U.S. DEPARTMENT OF ENERGY

Natural Gas Liquids Primer

With a Focus on the Appalachian Region

June 2018

United States Department of Energy
Washington, DC 20585

Note to Readers

The Office of Fossil Energy is pleased to provide this updated version of the *Natural Gas Liquids Primer*. Since the first publication of the primer in December 2017, the U.S. Energy Information Administration (EIA) published the *Annual Energy Outlook 2018* (AEO 2018). Updates included in this June 2018 version of the primer are:

- Updated statistics and projections from AEO 2018 Reference case relevant to natural gas and natural gas liquids;
- Updated statistics and projections from EIA's *Short-Term Energy Outlook* published in February 2018;
- Updated information regarding infrastructure developments in the Appalachian region; and
- Identification of research and development opportunities related to natural gas and natural gas liquids production, conversion, and storage.

Long-term projections depend on many assumptions. The AEO 2018 Reference case is one of several scenarios that explore uncertainties related to resource size, technology improvement rates, economic growth and global oil and natural gas prices. Additional cases are available in the AEO 2018.

Data used in the charts showing Appalachian production include all of the East region of the U.S. as defined by EIA for the purpose of modeling in the Oil and Gas Supply Module of the Annual Energy Outlook (https://www.eia.gov/outlooks/aeo/assumptions/pdf/oilgas.pdf). The Appalachian region includes the prolific Marcellus and Utica formations which lie within the borders of Kentucky, Ohio, Pennsylvania, and West Virginia. In 2016, natural gas production in these four states accounted for 97% of total East region production. While data in the charts represent the entire region, the figures are an appropriate representation of Appalachian production.

Executive Summary

The ongoing renaissance in oil and natural gas production in the United States has provided economic benefits across the country through higher employment and lower energy prices. The growth of production has occurred in regions of the country with significant resources in shale formations, which are unlocked through unconventional production techniques. One such region is Appalachia with the Marcellus and Utica shale formations.

The Appalachian region has experienced near-exponential growth in natural gas production (see Figure ES-1), and that production is expected to increase for decades to come.[1, 2] The U.S. Energy Information Administration (EIA) projects natural gas production in the East region, where the Appalachian Basin is the principal contributor to production, to quadruple from 2013 to 2050. The natural gas produced in Appalachia contains valuable resources in the form of natural gas liquids (NGL), including ethane and propane. When separated from the natural gas stream, ethane and propane are key feedstocks for the petrochemical industry, used to produce compounds for making plastics and resins. Appalachian natural gas plant liquids production is projected to increase over 700 percent in the 10 years from 2013 to 2023 (see Figure ES-2).[3]

Figure ES-1: East Region Natural Gas Production

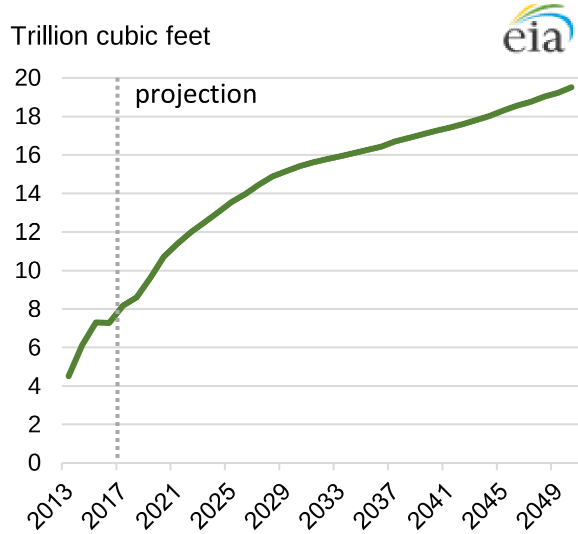
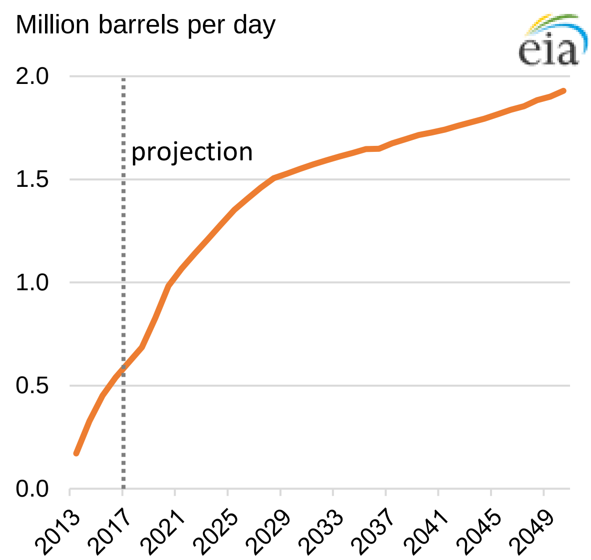


Figure ES-2: East Region Natural Gas Plant Liquids Production



Leaders across the Appalachian region have identified the potential economic opportunity presented by these significant NGL resources. To contribute to this dialogue, the U.S. Department of Energy (DOE) created this primer to educate the public on NGLs – what they are, how they are used, recent market developments, and the supporting infrastructure in the region. This document includes the most recent information from DOE and EIA on Appalachian NGL supply, demand, and infrastructure.

Industry has made significant investments in natural gas and NGL infrastructure to support the boom in production in Appalachia this decade. New investments to take advantage of the NGL resources in the region have been identified by industry, and forecasts for production over the decades to come highlight the opportunity for additional investments across the NGL supply chain.

NATURAL GAS LIQUIDS PRIMER

With a Focus on the Appalachian Region

Table of Contents

I. Introduction

The application of horizontal drilling and hydraulic fracturing techniques in oil and gas production has revolutionized the energy system of the United States. By unlocking the hydrocarbon resources in low permeability shale formations, the United States produces more natural gas than any other country in the world. This oil and gas production renaissance has created new economies in regions of the country that previously had little conventional production, such as Ohio, Pennsylvania, and West Virginia. The Appalachian region has experienced near-exponential growth in natural gas production over the past decade; Pennsylvania alone produces more natural gas than all but five countries.[4]

Natural gas production in the Appalachian region yields an added benefit in the form of natural gas liquids (NGLs). NGLs are hydrocarbons — in the same family of molecules as natural gas and crude oil, composed exclusively of carbon and hydrogen. Ethane, propane, butane, isobutane, and natural gasoline (pentanes plus) are all NGLs. Use of NGLs spans nearly all sectors of the economy. NGLs are used as inputs for petrochemical plants, burned for space heating and cooking, and blended into vehicle fuel. Significant volumes of NGLs are being produced in the Appalachian region. These resources are often shipped to other domestic markets for use or left unseparated in the natural gas stream, representing unrealized potential.

The opportunity to take advantage of the full economic value of NGLs produced in Appalachia has been identified by regional leaders. The Department of Energy (DOE) has prepared this document to educate the public and enhance the discussion regarding NGL resources and related infrastructure in the Appalachian region. Unless otherwise noted, projections in this document are from the U.S. Energy Information Administration. The Office of Oil and Natural Gas in DOE's Office of Fossil Energy prepared this primer. The following sections will define NGLs and their uses, forecast regional natural gas and NGL production, provide an overview of regional infrastructure for NGL production and use, highlight infrastructure developments in the region, and identify research and development opportunities related to natural gas and natural gas liquids production, conversion, and storage.

II. What are natural gas liquids?

Natural gas liquids are versatile products used in every end-use sector—residential, commercial, industrial (manufacturing and agriculture), transportation, and electric power. The table below lists the chemical composition, uses, products, and sectors for NGLs.[5]

Table 1. Natural gas liquids, uses, products, and consumers

NGL	Chemical formula	Uses	End-use products	End-use sectors
Ethane	C_2H_6	Petrochemical feedstock for ethylene production; power generation	Plastics; anti-freeze; detergents	Industrial
Propane	C_3H_8	Fuel for space heating, water heating, cooking, drying, and transportation; petrochemical feedstock	Fuel for heating, cooking, and drying; plastics	Industrial (includes manufacturing and agriculture), residential, commercial, and transportation
Butanes: normal butane and isobutane	C_4H_{10}	Petrochemical and petroleum refinery feedstock; motor gasoline blending	Motor gasoline; plastics; synthetic rubber; lighter fuel	Industrial and transportation
Natural gasoline (pentanes plus)	Mix of C_5H_{12} and heavier	Petrochemical feedstock; additive to motor gasoline; diluent for heavy crude oil	Motor gasoline; ethanol denaturant; solvents	Industrial and transportation

A. Ethane

Ethane is mainly used to produce ethylene, which is then used by the petrochemical industry to produce a range of intermediate products, most of which are converted into plastics. Ethane consumption in the United States has increased over the past several years because of its increased supply and lower cost relative to other petrochemical feedstocks like propane and naphtha. Ethane can also be used directly as a fuel for power generation, either on its own or blended with natural gas.

Because demand for ethane is almost entirely in the petrochemical sector, and because this product is difficult to transport by any mode other than in dedicated pipelines, supply and demand for ethane must be closely matched. The increase in the supply of ethane starting in 2008 has resulted in some natural gas processors choosing not to recover the ethane that is produced with raw natural gas. Instead, this ethane is left in the natural gas that enters the interstate natural gas pipeline system. This process is referred to as ethane rejection, because the producer rejects the ethane stream into the dry natural gas instead of recovering it along with other NGLs.

B. Propane

Most of the propane consumed in the United States is used as a fuel, generally in areas where the supply of natural gas is limited or not available. This use is highly seasonal, with the largest consumption occurring in the fall and winter months. Propane sold as a fuel for the consumer market is generally defined as HD-5, which contains a minimum of 90% propane by volume, with small quantities of other hydrocarbon gases. HD-10, which contains up to 10% propylene, is the accepted standard for propane in California.

There are two general market categories for propane: consumer (primarily as fuel) and non-consumer (primarily for non-fuel or feedstock uses). There are four major consumer uses of propane:

- In homes, for space heating and water heating; for cooking; for drying clothes; and for fueling gas fireplaces, barbecue grills, and backup electrical generators.
- On farms, for heating livestock housing and greenhouses, for drying crops, for pest and weed control, and for powering farm equipment and irrigation pumps.
- In businesses and industry, to power fork lifts, electric welders, and other equipment.
- As a fuel for on-road internal combustion engine vehicles such as cars, school busses, or delivery vans, and non-road vehicles such as tractors and lawn mowers.

The non-consumer market for propane is the petrochemical industry. The primary use of propane in the petrochemical industry is as a feedstock, along with ethane and naphtha, in petrochemical crackers to produce ethylene, propylene, and other olefins. Propane can also be used as a dedicated feedstock in the petrochemical industry for on-purpose propylene production. Propylene and the other olefins may be converted into a variety of products, mostly plastics and resins, and also glues, solvents, and coatings.

C. Butanes

Although some normal butane is used as a fuel for lighters, most of it is blended into gasoline, especially during the cooler months. Because demand for isobutane exceeds supply, normal butane is also converted into isobutane through isomerization. Normal butane can also be used as a feedstock in the petrochemical industry. When normal butane is used in petrochemical cracking, the process yields (among other chemicals) butadiene, which is a precursor to synthetic rubber.

Isobutane, whether from natural gas plants, refineries, or isomerized from normal butane, is used to produce alkylates, which increase octane in gasoline and control the volatility of gasoline. High-purity isobutane can also be used as a refrigerant.

D. Natural Gasoline (Pentanes Plus)

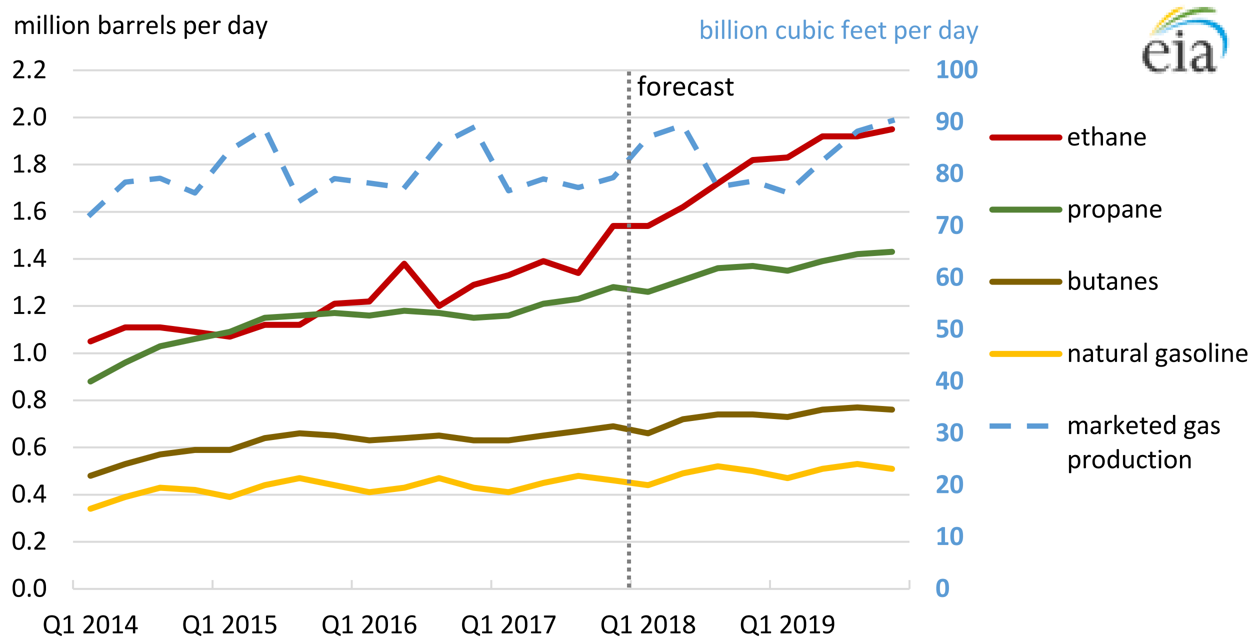
Natural gasoline (also known as pentanes plus) can be blended into the fuels used in internal combustion engines, particularly motor gasoline. In the United States, natural gasoline is added to fuel ethanol as a denaturant to make the ethanol undrinkable, which is required by law. Some ethanol producers use natural gasoline to make E85.

About half of U.S. natural gasoline production is exported to Canada where it is used as a diluent to reduce viscosity of heavy crude oil, so that the crude oil can be more easily moved in pipelines and railcars.

