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To: Environment Committee of the Refinery Advisory Group

From: Dr. Nadine Gruhn, Managing Director, and Prof. Karen Goldberg, Director, Vagelos Institute for Energy Science and Technology, University of Pennsylvania

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Subject: Comments for August 27th public meeting: a non-petroleum-based future for the PES site in the new chemical economy

The history of the Philadelphia Energy Solutions (PES) Philadelphia Refining Complex is a prime example of how the petroleum industry helped transform the world from the pre-industrial society of the 19th century to the current day. This site has produced petroleum-based fuels since 1866. The first major product was kerosene, used for lighting. The site began manufacturing gasoline in 1915 and continued to do so into the current day. The technologies used to make gasoline and other liquid fuels from petroleum are based on a series of chemical and physical transformations. While chemistry and other sciences and technologies have made enormous advances in the past 100 years, petroleum refineries such as PES have continued to operate in almost the same way since the early 20th century. As new technologies are developed that produce the goods that society needs in ways that produce less waste and pollution and are simply more economical, old school refineries face a continued uphill battle to remain open, even without a devastating accident such as the one at PES. Furthermore, with the advent of renewable energy and the rapid rise of solar and wind, petroleum refining will not be able to continue as it has for the past 100 years. Companies are already moving to retrofit refineries around the globe to attempt to convert a larger fraction of crude oil to chemicals rather than gasoline.[1] This is a challenging endeavor from an economic standpoint and it not clear that profit margins that were based on the large amounts of gasoline produced through refining will be sustainable in the future. Chemicals, on the other hand, are used to make a large range of

[1] "Why the future of oil is in chemicals, not fuels", Chemical and Engineering News, Volume 97, issue 8, February 20, 2019. https://cen.acs.org/business/petrochemicals/future-oil-chemicals-fuels/97/i8

consumer goods including plastics, textiles, agricultural products and pharmacueticals. *We are at a critical moment to plan proactively for the inevitable separation of the chemical and petroleum sectors.* Transitioning from petroleum as the source of our carbon-based chemicals presents a tremendous opportunity to design the businesses, chemicals and processes that will enable a sustainable and prosperous future.

Petroleum refining led to today's chemical industry. Indeed, the two are so closely linked that the terms "chemical industry" and "petrochemical industry" are used interchangeably. The global chemical industry is a major pillar of modern society and one of its greatest success stories. Virtually all of the material goods that we use – polymers and plastics; medicines; the fibers used to make clothing, textiles, and carpets; paints and glues; detergents, soaps, shampoos and body care products; and pesticides and fertilizers, are made from "chemicals." In the U.S. the chemical industry comprises approximately 15% of the nation's manufacturing sector with a gross output of $862.5 billion in 2018,[2] and makes a major positive contribution to our trade balance. It directly employs over a million people, and moreover, every chemical manufacturing job creates over seven additional jobs elsewhere in the economy.[3] Society's need for products made from "chemicals" will continue long after our energy sector has completely transitioned away from using petroleum.

Although petrochemicals only account for ~6% of fossil fuel usage, they account for ~90% of the total feedstocks used by the chemical industry. These critical carbon-based chemical building blocks are currently available in sufficient supply and at low cost due to the economy of scale of the enormous petroleum refining industry of which PES was a part. Indeed, in addition to fuels, PES produced cumene, a chemical that is a basic building block used to make many products including nylon, detergents, and medicines.

[2] U.S. Bureau of Economic Analysis, "Interactive Access to Industry Economic Accounts Data: GDP by Industry", Release Date: April 19, 2019. https://apps.bea.gov/iTable/iTable.cfm?ReqID=51&step=1
[3] Elements of the Business of Chemistry, American Chemistry Council, 2018. https://www.americanchemistry.com/2018-Elements-of-the-Business-of-Chemistry.pdf

A shift within the fossil fuel supply is already rapidly occurring, particularly in the US, from coal, and the conventional heavy petroleum that PES used at a starting material, to natural gas and light alkanes. On the demand side, meanwhile, refineries are facing a shift away from gasoline to diesel and jet fuel as fuel economies increase and as passenger vehicles transition to hybrid or full electrical power sources. These changes present huge challenges to the petroleum and chemical industries; they also represent huge opportunities. Fundamental changes in the chemical industry are required as the fossil fuel industry changes, and as the global energy supply necessarily shifts from fossil fuels to renewables, including solar and wind. This is one of the grand challenges and grand opportunities for science, technology, and business: enabling the transition of the chemical industry away from its petrochemical roots, and its transformation to a chemical industry appropriate for the late 21st century and beyond.

