U.S. OIL AND NATURAL GAS:

Providing Energy Security and Supporting Our Quality of Life

U.S. DEPARTMENT OF ENERGY | Fossil Energy

OFFICE OF OIL & NATURAL GAS

Over the past two decades,

Americans have witnessed dramatic growth in our nation's ability to produce the oil and natural gas needed to power our vibrant economy and support our modern lifestyle. This report focuses on the important benefits this increased supply of domestic energy produced, and the key advances in oil and natural gas production technology that made this growth possible. The Office of Oil and Natural Gas at the U.S. Department of Energy (DOE) produced this report to recognize the critical role of advanced energy technology innovation in maintaining U.S. economic success and providing a sustainable domestic energy supply for the future.

Table of Contents

Cover: Oil and gas are used every day as fuel for cooking, as a feedstock for fertilizers, to make plastics for agricultural and other uses, and to make fuels for transportation.

September 2020

EXECUTIVE SUMMARY

Oil and natural gas play an essential role in powering America's vibrant economy and fueling a remarkable quality of life in the United States. Together, oil and natural gas provide more than two-thirds of the energy Americans consume daily, and we will continue to rely on them in the future. In addition to meeting our energy needs, oil and natural gas are integral to our standard of living in ways that are often not apparent. Several key advances in technology enabled a dramatic increase in domestic oil and natural gas production over the past 20 years. This increased production provides energy security and economic benefits to the entire country, and ongoing technology advances will help us to enjoy those benefits into the future.

OIL AND NATURAL GAS ARE ESSENTIAL FOR AMERICA'S NEEDS

Oil and natural gas are used in many ways that are familiar to consumers. Petroleum products power transportation, providing fuel for cars, trucks, marine vessels, locomotives, and airplanes. Natural gas generates more than one-third of the electricity needed for dependable heating, air conditioning, lighting, industrial production, refrigeration, and other essential services, and tens of millions of Americans rely on oil and natural gas to heat their homes directly and on clean-burning natural gas to cook their food. But petroleum products do so much more than fuel our cars and power our homes and businesses.

While perhaps less recognized, oil and natural gas also play critical roles in supplying essential products and materials, increasing agricultural productivity, and supporting the expansion of new energy sources.

Oil, natural gas, and **natural gas liquids*** are building blocks for a range of modern materials used to produce life-changing prosthetics, energy-efficient homes, safer cars that go farther on a gallon of gasoline, and hundreds more consumer products that Americans use every day. Plastics and chemicals derived from oil and natural gas make our food safer, our clothing more comfortable, our homes easier to care for, and our daily lives more convenient.

Natural gas is also a key ingredient for chemical fertilizers, helping increase crop production and yield per acre planted, and powering many important operations on the farm like crop drying.

*Throughout this report, words in bold green are explained further in the Glossary (pages 58-66). Only the first instance of the word or phrase in the report is shown in bold green.

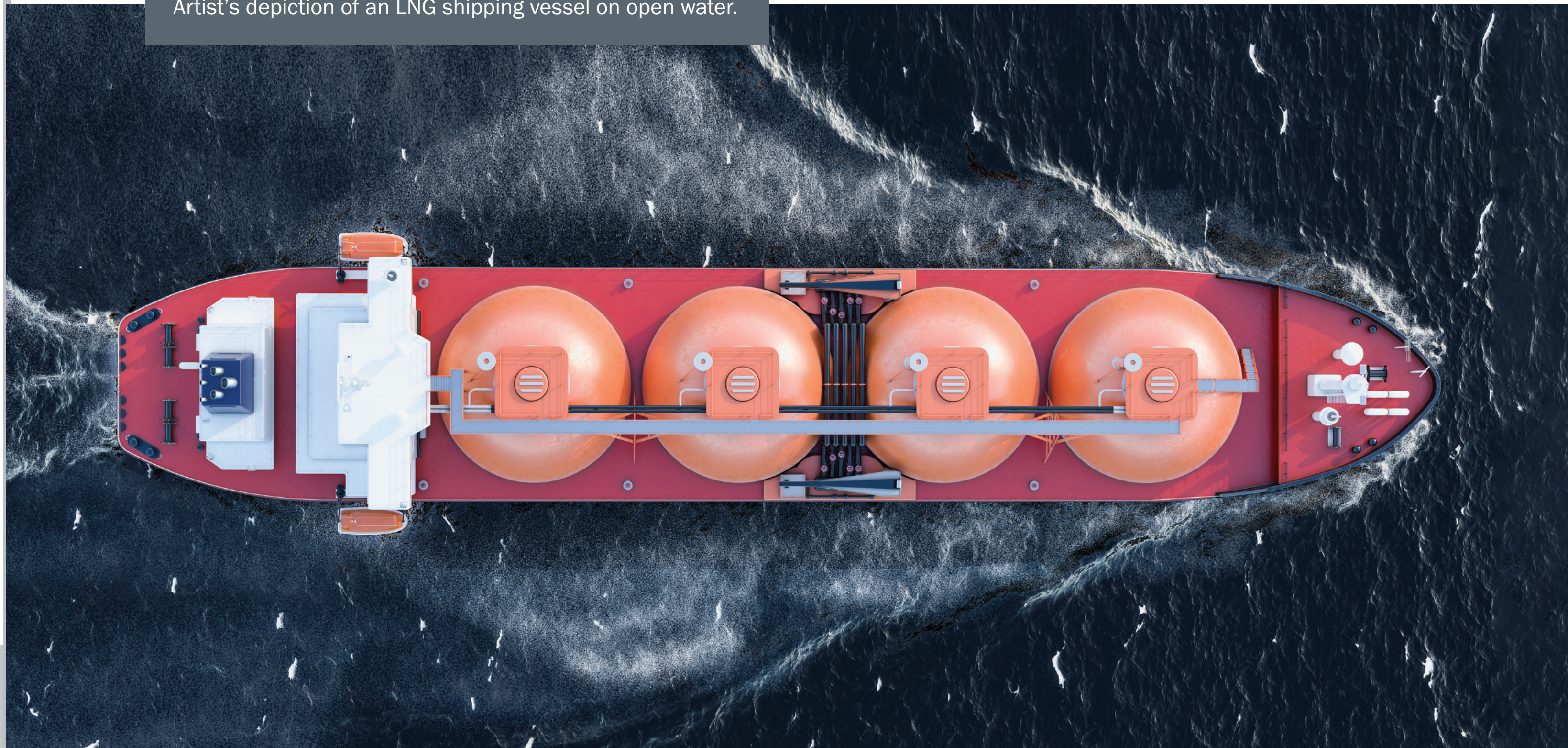
Lightweight, durable plastics produced with oil and natural gas are used by most wind turbine and solar panel manufacturers. During times when there is no wind or sun, gas-fired turbines provide secure, on-demand power that keeps America's integrated energy grid operational. Additionally, hydrogen produced from fossil fuels is a versatile energy carrier that can play an important role in the transition to a low carbon economy. Already, 99 percent of U.S. hydrogen production is sourced from fossil fuels, with 95 percent from natural gas by **steam methane reforming (SMR)**.

THE BENEFITS OF DOMESTIC OIL AND NATURAL GAS ARE SECURED BY TECHNOLOGY INNOVATION

All Americans – not just those living in the 34 oil and natural gas-producing states or working at oil and natural gas jobs – directly benefit from increased domestic production. The benefits include significant savings for American consumers due to lower energy costs, increased revenues for state and local governments, growing numbers of well-paying jobs, a revitalized U.S. petrochemical manufacturing industry, and increased commerce from exporting **liquefied natural gas (LNG)**.

At the same time, reducing the environmental footprint per unit of oil and natural gas produced by implementing lower-impact extraction technologies has made oil and natural gas competitive with other energy sources in terms of environmental sustainability.

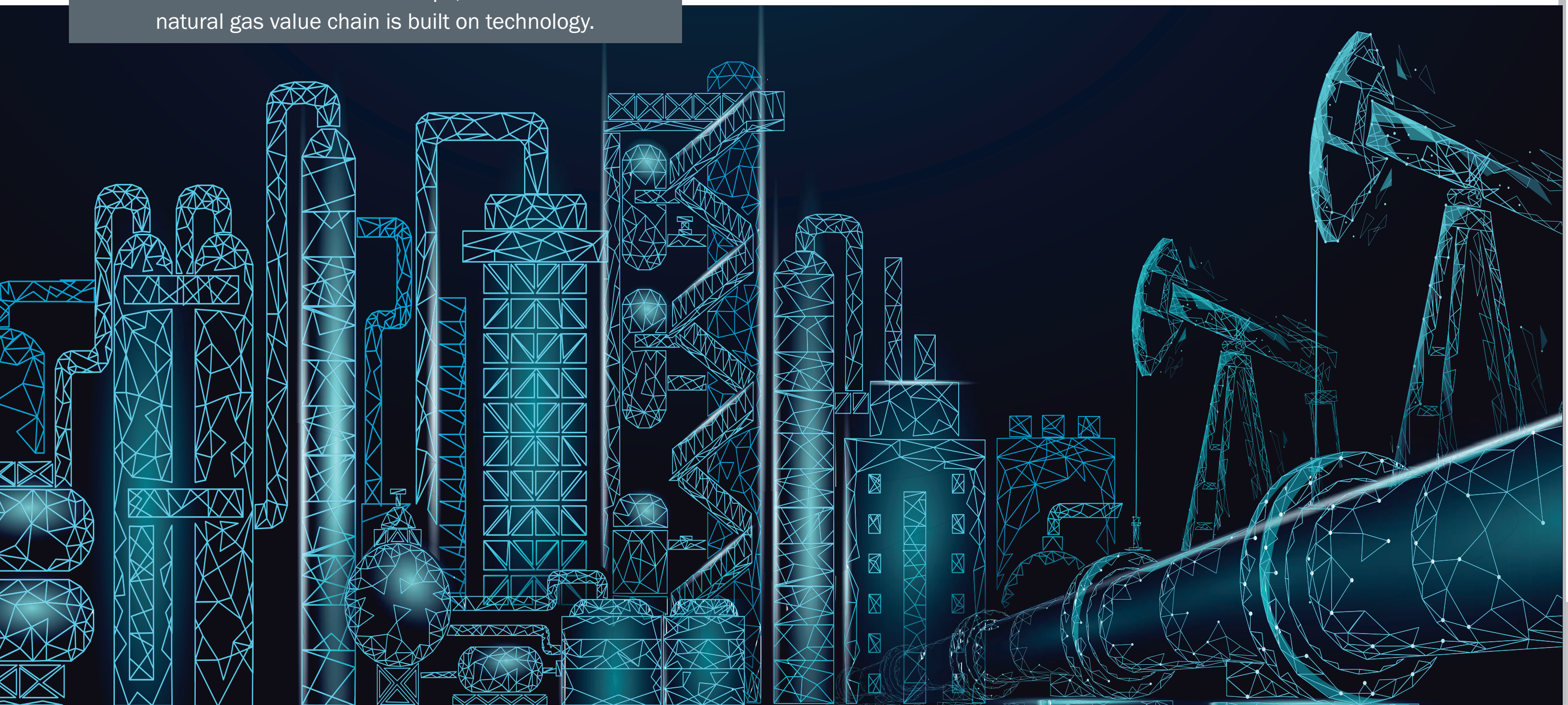
Artist's depiction of an LNG shipping vessel on open water.



Technology innovations have transitioned the United States away from dependence on energy imports and alleviated concerns about energy resource scarcity. Economically recoverable domestic energy resources are now much more plentiful, and the United States has become a more influential force in international energy markets. More than 40 years of industry and government investments in research and technology development dramatically changed the technical capability of the domestic oil and natural gas industry, unlocking the oil and gas trapped in unconventional reservoir rocks and providing abundant and affordable supplies for many decades. The science and technology behind this trend include:

- Advances in production methods enabling the recovery of oil and natural gas from previously uneconomic sources, responsible for much of America's growing energy abundance.
- Enhancements in technologies for using carbon dioxide to extract more oil from older wells while safely storing this **greenhouse gas (GHG)** underground.
- **Floating platforms** and subsea producing systems that expand the volumes of oil and natural gas resources recoverable from the deeper water areas of the ocean.
- Production efficiency gains made possible by leveraging data through artificial intelligence and machine learning.
- New approaches enabling oil and natural gas production in more environmentally sustainable ways and supporting sustainable oil and natural gas resource development.

From wells to wheels or burner tips, the entire oil and natural gas value chain is built on technology.



Dramatic increases in domestic oil and natural gas production enabled the United States to move from being an energy importer to being a net energy exporter. This shift means we are no longer dependent on other countries to meet our domestic energy needs. As a growing supplier of natural gas to global markets, the United States is now in a position to help its allies worldwide power their economies.

Affordable oil and natural gas production will continue to play an important role in America's energy supply for the foreseeable future, underpinning U.S. economic and energy security. Oil, natural gas, and natural gas liquids are still projected to account for the majority of U.S. energy consumption two decades from now, despite the steady growth of renewable energy sources like wind, solar, and biomass.

A critical role remains for oil and natural gas even as countries transition to a lower carbon energy future. Natural gas will continue to help decrease carbon dioxide emissions from electricity production while providing secure, on-demand power needed for wind and solar energy to scale up. Oil and natural gas also will continue to supply high-tech materials that make renewable, low-carbon energy sources economically feasible.

Investments in research and technology during the past few decades enabled the United States to become a world leader in oil and natural gas production, yielding valuable benefits enjoyed by Americans of all walks of life. The Office of Oil and Natural Gas at the U.S. Department of Energy (DOE) played an important role partnering with industry, academia, state agencies, and non-governmental organizations in developing some of those technologies – and continued technology advances will lead to even better performance and more benefits in the future. As the country rises to address new challenges, DOE and America's public and private researchers remain focused on fostering technological innovation that ensures sustainable domestic energy supplies.

SECTION 1

OIL AND NATURAL GAS POWER AMERICA'S ECONOMY

Americans depend on a plentiful supply of affordable, domestically produced energy to not only meet our basic human needs, but also provide the comforts and conveniences we've come to expect in our modern lifestyle. Every day, energy sets off our alarm clocks and heats our morning coffees. It fuels our transportation to work and school, and the devices and tools used there. It gets us back home and cooks our dinner, illuminates our time with family, powers our digital world, and keeps us warm (or cool) at night. It also supports the emergency responders who keep us safe.