III. Domestic Natural Gas Liquids Market

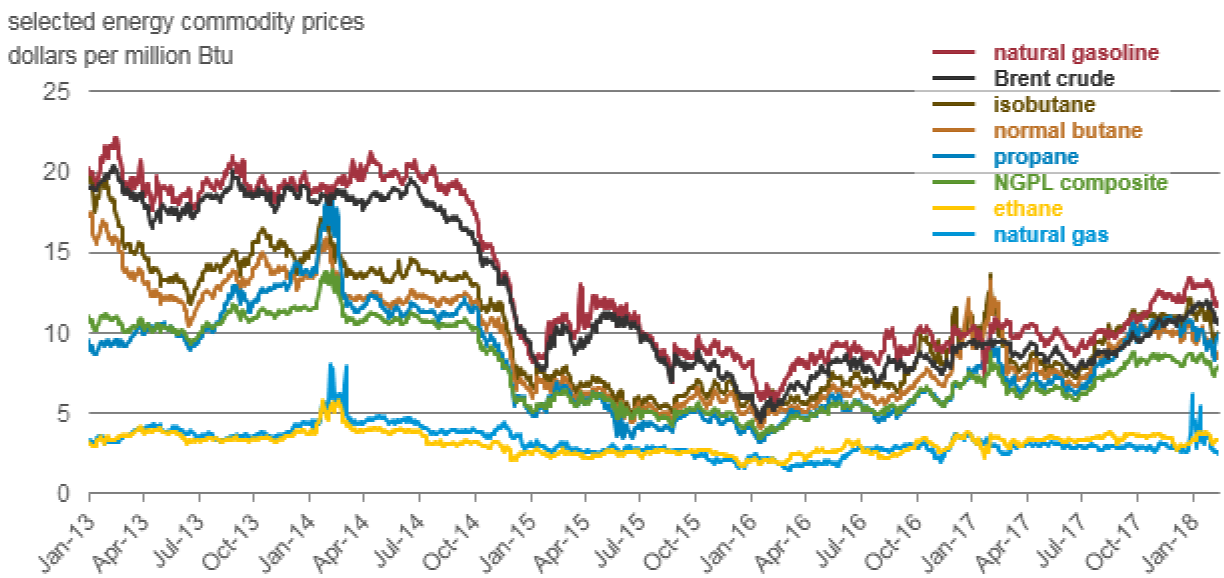
The discussion in this section is based on the February 2018 EIA Short-Term Energy Outlook (STEO) unless otherwise noted. U.S. liquid fuels production increased by 5.9 million barrels per day (b/d) between 2009 and 2017, from 8.0 million b/d to 14.2 million b/d. The increase in NGL production accounted for 29% of this growth. By definition, NGL production happens at natural gas processing plants and petroleum refineries, but between 2009 and 2017, all of the growth in NGL production occurred at natural gas processing plants as a byproduct of processing the growing supply of natural gas from shale gas and tight oil formations.

Figure 1. Natural Gas Plant Production of NGLs[6]



As depicted in Figure 2 below, domestic spot prices of NGLs generally fall between crude oil and natural gas spot prices on a heat-content basis ($/million British thermal units (MMBtu)). Propane, butane, and natural gasoline spot prices, which have historically moved with crude oil prices, have stayed consistently above the Henry Hub natural gas spot price since 2008, providing positive margins when these products were recovered at natural gas plants. On the other hand, an oversupply of ethane kept ethane prices at or below the Henry Hub natural gas price from mid-2012 to late-2015. When ethane margins are negative, producers have an incentive to reject ethane, leaving it in the dry pipeline natural gas stream where it sells for its fuel value. However, U.S. Gulf Coast ethane prices moved back above Henry Hub natural gas prices in February 2017, and margins have been mainly positive through 2017 and 2018 to-date, as new petrochemical demand and exports reduced the oversupply of ethane.

Figure 2. NGL Prices Compared to Crude Oil and Natural Gas[7,a]



A. Ethane Outlook[8]

U.S. ethane consumption, which remained relatively flat between the last quarter of 2013 through mid-2015 (see Figure 3), is expected to increase significantly after growing just 100,000 b/d between mid-2015 and mid-2017. Ethane consumption domestically is projected to increase by 360,000 b/d from the last quarter of 2017 to the end of 2019.

Exports are expected to also lift total ethane demand. After the first exports by pipeline started flowing to Canada in 2014, exports of ethane expanded from essentially zero to 65,000 b/d by the end of 2015. Overseas exports of ethane out of the U.S. began in the first quarter of 2016, with the first shipment of ethane to Norway out of the Sunoco Logistics' Marcus Hook terminal outside Philadelphia, Pennsylvania, leading to further growth. From the start of 2016 to the fourth quarter of 2017, total U.S. ethane exports rose by over 160,000 b/d to 240,000 b/d. Growth in ethane exports is expected to continue, increasing to 330,000 b/d by the end of 2019.

Resulting from this rapid growth in demand for ethane, from both domestic U.S. consumers and international markets, U.S. ethane production at natural gas plants, which was relatively flat from late 2013 to mid-2015, is projected to continue increasing through the forecast period. After growing by 130,000 b/d from 2016 to 2017, ethane production is projected to grow by a further 500,000 b/d to the end of 2019.

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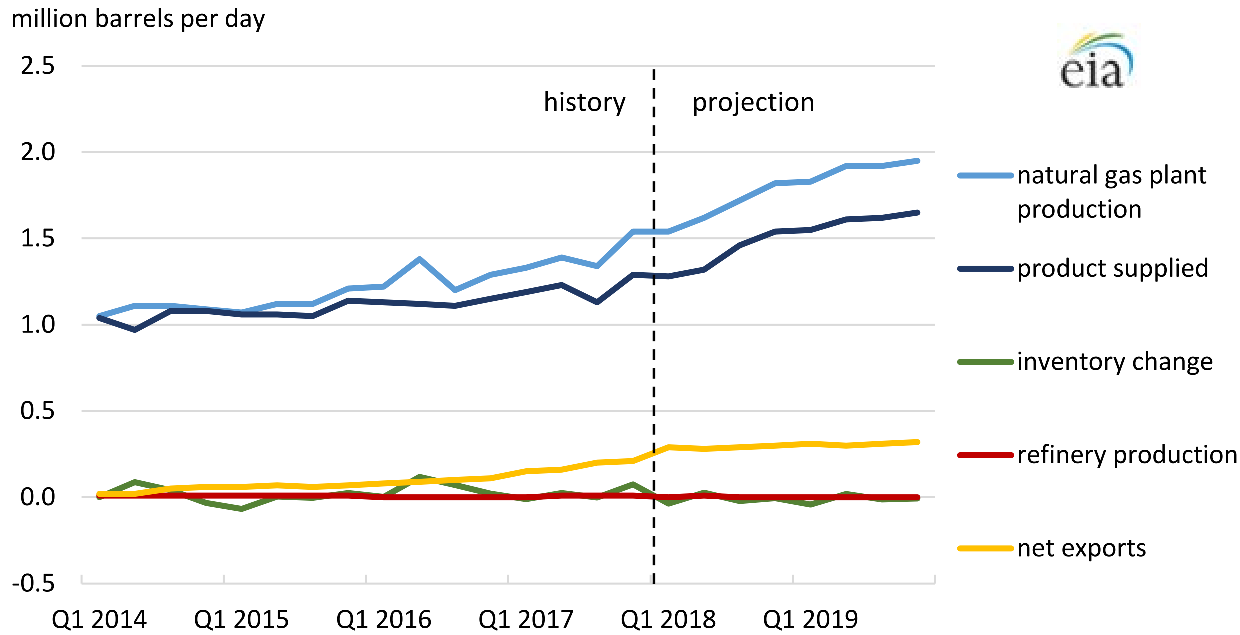
[a] All prices are daily end-of-day spot prices; natural gas is Henry Hub, and NGL components are Mt. Belvieu. Natural Gas Plant Liquid (NGPL) Composite calculated based on calorific contribution of each purity to total NGPL barrel heat value.

Figure 3. Ethane supply and disposition, quarterly 2014-19[9]



Annual average gas plant production of liquids is projected to grow to 4.56 million b/d in 2019, up from 3.73 million b/d in 2017, with increased ethane production accounting for two-thirds of this growth. Over the past several years, the amount of ethane contained in raw natural gas has exceeded U.S. domestic capacity to consume and export it. This excess supply kept ethane prices relatively low, hovering at or below the price of natural gas on a heat-content equivalent basis ($/MMBtu). The lower prices created an incentive for producers to reject ethane into pipeline natural gas to capture its value as a fuel, as opposed to recovering it at gas plants and marketing it as a separate product for use in petrochemical manufacturing. As expanding ethane-consuming petrochemical and export capacity reduces the ethane oversupply in 2017-19, ethane prices are expected to generally remain above natural gas prices in $/MMBtu, and ethane recovery is expected to rise to meet domestic and export demand growth.

The first half of 2017 saw two new petrochemical crackers come online and capacity expansions at two others completed. Near the end of the year, a third new cracker was brought into service, though most of the commissioning work will last through the first two quarters of 2018. Construction challenges, in no small part due to the impacts of Hurricane Harvey, caused delays at various other projects, which are now expected to be completed over the course of 2018, with others slated for completion further out in the forecast.

U.S. ethane exports grew in 2017, including volumes leaving the Morgan's Point, Texas terminal, to over 120,000 b/d in the last quarter of 2017. Growth in export volumes, coupled with the increase in domestic consumption resulting from abovementioned project completions, was sufficient to drive up ethane recovery at natural gas processing plants to 1.52 million b/d in December 2017. This trend also pushed ethane wholesale prices above natural gas on a heat-content equivalent basis starting in February 2017, and they have remained there ever since.

As domestic U.S. petrochemical demand for ethane continues to grow through 2018 and 2019, and export volumes reach an expected 330,000 b/d to 350,000 b/d plateau, ethane recovery is projected to more closely align with total available ethane (produced + currently rejected). This market rebalancing is, in turn, expected to push ethane prices higher relative to natural gas, improving margins for producers, and allowing further improvements in NGL infrastructure to move forward, including new pipelines, de-ethanization plants, and storage capacity that allow more ethane to be separated from natural gas and transported to demand centers.

Natural Gas Plant Production of Ethane

As the lightest hydrocarbon molecule (aside from methane, the main component of natural gas), ethane requires more energy to recover and more specialized handling after recovery than other NGLs. The additional costs imposed on natural gas processors require a price that provides for sufficient recovery of costs to cover the production and transportation of ethane. Low demand growth and weak prices over the 2013-16 time period provided a disincentive for ethane recovery at natural gas plants and encouraged producers to reject some ethane into pipeline gas to capture its value as a fuel at natural gas prices (see Figure 2 above).

Many of the petrochemical and export projects announced since 2012 are now reaching the commissioning phase, driving ethane demand higher. Between 2012 and 2017, new and expanded petrochemical cracking capacity raised annualized domestic ethane demand by approximately 250,000 b/d, while rising exports contributed another 180,000 b/d to total demand for ethane. Natural gas plant production of ethane responded, expanding by over 430,000 b/d, with 200,000 b/d of this growth occurring in just the last quarter of 2017. Ethane production and prices are expected to rise further on the back of continuing growth in petrochemical and export demand, with continuing growth in ethane infrastructure allowing this new production to reach new markets, where it can fetch a higher price.

Increased ethane recovery is expected to result in ethane production (excluding rejection) growth that is much stronger than natural gas production growth, with annualized ethane production rising by a cumulative 50% between 2016 and 2019 and marketed natural gas production rising just 15%. Annual ethane production is projected to increase by 270,000 b/d in 2018 and by 230,000 b/d in 2019, compared with annual average growth of 70,000 b/d between 2008 and 2016. Growth is expected to be widespread, with contributions from the Appalachian basin complemented by higher recoveries in the Gulf Coast region and the Rockies.

Table 2. Ethane supply and disposition, 2014-19[10, b]

	Millions of barrels per day				Projection	
	2014	**2015**	**2016**	**2017**	**2018**	**2019**
Gas Plant Production	1.09	1.13	1.27	1.40	1.67	1.90
Refinery and Blender Net Production	0.01	0.01	0.00	0.01	0.00	0.00
Net Imports	-0.04	-0.06	-0.09	-0.18	-0.29	-0.31
Refinery and Blender Net Inputs	0.00	0.00	0.00	0.00	0.00	0.00
Stock Build	0.01	-0.01	0.04	0.03	0.01	-0.01
Consumption	1.04	1.07	1.13	1.21	1.40	1.61

Domestic Consumption of Ethane

Annualized ethane consumption is projected to rise by nearly half a million barrels, from 1.13 million b/d in 2016 to 1.61 million b/d in 2019. Ethane is used almost exclusively as a feedstock for ethylene production at petrochemical plants, a use that is expected to expand as new ethylene plant capacity comes online. The relatively low cost of U.S. ethane led to a wave of investment in ethylene plant projects, including plant restarts, capacity expansions and feedstock conversions at existing plants, and new ethylene plants. These investments are expected to increase domestic ethane throughput capacity by nearly 600,000 b/d by the end of 2019.

A number of projects to restart or expand the capacity of ethylene-producing plants to use ethane as their feedstock increased ethane throughput capacity by about 140,000 b/d between 2013 and 2015, and another 55,000 b/d between the start of 2016 and last quarter of 2017. Most of this new capacity was from expansion projects scheduled to come online in late 2015, which had a delayed impact on feedstock demand that began to materialize in the second quarter of 2016. Just one major capacity expansion, of LyondellBasell's Channelview cracker, came online in 2017, adding 12,000 b/d of ethane demand, while a restart of the Carlyss cracker by Indorama Ventures, initially slated for 2017, is now expected to occur in 2018.

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[b] EIA's measure of product supplied approximately represents consumption of petroleum products. Annual averages.

