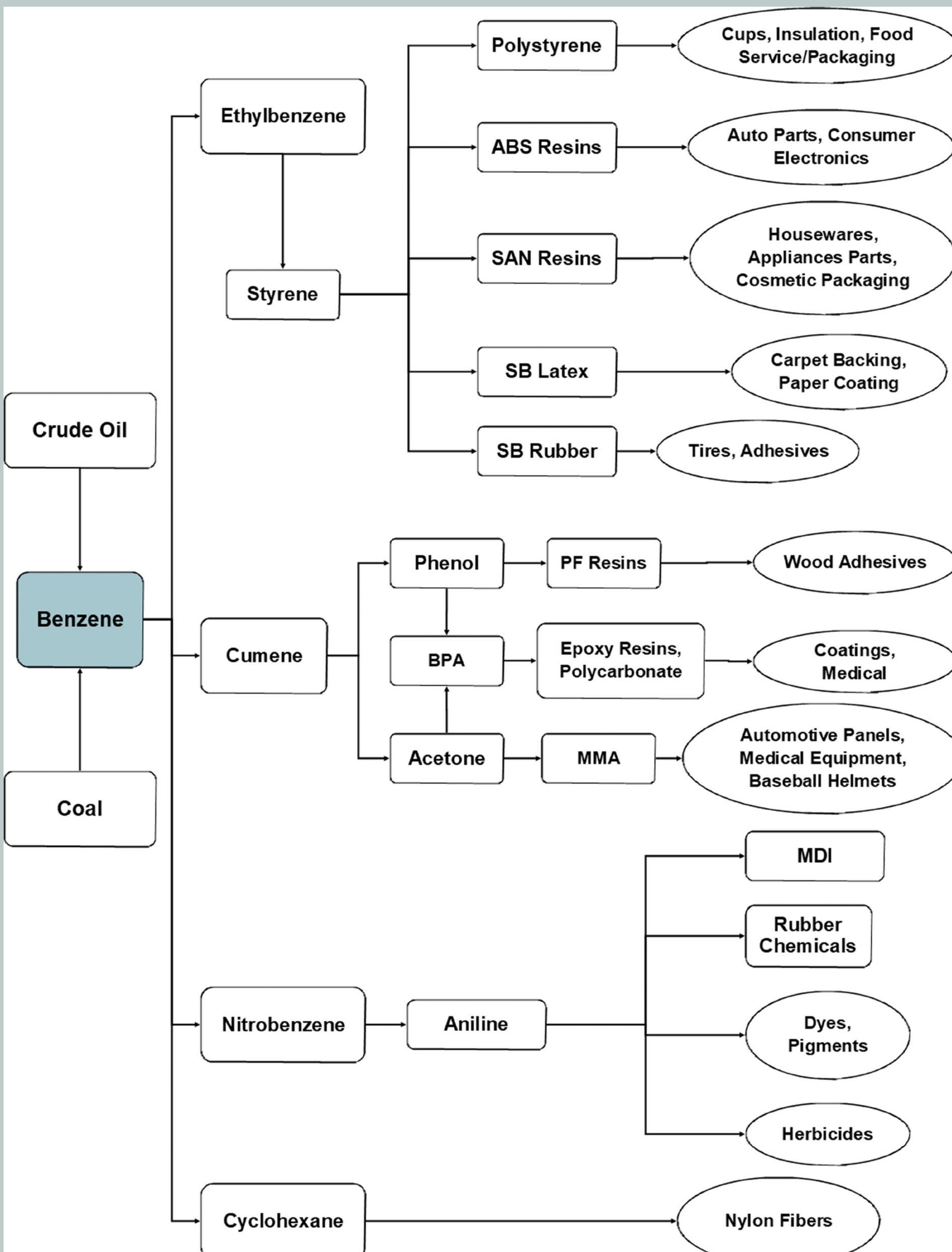
The industry's fossil feedstock infrastructure continues to be heavily subsidized, with about $20 billion per year in direct subsidies.[29] Indirect subsidies could top $649 billion, more than the U.S. defense budget and 10 times more than federal spending on education, according to a 2015 estimate by the International Monetary Fund that accounted for the industry's health and environmental costs.[30,31] Investors looking for secure, short-term returns have reinforced and exacerbated the industry's current structure by financing primarily commodity chemicals and particularly plastics production.[32,33]