Many companies are currently opening both pilot and production size plants with new technology that do not rely on petroleum. Much more basic knowledge and new methods are in development in academic, government, and industrial research and development labs that will accelerate the shift to new technologies. Together, these market and technology drivers are making it increasingly difficult for plants using old refining technology to make a profit, a situation that will continue to become more and more difficult. The following paragraphs describe a few transformations that have particular promise for altering the chemical industry. These examples include areas where the faculty, postdocs and students in the Vagelos Institute for Energy Science and Technology at the University of Pennsylvania are working to develop new methods that will use less energy and help the transition away from petroleum as the source for chemicals.

One transformation of interest is the reduction of carbon dioxide (CO_2) to make methanol. Methanol is one of the current chemical building blocks of the chemical industry (110 million metric tons per year) with a host of commodity chemicals and even hydrocarbon fuels produced from this versatile building block that is currently made from petroleum or natural gas.[4] The use

[4] Methanol Institute. Methanol Price and Supply/Demand. https://www.methanol.org/methanol-price-supply-demand/

of CO_2 to produce methanol is currently operational in one location in Iceland at the George Olah Renewable Methanol Plant.[5] Iceland's access to abundant geothermal energy affords a competitive advantage to implement this process; the technology has not yet been adopted elsewhere due to the large energy cost required to generate H_2.

However, as the energy sector moves to renewables, electricity and hydrogen from water splitting are beginning to become widely available and cost effective. For example, in 2020 Air Liquide Canada and Hydrogenics are opening the world's largest electrolyzer to make carbon-free hydrogen.[6] The facility's proximity to major industrial markets in Canada and the United States will supply low-carbon hydrogen for industry and mobility usage. Hydrogenics has more than 500 active electrolyzers in operation globally.

There is an inexhaustible global supply of methane for the foreseeable future. The U.S. Energy Information Administration estimated in 2016 that there were more than 2,400 trillion cubic feet of recoverable natural gas in the United States alone; a 100-year supply. Further, estimates of methane clathrate deposits far exceed the world's petroleum, natural gas and coal reserves combined. From this viewpoint, methane is a unique candidate molecule as a starting point for a new chemical industry. It is energy-rich, abundant, and a potential source for all the basic chemical building blocks. Commercial methane valorization still relies largely on steam reforming, which requires enormous production facilities operating at very high temperatures. Indeed, half of the methane input for steam reforming is burned to achieve those high temperatures. Many stranded methane sources are simply flared, wasting a potentially valuable resource. This scenario is not sustainable. One particular focus of the research in the Vagelos Institute is developing strategies for the utilization of methane through partial oxidation, including the use of abundant and benign oxygen from the air as an oxidant.

[5] Carbon Recycling International. The George Olah Renewable Methanol Plant. https://www.carbonrecycling.is/george-olah
[6] Air Liquide Canada Invests in World's Largest Hydrogen Electrolysis Plant. https://www.energymanagertoday.com/hydrogen-electrolysis-0181719/

As one last example of the likely future of the chemical industry, a consortium of companies including Enerkem and Shell are opening a trash-to-chemicals plant in Rotterdam. The plant will annually convert 300,000 tons of waste—equivalent to the waste from over 700,000 households—into bio-methanol. Enerkem is said to be looking to open additional plants in several other locations including sites in the United States.[7]

In summary, now is the time to ask what *would the chemical industry look like if we built it again?* Starting from "scratch" provides the opportunity to build a smart chemical industry. To date, the industry has been dominated by building blocks made available and economical by the large-scale processing of oil. This inter-relationship is being disrupted from several sources. Transitions must begin now, understanding that the chemical industry operates on a decadal time frame to bring new large-scale commodity manufacturing technologies to market. Sound principles upon which this new economy and industry will be based must be articulated so that goals are clear for technology development. It is essential to cultivate an industry that does not waste resources, one that intelligently captures the resources the earth offers, and that generates products with low impact life cycles. While transitioning from petroleum as the source of our carbon-based chemicals poses a great challenge, it also presents a tremendous opportunity for a sustainable and prosperous future.

[7] Shell joins Air Liquide, Nouryon in Enerkem waste-to-chemicals project in Rotterdam: the complete story. http://www.biofuelsdigest.com/bdigest/2019/03/01/shell-joins-air-liquide-nouryon-in-enerkem-waste-to-chemicals-project-in-rotterdam-the-complete-story/