The national economy is fundamentally dependent on energy at every level: to extract raw materials, grow food or manufacture products, move them to market, operate the systems needed to manage our commerce, and provide us with information that is vital to our lives, businesses, and democracy. Americans have a high energy demand: our robust economy and our energy use are inextricably linked.

While the lifestyle Americans enjoy requires substantial energy input, efforts have been made to improve energy efficiency which support long-term security and reduce the impacts of energy production and delivery.

Our robust economy and our energy use are inextricably linked.

In 2007, the National Petroleum Council[1] developed policy recommendations to reduce energy demand by improving efficiency, including:

- Raising vehicle fuel efficiency standards;
- Encouraging energy efficient building codes and appliance standards;
- Conducting research to reduce the costs of industrial energy efficiency-enhancing technologies; and
- Improving energy data collection.

Maximizing the benefits per unit of energy consumed through energy efficiency enhancements is key to maintaining our vibrant American way of life and has been a goal for energy technology advancements over the past two decades.

CURRENT DOMESTIC ENERGY SUPPLY:

Fossil Fuels Key to an Integrated System

Where does our energy come from? How is it used?

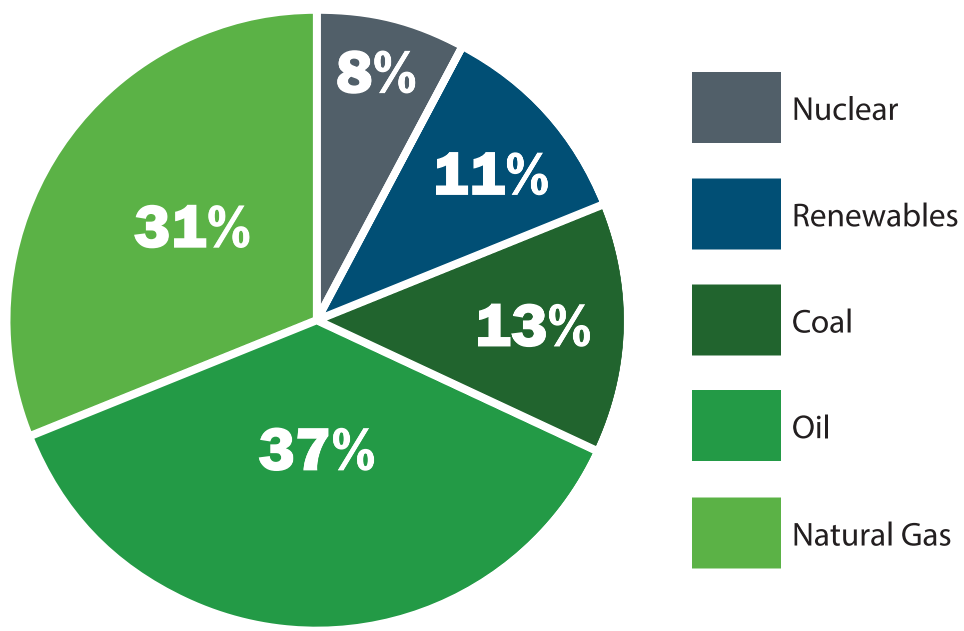
America's energy comes from a variety of sources:

- Fossil fuels such as oil, natural gas, and coal.
- Nuclear energy.
- Renewable forms of energy such as biomass (which includes fuel ethanol from corn and biodiesel), solar, wind, hydroelectric, and geothermal energy.

Fossil fuels provide the lion's share of the energy we consume, with oil and natural gas comprising the majority of that contribution (see Figure 1).

Figure 1 **Oil & Natural Gas Power More Than Two-Thirds of U.S. Energy Consumption[2]**

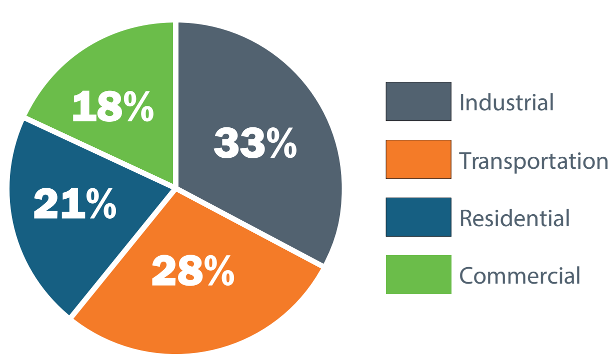
Nearly 70% of energy consumed in the United States comes from oil and natural gas products.



Four major economic sectors use energy relatively equally in the United States: transportation, industrial manufacturing, commercial activities, and residential use (see Figure 2).

1. The transportation sector's primary use is gasoline and diesel fuel for cars and trucks. It also includes fuel for marine vessels, locomotives, and airplanes.
2. Industrial sector use includes fuel or electric power for the facilities and equipment used for producing, processing, or assembling goods, including heating, air conditioning, and lighting. Fossil fuels, primarily natural gas liquids, also are used as raw materials for manufactured products.
3. Commercial sector use includes fuel for service-providing businesses, governments, and organizations, including heating, air conditioning, lighting, refrigeration, and cooking.
4. The residential sector uses energy for heating, air conditioning, lighting, refrigeration, and cooking in private households.

Figure 2 **Four Major U.S. Economic Sectors Used Energy Relatively Equally in 2019[3]**



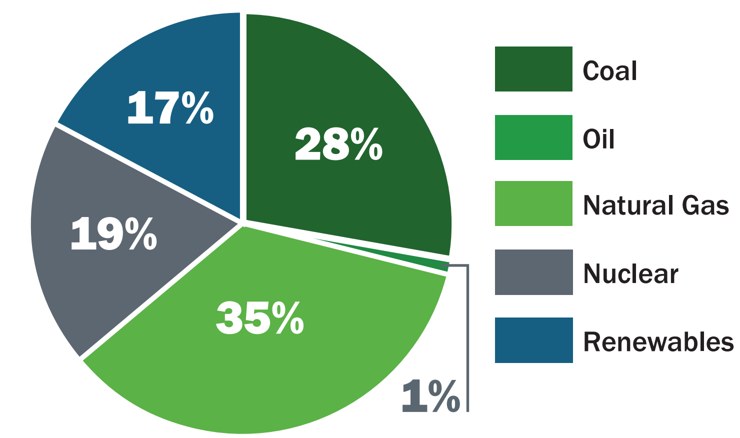
Electricity is an important energy input to the residential, commercial, and industrial sectors, providing between a quarter and three quarters of the energy consumed in each of these, including delivery losses, depending on the sector. The commercial and residential sectors use the most.

Currently, more than a third of the nation's electricity is generated by burning natural gas (see Figure 3). While coal still plays an important role in electricity production, natural gas as well as a variety of renewable sources – such as wind and solar – have been increasing their contribution to the nation's electric power generation capacity in more recent decades.

Natural gas also has a critical role to play in supporting the increased prevalence of renewables. Wind and solar inputs (sunshine) fluctuate while electric power demand is constant. Natural gas provides a secure and reliable energy source during interruptions in renewable energy supply, such as times of low wind or sun.

Figure 3 **Sources of U.S. Electricity Generation in 2019[4]**

More than a third of the nation's electricity is generated by burning natural gas.



Fossil fuels provide the lion's share of the energy we consume, with oil and natural gas comprising the majority of that contribution.

Flexible natural gas-fired power generation plants (left) help ensure that wind power remains reliable (right).

Insight

NATURAL GAS:

A CRITICAL PART OF ELECTRIC POWER PRODUCTION

A decade ago, natural gas provided about a quarter of the energy used to create electricity in the United States. Today, it provides nearly 40 percent and is expected to continue to claim this share for decades to come.[5] While the share of power produced by renewable energy sources like solar and wind is expected to grow, these sources are “intermittent” – wind energy fluctuates with the wind intensity and solar energy fluctuates with cloud cover and nighttime darkness – so there has to be a reliable, secure means to provide continuous electricity to consumers. The larger the contribution of renewables to the electric power grid, the bigger this challenge can be.

An effective solution is installation of fast-ramp-up natural gas power plants, which can be switched into the power generation system quickly whenever renewable generation slips. Such plants are capable of reaching full power outputs of hundreds of megawatts in less than 30 minutes and can be scaled back quickly when the wind picks up or the sun comes out.[6] This role for natural gas will continue until low-cost, environmentally sustainable, large-scale power grid batteries capable of storing solar or wind-generated energy and discharging it instantaneously are available.

In this context, natural gas supports an integrated energy system by enabling increased development of renewable sources for power generation, while decreasing carbon emissions (relative to other hydrocarbons) per unit of energy generated.

THE ROLE OF OIL AND NATURAL GAS BEYOND ENERGY

While their contribution to our nation’s energy supply is well recognized, **oil and natural gas support our modern lifestyle in countless ways** beyond their common uses for heating, electric power generation, and transportation fuel – ways that are not always obvious, but are integral to our daily lives (see Figure 4).

Figure 4 **Many common household items are made of compounds derived from oil and natural gas.**

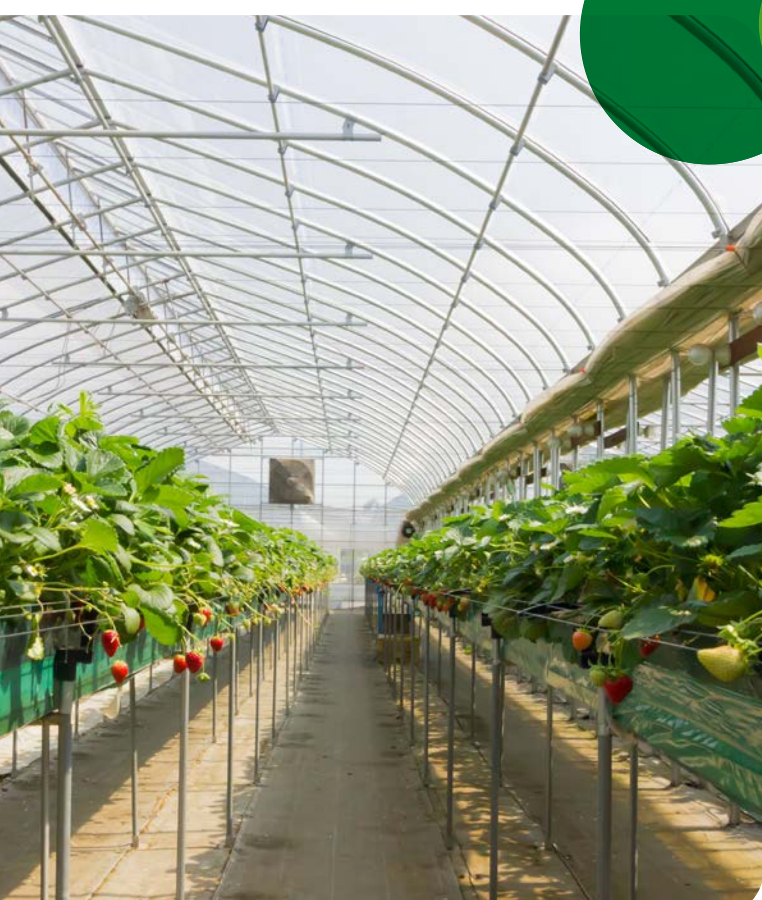
Oil, natural gas, and coal are **hydrocarbons** – chemical compounds made up primarily of hydrogen and carbon found in subsurface deposits. Oil and natural gas were created when organic materials that accumulated along with sediments in ancient sedimentary **basins** were subjected to heat and pressure over millions of years.

Hydrocarbons like ethane are the core ingredient in plastics, and are essential to modern healthcare, agriculture, the automotive industry, construction products, consumer products, and even renewable energy. Ethane is a liquid hydrocarbon removed from natural gas during post-production processing. While a relatively small portion of liquid hydrocarbons (about seven percent)[7] are used to produce non-energy products, these products’ omnipresence in our daily lives bears highlighting. We cannot live our 21st century lives without them.

Healthcare

Plastics made from natural gas liquids, such as ethane, have helped revolutionize healthcare delivery. Surgical gloves, antiseptics, medications, anesthetics, and a variety of medical devices from heart valves to prosthetics to eyeglasses are just a few examples.

Durable plastic packaging enables improved safety and more efficient delivery, from tamper-proof caps to shatter-proof bottles to protective coatings and non-permeable biohazard bags to transport medical waste. Plastic is widely used in surgical devices and procedures – modern pacemakers, stents, and joint replacement devices rely on its ability to be molded to intricate specifications. All of these applications are available at much lower cost and require much less maintenance than their metal and glass predecessors.



Agriculture

Natural gas and natural gas liquids serve as the source of hydrogen needed to combine with nitrogen to make ammonia, the foundation of chemical fertilizers that have helped increase U.S. crop production and yields, particularly for high demand crops like soybeans and corn, to record highs over the past 60 years.[8]

Natural gas also is used to dry these crops. Further, plastics made from hydrocarbons provide bags for hay and silage, greenhouse covers, bale wrapping material, mulch film to prevent weed growth, and plant nursery containers. **These natural gas-based products help maximize economic efficiencies in the agriculture sector.**

Automotive Industry

Plastics are integral to advances in the automotive industry. Automakers have met increased fuel efficiency standards in part by replacing heavier metal parts with lightweight plastic materials. Plastics make up 50 percent of today's cars by volume, but only 10 percent by weight[9] – a shift in design that has dramatically improved gas mileage.

Plastics also play a key role in most auto safety features, such as seat belts, air bags, interior cushioning, and crumple zones. Automakers are expected to rely even more on high strength composite materials that combine plastics with glass fibers, carbon fibers, or other materials to create car parts that often are stronger and lighter than metals, as well as corrosion resistant.

Home Construction

Homebuilders use many natural gas-based materials to build affordable and safe homes, including plastic foam insulation and sheathing materials, vinyl siding, weatherproof window frames, high performance caulks and paints, asphalt roofing materials, polyvinyl chloride (PVC) pipe, and chemically treated lumber.

Within our homes, plastic foam insulation helps refrigerators, freezers, dishwashers, and heating and air conditioning systems operate quietly and efficiently. Fire retardant furniture and mattresses are made from synthetic fibers derived from natural gas.