Only the pharmaceutical, agricultural, and specialty chemical sectors have sustained the rate of discovery and development that marked the chemical industry in its heyday. Growth in innovative drugs, pesticides, electronics chemistries, and specialty polymers has occurred as a result of effective supply-chain and public–private partnerships, smaller volumes, higher margins and returns on investment, a focus on functionality tailored to specific applications, and operational flexibility to adapt to market needs. Hundreds of new specialty chemical manufacturers have entered the industry in past decades, and more are expected due to the growth of biotech and digital technologies.[34]

The chemical industry has increasingly become a global industry. Since the 1980s, production has shifted to Asia and newly emerging economies, such as in the Middle East and Africa. China has quickly become the world's largest chemical producer, followed by the European Union and the United States, with 39%, 15%, and 14% of global sales in 2019, respectively.[35] Internationally, the sector is growing by 2–3% annually in developed economies and by 6–10% per year in emerging markets.[36] In China, 20 million metric tons per year of new ethylene capacity is planned, following the 2015 opening of state-controlled refining and upstream petrochemical investments by multinational corporations.[37] In Saudi Arabia, Saudi Aramco's petrochemical subsidiary SABIC has state-of-the-art refineries under construction that are expected to produce 3 million tons of ethylene annually, a quarter of the capacity being built on the U.S. Gulf Coast.[38] Most growth is therefore expected in regions with the least developed policy frameworks and infrastructure to address the industry's impacts.

If trends continue, including increasing consumer demand for products in industrializing economies, basic chemicals production will increase by about 30% by 2030 and almost 60% by 2050, and plastics production by 30% over the next 5 years.[39] Product recycling, bans on certain chemicals, and consumer attitudes towards chemicals in products in high-consumption countries will increasingly tilt the chemical industry's

Figure 2. The Benzene Chain as an Example of the Interconnections Between Basic Petrochemicals and Their Derivatives



Source: ACC Guide to the Business of Chemistry 2020, p. 87.

markets toward emerging economies. As fossil fuel producers watch the decarbonization trajectory in the energy and transportation sectors of some regions, they will likely seek alternative fossil fuel markets with higher margins, particularly plastics.

Despite its size, importance to global manufacturing, and projections for future growth, the chemical industry is on shaky footing. In 2019, it suffered the effects of overcapacity and a global manufacturing slowdown, down 4.9% compared to 2018 revenues.[40] A McKinsey analysis showed that, before the pandemic, nearly half of the top 100 chemical companies responded to business challenges by adapting their corporate portfolios through divestitures, mergers, acquisitions, or by shutting down assets, rather than evolving their product portfolio, or moving to new operating models.[41] Lower oil prices have significantly slowed the industry's move to natural gas feedstocks, resulting in bankruptcies, stalled projects, and significant profit losses for older technologies.[42,43]