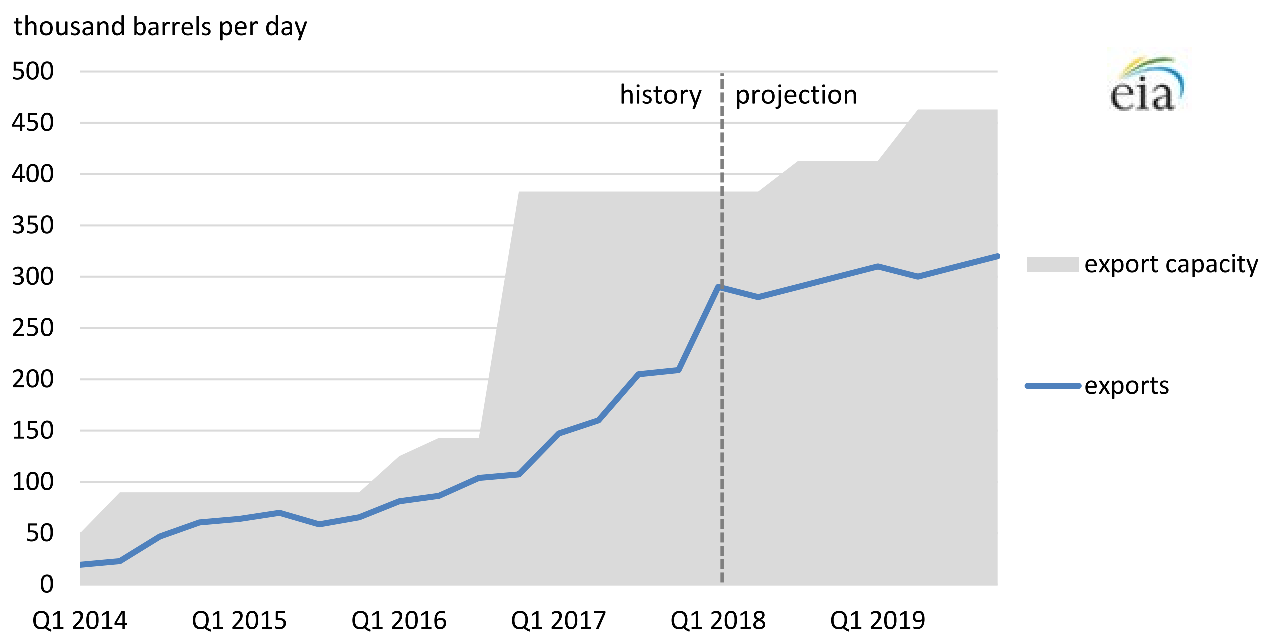
The first new petrochemical cracker since 2001 in the United States was completed in February 2017 – the OxyChem/MexiChem petrochemical cracker at Ingleside, Texas. In March 2017, Dow Chemical Company completed its new cracker at Freeport, Texas. In December 2017, Chevron Phillips Chemical Company (CPChem) began commissioning work on their Sweeny, Texas cracker. Together, the three plants added 545,000 metric tons per year (mt/y), 1.5 million mt/y, and 1.5 million mt/y of ethylene production capacity, respectively, accounting for over 210,000 b/d of new ethane demand.

Two more new ethylene crackers (from ExxonMobil and Shinetsu) are under construction and are expected to begin operating in 2018. The 2018 completions of new crackers, plus the Indorama Ventures restart, are expected to expand ethane throughput capacity by approximately 235,000 b/d in 2018. In 2019, EIA expects a further three plants to come online, the Formosa cracker at Point Comfort, Texas, and the Sasol and the Westlake/Lotte crackers, both at Lake Charles, Louisiana. The three plants together represent a further 245,000 b/d of feedstock demand. The new plants are designed to consume predominantly light feedstock, and ethane is expected to constitute most of their input.

Net Exports of Ethane

In 2014, the United States switched from being a net importer of ethane to a net exporter after the opening of two new ethane pipelines that began transporting ethane from North Dakota and southwestern Pennsylvania to Canada. Annual average ethane net exports are expected to increase from 60,000 b/d in 2015 to a plateau of 330,000 to 350,000 b/d in 2019, as new export facilities allow ethane to reach foreign markets.

Figure 4. Ethane export capacity and net exports, 2014-19[11]



Growth in ethane exports has accelerated since the introduction of waterborne ethane trade, starting in early in 2016 when the United States began exporting ethane to Europe from Sunoco's Marcus Hook facility near Philadelphia, Pennsylvania. Under a 15-year contract, new purpose-built tankers move the ethane from Marcus Hook to Scotland and Norway for use in INEOS Olefins & Polymers Europe (INEOS) petrochemical plants.[12] Borealis Group's petrochemical cracker at Stenungsund, Sweden, will also become a regular destination for ethane exports out of Marcus Hook.[13] Regular exports of ethane from this facility are expected to begin reaching Sweden by mid-2018.

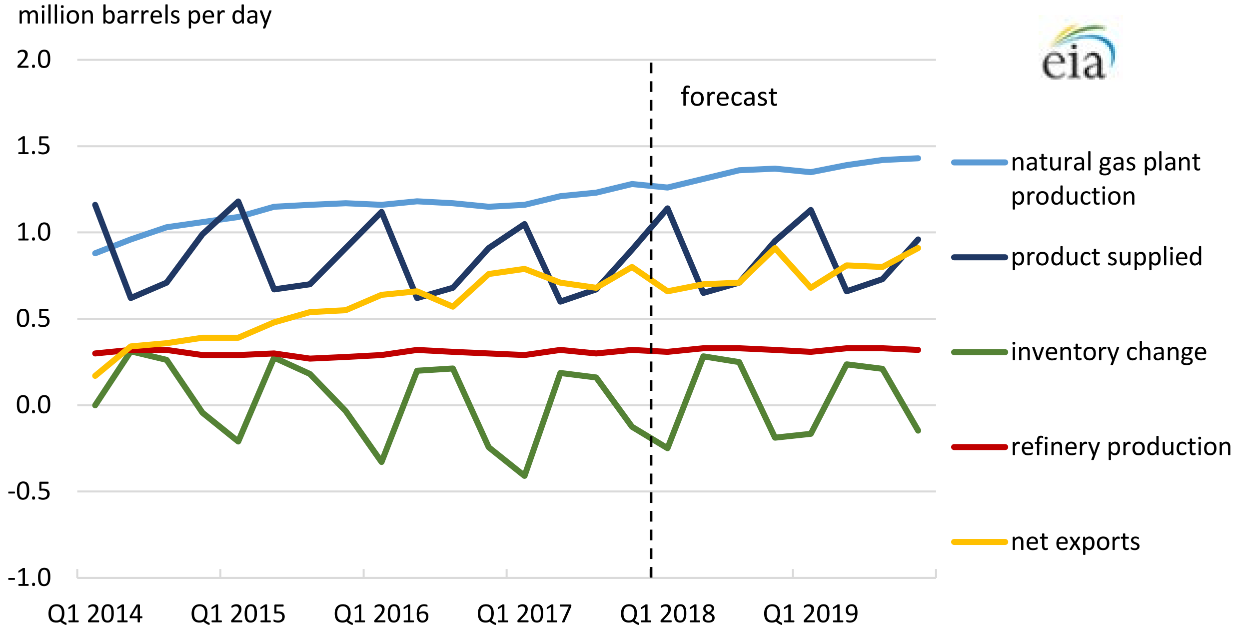
In the third quarter of 2016, Enterprise Product Partners (EPP) commissioned its new ethane export facility at Morgan's Point, Texas, which has a nameplate capacity to export up to 240,000 b/d. This new terminal is currently exporting on average 125,000 b/d of ethane to destinations as remote as India and Brazil, as well as Fife, Scotland and Pajaritos, Mexico, in addition to the same destinations served by Marcus Hook in Northern Europe.

Companies around the world have modified their facilities to accept waterborne U.S. ethane. Reliance Industries, a major Indian refiner and petrochemical producer, built an import terminal and ethane pipeline, and ordered the construction of six very large ethane carriers (VLEC) to transport ethane to India.[14] Each such vessel is capable of transporting over 800,000 standard barrels of ethane, with on average two of these ships loading at Morgan's Point every month. SP Chemicals of China is also tailoring its operations for the receipt and processing of U.S.-sourced ethane in its Taixing City petrochemical cracker in Jiangsu province. The company has entered into a supply agreement with INEOS, who will supply the ethane on newly-built ethane carriers operated by their long-term shipping partner Evergas.[15] EIA projects exports to China to begin in the last quarter of 2019, driving U.S. ethane exports up to a 330,000 b/d to 350,000 b/d range by the end of the STEO projection.[16]

B. ***Propane Outlook***[17]

The outlook for propane is marked by continued growth in gas-plant production, albeit at a slower pace than in recent years, relatively flat domestic consumption levels, and continued growth in net exports (see Figure 5 below). Natural gas plant production of propane is projected to increase by 110,000 b/d in 2018 and another 70,000 b/d in 2019, after remaining essentially flat for the duration of 2016. After a 40,000 b/d annual decline in 2017, propane consumption, measured as product supplied, is expected to rise 60,000 b/d in 2018 on the back of more normal winter weather, rising to an annual average of 860,000 b/d. Net exports, which increased from just under 200,000 b/d in 2013 to 660,000 b/d in 2016, are expected to increase to approximately 800,000 b/d in 2019.

Figure 5. Propane gas plant and refinery production, imports, consumption, exports, and inventory change, 2014-19[18]



Natural Gas Plant Production of Propane

Gas plant production of propane more than doubled between 2008 and 2015, with most of the growth occurring since 2011. The rate of growth in gas plant propane production, like that of other natural gas plant liquids, outpaced that of natural gas, as increased natural gas processing and fractionation capacity allowed producers to separate more liquids from raw natural gas, which itself has become more liquids-rich.

Growth in marketed natural gas production flattened at around 77 billion cubic feet per day (Bcf/d) throughout 2015 and 2016, while production of propane slowed to just 2% in 2016 and 4% in 2017, after rising 16% in 2015. By the end of 2017, however, with rising exports, natural gas production began to increase again, and this trend is expected to continue throughout the forecast period. This growing natural gas production is expected to lead to a rebound in the growth rate of propane production to an average of nearly 10% in 2018. The projection for gas plant production of propane averages 1.4 million b/d in 2019, 180,000 b/d above average annual production reported in 2017.

Domestic Consumption of Propane

In 2017, the United States consumed 790,000 b/d of propane for a combination of uses. In the United States, propane is used mainly for space heating and as a feedstock for petrochemical plants, and to a lesser extent for agricultural applications and transportation. Use of propane as a heating fuel is primarily responsible for the seasonal pattern in its consumption, which peaks in the winter (fourth and first quarters) (see Figure 5 above). The combination of relatively mild weather in the 2016/17 winter, which depressed demand for propane as a heating fuel, along with estimated decline in the use of propane as a petrochemical feedstock due to elevated domestic propane prices, translated into a decrease of 40,000 b/d in U.S. domestic demand relative to annual 2016 propane product supplied (implied consumption).

As a feedstock, propane is used by the petrochemical industry to produce ethylene and propylene for chemicals and plastics. Some ethylene-producing plants can process propane into ethylene, propylene, and a slate of other olefins. As these plants become more reliant on ethane feedstock, propylene production at ethylene plants has been declining. To offset the decline in ethylene cracker propylene production, petrochemical companies have invested in propane dehydrogenation (PDH) plants that are dedicated to producing propylene from propane feedstock.

The United States currently has three PDH plants. The first plant, with an estimated propane feedstock capacity of 30,000 b/d, was commissioned by Petrologistics in 2010, and has since been sold to Flint Hills Resources. A second plant, owned by Dow Chemical, with a propane feedstock requirement of 35,000 b/d, began commercial operation in December 2015. The Enterprise Product Partners' PDH plant at Mont Belvieu, Texas became the third plant to become operational in February 2018. Like the Dow PDH plant, the Enterprise-operated plant's feedstock requirement is estimated at 35,000 b/d of propane. Further PDH capacity is not expected to come online in the United States over the next several years. As stated above, the construction of new PDH plants may result in a net reduction in petrochemical propane consumption, because a PDH plant produces more propylene per barrel of propane feedstock than an ethylene plant.

Net Exports of Propane

On a net basis, propane net exports are projected to average 750,000 b/d in 2018 (Table 3) and rise to 800,000 b/d in 2019, reflecting the completion of most export terminal projects.

On an annual basis, imports have been relatively steady, reflecting flat Canadian production and seasonal U.S. demand for heating-season supply. Prior to 2012, in years when demand surged past volumes available from domestic production and imports from Canada, overseas imports filled the gap. Since 2012, however, as U.S. domestic propane production began to expand, imports from overseas producers were reduced to just a few cargos to regions not well served by domestic supplies, such as New England or Hawaii. At 120,000 b/d in 2018, imports of propane are projected to reflect continuing surplus Canadian production. By 2019, as an export terminal on Canada's west coast begins shipping propane directly to Asian markets, EIA expects U.S. imports of propane to decline by 20,000 b/d.

Exports of propane had been relatively steady for the ten years between 1999 and 2008, hovering each year between 30,000 b/d and 50,000 b/d, reflecting seasonal imbalances and some re-exports to Canada's eastern provinces. By 2009, export volumes began to grow, exceeding 100,000 b/d in 2010. In 2011, the U.S. became a net exporter of propane on an annual basis, as the 124,000 b/d of propane exports surpassed the 82,000 b/d of propane imports – nearly all from Canada. By 2012, the U.S. became a year-round net exporter of propane, and exports have grown since, reflecting both increasing domestic production and growing capacity to export.

Table 3. Propane supply and disposition, 2014-19[19, c]

	Millions of barrels per day					
					Projection	
	2014	2015	2016	2017	2018	2019
Gas Plant Production	0.98	1.14	1.17	1.22	1.33	1.4
Refinery and Blender Net Production	0.31	0.28	0.31	0.31	0.32	0.32
Net Imports	-0.33	-0.51	-0.68	-0.75	-0.75	-0.80
Refinery and Blender Net Inputs	NA	NA	NA	NA	NA	NA
Stock Build	0.09	0.05	-0.04	-0.05	0.02	0.03
Consumption	0.87	0.86	0.83	0.81	0.86	0.87
PDH feed capacity (end of year)	0.03	0.03	0.07	0.07	0.10	0.10
Propane/butane export capacity (end of year)	0.60	1.14	1.29	1.29	1.57	1.57

The relatively low cost of U.S. propane has spurred international demand and changed international trade patterns. Growth in propane exports is expected to be mainly driven by petrochemical demand in Asia and, to a lesser extent, Europe. U.S. wholesale propane prices are expected to increasingly reflect international-market prices, as domestic export capacity, combined with a near-doubling of the world's liquefied petroleum gas shipping fleet and the opening of the wider locks of the Panama Canal, have resulted in significant reductions in costs associated with reaching distant markets.