Consumer Products

The list of products Americans use daily that are derived from oil and natural gas is almost endless. Clothing, water bottles, food packaging, sports equipment, computers, cell phones, furniture, carpets and rugs, and other home furnishings are some examples. Natural gas and natural gas liquid-derived chemicals are components of a wide variety of health, personal care, and beauty products that range from antiseptics to deodorants, vitamins to nail polish, and shampoo to shaving cream.

It's difficult to imagine what life would be like without the hundreds of items we rely on every day for safety, durability, comfort, and convenience that come from oil and natural gas.

Renewable Energy

Even the renewable energy sector relies on the oil and natural gas industry. Most wind turbine manufacturers today use lightweight plastic composites derived from hydrocarbons to create strong, aerodynamic turbine blades.

Some researchers suggest plastic-based solar cells may become more common in the future due to their flexibility, light weight, and ability to form extremely thin components – potentially for printing and placing onto walls, windows, and a variety of other flat and curved surfaces.

FUTURE DOMESTIC OIL AND NATURAL GAS SUPPLY

The United States' ability to produce oil and natural gas has grown dramatically over the past 20 years, thanks to continued innovations in technology. The U.S. Energy Information Administration (EIA) at DOE expects that continued robust production levels of these fossil energy resources will support both increased domestic use and increased exports for decades (see Figure 5).

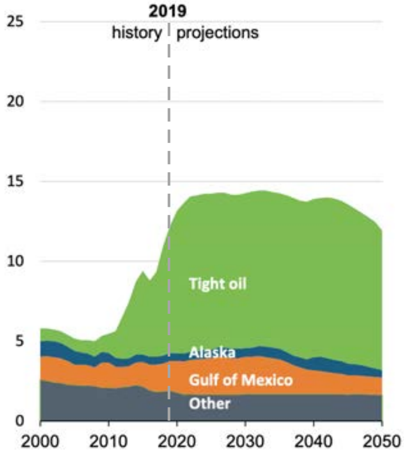
U.S. crude oil production will continue to be dominated by production from **tight oil plays** – areas where crude oil is contained in oil-bearing formations of low **permeability**, often shale or tight sandstone – such as those in the **Permian Basin** of Texas and New Mexico and the Williston Basin of North Dakota.

Natural gas production will continue to be dominated by production from **shale gas plays** such as the **Marcellus Shale** in the **Appalachian Basin** and **associated gas** from tight oil plays.

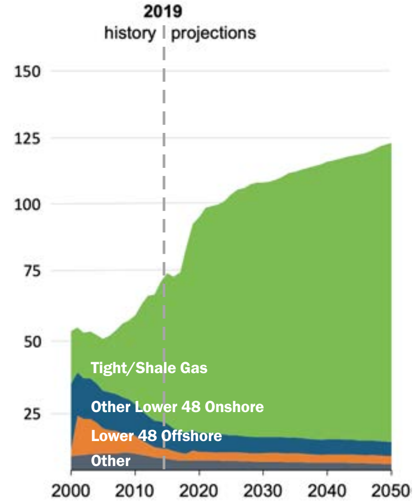
Figure 5

Sources of U.S. Crude Oil and Natural Gas Production Through 2050[10]

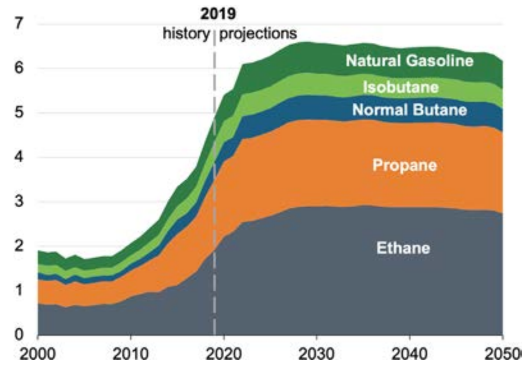
Crude oil production by type (million barrels per day)



Dry natural gas production by type (billion cubic feet per day)



U.S. natural gas plant liquids production by type (million barrels per day)

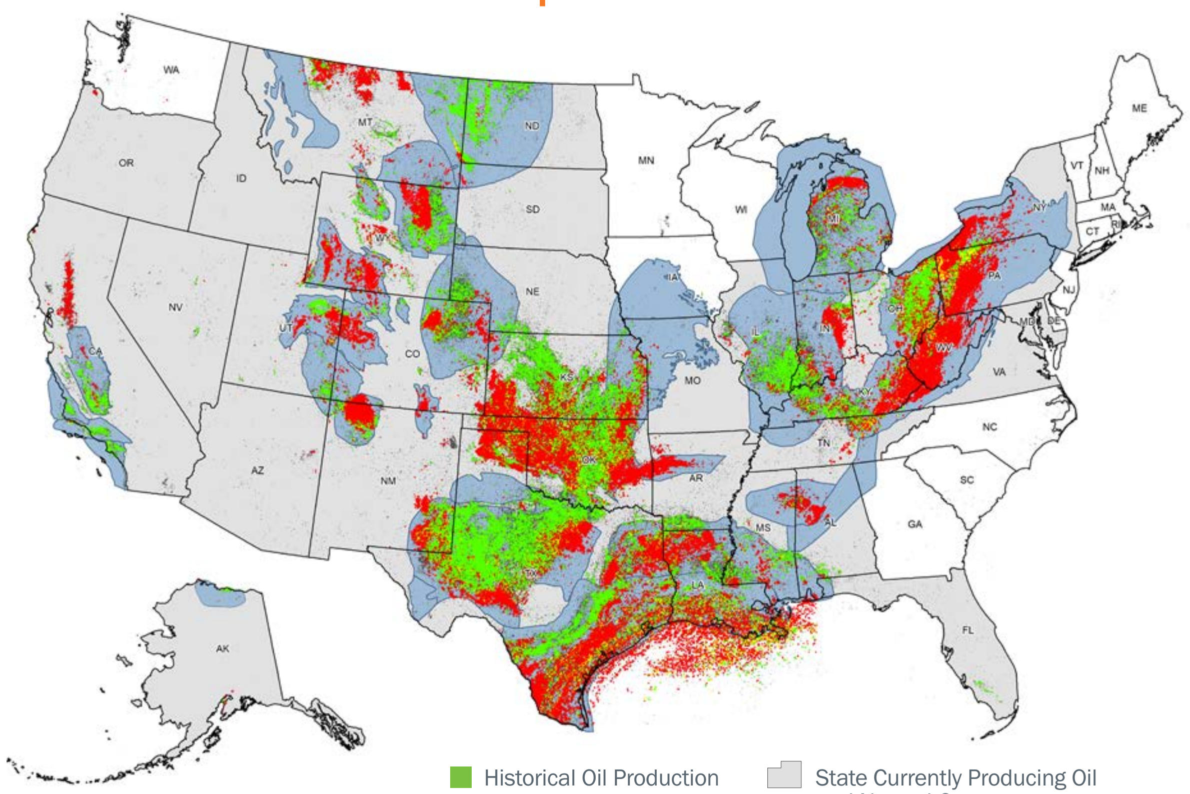


Continued robust production of domestic oil and natural gas will support increased U.S. demand and increased exports for decades.

In addition to the **unconventional** tight oil and shale gas reservoirs that are projected to provide the majority of future production, mature **conventional oil** and natural gas reservoirs also will continue to contribute to the nation's energy supply. Significant oil and natural gas production occurs in 20 of the 50 states and minor amounts are produced in 14 more (see Figure 6).

Figure 6 **U.S. Crude Oil and Natural Gas Fields**[11]

Energy from the 34 states that produce oil and natural gas benefits all Americans.



Drilling rig along the Rocky Mountain front, west of Dupuyer, Montana.

Oil and natural gas sustain our modern way of life and will continue to do so for the foreseeable future.

Beyond domestic supply, sustained production from domestic oil and natural gas reservoirs is projected to support increased levels of natural gas exports as liquefied natural gas (LNG) as well as growing exports of crude oil and refined petroleum products.

Oil and natural gas sustain our modern way of life and will continue to do so for the foreseeable future. Even efforts to reduce our reliance on fossil fuels still require that we use hydrocarbons – derived from oil and natural gas – to create and maintain the products and technologies that make these alternative energy sources reliable and economically possible.

A few key technological innovations helped drive the remarkable increases in U.S. oil and natural gas production over the past two decades. Such innovations will need to continue to provide Americans abundant, reliable, and secure sources of energy.

SECTION 2

INNOVATIONS IN OIL AND NATURAL GAS RECOVERY

Today, the United States is energy independent on a **net energy basis** – that is, we export more energy than we import. The trajectory of the domestic oil and natural gas industry has taken us from fears of scarcity to expectations of abundance.

Despite a history that includes long lines at gasoline pumps and curtailments of natural gas at schools and factories during the 1970s, and dire warnings of impending "peaks" in domestic oil and natural gas production capacity in the 1990s, the United States now exports natural gas and natural gas liquids, and imports progressively lower volumes of crude oil. As domestic oil and gas production has expanded, America's reliance on foreign energy supplies has declined, dramatically enhancing U.S. energy security. Our increased ability to supply energy to allies around the world also enhances U.S. flexibility in dealing with global diplomatic challenges, further strengthening security.

While unexpected events can cause short-term deviations, there is a clear trend toward energy self-sufficiency. This transformation has provided significant benefits to the domestic economy and consumers.

Four decades of investments in research and technology development dramatically changed the technical capacity of the domestic oil and natural gas industry, enabling it to provide abundant and affordable oil and natural gas supplies. Research investments of the 1980s and 1990s, made by industry and DOE's Office of Oil and Natural Gas in response to the oil and natural gas supply crises of the 1970s, built the scientific knowledge foundation that was needed to unlock new sources of oil and natural gas, particularly those found in "unconventional" reservoirs such as **organic-rich shales**.[12]

The application of this science and knowledge during the subsequent two decades led to the shale revolution. The rapid increase in oil and gas production from shales and other tight formations completely changed the energy landscape. The United States went from importing more than 50 percent of our oil to being an exporter, and from importing natural gas to being a global supplier.[13]

Concurrent research and technology development also led to the capability to produce oil and natural gas from fields in **ultradeep offshore waters**, to apply **carbon dioxide enhanced oil recovery (CO_2-EOR)** in new geologic settings, and to dramatically lower environmental impacts from oil and natural gas development.

Among many technology advances, more detail is provided for the following five examples:

1. Advances in science and new extraction methods foster unconventional resource development.
2. **Floating platforms** and subsea completions overcome the deepwater offshore barrier.
3. New geologic settings and sources of carbon dioxide support expanded use of CO_2-EOR and carbon dioxide storage.
4. Artificial intelligence and machine learning enable more cost-effective extraction and transportation of oil and natural gas.
5. New technologies mitigate the environmental impacts and improve safety of oil and natural gas production.

There is more change in store for the domestic oil and gas industry. Driven by market forces and public expectations, the industry is pursuing the dual challenge of expanding energy supplies while transitioning to lower carbon energy sources and sustaining high environmental and safety performance levels.

Today, the United States is energy independent on a net energy basis, exporting more than we import.

Following are summaries of each of the five key technology advances outlined above, including the associated future pathways and necessary advances in technology that will help the oil and gas industry to succeed during this transition.

2.1

ADVANCES IN SCIENCE AND NEW EXTRACTION METHODS FOSTER UNCONVENTIONAL RESOURCE DEVELOPMENT

The technologies underlying the expansion of natural gas supplies from shales were first applied to shale formations containing natural gas, with this gas subsequently called shale gas. With additional research and geologic evaluations, these technologies were adapted and applied to the more challenging shale formations containing crude oil. The **horizontal drilling** and hydraulic stimulation technologies central to shale development were applied to expand supplies from conventional oil and natural gas reservoirs by providing more cost-effective oil and natural gas development options for small, independent producers.

Shale Gas. Initial efforts for defining and testing organic-rich shales as a new source of domestic natural gas supplies started in the 1980s, first in the shallow Devonian-age shales of the Appalachian Basin (called the Ohio Shale) and subsequently in the even shallower **Antrim Shale** of the Michigan Basin.[14] While geological studies had identified a series of much deeper (5,000 to 10,000+ feet deep) organically-rich domestic shale formations **(source rocks)**, the accepted view, gained from previous attempts to produce natural gas from **deep coal seams (coalbed methane or CBM)** was that the **permeability (flow capacity)** of deep shales was too low to support economic flow rates of natural gas.

Building on decades of investments in science, geological appraisals and advanced **well stimulation** and **well completion** technologies, the "technology lock" for deep shale gas was broken in the **Barnett Shale** of Texas, launching the shale revolution. The key steps in breaking this lock were building a base of scientific knowledge, turning the drill bit from vertical to horizontal, and then vigorously stimulating (breaking the shale rock) around the horizontal wellbore (see Case Study #1: "Breaking the Shale Gas Technology Lock: The Barnett Shale").