Significant Impacts on the Planet: Climate, Toxics, and Plastics

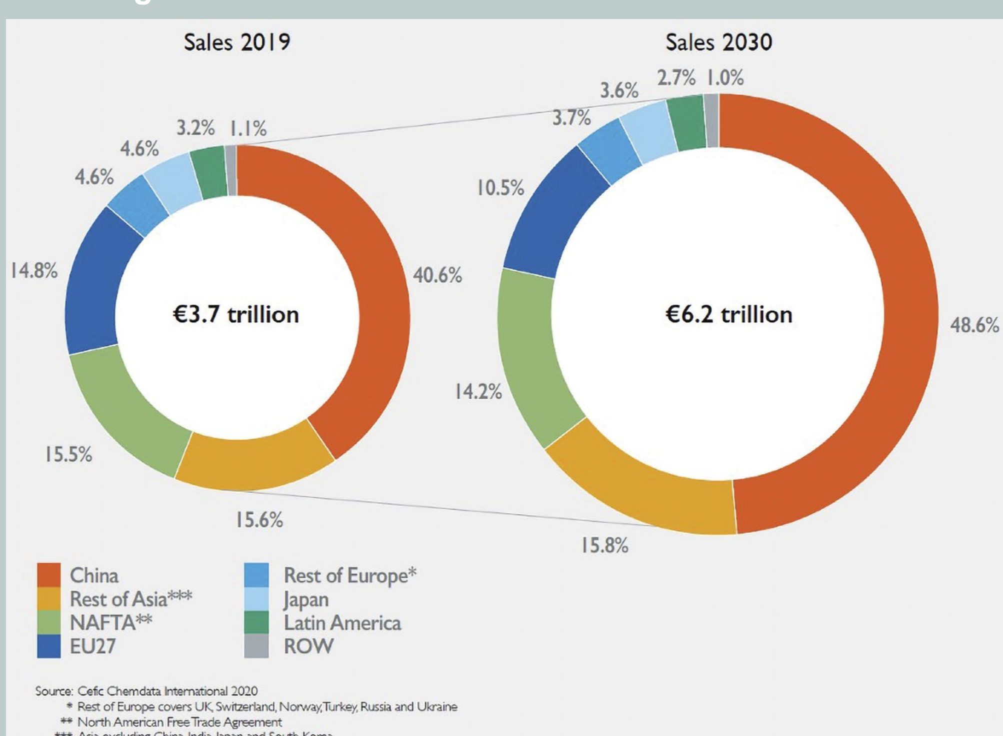
The industry's operations have resulted in well-established impacts on human, ecosystem, and planetary health, the costs of which are mostly externalized and hence not incorporated into the final costs of its products. Many of the chemicals on the market today were developed between the 1940s and 1960s with cost and performance, not health and safety, in mind. There was little, if any, government regulatory oversight of the industry. Since the 1970s, a plethora of U.S. and international laws have helped to reduce the industry's impacts on air and water pollution, hazardous waste generation, and human and environmental health and safety in high-income countries. However, these policies often take a "safe until proven dangerous" approach to impacts; are slow to address "emerging contaminants" where scientific uncertainty still exists; and often do not address the hazardous chemicals in products, disproportionate impacts on vulnerable and low-income populations, or the climate change impacts of the industry.[44]

Climate

The modern petrochemical industry accounts for 30% of global industrial energy demand, outstripping that of the iron, steel, and cement sectors. Annually, it generates 1.5 Gt of CO_2 globally, 18% of the industrial sector's greenhouse gas emissions. Nearly 85% of the chemical industry's CO_2 emissions come from its energy usage, with the remaining 15% generated as process emissions.[45] Overall, chemicals are responsible for 7% of global greenhouse gas emissions.[46] Non-CO_2 greenhouse gas emissions from the chemical sector are estimated at an additional 350–400 million tons of carbon dioxide equivalents ($MtCO_2$-eq).[47]

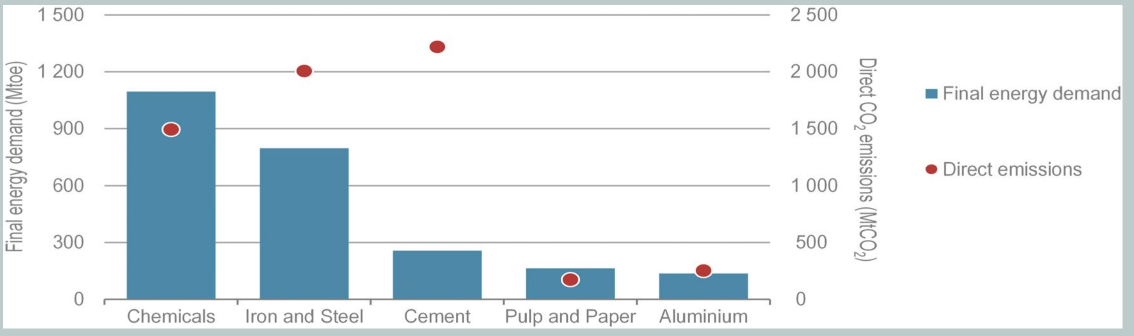
The manufacture of just 26 basic chemicals represents some 75% of the chemical sector's total energy use

Figure 3. Growth in World Chemical Sales 2019–2030



Source: Cefic Facts and Figures 2021 Leaflet, p. 7.

Figure 4. Global Final Energy Demand and Direct CO2 Emissions by Sector in 2017



Source: IEA/OECD (2018) The Future of Petrochemicals.

