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OIL SHAKE-UP: REFINING TRANSITIONS IN A LOW-CARBON ECONOMY

DEBORAH GORDON AND MADHAV ACHARYA | APRIL 2018

Government policies aimed at reducing environmental threats from climate change have fueled renewable energy breakthroughs and cost reductions over the past decade. But even as nations and several U.S. states set renewable energy targets out to 2050 and push for 100 percent renewable energy usage, questions remain about whether these energy sources can sufficiently power the electric grid. At the same time, the maturation of electric cars and trucks, further increases in vehicle fuel efficiency, and other breakthrough technologies are raising critical questions about future oil demand.

There's a loud buzz about the coming demise of internal combustion engines, an outcome that would significantly reduce gasoline and diesel consumption. But just how such disruptive transport innovations might ripple through the petroleum sector has not been adequately explored.

Most analyses take a simplistic view of one of the world's most complex and tightly integrated manufacturing operations—refining. They miss the underlying dynamics of refining processes that form the building blocks upon which modern society rests. And those dynamics illuminate the difficulties that could arise in transitioning away from oil.

In practical terms, that transition can have unintended consequences if attempts are made to replace petroleum products slowly and in an isolated, piecemeal fashion. Driving change in this sector will require that policymakers look holistically at the entire refining process, probe the potential for its own disruptive innovations, and steer the low-carbon oil transition toward a new slate of petroleum products. The better decisionmakers understand the workings of the economic activity—petroleum refining—that is poised to be disrupted, the more likely it is that sustainable outcomes will result.

PETROLEUM'S VALUE PROPOSITION

Products of petroleum refining are typically associated with fueling our mobility—cars, trucks, trains, ships, and planes. While it's true that about two-thirds of the world's refined oil ends up flowing to the transportation sector, the remaining petroleum products are present, yet largely invisible to the public, in just about every other economic sphere—industrial, commercial, agricultural, and residential. Petroleum finds its way into pharmaceuticals, textiles, cosmetics, medicines,

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Figure 1: Petroleum in Daily Life

Common Petroleum Products

Consumer Fuels
- Gasoline
- Diesel
- Heating Oil
- Propane
- Kerosene
- Liquefied Petroleum Gas
- Natural Gas

Commercial and Industrial Fuels
- Bunker Fuel
- Jet Fuel
- Petroleum Coke
- Fuel Oils and Distillates

Industrial Inputs
- Petrochemicals
- Sulfur

Infrastructure
- Asphalt
- Tar

Other
- Paraffin Wax
- Lubricants

Petroleum in Common Products

Health and Beauty
- Cosmetics
- Shampoo/Soap
- Bandages
- Petroleum Jelly
- Vitamin Capsules

Electronics
- Computers
- Televisions
- Smartphones

Household
- Cleaning Products
- Trash Bags
- Candles
- Paint
- Roofing/Insulation
- Carpet/Upholstery

Personal Items
- Clothes
- Glasses/Contacts
- Dentures
- Toys/Crayons

Note: This not an exhaustive list; oil is used as feedstock for thousands of consumer goods and industrial processes.

electronics, and thousands of other common consumer products (see figure 1 for examples).

Even renewable energy sources such as wind turbines and solar panels require oil in their manufacturing, installation, and upkeep. And the millions of new electric vehicles (EVs) envisioned to reduce demand for oil contain many plastic parts (such as seats, dashboards, and bumpers) and rubber tires that are also derived from oil. So, while an EV doesn't need to be fueled by oil, its existence still involves oil and its many by-products.

The sheer diversity of the resource's applications has embedded oil in society over the course of millennia. As long ago as 4,000 BCE, petroleum asphalt was quarried and used as mortar between building stones, as caulking for ships, as waterproofing for baths, and as an adhesive for weapon handles. In China, by 1 AD, bamboo pipes carried oil and gas into homes for heat and light. The invention of the steam engine in the mid-1700s sparked the use of coal in transportation. But coal would soon be replaced as the dominant source of energy by petroleum when the first modern oil well was drilled in 1859.

The gush of crude oil that followed inspired new ways to get value from this commodity. In its raw form, crude oil is essentially useless to consumers. But after it is converted into petroleum products during the refining process, it is incredibly valuable. Today, the petroleum industry is the largest in the world, bigger than all other raw material markets combined.