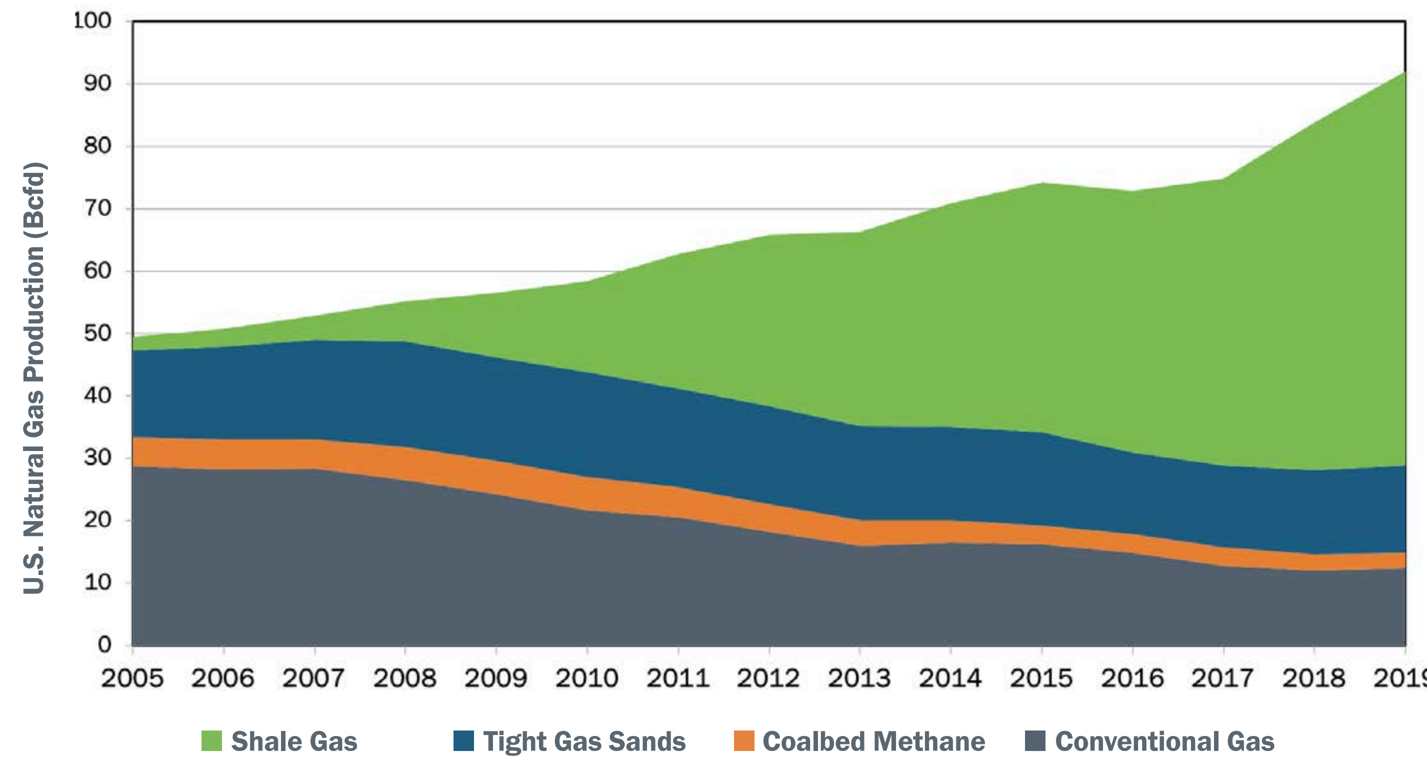
Continued pursuit of technology innovations and steady investments in research by both DOE and industry have enabled shale gas production to grow and become economically viable in a much larger set of geologic basins and shale formations, including the Marcellus (Pennsylvania), **Fayetteville** (Arkansas), **Haynesville** (Texas, Louisiana), and **Utica** (Ohio), among others.

With the application of knowledge and technology gained from research and development on shale formations, shale gas has become the dominant source of U.S. domestic natural gas production.

With the application of knowledge and technology gained from research and development (R&D) on shale formations, shale gas became the dominant source of U.S. domestic natural gas production, providing 63 billion cubic feet per day (Bcfd) in 2019.[15] Adding natural gas produced from similar low permeability formations, e.g., **tight gas sands (TGS)** and coal seams (CBM), these unconventional natural gas sources now provide 80 Bcfd of natural gas – as shown in the green, blue and orange bands below (see Figure 7) – accounting for 87 percent of domestic natural gas production.[16]

Figure 7 Shale and Other "Unconventional" Gas Production (Dry) – 2005 to 2019[17]

Shale gas has become the dominant source of U.S. natural gas production.



Shale is a common sedimentary rock, fine grained and thinly layered, and as a source of oil and natural gas it must be hydraulically fractured to permit flow.

A research well drilled in the Appalachian Basin, in partnership with the Department of Energy, is characterizing the natural gas potential of formations at depths up to 15,000 feet.

High on the list of energy transition priorities is increasing the production of domestic natural gas. Robust and growing natural gas supplies will be essential for: (1) replacing higher carbon sources of electric power production; (2) providing a secure back-up energy source for intermittent electric power from renewables; (3) serving as a feedstock along with use of **carbon capture, utilization, and storage (CCUS)** for low carbon ("blue") hydrogen;[18] (4) providing raw materials for making fertilizers, chemicals, and plastics; and (5) supporting a growing domestic LNG industry that is helping reduce carbon emissions globally.

The United States is fortunate to have a large remaining natural gas resource base. However, because some of the higher quality, lower cost portions of this resource base have already been produced (see Barnett Shale Case Study), continued improvements and advances in extraction technologies are essential to expand future production.

Shale Oil. **Step-out drilling** in shale formations, particularly into areas were the organic content of the shale was less mature (i.e., had not been "cooked" long enough to turn into methane), showed that shales also hold large in-place volumes of oil and **condensate**. However, this large oil resource remained locked in place because the accepted view was that the flow paths (**pore throats**) in shales, while adequate for flow of a gas molecule with a size of 0.4 nanometers (nm), were too small to allow flow of a much larger oil molecule (1 to 10 nm) through the shale matrix.[19]

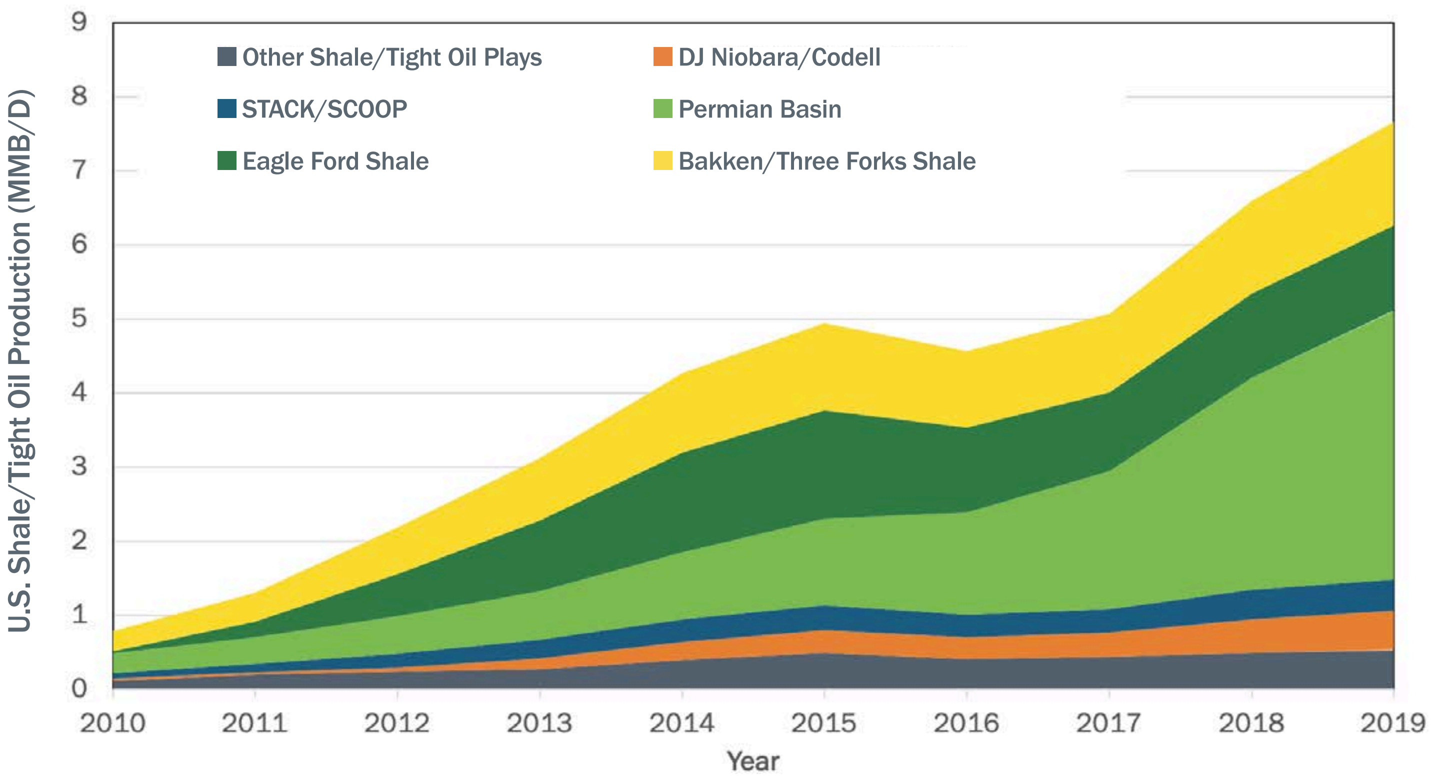
Fortunately, scientific studies of the flow paths through pore spaces in cores from oil-bearing formations in shale basins broke the knowledge lock for shale oil. Geoscientists and engineers determined that oil could indeed be produced from these tight (low permeability) rocks. The application of wells with longer **horizontal laterals**, and the use of even more intensive **multi-stage hydraulic fracturing** stimulations to create many more fractures per foot of wellbore, enabled shale oil wells to become economically viable in many settings – such as in the **Bakken Shale** of Montana and North Dakota, the **Eagle Ford Shale** in South Texas, the **Cana-Woodford Shale** in the **Anadarko Basin** of Oklahoma, and the giant **Wolfcamp Shale** in the **Permian Basin** of West Texas and New Mexico (see Case Study #2: Shale Gas Technology to Launch the "Shale Oil Revolution" of the Past Decade).

Domestic production of oil from shale has climbed from essentially zero in 2005 to seven million barrels per day in 2019. Adding production from similar low permeability formations, such as oil-bearing tight sands like the **Spraberry Formation** in western Texas, raises the contribution of "tight oil" to nearly eight million barrels of oil per day – a significant majority of total domestic oil production (see Figure 8).

Figure **8**

U.S. Shale/Tight Oil Production 2010 to 2019[20]

Oil production from tight (low permeability) formations in three major plays accounts for the majority of total U.S. shale/tight oil production.



After borrowing and then adapting the horizontal well drilling and hydraulic stimulation technology developed for unlocking shale gas, shale oil returned the favor by providing massive volumes of **associated gas** from shale oil wells, particularly in the fields of West Texas and North Dakota, enabling total shale gas production to continue to grow despite declines in production from some of the original shale gas fields.

Just as for shale gas, the higher quality (and thus lower cost to develop) "**core areas**" of domestic shale oil basins are rapidly being consumed, with new drilling targeting more challenging geological settings. However, a large portion of the shale oil resource is still left behind in existing shale basins because current primary production methods (**pressure depletion**) recover only five to 10 percent of the shale oil resource in-place.[21] Continuing research and development investments in advanced shale oil recovery methods and technologies, such as injecting carbon dioxide or other gases, will enable a much larger portion of the shale oil resource to become recoverable. This will expand domestic oil supplies and help keep marginal producers profitable during the energy transition.

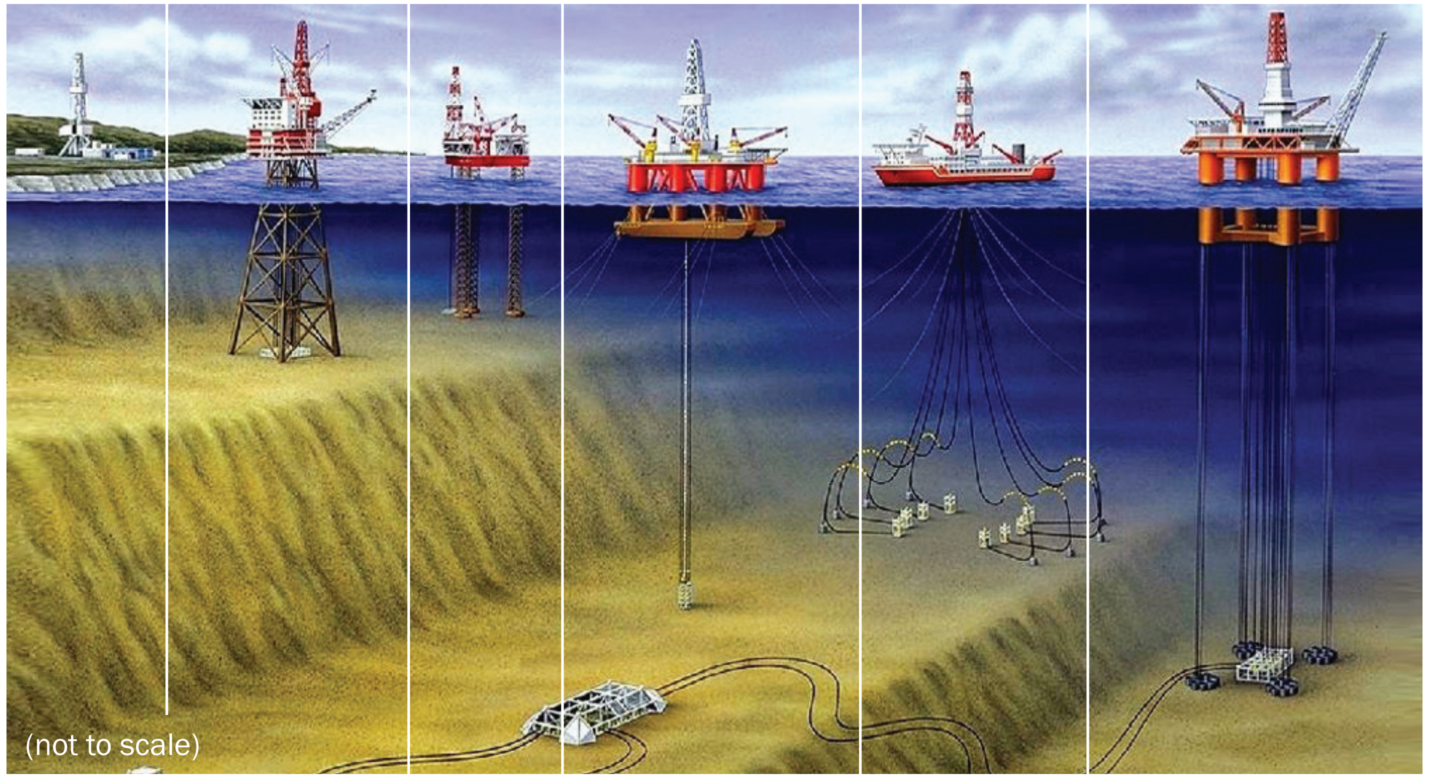
2.2

FLOATING PLATFORMS AND SUBSEA COMPLETIONS OVERCOME THE DEEPWATER OFFSHORE BARRIER

Resource studies in the 1970s and 1980s established that the **deepwater** portions (greater than 1,000 feet of water depth) of the Gulf of Mexico held large, geologically favorable prospects for oil and natural gas. This provided new impetus for the industry to explore and develop these resources. However, existing offshore practices and technology using **fixed-to-the-seafloor platforms** were not viable for producing oil and natural gas fields in water depths of 2,000 to 10,000 feet.