Propane Inventories

Inventories of propane, which expanded significantly earlier in the decade, are expected to decline on an annual basis, though still remain above pre-2013 levels. After hovering below 50 million barrels in 2010 and 2014, propane inventories grew to over 70 million barrels in 2014, and exceeded 91 million barrels in 2015. In 2016, on the back of strong export growth, inventories began to decline again, falling to 77 million barrels by year-end 2016, and ended 2017 below 61 million barrels. In 2018, as U.S. prices approach international prices and the

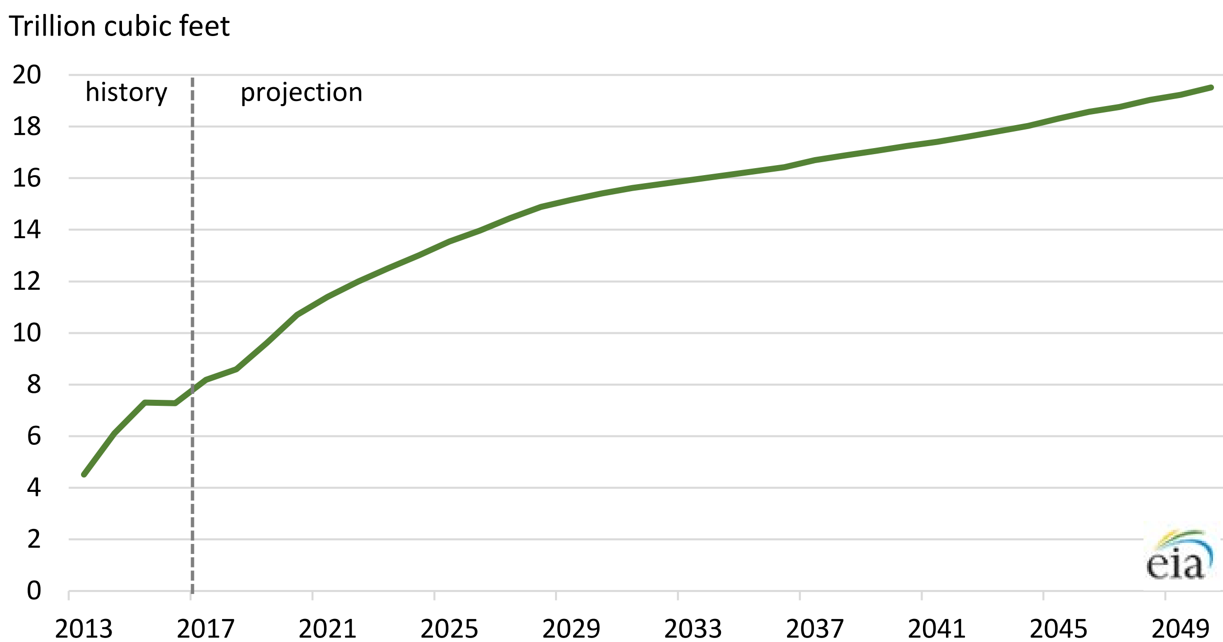
[c] Annual averages. Excludes propylene. EIA's measure of product supplied approximately represents consumption of petroleum products.

arbitrage opportunity for exporters recedes, inventories are projected to begin building again to end the year above 80 million barrels.

IV. Natural Gas and Natural Gas Liquids Resources in Appalachia

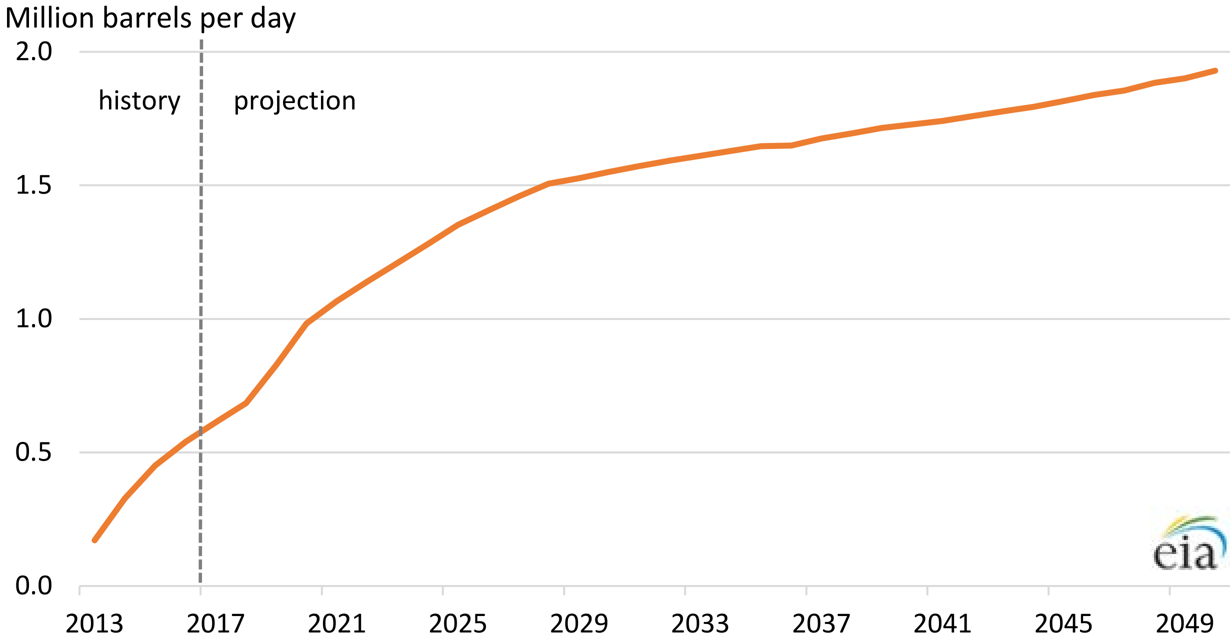
Over the coming decades EIA projects substantial growth in natural gas and NGL production in the East region, where the Appalachian Basin is the principal contributor to production. The EIA AEO 2018 Reference case results are presented in this section, however, there are variety of uncertainties related to resource size, technology improvement rates, economic growth and global oil and natural gas prices. Additional cases are available in the AEO 2018.

Figure 6. East Region Natural Gas Production[20]



Natural gas production in the Appalachian region (represented by the East region in EIA's Annual Energy Outlook) is projected to continue very steady growth in the short and long-term. Natural gas output, estimated at 8.19 trillion cubic feet (Tcf) in 2017, is projected to increase by 65% to 13.55 Tcf in 2025. Output in 2050 is projected at 19.5 Tcf.

Figure 7. East Region Natural Gas Plant Liquids Production[21, d]



NGL output from gas plants (natural gas plant liquids – NGPL) in the Appalachian region (reflected in EIA's projections for the East region in the Annual Energy Outlook) will continue to grow throughout the projection period. As natural gas production gradually migrates from richer gas areas, which are expected to slowly deplete, to dryer areas, the rate of growth in natural gas plant liquids production will slow relative to the rate of natural gas production growth. Gas plant NGL output from 2017 to 2025 will more than double from 610,000 b/d in 2017 to 1.35 million b/d in 2025. Gas plant NGL output is projected to reach 1.93 million b/d in 2050.

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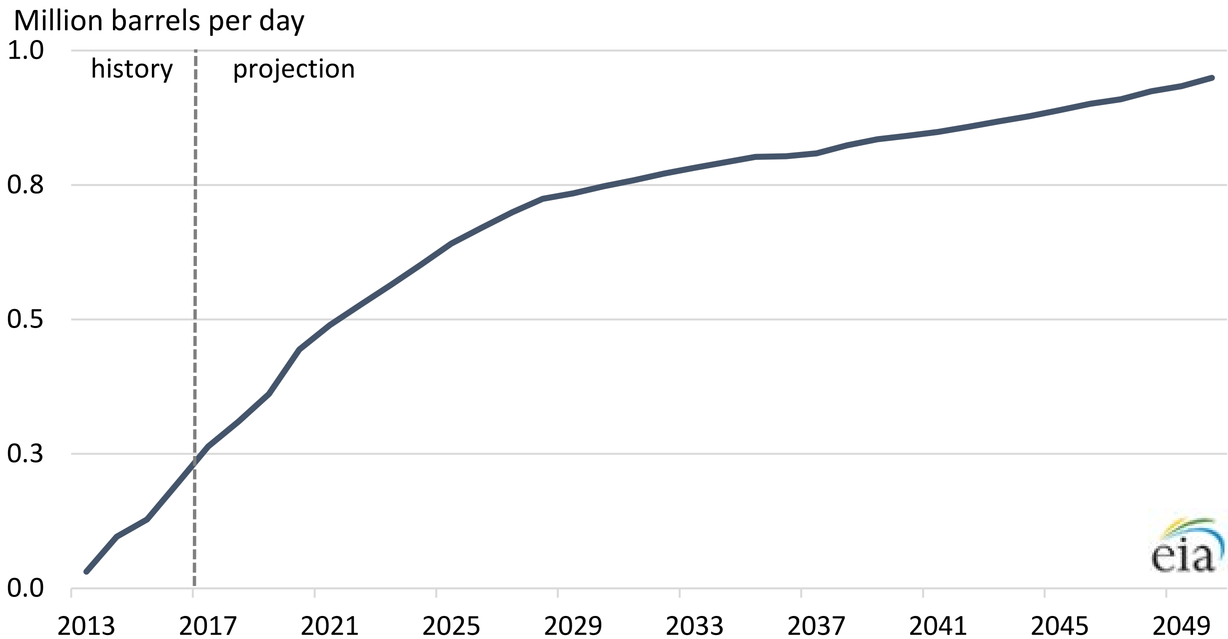
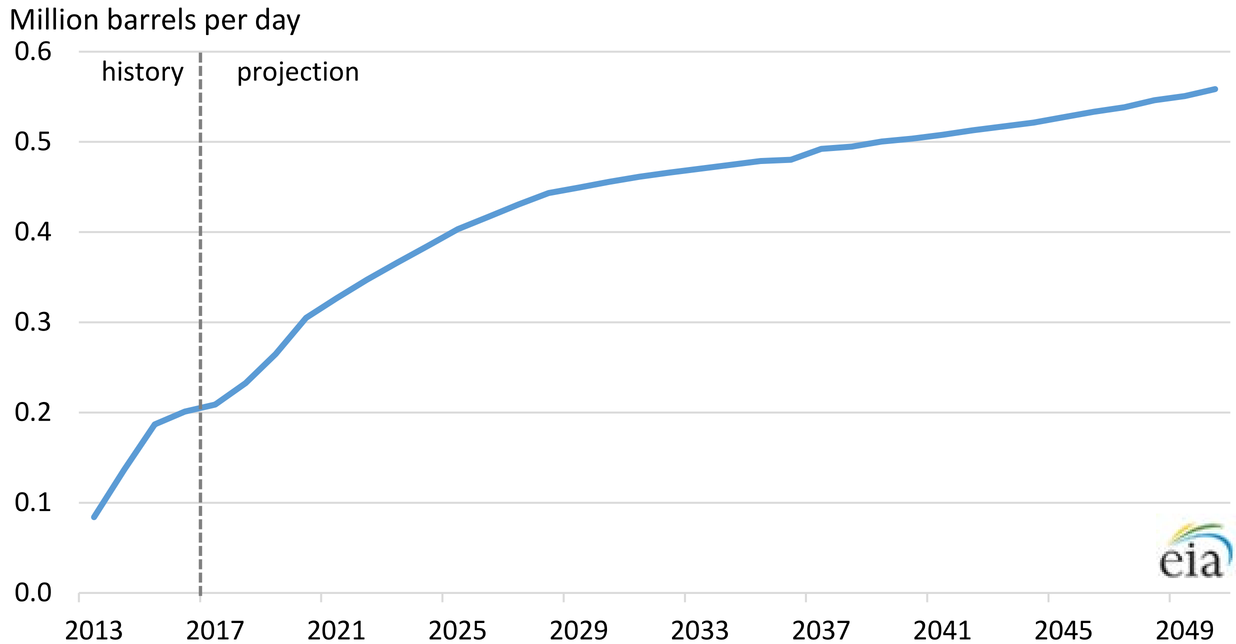
[d] The term "natural gas plant liquids" includes natural gas liquids that are separated from the natural gas stream in natural gas processing plants and excludes natural gas liquids that are produced from refineries.

Figure 8. East Region Ethane Production[22]



Gas plant ethane production in the region is projected to continue its rapid growth in the coming years. Projected production in 2025, at 640,000 b/d, is more than 20 times greater than regional ethane production in 2013. By 2050, ethane production in the Appalachian Basin, the primary contributor to East Region ethane production, is projected to reach 950,000 b/d, on the back of both higher natural gas plant liquids production in general, and higher recovery of ethane as gas plants improve their capacity to extract a higher proportion of ethane out of raw natural gas in order to satisfy growing demand.

Figure 9. East Region Propane Production[23]



Propane production in Appalachia (represented by the East region in EIA's Annual Energy Outlook) reached 210,000 b/d in 2017, a nearly three-fold increase over 2013. EIA projects in-region propane production to nearly double by 2025 to 400,000 b/d and continue growing to 560,000 b/d in 2050.

V. Natural Gas Liquids Infrastructure in Appalachia

The supply chain facilitating natural gas liquids production and use involves several distinct activities and related infrastructure. This section details those activities – from production wells to petrochemical plants – and describes existing and proposed infrastructure in Appalachia related to NGLs.

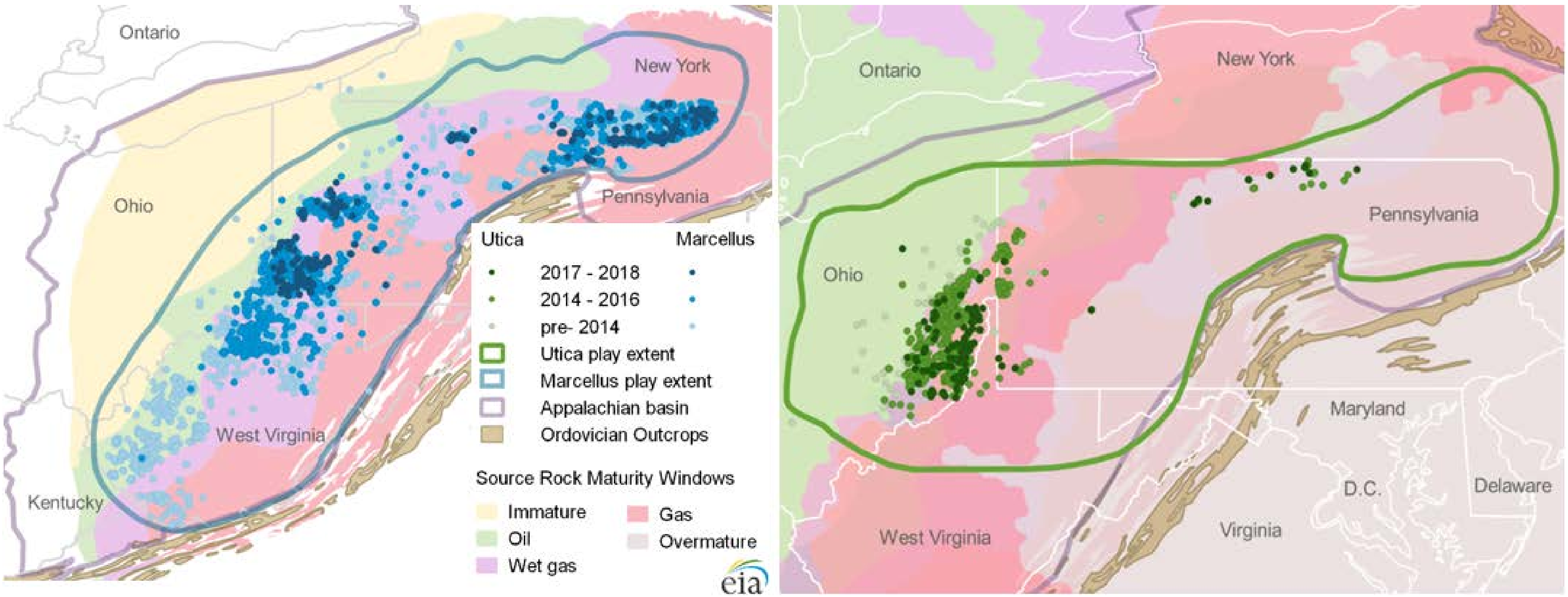
A. Wellhead Production

The Appalachian region, consisting of the currently-producing Marcellus and Utica shale formations as well as the undeveloped Rogersville shale, has experienced massive production growth in recent years. Natural gas production in the Marcellus/Utica region increased from 2.0 billion cubic feet per day (Bcf/d) in January 2010 to 26.0 Bcf/d in December 2017, which is roughly one-third of all U.S. dry natural gas production.[24]

NGPLs are found in raw natural gas and produced when extracted in a gas processing plant. NGPL output in the Marcellus/Utica region rose by 640,000 barrels per day (b/d) between January 2010 and December 2017, up from an estimated 20,000 b/d in 2010. This Appalachian production growth accounts for a third of total U.S. increase in NGPL production during this time.