(including its feedstock) and more than 90% of its greenhouse gas emissions.[48] Feedstock choice matters. Endowed with coal, China produces more emissions from many of its processes than countries utilizing lighter raw materials like oil and natural gas.[49]

Health

The human and ecological health impacts of chemical industry products are well established, from the ozone hole (chlorofluorocarbons) to the near loss of the bald eagle (DDT). Many petrochemicals, from benzene and vinyl chloride to various brominated and perfluorinated compounds, are hazardous to humans and ecosystems and can persist in the environment or bioaccumulate in biological tissues. The United Nations Global Chemicals Outlook identifies known or suspected health impacts from chemical exposures, such as cancer, nervous system damage, sensitization, and endocrine and reproductive-system damage, that result in health costs upward of 10% of global gross domestic product (GDP), while the United States-based Collaborative on Health and Environment links chemical exposures to more than 180 different illnesses.[50,51] The World Health Organization conservatively estimates that 1.6 million lives and 45 million disability-adjusted life-years were lost in 2016 due to exposures to selected chemicals (not including many chemicals with known chronic impacts).[52]

Chemical exposures can occur within the chemical and product manufacturing production processes, during use in commercial products, and when products are discarded as wastes.[53] Large-scale chemical production facility disasters, like the 1984 methyl isocyanate

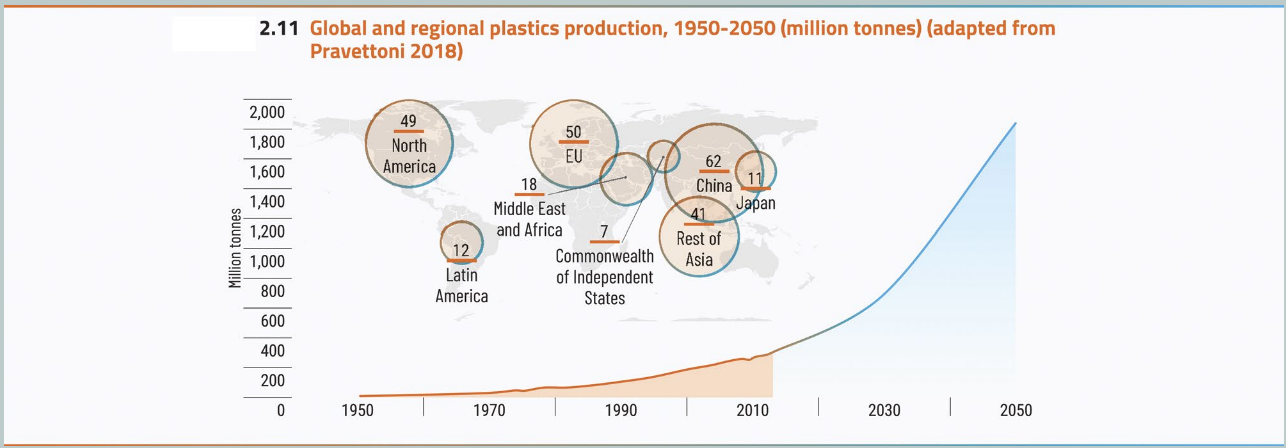
Unrecognized Impacts of Our Everyday Products—Environmental Justice

Areas of low income and communities of ethnic or racial minorities are often those most negatively impacted by chemical production facilities. Massive petrochemical complexes are necessarily sited near their fossil fuel supplies and transportation channels. This, combined with systemic discrimination and inequity, land use regulations, and lax oversight, has resulted in geographically concentrated petrochemical production facilities near socially and economically vulnerable communities.

Since 2015, seven new petrochemical facilities have been approved for siting along the stretch of the Mississippi River known as Cancer Alley, where nearby communities are often home to low-income and African American populations. A $9.4 billion petrochemicals and plastics megacomplex proposed by Taiwanese chemicals giant Formosa for this area would legally be allowed to emit more than 800 tons of toxic chemicals annually.[58] The United Nations Human Rights Commission condemned this, noting that it impacts the right to health and an adequate standard of living for these African American communities.[59]

Studies show that neighborhoods near chemical and energy production facilities in the United States have African American and Latino populations 75% and 60% higher than the national average, with 50% higher poverty rates.[60] Hazardous chemical waste treatment and disposal facilities are similarly disproportionately located in poor and minority communities worldwide. Modern e-waste, the most rapidly growing global waste stream, is commonly exported for processing to less developed countries, resulting in elevated human exposure to and environmental release of hazardous chemicals like heavy metals and dioxins.[61,62]

Figure 5. Global and Regional Plastics Production, 1950–2050 (million tons)



Source: UNEP Global Chemicals Outlook II 2019, p. 57 (adapted from Pravettoni 2018).