TURNING OIL INTO PETROLEUM PRODUCTS

A modern oil refinery is a gargantuan system of processing equipment that heats, cleaves, and mixes each drop that it is fed into something of value. This process entails a complicated balancing act that must take into account both the technical and the economic feasibility of turning useless crude oil into usable petroleum. In order to accomplish this, very little oil entering the refinery goes to waste. Such refining efficiencies make it difficult to achieve oil decarbonization goals because eliminating individual petroleum streams requires overall system reconfiguration that may not be possible under current conditions.

The first oil refineries were little more than kettles for boiling oil into kerosene, a cleaner-burning lamp oil that replaced whale oil and animal fat. Since then, major engineering efforts transformed refining as Henry Ford launched the world's first mass-produced car in the early 1900s, the Second World War called for high-octane fuels for aircraft and synthetic rubber for tires, and postwar car ownership and the use of plastics exploded. The uptake of petroleum products followed globally, fueled by policies that linked economic growth to energy use.

Today, refineries operate in nearly every industrialized country, and oil feedstock and end-use petroleum products are shipped worldwide. By January 2018, 91 million barrels of oil per day were being refined globally—roughly double the volume in 1970 and nine times more than in 1950.

The massive volume of oil and petroleum products moving around the globe is underpinned by capital investments that cover time periods of a half-century or longer, making them costly to dismantle in response to climate change. Refineries continue to expand and adapt as new oils are produced, such as fracked condensates and oil sands, in order to meet petroleum product demands.

REGIONAL REFINING DIFFERENCES

In some areas of the world, refining is in fact expanding quite rapidly. These expansions extend refinery lifetimes, making it increasingly difficult for nations to transition off oil. How this aligns with meeting climate goals is cause for concern.

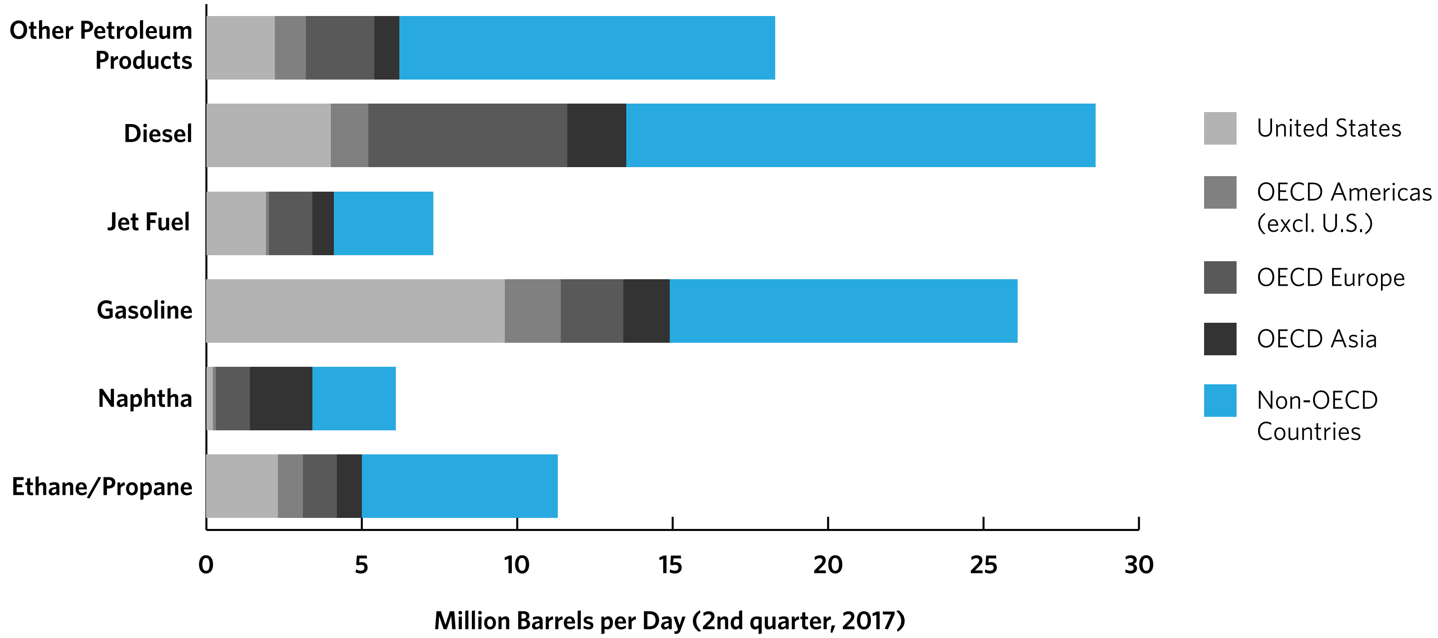
Between 2010 and 2017, nations' refining capacity—the volume of crude throughput—grew markedly in the Middle East and parts of Asia: : India (68 percent), Iraq (54 percent), China (53 percent), the UAE (43 percent), Iran (41 percent), and Saudi Arabia (40 percent). In many of these countries, new refinery construction also took off in this time frame. For example, India's Reliance Industries expanded its existing refinery into the world's largest single refinery complex with a capacity in excess of 1.2 million barrels a day. And additional new infrastructure is slated; in Iran and Saudi Arabia (where the ban on women driving will soon be lifted, potentially increasing the consumption of gasoline and diesel), a total of 8 million barrels per day of refining capacity is being planned.