In response, industry began to pursue the use of **floating platforms**, such as **tension leg** and **semi-submersible platforms**, to overcome water depth limitations (see Figure 9). Combining new platform designs with **subsea well** technology has enabled oil and natural gas fields found in increasingly deeper water depths to be developed and smaller size oil discoveries to become economically viable during the past two decades (see Case Study #3: The Auger Tension Leg Platform Helps Conquer the Deep Waters of the Gulf of Mexico).

Figure 9 **Artist's Depiction of the Evolution of Offshore Platforms and Rigs Toward Increasingly Deeper Water Depth**[22]



Building upon these advances, the future of offshore exploration and production during the energy transition is the **subsea factory**, particularly for **ultradeep** offshore settings. With a subsea factory, all operations are controlled remotely, all power is delivered via a seafloor cable, and all produced liquids and gases are processed at the seafloor. The subsea factory is also a critical next step in bringing CO_2-EOR to offshore oilfields.[23]

While CO_2-EOR is commonly used in onshore oilfields, taking this technology to offshore oilfields – particularly deepwater offshore oilfields – remains a major challenge. Even though the additional oil recovery and CO_2 storage opportunities offered by offshore oilfields are judged to be substantial, only a handful of projects in offshore Brazil and the North Sea have been initiated (see Figure 10). As such, bringing CO_2-EOR to the offshore oilfields of the Gulf of Mexico represents a significant research and development priority.

Figure 10 **Aker Sea Floor CO_2 Injection Project**

Artist's depiction of a subsea factory meant to replace floating or fixed production facilities. Individual wells are connected to centralized produced oil processing units. Injected CO_2 is removed from the produced oil and re-injected, all on the seafloor.

2.3

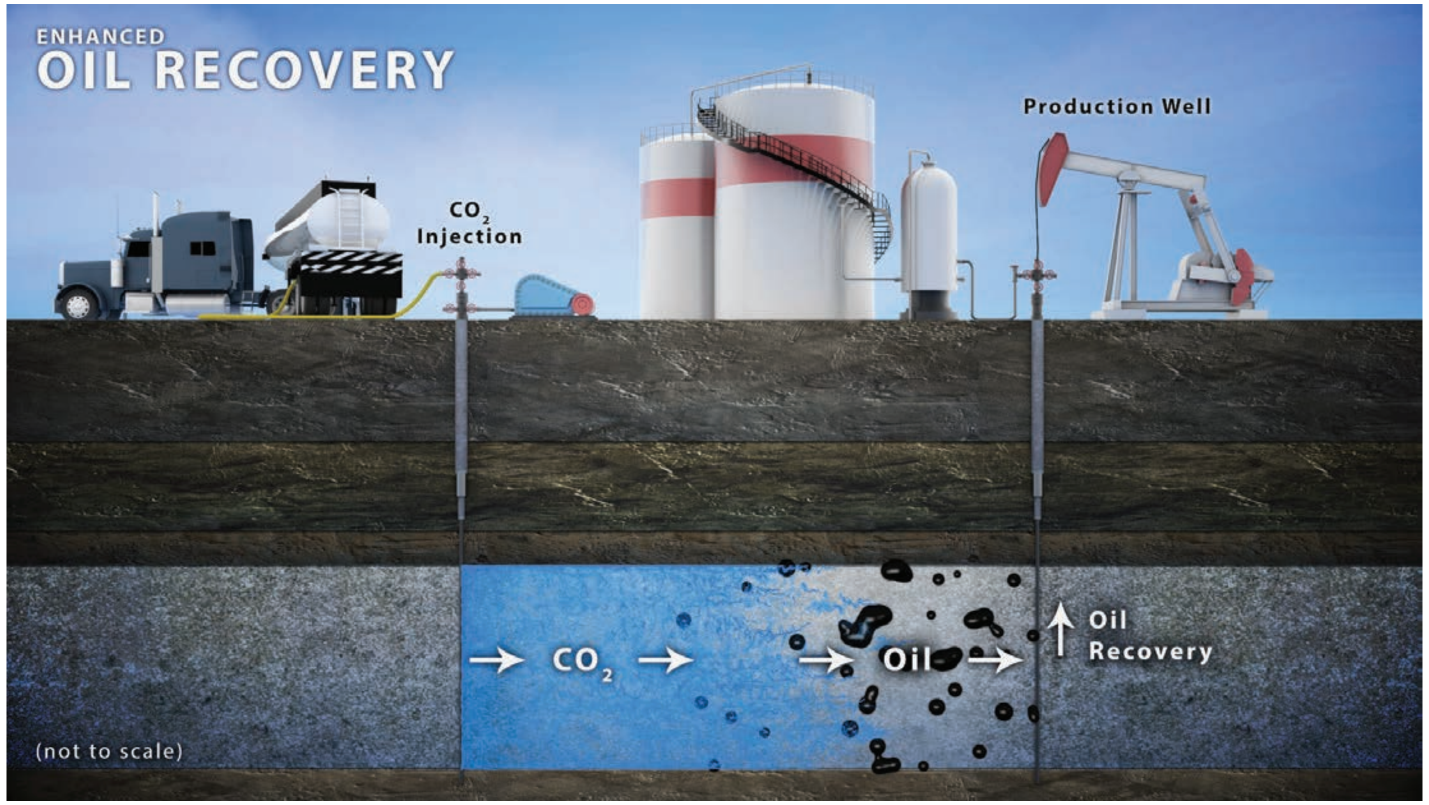
NEW GEOLOGIC SETTINGS AND SOURCES OF CARBON DIOXIDE SUPPORT EXPANDED USE OF CO_2-EOR AND CARBON DIOXIDE STORAGE

CO_2-EOR involves the injecting of high-pressure carbon dioxide into a previously produced oil formation, creating a miscible liquid mixture between the carbon dioxide and any residual oil "left behind" in the reservoir after traditional oil recovery practices. Continued injection of high-pressure carbon dioxide (alternating with water to help even out the advancing front of the injected fluid) drives this liquid mixture to a production well where it is pumped to the surface. The produced oil is separated from the produced carbon dioxide, and the carbon dioxide is then reinjected back into the oil formation to continue the process and eventually remain stored (see Figure 11).

Figure 11

Essential Features of the CO_2-EOR Process[24]

Artist's depiction of injected carbon dioxide dissolving oil from reservoir rock pores and pushing coalesced oil droplets toward a producing well.



CO_2-EOR was first applied in the **carbonate** (dolomite and limestone) reservoirs of the Permian Basin of West Texas. From a modest beginning involving injection of high-pressure carbon dioxide into the **Scurry Area Canyon Reef Operators Committee (SACROC) unit of the Kelly Snyder oilfield**, the practice of CO_2-EOR grew as new, large CO_2-EOR projects were started in the 1980s and 1990s in major West Texas oilfields such as Wasson, Slaughter, and Levelland that produced from the same carbonate formations. However, CO_2-EOR remained primarily confined to the Permian Basin because the prevailing view was that this technology would not be viable in other geologic settings, and because of limited supplies of carbon dioxide.

Scientific studies and **compositional reservoir modeling** conducted at government, university, and industry laboratories showed that the CO_2-EOR process could be effective in many other geologic settings, such as the sandstone reservoirs of the Gulf Coast, the Mid-Continent, and the Rockies. Joint industry and DOE field research pilot programs, involving use of foams for **mobility control** at the Rangley oilfield in Colorado and the testing of a **gravity stable carbon dioxide flood** at the Weeks Island field in Louisiana, demonstrated the viability of CO_2-EOR technology in other geologic settings, while also testing new ideas for improving the performance of this process.

Opportunities exist to expand the application of CO_2-EOR technology to even more locations. Geologic and reservoir modeling studies identified a greatly enlarged group of oilfield settings that would benefit from the application of CO_2-EOR for improving oil recovery while also providing a means for storing captured anthropogenic carbon dioxide, including **residual oil zones (ROZ)**,[25] fractured shale oil reservoirs, and offshore oil reservoirs. With many of these mature oilfields being held by small, independent producers, identifying new geologic settings for CO_2-EOR provides another business option for this important segment of the domestic oil industry. However, the increased application of CO_2-EOR to these newly defined oil reservoir settings is currently constrained by a lack of affordable, plentiful supplies of carbon dioxide.

The availability of large quantities of new carbon dioxide, along with **Section 45Q tax credits** for projects that capture carbon dioxide from industrial sources and then utilize and store carbon dioxide through EOR, will overcome the "lack of carbon dioxide supply" barrier to wider application.

With abundant new supplies of carbon dioxide and continued progress on CO_2-EOR technology, utilizing carbon dioxide for enhancing oil recovery can become a key pathway for the oil and natural gas industry during the energy transition. When oil produced by injecting carbon dioxide involves storing more carbon dioxide than that released by the barrel of produced oil when combusted, the carbon intensity of the domestic oil industry and energy imports will be reduced.

2.4

ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING ENABLE MORE COST-EFFECTIVE EXTRACTION AND TRANSPORTATION OF OIL AND NATURAL GAS

Artificial intelligence (AI) and automation are increasingly being employed as technologies for producing and transporting oil and natural gas, providing a valuable technology pathway during the energy transition. Companies are leveraging AI to improve production systems, automate processes, streamline manual business operations, and connect engineers with real-time monitoring systems – making all aspects of the oil and natural gas production operation more efficient.

Some examples of AI at work:

- Sensors and robotics can be used to execute repeatable tasks such as pipeline and production system inspections and maintenance.
- An **electronic digital twin**[26] (as is being installed for BP's Mad Dog Phase 2 oilfield platform) can be constructed to represent a virtual offshore platform and subsea operation, providing improved decision making, reduced personnel travel to offshore operations, and rapid intervention before safety problems arise.
- Sensors and real-time feedback systems, such as those that have already been developed for steering a drill bit, can be incorporated into EOR operations to manage and improve the flow of carbon dioxide through conventional as well as shale oil reservoirs.
- Rigorous collection of well performance data, linked to site-specific geological models, can further enable AI to identify best practices for well completions.

AI is helping make all aspects of oil and natural gas production more efficient.

2.5

NEW TECHNOLOGIES MITIGATE THE ENVIRONMENTAL IMPACTS AND IMPROVE SAFETY OF OIL AND NATURAL GAS PRODUCTION

Industry is committed to reducing the environmental impact of oil and natural gas production while improving the efficiency and safety of operations[27] through advances in technology and a committed health, safety, and environment-focused culture.

For example, the combination of hydraulic stimulation and horizontal drilling applied to multiwell drilling pads, while increasing production, also results in smaller per-well environmental impacts when compared to multiple individual vertical wells. **Multilateral drilling** takes this one step further – by drilling multiple horizontal wells from the same well. With these advancements, the size of industry's footprint, in terms of land use per unit of energy extracted, has been dramatically reduced.

DOE, states, and industry also are pursuing technologies and regulatory changes that will reduce the impacts to fresh water sources by encouraging reuse of **produced water**, treatment and beneficial reuse of produced water outside of the industry, and use of brines from saline aquifers in place of fresh water. U.S. oil and natural gas operators are pursuing methods to enable better management of the water they produce while simultaneously reducing the use of fresh water in their operations.[28]

For example, in 2018:

- Range Resources reused 100 percent of the water that flows back from the wells they fracture (**flowback water**[29]).
- Southwestern Energy recycled 99.9 percent of its **produced water** in Northeast Appalachia and 45 percent in Southwest Appalachia.[30] It also established a goal to remain "Fresh Water Neutral," as it has for the past three years.
- In Chevron's operations in the Permian Basin, more than 99 percent of the water it used in well completions in 2018 came from non-fresh and recycled produced water sources.[31]

In another example, a fracturing **proppant** coating technology is currently being tested that alters the **relative permeability** of the proppant pack in a stimulated well to preferentially encourage the flow of hydrocarbons over water, reducing the amount of salty brine that is produced per barrel of oil. A case study showed that after seven months, wells had a 15 percent decrease in water produced relative to oil (**water cut**) and a 17 percent increase in oil production, reducing the environmental risks of handling and disposing produced brine.[32]

New technologies help reduce the environmental impact of oil and natural gas production while also improving safety.

The iron roughneck automates the dangerous and repetitive tasks of connecting drill pipes on oil rigs.

Many companies are focused on improving energy efficiency in their operations, resulting in both reduced emissions and lower energy costs.[33] Notable measures include converting from diesel to electric drilling rigs and installing high efficiency **electric submersible pumps (ESP)**, water shutoff controls, **variable speed drives (VSD)**, high efficiency motors, and **long stroke pumping units.**[34] Just two of the more recent technologies being integrated into oil and gas industry operations that provide efficiency improvements, increased worker safety, and lower emissions include:[35]

- **Robotics:** The "iron roughneck," originally developed by National Oilwell Varco, automates the dangerous and repetitive tasks of connecting drill pipes on oil rigs.
- **Advanced Reconnaissance and Feedback:** Drones and advanced acoustics are being used to help industry quickly locate pipeline leaks, resulting in a 31 percent reduction in leak rates for oil and natural gas systems from 2005 to 2017.[36]

Reducing methane emissions has become a top priority for many companies in all aspects of their operations.[37] They are accomplishing this by expanding leak detection and repair campaigns, replacing or upgrading high-emitting devices, and reducing **venting**.

As of 2019, the 58 U.S. companies in The Environmental Partnership[38] surveyed more than 78,000 sites, inspected more than 56 million components, and retrofitted or removed from service 31,000 **high-bleed pneumatic controllers.**[39] In addition, the use of well completion strategies that minimize the loss of methane and other hydrocarbons during flowback, a technology known as **reduced emissions completions** (RECs) or "**green completions**," has contributed significantly to declining emissions in oil and gas operations.