leak at the Union Carbide plant in Bhopal, India, which killed thousands, are fortunately rare, but smaller accidents occur on a regular basis. A study for the Organization for Economic Cooperation and Development (OECD) found that between October 2016 and September 2017 there were 579 deaths and 668 accidents or near misses reported in news media related to chemical incidents.[54] These will likely increase as climate change increases the vulnerability of plants located near coastlines. Chemical manufacturing can expose workers to well-recognized occupational carcinogens, and neighborhoods near petrochemical manufacturing facilities have been found to exhibit elevated rates of some cancers.[55,56] In high-consumption economies the use, storage, or disposal of consumer products cause the most widespread, significant hazardous chemical exposures. In many developing countries, exposures come from pesticide use, small-scale industry, extractive activities, and waste dumps.[57]

Plastics

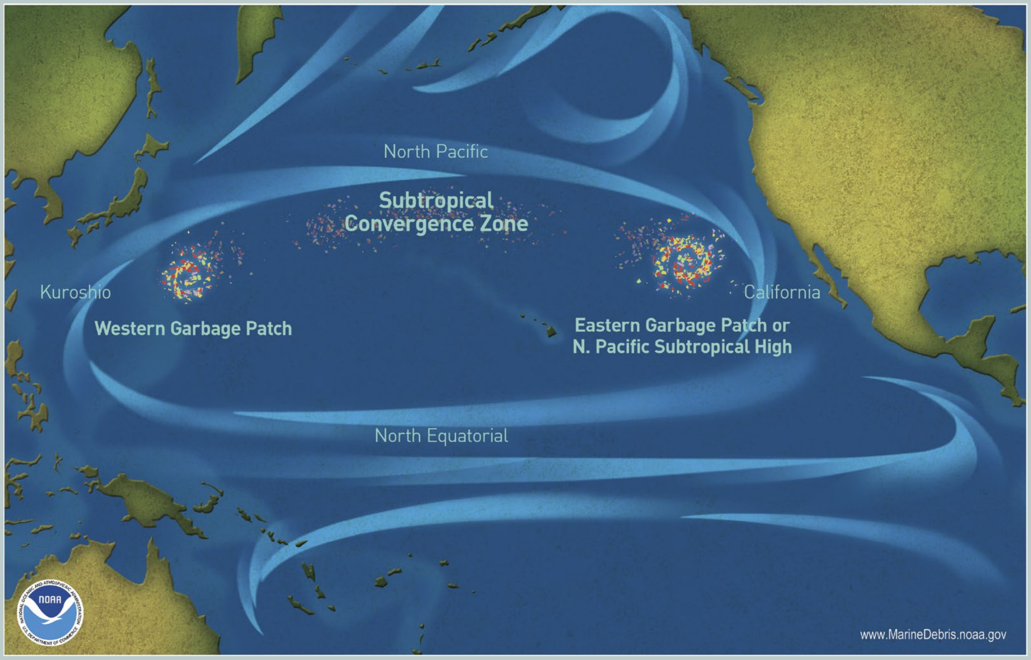
The most visible impact of the petrochemical industry is undoubtedly plastic waste. The properties that make plastics so attractive (durability, water resistance, lightweight, etc.) also make them problematic when released to the environment as wastes. Single-use plastics are the most common plastic product, accounting for one-third of all polymer production; their greenhouse gas emissions are projected to reach 309 million Mt by 2050.[63] With only about 9% of the 6.3 billion tons of plastic produced up to 2015 having been recycled, plastics create a pollution and global waste crisis, whether incinerated, collected in landfills, or disposed of in the ocean.[64]

Today 98% of single use plastics are manufactured with new (virgin) feedstocks. Material complexity, limited collection systems, high processing costs, and small markets for recycled materials have resulted in global recycling rates for most plastics under 10–15%.[65]

Without scalable end-of-life recycling and reuse solutions, plastics end up in landfills where they do not degrade, are dumped into rivers or open disposal facilities, or are burned for energy. Open burning, conducted in much of the world, is known to create persistent, bioaccumulative and toxic chemicals.[66] Incineration of various plastics, unless highly controlled, creates dioxins or heavy metals and generates carbon

Numerous plastic bottles and other waste floating on Bicaz Lake, Romania.