Even the massive U.S. refining sector, which is nearly twice the size of its nearest competitor (China), increased capacity by 4 percent during this period. There were also many countries whose refining capacity remained constant, including in Latin America and elsewhere in Asia.

These trends are driven by the need for greater short-term energy security and economic returns. In much of the world, the plan is for more oil to flow through refineries to consumers.

In Europe, refining trends are strikingly different. Other than Spain, where refining capacity increased appreciably (12 percent), many European Union nations didn't see a change in refinery throughput between 2010 and 2017. Overall, however, Europe's refining sector has been in noticeable decline—from Russia (down 6 percent) to France and the UK (down 29 and 26 percent, respectively).

Figure 2: Global Petroleum Product Demand



Note: Other petroleum products include products such as petroleum coke, lubricants, waxes, solvents, still gas, and sulfur. Ethane/Propane uses are split, depending on the region, between petrochemical feedstock (ethylene and propylene) and liquefied petroleum gas for fuel (propane and butane). Naphtha is a multipurpose petroleum product used to make high-grade gasoline, as a solvent (for example, as a paint thinner and in cleaning agents in dry cleaning), and to dilute heavier oils.

Source: Authors' calculations using International Energy Agency data, OECD (graph, page 5) and non-OECD (graph, page 9), https://www.iea.org/media/omrreports/fullissues/2017-08-11.pdf.

Reductions in Europe did not counterbalance the uptick in oil refining and petroleum consumption in Asia and the Middle East. While the OECD countries were once the largest consumers of petroleum products, today non-OECD countries are consuming nearly as much gasoline, diesel, jet fuel, and petrochemical feedstock (naphtha, ethane, and propane) for further processing into plastics, fertilizer, and chemicals (see figure 2). This is particularly true for petrochemical feedstock; in non-OECD nations, a significant amount of financing is flowing into new and expanded processing plants needed to produce petrochemicals. And the other refined oil products made from a barrel of oil—such as propane, petroleum coke, lubricants, waxes, solvents, and sulfur—are also in high demand in non-OECD countries. It doesn't appear that non-OECD countries that currently consume a growing proportion of the world's petroleum products will be able to easily wean themselves off the myriad of oil products. Those countries that try to cut consumption of select products like gasoline and diesel could find it to be much more complicated than they expect, given the intricacies of refining.

What is more, even if they succeed in refining and consuming less of individual products, they can export them. The ease with which petroleum products trade in international markets makes it all too easy for greenhouse gas emissions to leak beyond national borders.

REFINING UNDER A DECARBONIZATION IMPERATIVE

A number of recent national and international decisions target the refining system. In 2015, the G7 nations called for a first-of-its-kind complete decarbonization of their economies by the end of the century. Here Europe has an edge on others;

with downward trends in refining and consumption, European countries can bolster their climate goals with policies. The governments of the UK and France—representing the second- and third-largest car markets in the European Union, respectively—announced plans to ban petroleum-fueled vehicles by 2040. Germany's Bundesrat passed a nonbinding resolution—more sweeping than the UK and France's plans—that called for the European Commission to effectively ban internal combustion engine vehicles from EU roads by 2030. And Swedish automaker Volvo stated that it would design only hybrid and electric vehicles starting in 2019.

In Asia, however, hefty investments in refining infrastructure and expanded operations are not clearly aligned with decarbonization goals. So, as India and China work on plans to enable EVs—or perhaps ban cars that run only on fossil fuels—they are not sufficiently confronting the realities of how lower gasoline consumption will square with higher refining capacity, especially in an economic sector that is so efficiently designed.