The oil and natural gas industry is investing in emissions reduction technologies and working with other industries to continue to lower its GHG footprint that may shape how demand for fossil fuels unfolds over the next several decades.[40] Member companies of the Oil and Gas Climate Initiative (OGCI) established objectives to reduce the methane intensity of upstream oil and natural gas operations, decarbonize industrial hubs, build a commercial-scale CCUS industry, and eliminate routine flaring.[41] Opportunities also exist to reduce the carbon intensity of hydrocarbon combustion and include, as examples: (1) installing CCUS to baseload electric power plants fueled by natural gas, and (2) pursuing the conversion of natural gas to "blue" hydrogen for transportation fuels.

The number of **Class II water injection wells** in the United States varies from year to year based on fluctuations in oil and natural gas production. EPA reports that approximately 180,000 Class II wells are in operation in the United States,[42] with about 20 percent disposing water that comes to the surface during oil and natural gas production. It was discovered that a very small fraction of these is contributing to an increase in the frequency and intensity of small seismic events. In Oklahoma, researchers found some of these water disposal wells were the likely cause for this **induced seismicity** – low-level seismic events caused by fault activation associated with the injection of large volumes of water into disposal wells at great depths. The state installed a seismic monitoring network of hundreds of stations, developed detection and monitoring protocols to identify quake epicenters, and developed models to estimate seismicity as a function of injection rates (specific to a geologic setting). This enabled operators to identify and shut in disposal wells believed to be causing induced seismicity. As a result, the incidence of seismic events measuring greater than three on the Mercalli Scale in Oklahoma has declined from over 900 in 2015 to only 62 in 2019.[43]

In addition to improvements in environmental performance, even as oil and natural gas production has surged over the past decade, oilfield workplace safety has improved. According to the Bureau of Labor Statistics, the injury and illness rate for the U.S. oil and natural gas industry dropped by 41 percent from 2008 to 2017 and is 39 percent below the national average for the entire U.S. private sector.[44]

These pathways and advances in technology will continue to help foster a future with more efficient oil and natural gas operations, greater recovery of hydrocarbons from existing assets, reduced environmental footprint of operations, and greater focus on managing water use.

Technology innovations have transformed the U.S. oil and natural gas market from fears of energy scarcity to expectations of plenty.

CASE STUDY 1

BREAKING THE SHALE GAS "TECHNOLOGY LOCK:" THE BARNETT SHALE

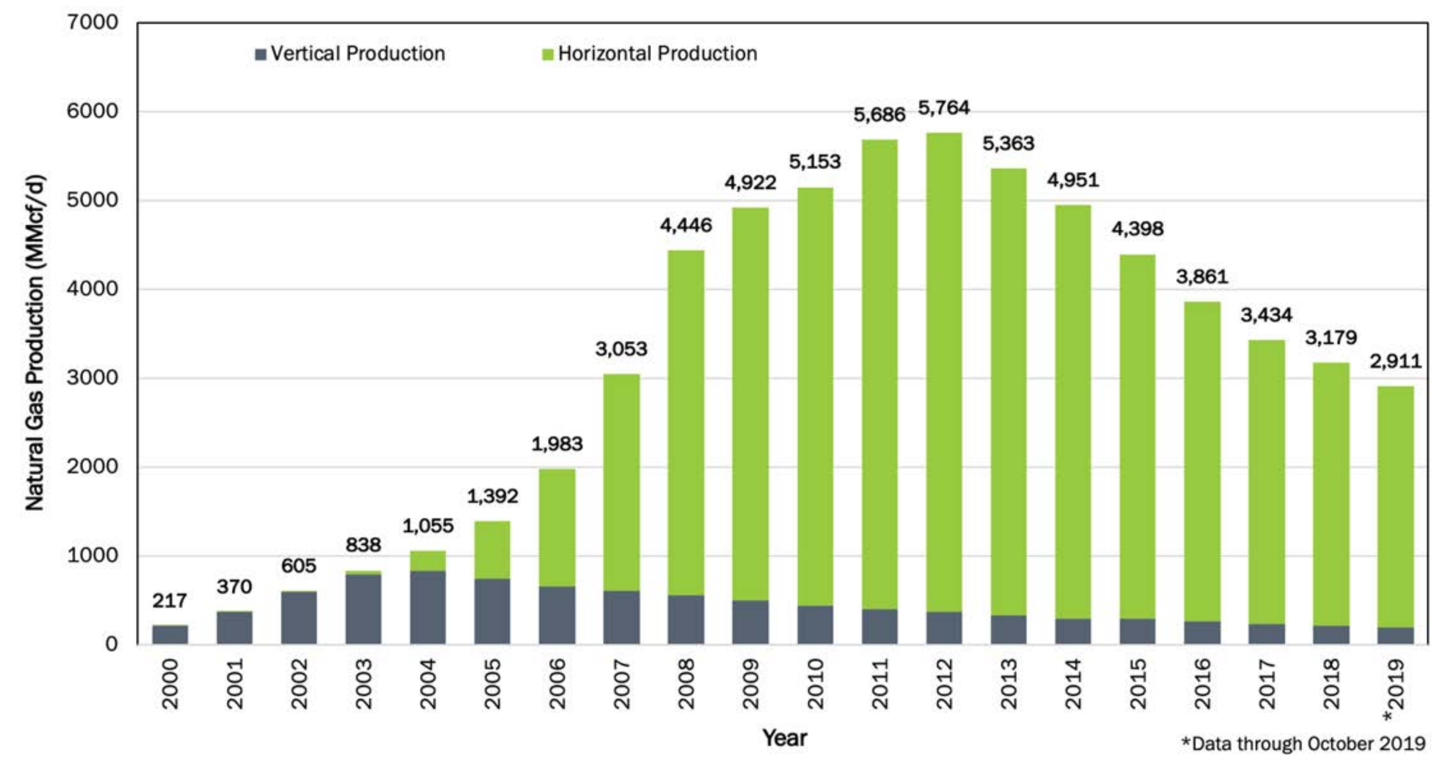
The potential for producing natural gas from deep shale formations was first identified in the 1990s when Mitchell Energy started drilling into the 8,000-foot deep Barnett Shale in the Fort Worth Basin of North Texas.[45] The company's initial approach using vertical wells and small-scale **hydraulic fracturing** stimulations resulted in low natural gas production rates and thus low **expected ultimate gas recoveries (EUGs)**, on the order of 0.5 billion cubic feet (Bcf) per well – less than what was economically viable at the time. Diagnostics of well performance showed that the vertical wells were draining only a small area of the reservoir, typically 10 acres, much less than the 320 acres of drainage area per well that was expected and considered to be "the best one can do" by industry and the technical literature at the time.[46]

This led to a breakthrough concept – if a well was drilled to contact more of the shale formation and this shale formation was vigorously stimulated, the volume of reservoir being drained would be considerably greater and well performance would be several-fold higher, making the Barnett Shale economically viable. The Stella Young #4 well, a slant well rather than a truly horizontal well, was designed and drilled to test this concept.[47] The well was stimulated with advanced, multi-stage hydraulic fracturing stimulation, a technology researched and tested in the Antrim Shale. The well achieved three times as much contact with the shale reservoir and had natural gas production nearly three times higher than the previously drilled vertical, limited stimulation Barnett Shale wells. Devon Energy, who had simultaneously been developing more reliable horizontal well drilling capabilities, understood the technology breakthrough, purchased Mitchell Energy in mid-2001, and helped launch the subsequent rapid development of the Barnett Shale.

The initial seven years of developing the Barnett Shale (1993 through 2000) were the "lean years" for the Barnett play, with natural gas production (developed with vertical wells and single stage hydraulic stimulations) only reaching 0.2 Bcfd. Horizontal drilling and multi-stage hydraulic stimulation – tested during 2001 through 2004 and widely applied starting in 2005 – enabled well performance to be further improved and Barnett Shale gas production to reach a peak of 5.8 Bcfd in 2012 (see Figure 12).

Figure 12 **The Birth, Growth, and Decline of the Barnett Shale**[48]

Development of the Barnett Shale after the mid-2000s was driven by horizontal drilling coupled with hydraulic fracturing.



Once the high quality "core" areas of the play were developed, natural gas production from the Barnett Shale declined, dropping to below 3 Bcfd in 2019 (see Figure 12). As such, the history of the Barnett Shale also makes the important point that natural gas production from existing shale plays will eventually decline. To counter this situation, new plays in new basins will need to be discovered and more efficient extraction technologies will need to be developed and applied to economically produce the less attractive areas of existing shale basins.

CASE STUDY 2

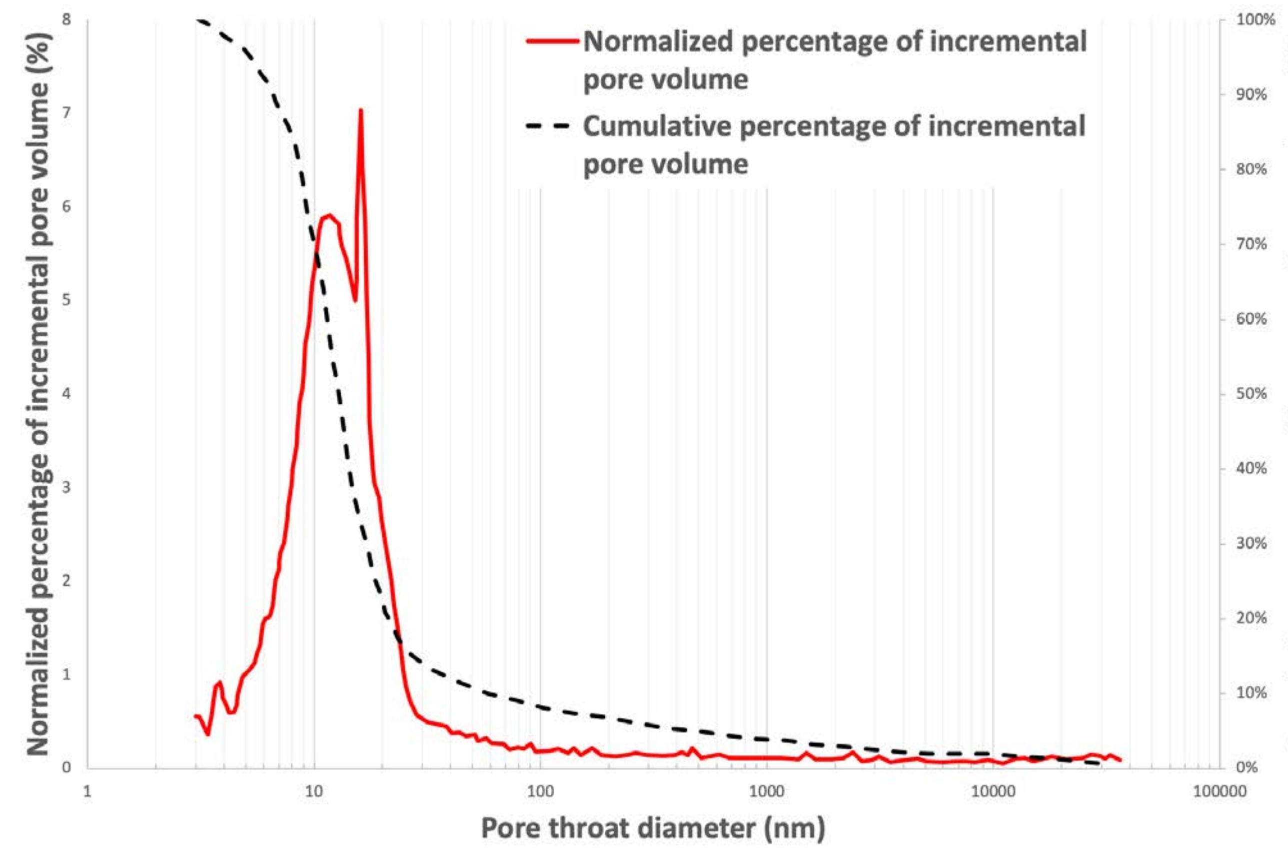
USING SCIENCE AND ADAPTATION OF SHALE GAS TECHNOLOGY TO LAUNCH THE **"SHALE OIL REVOLUTION"** OF THE PAST DECADE

Early geological studies of the Bakken Shale and other shale formations argued that not only natural gas, but also large volumes of oil were stored in organic shales.[49] This large resource remained untapped because the accepted view was that organically rich, oil-bearing shales could not become economically productive reservoirs as the flow paths (connected pore throats) in shales, while adequate for enabling the flow of gas molecules, were too narrow to permit the flow of much larger oil molecules through the shale matrix and into a wellbore; the rocks were too tight to produce much crude oil. Even though some Bakken Shale wells were being produced in the Elm Coulee Field of Montana, the specific flow interval in the Bakken Shale at Elm Coulee was believed to be a geologically unique case, not replicable in other shale oil settings or even across the extent of the Bakken Shale play itself.[50]

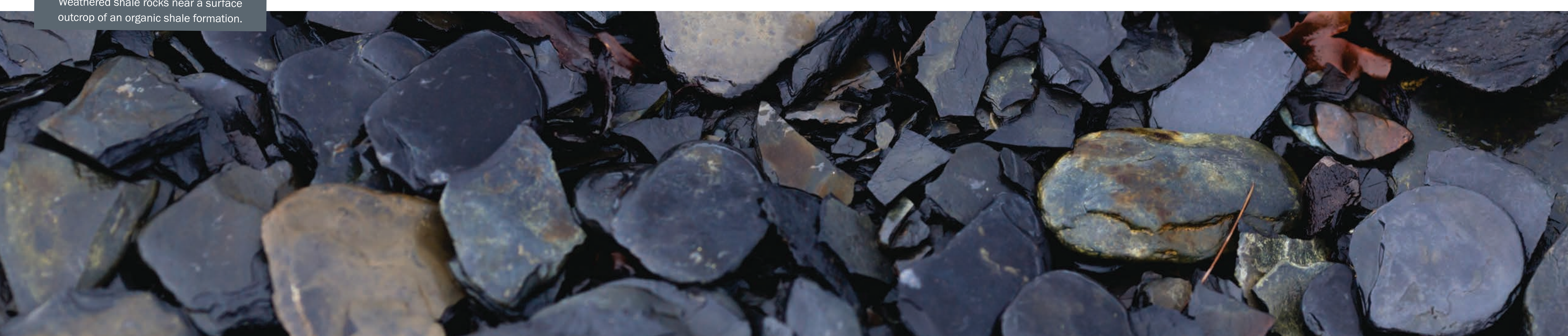
However, advanced diagnostic laboratory work by scientific investigators working with reservoir rock cores showed that shales exhibit a wide distribution of pore throat diameters, and when a sufficient number of these are at 10 to 20 nm or greater, conditions are favorable for producing oil from shale (see Figure 13). This new scientific knowledge was the first step toward unlocking the potential for increased production of crude oil from shale formations.[51]

Figure 13 Pore Throat Size Distribution of Eagle Ford Shale Sample[51]

Understanding that shales had enough large pores to permit oil and gas molecules to flow out of the rock matrix and into fractures made it possible for engineers to design well completion methods that enabled economic production rates.