Production in the western Marcellus/Utica region has mostly been focused on wet gas zones. Wet gas zones produce dry methane gas co-mixed with heavier NGL hydrocarbons. These complex wet gas areas – which yield larger quantities of ethane, propane, butanes, and natural gasoline – bring more value to producers than dry gas zones. Figure 10 below depicts the geographic extent of the Marcellus and Utica plays as well as where producing wells are located.

Figure 10. Marcellus and Utica Wells[25]



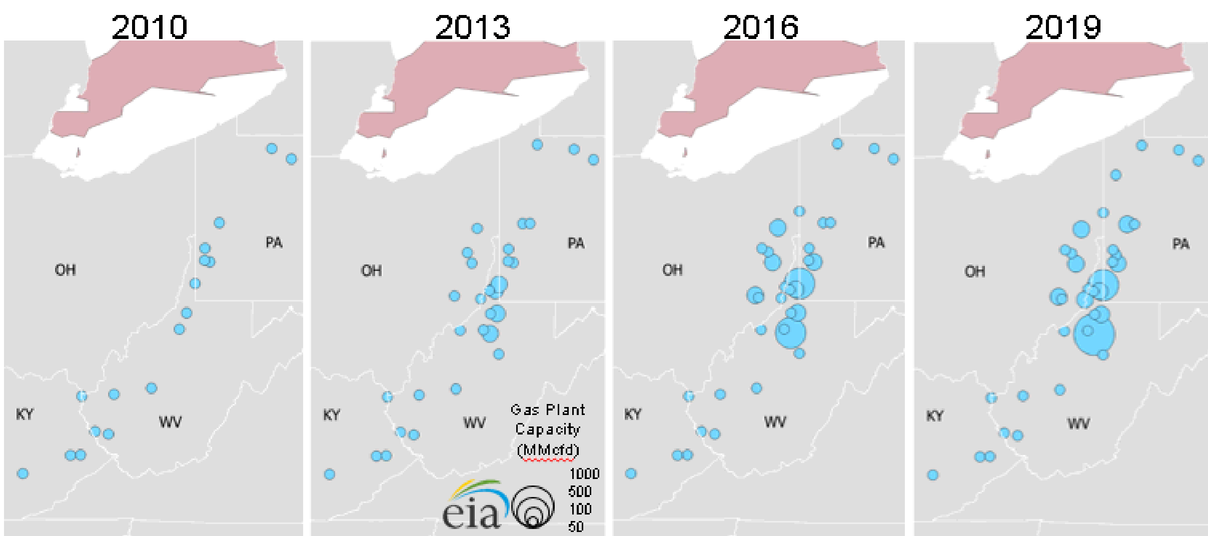
B. Natural Gas Processing

Natural gas processing plays a key role in the natural gas supply chain by treating the produced "raw" gas so it can be sent into a pipeline without causing excessive corrosion or mechanical issues. Natural gas processors typically remove water, CO_2, sulfur, and other impurities from the raw natural gas, and separate "dry" natural gas from NGLs, which can cause mechanical issues during pipeline transit and problems for natural gas consumers requiring a fuel with a particular heat content. Extracted NGLs are then sold at prices higher than those they would receive if marketed at their natural gas heat value ($/MMBtu).[26]

Accompanying the growth in natural gas output in Appalachia has been an unprecedented buildout of gas processing capacity in the states overlaying the formations. Between 2010 and 2016, natural gas processing capacity in Kentucky, Ohio, Pennsylvania, and West Virginia grew nearly tenfold, from 1.1 Bcf/d to 10.0 Bcf/d (Figure 11).[27] The additional capacity to process natural gas has in turn accelerated production of both natural gas and NGLs.

The new processing plants being constructed are modern, efficient units that use powerful compressors and chillers that cool natural gas to cryogenic temperatures (approximately -120°F) to separate the dry natural gas from the liquids.[28] There are other technologies processors can use to separate the gas and liquids streams, but cryogenic units allow for the highest percentage of liquids recovery. Additionally, plants with cryogenic units recover more propane and can more easily adjust their equipment to extract more or less ethane from the natural gas stream in response to the commodity price. When the price of ethane is low (i.e. near or below the price of natural gas on a heating-value-equivalent basis), many processors may choose to leave ethane in the natural gas stream (referred to as ethane rejection) and sell it as natural gas.[29]

Figure 11. Gas processing plants in the Appalachian region[30]



C. NGL Fractionation

After raw natural gas is processed, NGLs leave the gas processing plant as a mix called Y-grade, and are then further refined, or "fractionated," into distinct products of ethane, propane, normal butane, isobutane, and natural gasoline. Fractionation can take place at a co-located fractionator or at a stand-alone fractionator connected to multiple gas processing plants by pipelines.

While across many producing regions in the country fractionation may take place far from where the liquids are processed, in the Appalachian basin all liquids extracted are fractionated locally. Thus, the gas processing capacity buildout has been accompanied by incremental additions to regional fractionation capacity. Fractionation capacity in the Appalachian region has increased from just 41,000 b/d in 2010 to nearly 850,000 b/d in 2016, and may grow as high as 1.1 million b/d in 2019 (Figure 12). Figure 13 depicts the locations of gas processing plants and fractionators, both operating and planned, in the region.

Figure 12. NGL Fractionation plants in the Appalachian region[31]

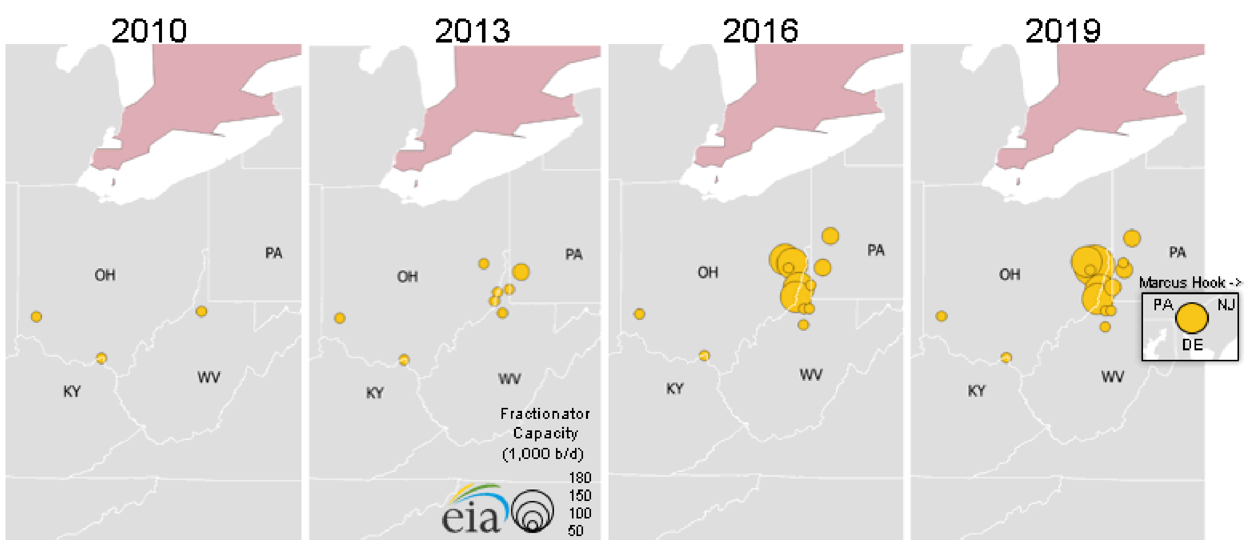
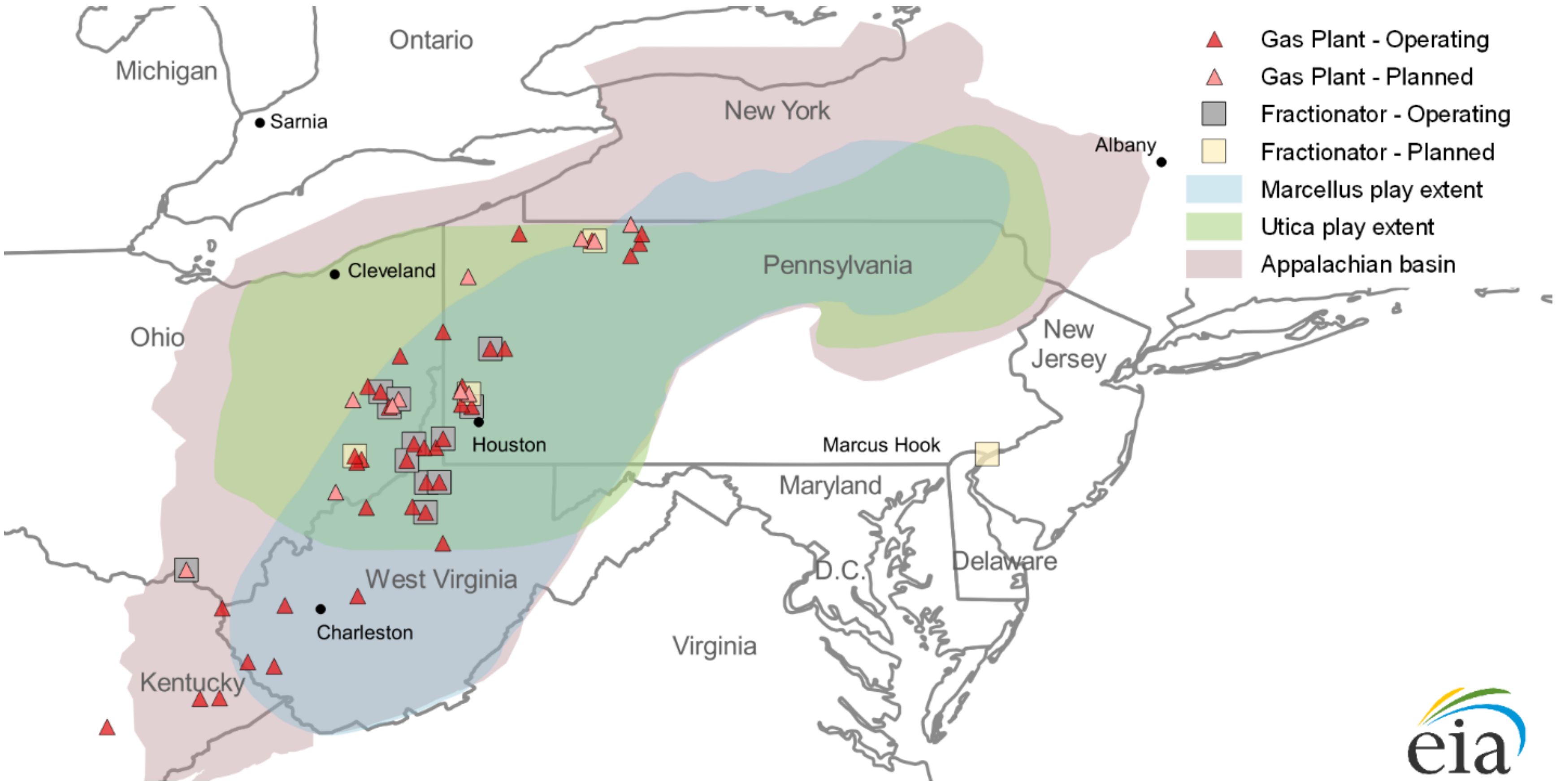


Figure 13. Location of Gas Processing Plants and Fractionators in Appalachia



D. NGL Transportation

In the Appalachian region, the increase in shale gas production since 2010 has spurred development of new midstream infrastructure, including pipelines and natural gas processing plants. At current levels, the NGL output exceeds in-region demand, necessitating transportation to other demand regions. Most NGLs in the U.S. are transported by pipeline; however, options for natural gas producers and processors in the Marcellus/Utica region to move NGLs to other markets via pipeline remain limited, and a significant share of production moves by rail. This has reduced the profitability of liquids production, especially after the 2014 oil-price decline, causing a temporary shift among producers to focus production on areas where liquids do not constitute a large component of the produced gas stream and dry gas infrastructure and deliverability is well developed.[32] More recently, activity has returned to the rich-gas areas of the Marcellus/Utica region as new natural gas pipelines and rising NGL prices have again made NGL production economic.

Currently, there are five pipelines that can move NGL production within and out of the region, with others in the planning or construction stage. Figure 14 below depicts NGL pipeline and cracking capacity by project and projected in-service date; and Figure 15 below shows the geographic locations of existing and proposed NGL pipelines in the region.