Beyond cars and trucks, there are yet other disruptive innovations envisioned that, taken together, could shrink the refining sector's current product slate. Tesla's Elon Musk, for example, is discussing intercontinental rockets that could replace today's airline travel. These could run directly on natural gas, which requires simpler processing facilities than a refinery. Musk, along with Virgin's Richard Branson, launched the Boring Company, which is building a pilot-scale hyperloop that uses pressurized tubes in underground tunnels to propel items at high speeds. Hyperloops would provide regional transport for passengers and freight, replacing airplanes running on aviation fuel, trains using diesel, and cars and trucks that travel longer distances and do not lend themselves to electrification.

The petroleum industry's response to efforts to decarbonize transportation has been quite varied. While European companies have started to slowly explore the opportunity to fuel electric vehicles or invest in renewable power, U.S. companies have tended to be more cautious, viewing the threat from alternatives to be of low consequence even by midcentury.

It is true that, at least in the near term, refineries in the West could export surplus gasoline displaced by EVs to non-OECD nations, especially those experiencing economic growth. (This is the most likely outcome of a slow increase in EV penetration.) Depressed gasoline and diesel prices that stem from the surplus would ignite new product demand. And the fact that fuel formulations are more tightly regulated in the West could cut out extra refining steps, marginally increasing those refiners' profit margins. In other words, if OECD refiners secure product markets in non-OECD countries, they may benefit economically even as domestic consumption is curtailed. Alternatively, the price of certain petroleum products, such as jet fuel, could rise as the consumption of gasoline and diesel fall.

In the long term, there are a number of ways to remix and reprice the underlying components of oil into different product formulations that could also help the industry respond to shifts in the market. It is more a matter of the price of those products relative to their substitutes, although safety, availability, ease of use, and other factors also weigh in. Generally, the lower the price, the greater the market potential for new petroleum product configurations.

But if automotive decarbonization policies materialize and hasten to spread globally, their effect, in theory, will be to undo the gradual, historic expansion from kerosene in lamps to gasoline in cars to jet fuel in planes that the industry has engineered over the past century. Such a major shift away from individual, established petroleum products has never been charted. Successfully decarbonizing refining will require reconfiguring major refining enterprises with global assets valued at nearly $1 trillion. Product shortages and price spikes could result, especially in the short term, if refiners cannot fulfill their market commitments to cost-effectively supply a wide array of petroleum products to consumers around the world.

REMAKING REFINING

While financial gains from producing oil and trading its by-products can be enormous, refineries—the middle men in the operation—have historically been far less lucrative, running on slim margins. When times are good, a single refinery with an optimal crude flow and strategic location can be a cash cow. But unplanned downtime of even a few days (as happened in the United States after Hurricane Harvey in summer 2017) can quickly turn a refinery into a money pit. Just like airlines, which only make money when their planes are in the air, refineries only make money when they're running flat out, making a full slate of petroleum products.

But what happens if society no longer utilizes a growing portion of a refinery's products? In principle, large portions of the product slate including petrochemical feedstock, gasoline, diesel, and fuel oil can be replaced in the short run through alternate routes (see figure 3 for the major products of refining). However, jet fuel, asphalt, lubricants, waxes, tar, and sulfur cannot; here it will be technologically more challenging—or perhaps even impossible—to develop market-ready, affordable, low-carbon substitutes.

The process of replacing jet fuel will certainly be far slower than the adoption of EVs, for instance. Bio-jet fuel is manufactured from renewable feedstocks such as sugar, corn, or forest wastes. While bio-jet fuel is being made in small amounts, it will likely be many decades before all airports and aircraft are retrofitted for its universal, safe use. The prospect that liquid fuels will be obtained directly from renewable energy (the so-called solar fuels) is even more distant.

The same is true of a product as humble—and cheap—as asphalt. Solar roadways, recycled tires and printer toners, and low-greenhouse-gas cement notwithstanding, the residual solids left over from refining heavy oils will continue to provide pavement on which cleaner cars are driven for countless miles.

If EVs replaced gasoline-powered cars or bio-based petrochemical feedstocks replaced ethane, for example, a refinery would not be able to sell the isolated, displaced commodities in its product slate. In response, markets would drive the value of these displaced products to zero; but refiners would still try to derive some benefit from their original oil building blocks.