Figure 6. Pacific Ocean Garbage Patches: The Largest Is Estimated to be Three Times the Size of France Now



Source: NOAA 2014 The Global Plastic Breakdown: How Microplastics are Shredding Ocean Health.

Plastics in the Environment

Plastics that end up in nature can accumulate and disrupt ecosystems, be ingested by or ensnare wild animals, and gradually degrade into microplastics (pieces less than 5 mm in size). Visible impacts—like the Great Pacific Garbage Patch, sea turtles with straws stuck in their noses, or ocean birds' skeletons showing accumulated ingested plastic—are well documented, and research is growing on the harms of microplastics and nanoplastics (<100 nm). Areas of concern include chemical adsorption, bioaccumulation, and cellular damage.[68]

emissions. It is estimated that 0.9 Mt of net CO_2-equivalent emissions is generated for every 1 Mt of plastic burned, after accounting for the electricity generated from the combustion.[67]

Lessons From the History of the Petrochemical Industry

The exponential growth of the chemical industry and its products over a 30-year period is one of the great success stories of global industrialization; however, this growth took place with little attention to environmental and health impacts, and it followed the path of greatest convenience, resulting in an inflexible and stagnant industry. Understanding the factors that led to that growth and trajectory can help us design a future-fit industry that is adaptable and dynamic, with less collateral damage.

- *Basic academic research and development linked to applied research and development in firms is essential to developing the scientific breakthroughs necessary to build new innovations.* The innovations scaled up by the chemical industry during the 1940s–1960s had their origins in academic, government, and industrial research labs in the United States and Europe. Early collaboration between academic and industrial scientists meant that when new petrochemical feedstocks and processing methods became available, it was possible to scale quickly and effectively.
- *Novel chemistry must be coupled with engineering and technology innovation in order to reach production scale.* Chemical engineering firms played a critical role in building the infrastructure and perfecting the processes of the chemical industry. Modern computing and digitization now offer the possibility of harnessing big data to guide chemical and process research and development, predict chemical functionality and hazards, identify production routes, and improve efficiencies. Facility operational technologies like sophisticated sensors and networks can help monitor

and adjust processes and predict future risks.

- *Both sustained government investment and intervention are essential to accelerate the development and deployment of new chemistries*. Government-directed wartime efforts like investment, guaranteeing demand through military purchasing, encouraging collaboration between firms and end users, and shared patenting and licensing helped the chemical industry to grow rapidly in the United States.[69] Continued subsidies of the industry's fossil fuel feedstocks as well as other incentives for new manufacturing facilities sustained that growth. Similar government intervention and incentives will be required to reshape the industry, including careful reallocation of fossil fuel subsidies.
- *Basing growth on a limited palette of chemicals with small profit margins leads to lock-in and the motivation to create new demand or applications instead of new chemistries*. The explosion of single-use plastic polymers, replacing traditional materials, demonstrates this lock-in. A future chemical industry must be structured so that it is more innovative, flexible, and adaptable to changing conditions and evolving knowledge and less dependent on scale.
- *The greatest successes are achieved when there is sustained collaboration and communication between producers and downstream consumers*. The growth of many chemical products and technologies was based on licensing and collaboration between rival firms. The operating model for specialty chemical companies focuses on market awareness and understanding of desired functionality, which keeps businesses in sync with their consumers. Collaboration is important as downstream brands and retailers are increasingly subjected to consumer pressures for more sustainable products.
- *New molecules, materials, and processes need to be evaluated for their health and safety, societal, and environmental implications*. The industry grew with little focus on the environmental and health impacts of its production and products, and the costs have been high. Liability for the cleanup of hazardous waste sites, the damages to worker and consumer health, and the huge costs of compliance with government regulations all occurred because the chemical industry did little to understand chemical risks and prevent health and environmental exposures from the outset. A strong and consistently applied regulatory framework for chemicals can drive innovation, as well as provide incentives to address potential impacts at the design phase of chemicals and chemical processes.

Toxic chemical exposures are a threat to human and ecosystem health.