Figure 14. Appalachia NGL Pipeline and Cracking Capacity, Existing and Announced[33]

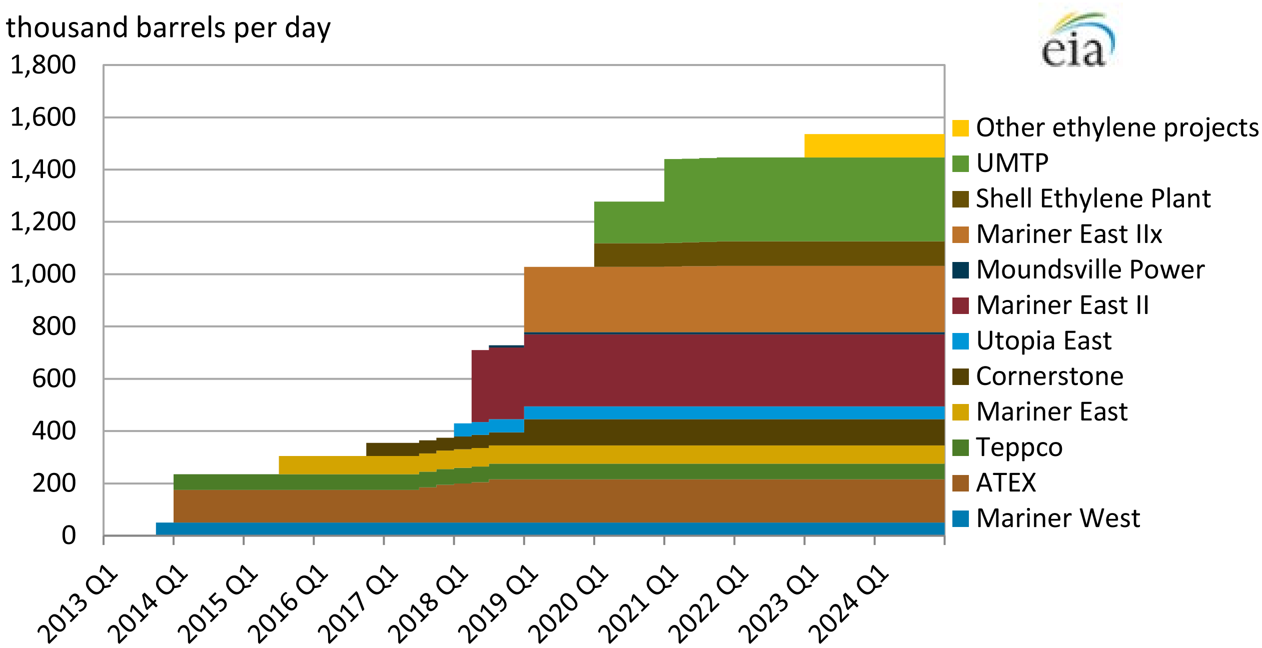
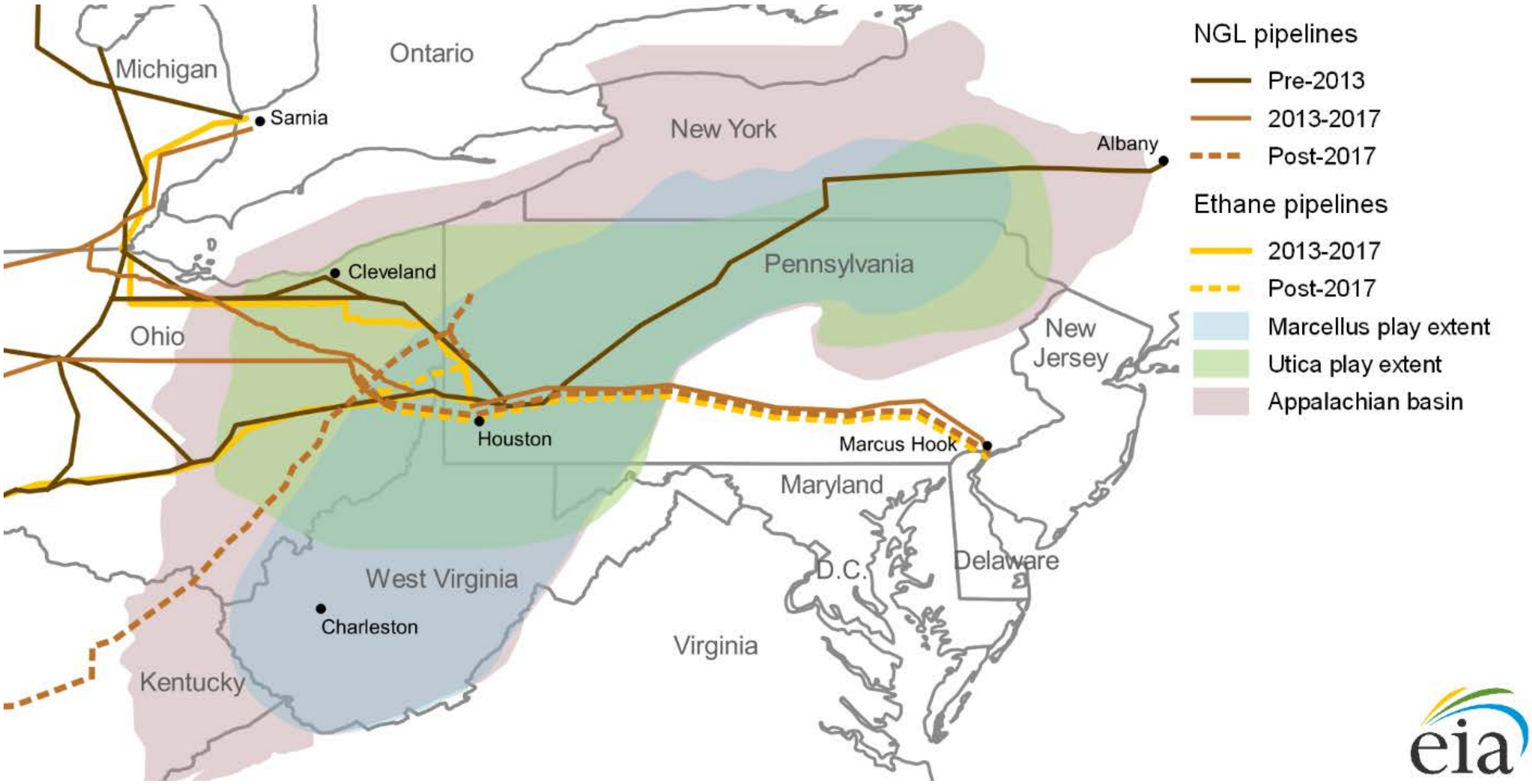


Figure 15. Appalachia NGL Pipelines, Existing and Announced[34]



Existing and under construction pipelines

The Enterprise Product Partners' (EPP) Appalachia-to-Texas Express (ATEX) pipeline, in service since early 2014, has allowed for the movement of up to 125,000 b/d of ethane out of the region to the Gulf Coast.[35] Enterprise is expanding capacity on the 14-inch ATEX line through additional pumping (up to 145,000 b/d at the end of 2017, and rising to 165,000 b/d by 2018 Q3). Anchor shippers on the line include Range Resources and Antero Resources. Should the need arise, ATEX may also offer the option of moving ethane north, from the Gulf Coast to Calvert City, Kentucky, where Westlake operates the only currently-active petrochemical cracker in the region.[36]

In addition to ATEX, EPP owns and operates the TE Product Pipeline Company (known as TEPPCO), which can receive approximately 60,000 b/d of propane at Houston, Pennsylvania for shipment north as far as Selkirk, New York. TEPPCO, which originally consisted of a 16-inch line and a 14-inch line with receipts starting at Mt. Belvieu and other Gulf Coast originations, now moves refined products exclusively on the 16-inch line. In 2014, TEPPCO suspended service on the 14-inch line, repurposing it for south-bound ethane shipments (see ATEX above). As a result of the 14-inch line repurposing, service originating on the Gulf Coast for many products, including propane, had been reduced. The TEPPCO pipeline connects to multiple storage facilities: Crestwood's Bath, New York storage facility; and EPP's Watkins Glen, New York and Hartford Mills, New York terminals; and previously served the Todhunter, Ohio storage terminal.[37] It also allows for propane deliveries (with limited on-site storage) to Coshocton, Ohio; Dubois and Greensburg, Pennsylvania; and Oneonta and Selkirk, New York.

Marathon Logistics (MPLX) completed the Cornerstone pipeline in September 2016, currently capable of moving natural gasoline and condensate from Cadiz, Ohio, via Scio, Ohio, to Canton, Ohio.[38] Product shipped on the pipeline can then move further west on Marathon's existing pipelines, reaching refineries in western Ohio and Michigan. Interconnections also allow shipments further west, and Kinder Morgan has reported receiving condensate and natural gasoline at its New Wabash Interconnect in St. Anne, Illinois into its Cochin pipeline for diluent use in western Canada. Marathon's open season documentation allowed for the possibility of shipping natural gasoline, condensate, diluent, as well as butanes on the line.[39] A further expansion of the Marathon system, called the Utica Build-Out Project, would expand capacity to 160,000 b/d and provide refineries in the region with a local source of butanes, which are now generally shipped in from the Gulf Coast on the TEPPCO pipeline. Marathon is also mining a 1.4 million barrel butane storage cavern below its Robinson, Illinois refinery, due for completion in 2018.[40, 41]

Sunoco Logistics operates two NGL pipelines originating in western Pennsylvania.[42] The Mariner West pipeline, completed in December 2013, has the capacity to move up to 50,000 b/d of ethane to Sarnia, Ontario, where it serves the feedstock requirements of NOVA Chemicals' Corunna cracker, with some volumes also available for Imperial's Sarnia cracker.[43] The 70,000 b/d Mariner East Phase I pipeline is capable of shipping ethane and propane to Marcus Hook, Pennsylvania, where Sunoco Logistics operates an export terminal capable of loading cryogenic ethane and refrigerated propane to overseas destinations.[44]

Sunoco is in the process of building out its Mariner East system with a 20-inch, 275,000 b/d Mariner East II (ME2) and 16-inch, 250,000 b/d Mariner East IIx (ME2x).[45] Sunoco Logistics' parent company Energy Transfer Equity now expects ME2 to be completed in 2018 Q3, whereas ME2x is expected to be completed in mid-2019.[46] The two new pipelines, in combination with Mariner East I, will operate as a system, capable of moving nearly 600,000 barrels of liquids – from ethane up to condensate and refined petroleum products – east from Scio, Ohio and Natrium, West Virginia; via Houston, Pennsylvania out to open water via the Marcus Hook, Pennsylvania marine terminal.

Placed into service in January 2018, Kinder Morgan's Utopia East pipeline has an initial capacity of 50,000 b/d of ethane, running northwest out of Cadiz and the Scio gas processing plant in Harrison County, Ohio, and terminating at an interconnect with the remnant of the Cochin pipeline in Riga, Michigan.[47] Kinder Morgan's Cochin pipeline, once a significant source of propane shipped from Western Canada to terminals throughout the Midwest, was repurposed to flow from the Kankakee terminal in Illinois to the north, delivering diluent for the shipment of Canadian bitumen. The segment between Kankakee and St. Anne, Illinois was recently brought back into service to allow for shipments of Marcellus/Utica condensate that are now injected from the Marathon pipeline system (see Cornerstone above), while the section from St. Anne to Marysville, Michigan remains abandoned. The new Utopia pipeline will bring back into service the stretch from Riga, Michigan to Windsor, Ontario, crossing the St. Claire River (and the U.S./Canada border) to Sarnia.[48] The pipeline consists of 150 miles of newly built, 12-inch pipe from Harrison County to Seneca County, Ohio; 63 miles of 12-inch pipeline acquired from a third party from Seneca County, Ohio to Riga; and 56 miles of 12-inch pipeline from Riga to Windsor, Ontario that was previously part of the Cochin pipeline. Line-fill began in December 2017 and deliveries commenced in January 2018. NOVA Chemicals, Canada's largest petrochemical company, is the anchor shipper on the line, using ethane delivered on Utopia to supplement receipts of ethane on the Mariner West pipeline.

Table 4. NGL pipelines, capacities, and in-service dates

Pipeline	Total Capacity (thousand b/d)	In-Service Date
Mariner West	50	December 2013
ATEX	125*	January 2014
TEPPCO	60	January 2014
Mariner East	70	September 2015
Cornerstone	50+	September 2016
UTOPIA	50	*January 2018*
Mariner East II	275	*Planned October 2016* *Now 2018 Q2*
Mariner East IIx	250	*Planned January 2017* *Now 2019 Q1*

*currently undergoing expansion to 165 thousand b/d by 2018 Q3

E. NGL Storage

Storage of NGLs is necessary since the production profile – generally flat throughout the year – does not align with demand, which for NGLs can vary significantly throughout the year. Large volumes of NGLs are primarily stored as a pressurized liquid in underground caverns, but some areas without suitable geology may use aboveground tanks. Most underground caverns are in salt formations, but some propane storage caverns are mined out of shale, granite, and limestone rock. After NGLs are transported to consumers, they are stored in pressurized tanks above or below ground.

The Appalachian region, and a greater area around it, has generally been dependent on storage outside the region to satisfy peak-season NGL demand. Only a few facilities satisfy the criteria of being significant to the market, nearly all of which store propane and are connected to the TEPPCO pipeline.[49]

EPP has invested in expanded access and deliverability at its Harford Mills, New York site, which is connected to the TEPPCO pipeline.[50] In addition to aboveground surge tanks Enterprise currently reports 680,000 barrels of underground propane storage capacity – an increase over the 500,000 barrels of capacity reported in 2014. In 2014 alone, Enterprise invested $6 million to improve rail and truck loading and unloading capability at the terminal. [51]

Crestwood's proposed Finger Lakes NGL Storage Facility at Watkins Glen, New York, has been held in regulatory stasis for over seven years, first filing a request to convert the depleted salt caverns to hydrocarbon storage in 2009, and satisfying all New York State DEC requirements by mid-2013.[52] The project involved the use of two existing caverns on the shore of Lake Seneca at Watkins Glen, New York, near the EPP Watkins Glen terminal and with a connection to the TEPPCO pipeline.[53] As originally proposed, the facility would have been capable of holding 2.1 million barrels of propane and butane. Crestwood, seeking support from the adjacent communities, has revised the project numerous times, most recently by reducing scope to storing just propane, and in only the larger, 1.5 million barrel cavern.[54] It has also shifted away from building the terminal with rail and truck access, with pipeline access now the only option. In September 2017, one of the last challenges to Crestwood's DEC application was struck down, allowing the project to possibly proceed.[55]