This new understanding, coupled with the adaptation of previously developed shale gas extraction technology involving horizontal wells with even more intensive multi-stage hydraulic stimulation, fully broke the shale oil production technology lock and launched the shale oil revolution that followed the shale gas revolution (see Figures 14 and 15).[52,53]



Weathered shale rocks near a surface outcrop of an organic shale formation.

Figure 14

Shale Gas Horizontal Well Completion with Multiple Hydraulic Fracture Stimulation Stages[52]

A horizontal well completion with 10 hydraulic stimulation stages spaced at 300 foot intervals was sufficient to develop shale gas formations where lower viscosity natural gas flowed more easily.

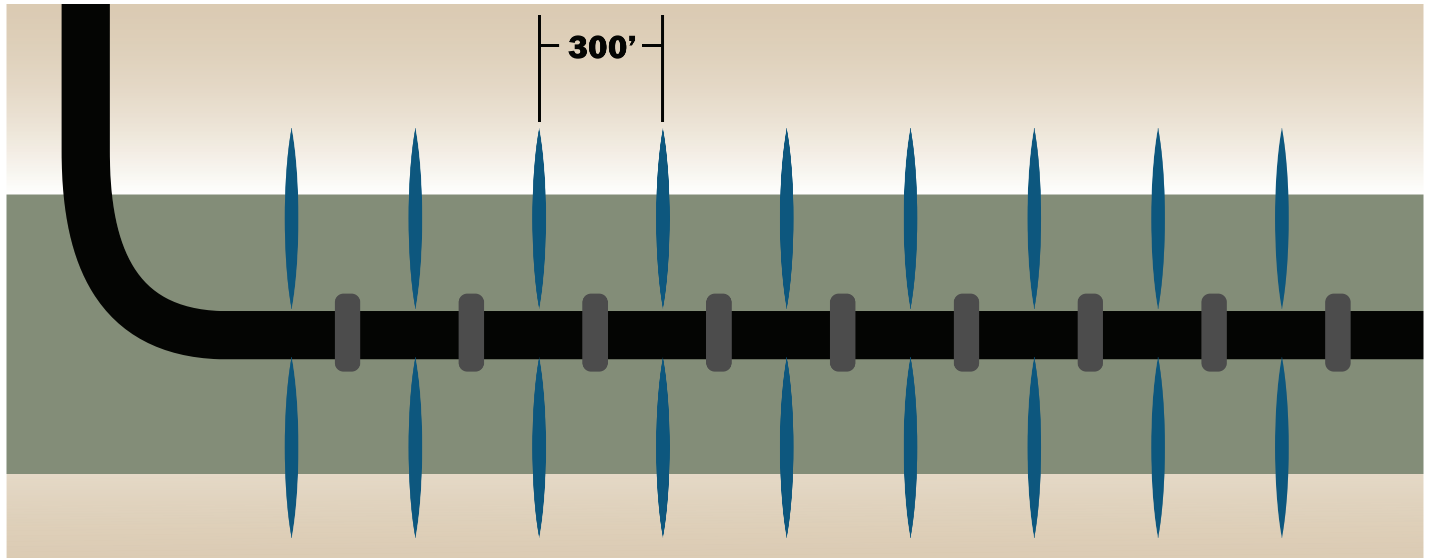
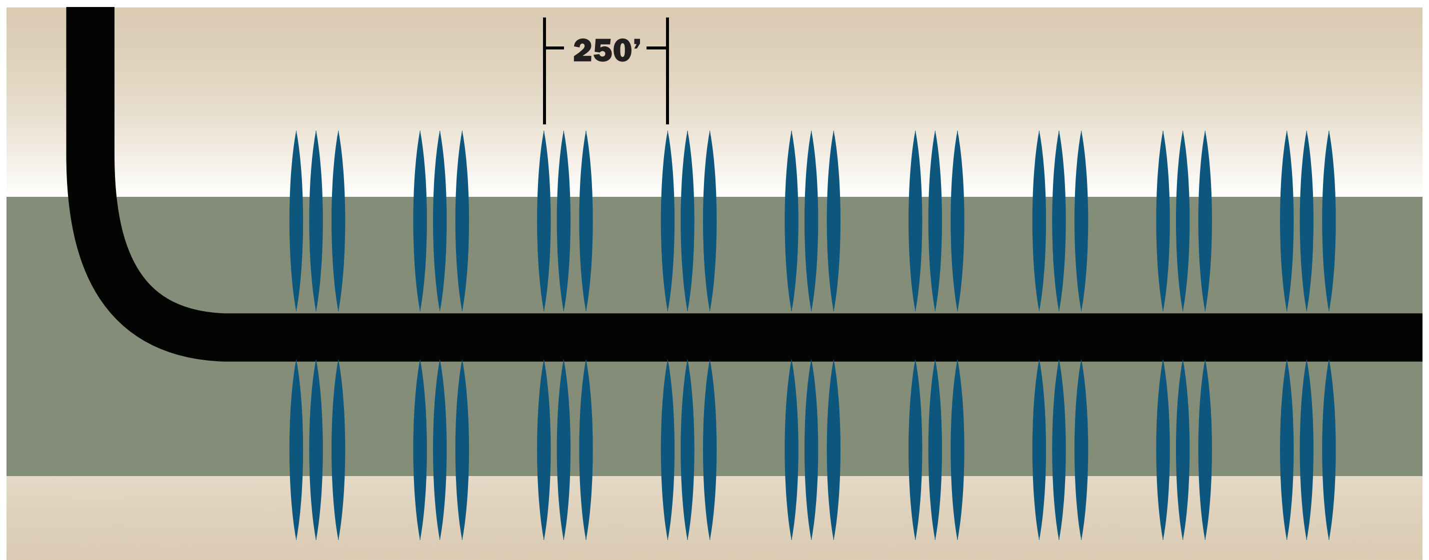


Figure 15

Shale Oil Horizontal Well Completion with Multiple Hydraulic Fracture Stimulation Stages[53]

Horizontal well completions with more intensive well perforation clusters and up to 36 hydraulic stimulations spaced more closely together unlocked the tight shale oil resources that were developed later.



Continuing advances in horizontal well drilling technology, such as **logging-while-drilling (LWD)** and **measurement-while-drilling (MWD)**, provide real-time feedback on reservoir properties and precise drill bit location. When combined with **steerable drilling systems** and advanced drill bit designs, horizontal wells can be drilled in less than half the time as in the past.[54] These advanced technologies enable oil and natural gas companies to place a drill bit in an oil reservoir target location about the size of a basketball hoop two miles away after drilling two miles down.[55]

CASE STUDY 3

AUGER TENSION LEG PLATFORM

HELPS CONQUER THE DEEP WATERS OF THE GULF OF MEXICO

Even as the shallow water (less than 1,000 feet of water depth) oil and natural gas fields of the offshore Gulf of Mexico were becoming mature, large volumes of hydrocarbons remained underdeveloped in the Gulf's deep and ultradeep waters, beyond the reach of existing technology at the time. The limit of deepwater development was established in 1988 by the Bullwinkle platform, a massive fixed-to-the-seafloor platform. The Bullwinkle platform was the last of its kind as the costs of constructing anything larger were simply prohibitive.[56]

Moving into deeper waters would require alternative technologies such as **tension-leg platforms (TLP)**, floating production systems, and subsea wells. The search for these alternatives led to the installation of the Auger TLP in 1994, breaking the deepwater barrier for fixed-to-the-seafloor structure.[57] The Auger TLP was tethered to the seafloor at 2,860 feet of water depth with 12 steel tension cables, each with a 26-inch diameter inside steel cylinder and a 1.3-inch wall thickness. The platform, in the Garden Banks 426 offshore block of the Gulf of Mexico (known as GB 426), is located 214 miles southwest of New Orleans, Louisiana. The TLP structure consists of a floating hull and cylindrical columns, with ballast tanks, pumps, and controllers weighing 20,000 tons; a deck section with living quarters; a drilling rig and surface facilities weighing 23,000 tons; and steel cables weighing 5,000 tons.[58] The concept of tethering the floating platform to the seafloor provided stability for drilling and production operations over many years while avoiding the need to fix the platform to the seafloor.

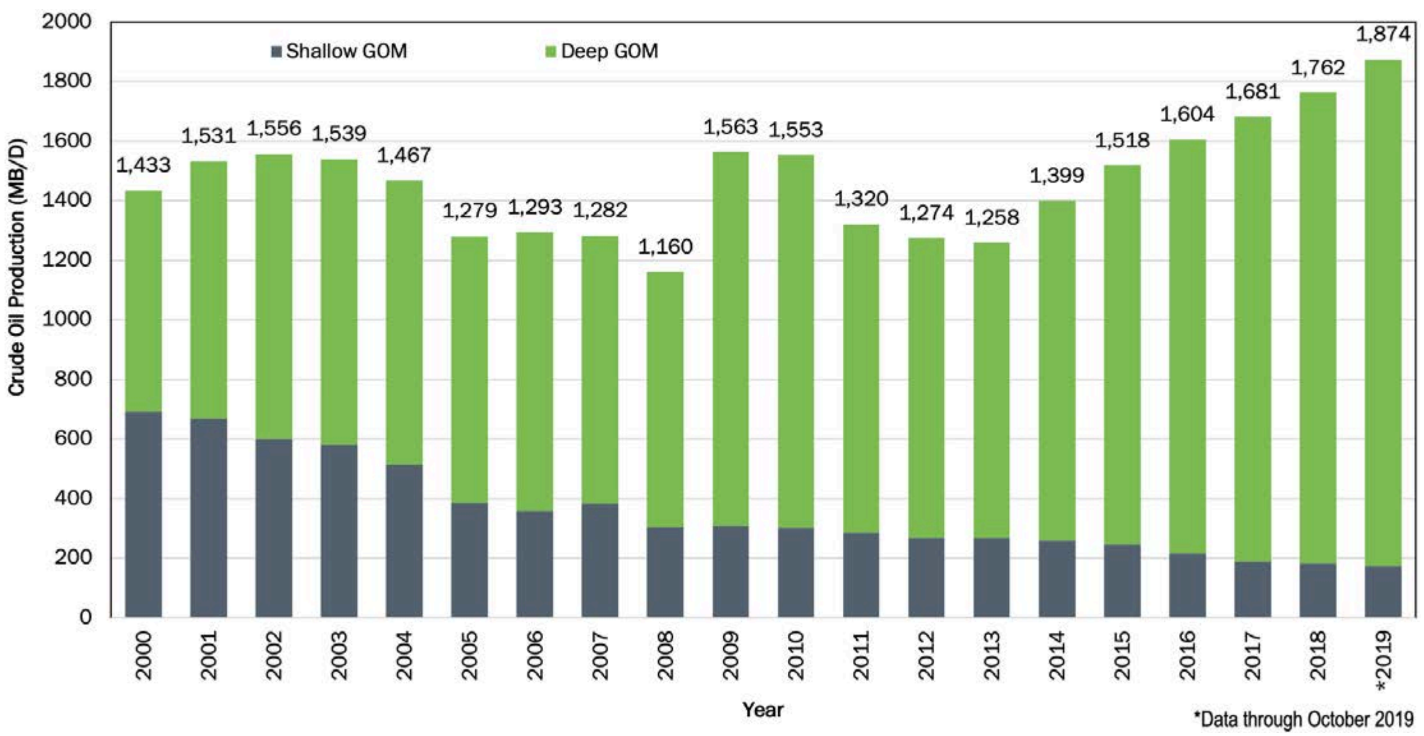
Further, the use of subsea well completions in the Gulf of Mexico, a technology that came of age at Auger and has expanded broadly since, enabled industry to reach and develop numerous smaller oilfields as far as 20 miles from the platform, such as Oregano (GB 559), Macaroni (GB 602), Habanero (GB 341), Serrano (GB 516), and Llano (GB 387), having a combined 165 million barrels of original oil reserves. Given the relatively small size of these fields, they could never have been economically developed independently with each supporting its own platform. However, advances such as subsea well completions and flowline tiebacks to the established central platform helped to make these marginal "satellite" fields economically viable. Once advanced seismic technology enabled visualization of structures below the thick salt deposits that exist in portions of the Gulf of Mexico's deep subsurface, the large Cardamom oil and natural gas field (GB 427), located at a record depth of four miles below the seafloor,[59] was also connected to the platform in 2014, further extending the life of the Auger TLP.