There is a range of options refiners would want to consider. They could burn the "zero-value" products to generate energy. While this would help refiners efficiently use all their products, it would not reduce overall greenhouse gas emissions. Additional carbon-capture equipment might be required on-site, which would greatly increase cost and shift operational priorities.

Alternatively, they could develop new formulations of existing products or create new petroleum products altogether using these unwanted molecules, provided that these options are technically feasible and affordable, and that they achieve climate goals.

Reworking all the processes in the refinery so that molecules can be converted into a subset of desired end products is also a possibility. Such change will come at a price. Refinery modifications tend to be very capital intensive; witness the tens of billions of dollars that the United States spent a decade ago to retrofit its refineries so they could process Canadian oil sands. In the long run, large, integrated refinery-petrochemical plants could give way to smaller, bespoke operations that convert different feedstocks into a small number of finished products.

Or refiners could explore using new techniques with microbes and nanotechnology to effectively refine oil underground in order to selectively produce low-carbon petroleum products. The complexity of such a task would likely be beyond the scope of any single petroleum producer.

Any of these options, as well as other future possibilities, could result if refiners jettison parts of their product slate. This could further complicate decarbonization efforts.

MAKING THE SHIFT

Energy transitions typically take much longer than policymakers envision. A new approach to oil refining will require major modifications to the long-honed, durable petroleum system. If economy-wide decarbonization is going to be

Figure 3: Refining Shifts to Low-Greenhouse-Gas Product Slates

PETROLEUM PRODUCTS	Cost and Technical Barriers	LOW-GHG SUBSTITUTES
Gasoline and Diesel (cars, trucks)	LOW	**Electric Vehicles (with renewable power)**
Fuel Oils and Distillates (engines, boilers)		**Direct From Natural Gas (no methane leakage)**
Liquefied Petroleum Gas: Propane and Butane (cooking, heating, vehicles)		**Bio-Based Liquefied Petroleum Gas**
Ethane and Naphtha (plastics, solvents, fuel additives)		**Bio-Based Petrochemical Feedstock**
Residual Fuels and Bunker Fuels (ships, power plants, industry)		**Liquefied Natural Gas**
Asphalt (roadway paving)		**Low-GHG Concrete**
Hydrogen (refining, fertilizers, pharmaceuticals, polymers)		**Renewable Electrolysis of Water**
Jet Fuel (airplanes) **Lubricants** (transport and industrial applications, metalworking) **Waxes** (foods, cosmetics, polishes, coatings, 3D printing) **Tar** (paints, sealers)		**Bio-Based Alternatives**
Sulfur (rubber, gunpowder, fungicide, medicines)	HIGH	**Surface Mining From Volcanoes**

accomplished, it will not be enough to simply advance sales of cleaner substitutes like EVs. It is one thing to craft a policy that steers cars and trucks away from petroleum. It is quite another to assume that these will result in successfully backing oil out of the economy.

For the global refining sector to profitably make an ever-shrinking slate of products, the petroleum industry will need a twenty-first-century technology makeover. Making the shift against a dynamic backdrop of market, geopolitical, and social pressures on refiners will be even more difficult. Refining innovations will have to square with policy mandates to meet decarbonization goals as well as address local environmental challenges. Refiners will have to be conscious of fickle consumer preferences and changing product demands as they respond to disruptive innovations in all economic sectors.

The challenge to develop new and retrofit old processes will require mobilizing technical resources on national and international scales—especially in non-OECD countries where new refining capacity is expanding, but also in the United States where there is a large amount of existing capacity. Even if new manufacturing units, such as bio-refineries or renewable-energy-powered electrolyzers, are technically feasible, entirely new processes and capital will need to be put in place to make the necessary shifts a reality, and the price tag for that will not be low. It might require the establishment of joint public-private blue-ribbon panels to identify key technical gaps in the fuel and chemical manufacturing processes of the future. This could be integrated with creative mechanisms and competitions, such as the X Prize, that fund the design and implementation of models that solve challenges on a global scale.

As momentum builds behind efforts to shift to a low-carbon global economy, it is critical to start thinking about how decarbonization efforts will impact a strategically honed industry like oil refining that's over a century in the making. To minimize unintended energy, economic, and environmental consequences, a road map for the future needs to account for all petroleum shifts, not just the ones that capture the most attention.

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