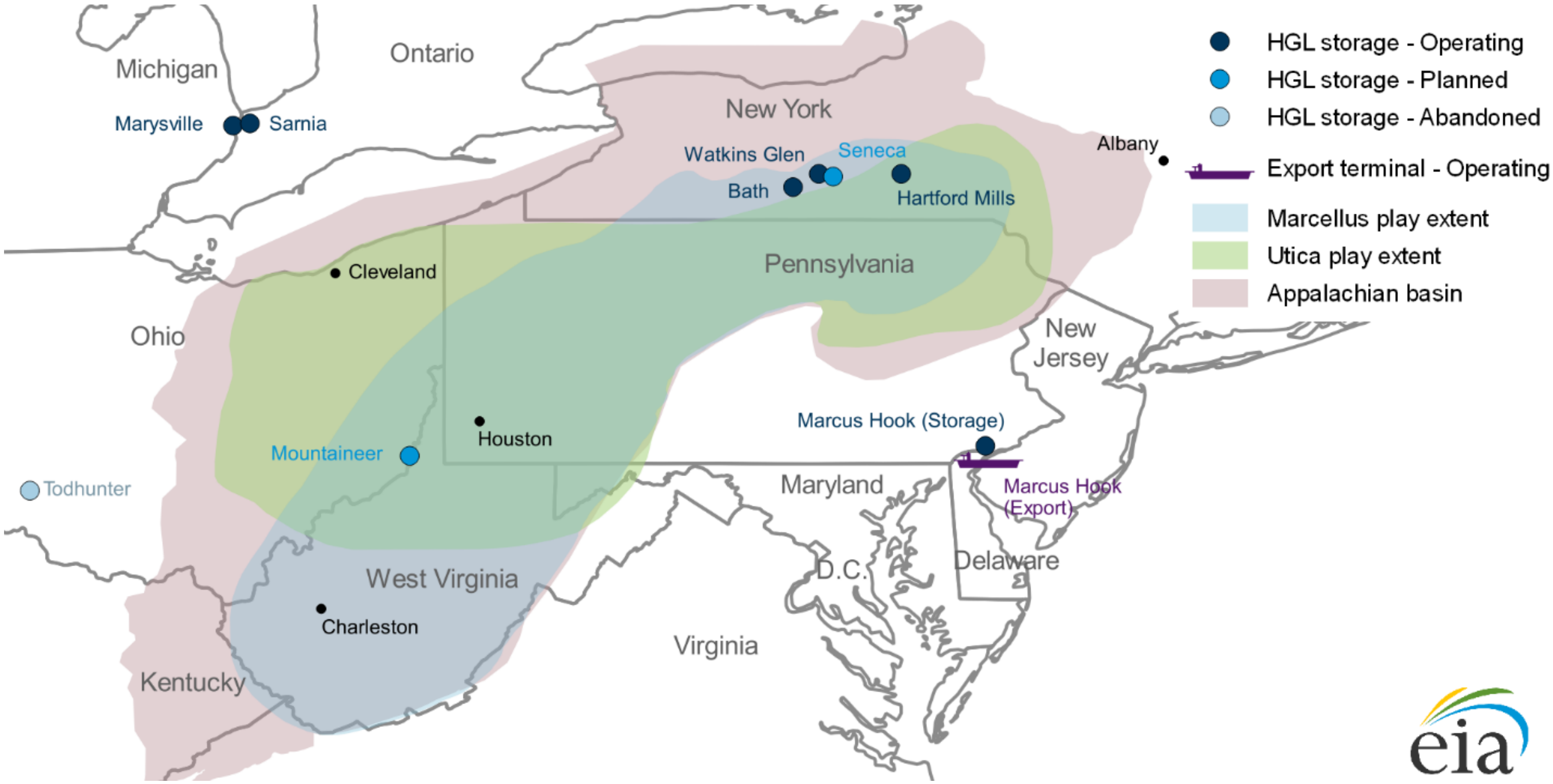
Sunoco's site at Marcus Hook, Pennsylvania, sits 300 feet above five granite caverns capable of storing a combined 2 million barrels of NGL and olefins.[56] These caverns were mined in the 1950s, 60s, and 70s, and were an integral part of operations at the shuttered Marcus Hook refinery.[57] The smallest cavern, at approximately 200,000 barrels capacity, now belongs to Braskem and is integrated into their polypropylene plant operations. The remaining capacity, at around 1.8 million barrels, belongs to Sunoco with the largest cavern capable of holding approximately 1 million barrels. Some of the capacity is set aside to serve the Paulsboro, New Jersey, refinery located across the Delaware River, while the rest facilitates Sunoco's operations at the Marcus Hook terminal, including exports.

As part of the Mariner East project, storage at the site was expanded. The initial phase of the project, which accompanied the Mariner East pipeline reversal and repurposing for NGPL service, included a 300,000 barrel ethane tank and a 500,000 barrel propane tank.[58] Expansion plans include adding additional storage capacity of a 900,000 barrel propane tank, a 589,000 propane storage tank, a 575,000 butane tank, and a new 300,000 barrel ethane tank (estimated).[59] Completion of work on site was originally scheduled to coincide with the commissioning of the ME2 and ME2x pipelines in late 2017 but the pipeline project has experienced some temporary setbacks and has been delayed.

Energy Storage Ventures LLC, a joint venture between Mountaineer NGL Storage and Powhatan Salt Company, is developing a NGL storage facility in Monroe County, Ohio. As part of its Phase I offering, the subterranean storage facility will operate multiple caverns with a total of 2 million barrels of NGL storage solution-mined in the Salina bedded salt formation roughly 6,500 feet below the Ohio River Valley.[60] The storage facility will serve as a centrally-located storage point for ethane, propane, butanes, and ethylene in the Appalachian region with rail and truck loading capacity as well as two 10-inch, bi-directional pipelines to Blue Racer's nearby Natrium fractionator.[61, 62] Initial storage is scheduled to begin at the end of 2018 and ramp up to full operable capacity by mid-2020. With sufficient interest, project sponsors may develop Phase II and expand the facility up to its permitted 3.25 million barrels capacity.

Appalachia Development Group LLC (ADG) is a collaborative platform formed to develop the Appalachia Storage and Trading Hub (ASTH), a proposed facility with underground storage for natural gas liquids. The proposed project is intended to be a catalyst for further mid- and downstream development associated with the Marcellus, Utica, and other shales. To determine its basic eligibility for a federal loan guarantee, ADG submitted a Part I application in September 2017 to the U.S. DOE Loan Program Office (LPO). In January 2018, the LPO invited ADG to submit a Part II application for a loan guarantee under the DOE Title XVII Loan Program, which entails submitting a comprehensive application for the proposed project. ADG is seeking a $1.9 billion loan guarantee that will first require securing an additional $1.4 billion in equity. The site of the proposed hub has yet to be determined. [63]

Figure 16. NGL Storage and Export Facilities[64]



F. Ethylene Crackers

When raw natural gas is processed at the gas processing plant, the natural gas plant liquids are recovered and transported (generally by pipeline) to a fractionator, where they are separated into individual products. Ethane, the lightest and most abundant of these products, is then transported to and fed into a hydrocracker that, under high temperature and pressure and in combination with steam, "cracks" or transforms the ethane (C_2H_6) molecule into primarily ethylene (C_2H_4), as well as co-products such as methane, hydrogen, and other molecules. Ethylene, the target molecule, is then moved further into the petrochemical value chain, where it serves as an intermediate input and a building block in the production of plastics and other petrochemical products.

Unique to the region, gas processing plants in Appalachia extract most ethane separately from the remaining NGL stream and have been increasing their capacity to do so faster than fractionation capacity overall. De-ethanization capacity has grown from zero in 2010 to over 200,000 b/d in 2016, and may reach 350,000 b/d by 2019.[65] The capacity to extract ethane separately from other NGLs is crucial for gas processors looking to balance gas quality requirements set by natural gas pipeline operators, and is key to satisfying local and out-of-region demand for ethane as a petrochemical feedstock.

Table 5. Proposed major Appalachian ethylene crackers

Company	Location	Announced Capacity (tpa)	Ethane Feed (1,000 b/d)	Possible Completion
Shell Chemicals	Monaca, PA	1.5 mil.	90	2020-21
Odebrecht/Braskem	Washington Bottom, WV	1 mil.	60	2022+
PTT Global / Daelim Industrial Co.	Shadyside, OH	1.5 mil.	90	2022+

First proposed in 2012, Shell Chemicals' project is the first ethylene cracker project in the Appalachian region to move to the final investment decision stage (FID); it is also the biggest.[66] Shell's project will have the potential to consume up to 96,000 b/d of ethane for the production of 1.6 million metric tons per year of ethylene, and will feature on-site capacity to then convert this ethylene into derivative products: low- and high-density polyethylene (LDPE and HDPE).[67] The facility, once built, will increase ethane demand in the region on the scale of a medium-size pipeline. It will also significantly increase the supply of plastics feedstock in a region that is currently a net importer of these materials. With four other cracker projects proposed for the region, local demand for NGL feedstock, primarily ethane, could be as high as 275,000 b/d – nearly as much as current capacity for moving all liquids out of the region.

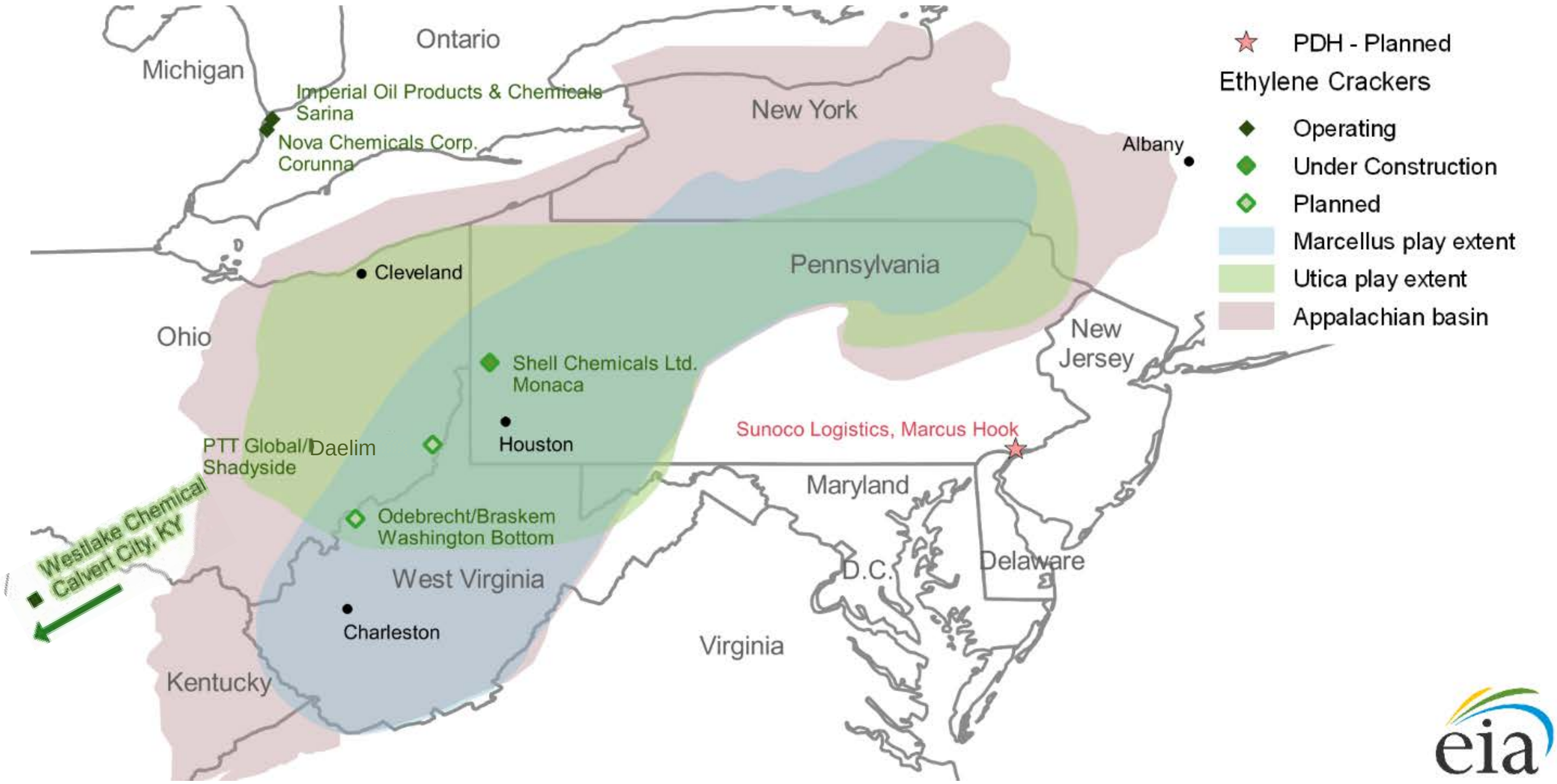
In addition to Shell, PTT Global Chemical of Thailand has proposed building a petrochemical cracker at Shadyside in Belmont County, Ohio. PTT has delayed making FID, and recently partnered with Daelim Industrial Co. of South Korea, a major construction and petrochemicals company. Both PTT Global and Daelim, through its Yeochun subsidiary, are leading petrochemical producers in their respective countries. The companies will jointly conduct a feasibility study, and expect making a final investment decision at the end of 2018.[68] PTT Global has set capacity for the planned cracker at 1.5 million metric tons per annum, translating into 90,000 b/d of ethane feedstock demand.[69] Like Shell's ethane cracker under construction in Monaca, Pennsylvania, the PTT/Daelim project would include derivatives production – with polyethylene most likely, but monoethylene glycol also a possibility. The joint experience in petrochemicals of both PTT Global and Daelim provides a general sense of optimism that this project will eventually move forward.

The Ascent Project, Odebrecht/Braskem's cracker proposed for Washington Bottom in Wood County, West Virginia, was an early candidate for success.[70] Challenges at parent company Odebrecht have delayed this potential major investment. Braskem developed a new petrochemical project in Mexico in a joint venture with IDESA in mid-2016;[71] the 1.05 million mt/y cracker is paired with HDPE and LDPE lines that generate polyethylene pellets for Mexican and overseas markets. Feedstock for the cracker is supplied by Pemex from three of its gas plants, which is intended to provide built-in redundancy for sufficient ethane supply.[72] The proposed cracker in West Virginia would be built very much along the lines of the Braskem/IDESA project, including sourcing ethane from multiple gas plants to avoid the need for storage facilities.

The potential for two other, minor cracker projects, Aithner Chemicals at South Charleston in Kanawha County, West Virginia, and Appalachian Resins at Salem Township in Monroe County, Ohio, is highly uncertain at the present time.[73, 74] This is due to a large degree to the fact that the Aithner 500,000 mt/y cracker and the Appalachian Resins 600,000 mt/y project have not secured interest in funding or offtake agreements.[75] The current pricing environment, where the oil-to-gas price margin has narrowed, makes smaller projects that lack the capital of multinational corporations very risky for investors to take on.

The sole existing petrochemical cracker in the region is the Westlake Calvert City, Kentucky plant. Initially, the cracker used propane as a feedstock, receiving its supply via the TEPPCO pipeline as well as by rail and truck from in-region producers. In early 2014, the feedstock slate at the 204,000 mt/y cracker changed to 100% ethane, as the ATEX pipeline came online carrying Appalachia-produced ethane south and via the existing TEPPCO lateral line connecting to the plant.[76] Moving away from propane has resulted in the elimination of propylene from the cracker's product output slate, which has impacted in-region polypropylene producers. Nonetheless, adoption of locally-produced ethane as the feedstock allowed the cracker to reduce its feedstock costs and supply risk, improving plant economics and facilitating another capacity expansion and further investment in the plant, reported by Westlake as being in excess of $300 million.[77] The plant's current 330,000 mt/y capacity translates to approximately 20,000 b/d of ethane feedstock demand, all sourced from the Appalachian basin via the ATEX pipeline.