A Call to Action: The Chemical Industry Must Chart a New Course

Awakening to the climate and plastics crises, the chemical industry has begun to recognize its impacts and respond with new visions and initiatives, such as the European Chemical Industry Association, European Chemical Industry Council's Mid-Century Vision, and efforts such as the Alliance to End Plastics Waste.[70,71] While these steps are in the right direction, they focus on minimizing the impacts of the same chemistries and materials made in the same facilities with the same processes. Biologist Barry Commoner, after witnessing just two decades of the petrochemical revolution, called for a fundamental rethinking of the industry, observing in a 1973 keynote speech to the American Chemical Society: "What we can learn from the environmental impact of the petrochemical industry is that the industry needs to be redesigned to fulfill the needs of society, rather than its own internal economic logic; and to accord with the imperatives of the ecosphere and of the enhancement of human welfare."[72] Yet the status quo has persisted another four decades since then.

A transition strategy that results in a lower impact, more sustainable chemical industry is both necessary and urgent to address:

- *Fossil fuel dependency*. To meet the 2°C Paris Agreement target, one-third of oil reserves, half of gas reserves, and more than 80% of current coal reserves (the stranded assets) must not be combusted from 2010 to 2050.[73] The resources remaining must be used thoughtfully and in conjunction with clean energy and renewable feedstocks for chemical production.
- *Burdensome capital investments that prolong impacts*. Large capital investments in fossil-fuel-based infrastructure are barriers to adoption of new

The petrochemical industry is a significant contributor to the climate crisis.

technology and manufacturing models. Costly "steel in the ground" hampers new innovations and entrants to the market and inhibits the search for smaller scale, more flexible production technologies.

- *Supply chain vulnerability*. Disruptions caused by natural disasters, geopolitical turmoil, and changing government regulations can ricochet in a concentrated, integrated industry, impacting prices, feedstock, and product availability. The COVID-19 pandemic demonstrated the costs of sudden changes in government restrictions and trade dynamics to multi-tier supply chains.
- *Poor financial performance*. Many petrochemical products have low market returns and are only financially viable due to the profits of other co-products. In 2019, prepandemic earnings before interest and tax for the top 100 chemical companies fell on average 17.4% due to downward pressure on volumes, prices, and margins.[74]
- *Depressed research and development investment signals*. The industry has lost its once-lauded innovation leadership. Many major corporations have downsized their research divisions and limited investment in basic chemicals research and development. While China has prospered with growing numbers of patents, research output in most countries has fallen.[75]
- *Climate change pressures*. The global industry is a major source of greenhouse gas emissions. Renewable energy could eliminate 85% of the sector's CO_2 emissions, but feedstocks will also need to come from non-fossil sources.[76] The chemical industry must commit to the actions necessary to achieve the sectoral commitments that will support the achievement of Paris Agreement global warming goals.
- *Public health and environmental concerns*. A growing number of chemicals are being found in the environment and human tissues globally, with increasing evidence of myriad impacts on health and ecosystems. Chronic disease attributable to chemical exposure continues to create large social and economic costs, particularly on vulnerable populations.
- *Shifting consumer markets*. In many high-consumption economies, awareness of the hazards of climate change, plastics, and toxic chemicals is driving consumers to seek "greener" products, avoid single use plastics, and demand a nontoxic environment. Eco-friendly products are growing more rapidly in the marketplace than incumbents.[77] As consumer markets in industrializing countries grow, the demand for health-conscious and environmentally friendly products will increase. Increased recognition of the importance of reduced consumption of short-life and nonrenewable products is likely to occur.

Efforts to develop renewable feedstocks, substitute fossil energy, replace toxic chemicals, and design out waste and pollution are all worthwhile and needed. However, they are piecemeal initiatives and will be insufficient to accomplish the systems change necessary. The chemical industry must begin a global transition toward a new, sustainable paradigm. Investment in the polluting petrochemical production of the past must end, and investments in the research and broad development and deployment of the sustainable products and processes of the future must accelerate.

History shows that not only is industrial metamorphosis possible, but it drives innovation, job growth, and economic development. The global chemical industry needs to shift from its fossil fuel base and ensure that its growth, now predominantly in industrializing countries, will be safe and sustainable. Looming climatic, ecological, and human health tipping points more than validate a coordinated wartime-level approach—that begins with a strategic transition roadmap. Investments in the COVID-19 pandemic recovery pose an unprecedented opportunity to "Build Back Better," and the chemical industry must play an integral part if the effort is to be fully successful.

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NOTES

* We discuss the outline of a roadmap to transition the chemical industry in the forthcoming article "Transitioning the Chemicals Industry: Developing a Roadmap for Sustainable Chemicals and Materials," to be published in an upcoming issue of *Environment* Magazine.

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