Figure 17. Ethylene Crackers and Propane Dehydrogenation Plants



G. Propane Dehydrogenation

Propane dehydrogenation (PDH) is the process of directly converting propane into propylene through the use of specialized catalysts. Propylene is the second most common petrochemical molecule after ethylene, and is converted by the petrochemical industry primarily into plastics. The Appalachian region currently has no existing PDH capacity and features little propylene production, causing propane to be shipped to other chemical processing regions and propylene for polypropylene production to be shipped in by rail.

Sunoco Logistics has proposed building a PDH plant at its Marcus Hook, Pennsylvania site.[78] The PDH unit, of up to 1 million mt/y of capacity, would aim to convert propane to propylene, and supply this propylene to producers of polypropylene, as well as potentially to producers of alkylate – a high-octane gasoline blending component – to plants within a 600-mile radius. This project has made little headway to date given no progress in securing offtake agreements for the propylene.

VI. Research and Development Opportunities

The shale revolution is a story of technological innovation driven by both the public and private sectors. The U.S. Department of Energy sponsored research between the 1970s and 1990s that advanced key methods required for today's unconventional oil and gas production, including horizontal drilling and hydraulic fracturing. While the U.S. is now experiencing record levels of oil and natural gas production, opportunities exist for continued research to improve the effectiveness of oil and gas production and enhance utilization strategies that collectively ensure energy security while mitigating impacts. The Department of Energy has identified the following areas as potential topics for further research to take advantage of the nation's abundant oil, gas, and natural gas liquids resources.

- **Enhancing Recovery of Unconventional Resources**
  Estimates of recovery from unconventional reservoirs are as low as 5 percent of the original hydrocarbon in place in some formations, which means that a vast majority of the resource is likely to be left permanently in the ground.[79] The total U.S. unconventional oil and gas resource base is estimated to be in the thousands of trillions of cubic feet of gas and hundreds of billions of barrels of oil and natural gas liquids.[80] Based on these volumes, a concerted science and technological effort to achieve even a few percentage points improvement in recovery efficiency would result in a significant addition to domestic energy security.

  The challenge in unconventional oil and natural gas development is finding an efficient way to produce hydrocarbons from a volume of reservoir by completing wells in a way that maximizes their combined stimulated rock volume, a challenge that has led to increased fracturing stages per well, increasingly tighter well spacing, and the introduction of more effective fracturing techniques. Another recovery enhancement approach in unconventional plays is re-fracturing existing, older wells utilizing today's improved techniques and understanding of unconventional reservoirs.

  The systematic study of the fundamental processes involved in hydrocarbon extraction from shale, combined with the investigation of methods to improve safe and efficient recovery, would advance the fundamental understanding of prudent hydrocarbon extraction from unconventional shale resources to improve technologies for efficient and sustainable production. Additionally, market analysis could quantify the long-term benefits derived from improved U.S. competitiveness, and identify the necessary infrastructure to take full advantage of the resource. Potential areas of focus include:
  - *Fracture Dynamics*: Further research is needed on fracture properties and multiphase flow in hydraulic fracture systems, including the development of tools for analyzing hydraulically fractured reservoir performance, predicting hydrocarbon production, and identifying targets for improving the efficiency and performance of hydraulic fracturing operations.

- *Proppant Transport and Fate*: Further research is needed on proppant transport and long-term fate in brittle and ductile shales to determine how to optimize the use of proppant in hydraulic fracturing operations while minimizing negative impacts associated with proppant embedment and pulverization.

- *Water-Shale-Hydrocarbon Interactions*: Further research is needed on water-rock interactions in shale, including understanding controls on flow-back fluid composition and multiphase flow properties in order to optimize fracturing fluid composition, minimize the production impacts of water blocking and mineral precipitation, and address the environmental risks associated with water management.

- *Non-Water Based Fracturing Fluids*: Further research is needed on non-water based fracturing fluids and their impact on shale gas/oil mobilization, including identification of optimal fluid formulas that increase productivity and reduce water use in unconventional oil and gas development.

- *Improved Development Strategies*: Further research is needed on the effectiveness of improved development strategies (e.g. enhanced production techniques) to identify methods that optimize prudent hydrocarbon extraction.

- **Improving Conversion of Natural Gas and NGLs into Feedstocks and Products**
  Natural gas conversion is a broad and active area of research that spans many potential chemical products that can be addressed individually. Accelerating the development of direct conversion methods would enhance both energy and economic security by broadening the slate of products available from domestic natural gas. However, the processes that can generate these products suffer to varying degrees from a set of disadvantages that can be overcome with focused research and development. Two areas for additional research include:
  - *Improving Oxygen Separations*: Oxidative pathways for methane conversion (e.g. oxidative coupling of methane, advantaged syngas production, or oxidative dehydrogenation of NGLs to produce aromatics) often rely on separation of oxygen from air. Current separation processes are often very thermodynamically inefficient. Improvements in oxygen separation can be impactful to the natural gas conversion industry as well as other chemical industries. Similarly, most direct routes for methane upgrading have low conversion rates which require improved separation from undesired components.

  - *Modular Systems*: Where natural gas is produced in smaller-scale, distributed wells, modular solutions for new systems that propose mechanisms to close these technical gaps are required. To fully enable modularity at small scales, the new natural gas conversion processes must be intensified in such a manner as to reduce footprints as much as practical. Reducing the capital cost of new and current equipment designs, especially at smaller sizes where economies of scale diminish, will serve to enable cost-effective implementation of thermodynamic improvements.

- **Enhancing the Safety and Efficiency of NGL Storage**
  As described previously in this document, storage of NGLs is necessary since produced volumes typically do not align with the seasonal nature of NGL demand. Large volumes of NGLs are primarily stored as a pressurized liquid in underground caverns. Most underground caverns are in salt formations, but some propane storage caverns are mined out of shale, granite, and limestone rock. When stored underground, NGLs are injected down a wellbore and into a subsurface geological formation. The long-term isolation of the storage zone from the surrounding environment is largely dependent on the durability of well casings and cement, and the effective sealing of the wellbore annulus.

  Maintaining wellbore integrity is an area for further research relevant to underground hydrocarbon storage (as well as production). Focused research and development activities on developing adaptive and self-healing cement materials, next-generation diagnostic (e.g. logging) tools, and subsurface sensors can enhance wellbore integrity.
    - *Self-Healing Cement Materials*: Sealing of wellbores by filling the annulus with cement is a well-established practice. Cracks may occur over time in the cement as a result of physical and/or chemical stress. Identifying and repairing these cracks can be difficult and costly. There is the opportunity for additional research into inorganic-cement and organic-cement composites that possess self-repairing capabilities and strong adhesion to steel casing properties.

    - *Next-Generation Diagnostic Tools*: Robust logging systems, fit for the purpose of the well, are needed to diagnose the precise location and character of well integrity problems. These tools could utilize specific physical signals or could involve the development of analytical techniques based on more general tools that allow reliable diagnostics of the integrity of the wellbore. These diagnostics would facilitate accurate targeting of remediation efforts and the selection of the appropriate remediation methodology. Opportunities exist to develop improved technologies and techniques for diagnosing near-wellbore conditions and interpretation methods. Additionally, the development of surface-based wellbore leakage diagnostics systems would mitigate the costs and effort associated with the deployment of wellbore-based tools.

- *Subsurface Sensors*: There is a paucity of autonomous "health-of-system" downhole monitoring options available today following the construction phase of a well. These sensing systems are needed across a wide spectrum of applications and across timeframes not available today. For example, the ability to monitor and transmit parameters such as hydraulic containment, casing stress, corrosion, rock/cement/casing bond, and other system performance parameters are not available but are of great interest in all borehole applications, including underground storage.

VII. Concluding Remarks

The Appalachian region is endowed with significant NGL resources projected to be economically recoverable over at least the next three decades. Since the boom in natural gas production – unlocked by technological innovation – industry has invested billions of dollars in natural gas and NGL infrastructure in Appalachia. Increased recovery of ethane, instead of rejecting it in the dry natural gas stream, presents opportunities for new downstream investments using ethane as a feedstock.

This primer addressed fundamental aspects of the NGL market and supply chain in Appalachia. There are opportunities for further analysis related to NGL resources in Appalachia. DOE has identified the following areas that may merit further in-depth study.

NGL Downstream Market Scenario Analysis

- Explore scenarios for the development of a regional petrochemical industrial center. Analyze how ethylene and propylene markets may develop in the future to drive new investments in petrochemical plants and supporting infrastructure.
- Evaluate the potential downstream economic impacts of NGL utilization on the local, regional, and national economy.
- Study the impact additional U.S. NGL and product exports may have on international markets. Will new markets emerge and new trade patterns be established with increased U.S. NGL production and petrochemical plant capacity?

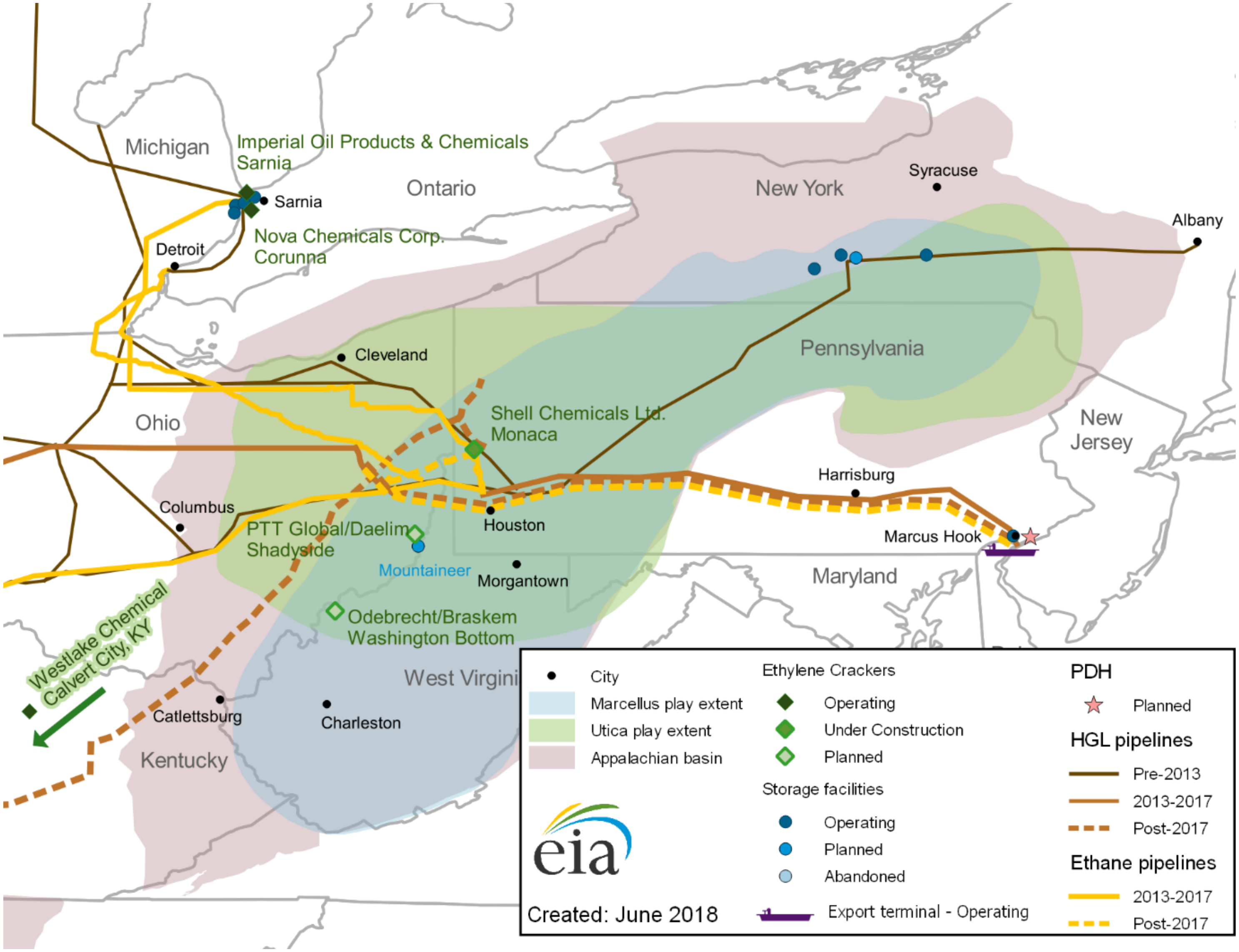
Reliability and Resilience

- Define resilience for the NGL supply chain and petrochemical industries. Identify aspects of the natural gas and NGL system that contribute to reliability and resilience.
- Develop methods to evaluate the energy security implications of the domestic NGL supply chain and U.S. petrochemical plant capacity. Identify appropriate metrics to evaluate the energy security of the nation's NGL and petrochemical systems.

Research and Development Opportunities

- Explore technologies and techniques to enhance the recovery efficiency of unconventional natural gas production.
- Conduct research in materials, technologies, and methods for improved conversion of natural gas and NGLs into feedstocks and products.
- Explore technologies to enhance the safety and efficiency of NGL storage, including the development of new materials and sensors to detect and prevent losses.

Appendix A: Pipelines, Storage, Export, and Petrochemical Plant Map[81]



Appendix B: Abbreviations and Units

AEO	Annual Energy Outlook
ATEX	Appalachia-to-Texas Express
B/d	Barrels per day
Bcf/d	Billion cubic feet per day
C_2H_4	Ethylene
C_2H_6	Ethane
CO_2	Carbon Dioxide
DOE	Department of Energy
EIA	Energy Information Administration
EPP	Enterprise Product Partners
FID	Final Investment Decision
HDPE	High-density Polyethylene
HGL	Hydrocarbon Gas Liquids
LDPE	Low-density Polyethylene
LPG	Liquefied Petroleum Gas
ME2	Mariner East II
ME2x	Mariner East IIx
MMBtu	Million British thermal units
MPLX	Marathon Logistics
mt/y	Million tons per year
NGL(s)	Natural Gas Liquid(s)
NGPL	Natural Gas Plant Liquid(s)
PDH	Propane Dehydrogenation
STEO	Short-Term Energy Outlook
Tcf	Trillion cubic feet
Tpa	Tons per annum
TEPPCO	TE Product Pipeline Company
VLEC	Very Large Ethane Carriers

Endnotes

[1] Data used in the charts showing Appalachian production include all of the East region of the U.S. as defined by the United States Energy Information Administration (EIA) for the purpose of modeling in the Oil and Gas Supply Module of the Annual Energy Outlook (https://www.eia.gov/outlooks/aeo/assumptions/pdf/oilgas.pdf). The Appalachian region includes the prolific Marcellus and Utica formations which lie within the borders of Kentucky, Ohio, Pennsylvania, and West Virginia. In 2016, natural gas production in these four states accounted for 97% of total East region production. While data in the charts represent the entire region, the figures are an appropriate representation of Appalachian production.

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