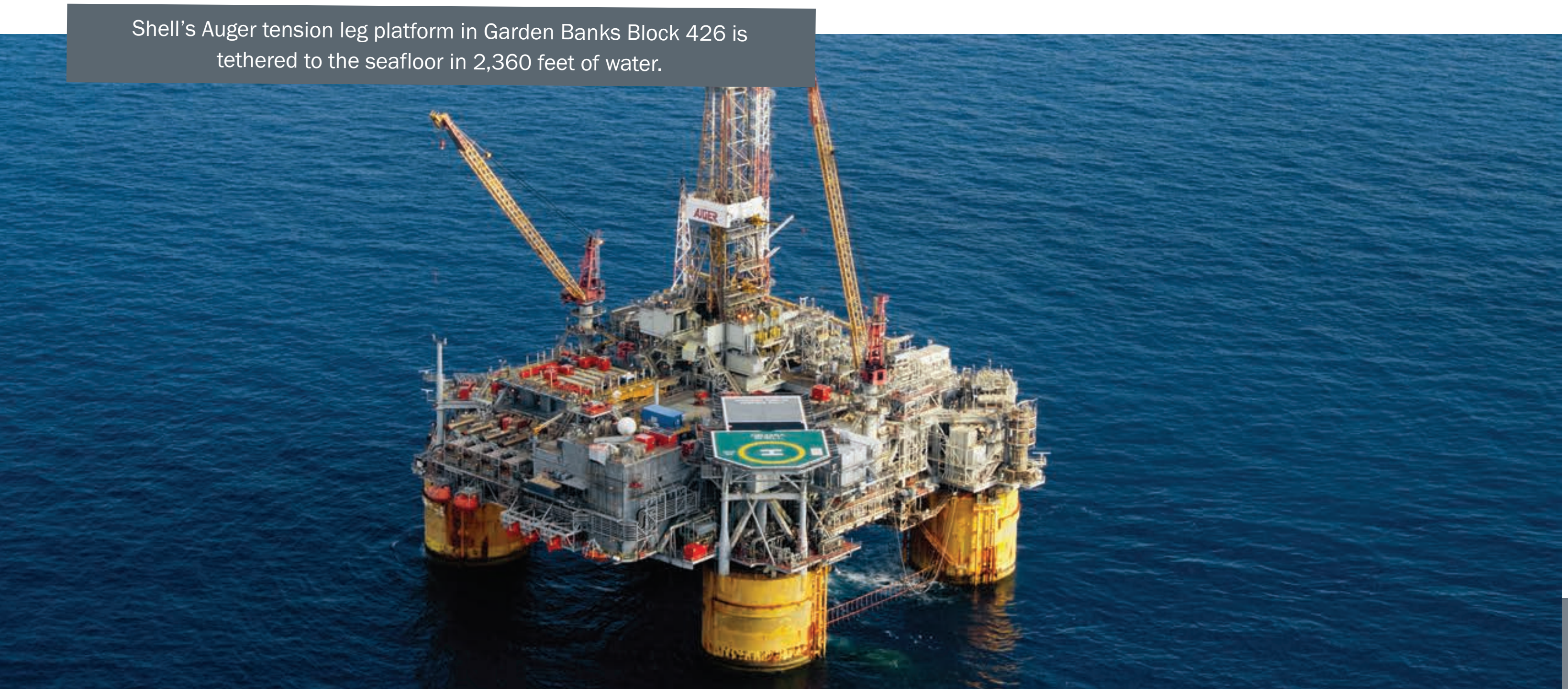
Although there are now nine TLP platforms in the Gulf of Mexico, the TLP design does not represent the final step in conquering its deep waters. Beyond water depths of 4,000 feet, the weight of the tension cables becomes too great.[60] Additional ultradeep water (7,000 to 12,000 feet of water depth) structure designs have been developed, such as floating platforms, spars, and even a large-diameter vertical cylinder for supporting a deck for drilling and oil and natural gas processing.

From about two dozen deepwater projects in 1999, several hundred deepwater fields are being engaged today, producing 1.7 million barrels of oil per day (plus 2.0 Bcf of natural gas per day), providing over 90 percent of the oil production from the offshore Gulf of Mexico in 2019 (see Figure 16).

Figure 16 **Offshore Gulf of Mexico Crude Oil Production – Shallow Water versus Deepwater[61]**

The volume of oil produced from deepwater fields has grown steadily since 2000 as technology has enabled production to remain steady or grow as shallow fields deplete.

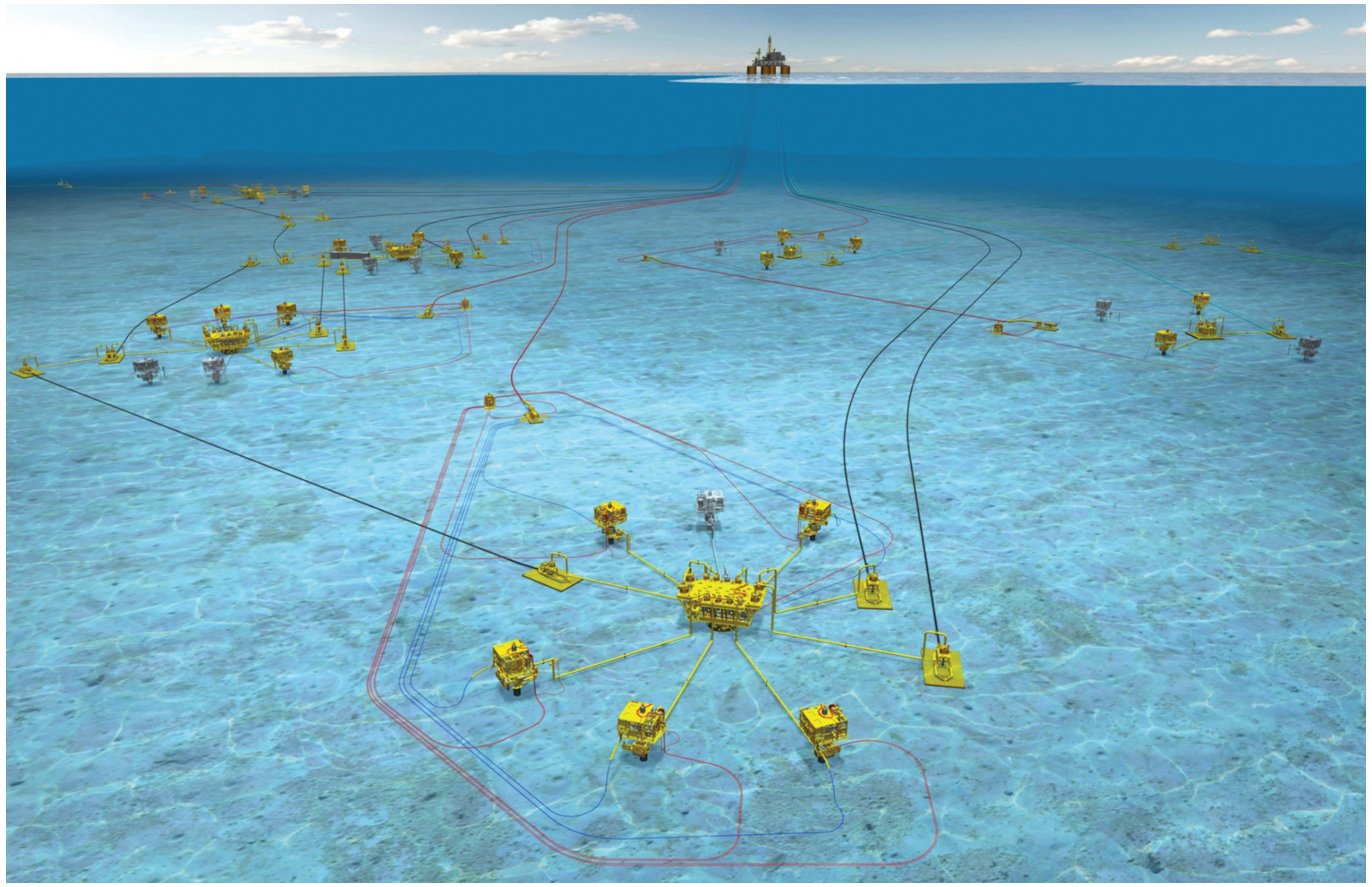



Shell's Auger tension leg platform in Garden Banks Block 426 is tethered to the seafloor in 2,360 feet of water.

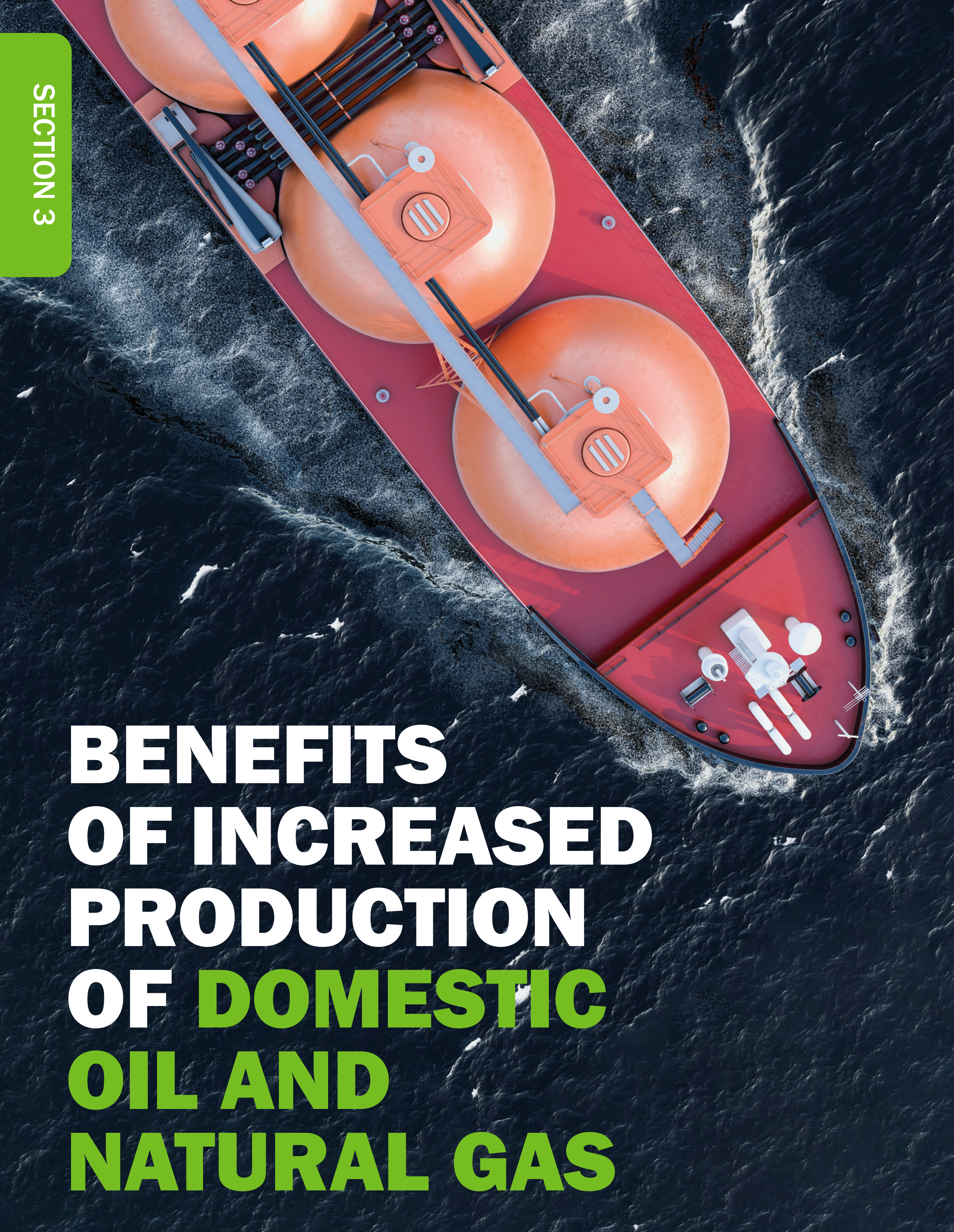
The future of domestic offshore oil and natural gas development will be increasingly in ultradeepwater fields such as Appomattox (Mississippi Canyon Block 392) (see Figure 17). It will also involve increased use of CO_2-EOR for improving oil recovery while geologically storing carbon dioxide several miles below the seafloor.

Figure 17 **Appomattox Field Development, Deepwater Gulf of Mexico[62]**

Shell's Appomattox Field includes a semi-submersible, four-column production host platform and a subsea system featuring six drill centers, 15 producing wells, and five water injection wells, all in 7,400 feet of water.



SECTION 3



BENEFITS OF INCREASED PRODUCTION OF DOMESTIC OIL AND NATURAL GAS

Advances in technology, coupled with the discovery of new, geologically challenging sources of oil and natural gas, underlie the energy abundance Americans enjoy today. While the technology advances of the past two decades have spurred record-breaking offshore deepwater activity, cost effective production of tight gas and coal seam gas (coalbed methane) from the Rocky Mountain states, and the expanded pursuit of CO_2-EOR in new geological settings beyond West Texas, the shale revolution has had, by far, the greatest impact on domestic oil and natural gas supplies.

The shale revolution and other sources of increased production of domestic oil and natural gas have provided numerous benefits to consumers, state and local governments, the domestic industry, and the labor market. Because the nation's extensive energy delivery infrastructure enables oil and natural gas supplies to reach nearly all corners of the country, the majority of the benefits below are relevant to all Americans – not just to those living in oil and natural gas-producing states or working at oil and natural gas jobs.

Key benefits of increased production of domestic oil and natural gas include:

- Significant savings to consumers.
- Increased revenues for state and local governments.
- Increased numbers of well-paying domestic jobs.
- Revitalized U.S. chemical manufacturing.
- Launching a world-class domestic LNG export industry.
- Reduced environmental footprint from increased production of natural gas with lower impact extraction technologies.
- Enhanced energy security.

Following are more details about these seven benefits.

Significant Savings to Consumers

The lower oil and natural gas prices resulting from increased domestic oil and natural gas production provided $203 billion annual savings to U.S. consumers – equal to $2,500 per year for a family of four. About 80 percent of the savings is from lower prices for natural gas (including lower electricity prices due to increased use of natural gas in the power sector), with the remainder due to reductions in world oil prices resulting from increased U.S. supplies.[63]

To estimate the above consumer benefits, a Council of Economic Advisers Study estimated that the price of natural gas in 2018 without the shale revolution would be $7.79/Mcf and with the shale revolution would be $2.87/Mcf, a decline of 63 percent. This is roughly equivalent to the percentage decline in the **Henry Hub price** of natural gas between 2007 and 2018.

> **"Growth in extraction of oil and natural gas from shale and similar geological formations – often referred to as the shale revolution – is arguably the most consequential energy development in the last half century."**
>
> -Council of Economic Advisers, October 2019

Increased Revenues for State and Local Governments

Oil and natural gas production provides significant revenues to state and local governments from severance taxes, added-value taxes, and other fees. **These revenues provide major portions of the funding for schools and public services in many producing states.** A more detailed look at Texas, the largest oil and natural gas producing state, helps to further quantify these revenue benefits. In 2019, taxes and mineral royalties paid by the oil and natural gas industry to the state of Texas was a record $16.3 billion. During the past ten years these revenues totaled $116 billion. As set forth in the recent Texas Independent Producers & Royalty Owners Association (TIPRO) "2020 State of Energy Report," these revenues "...have continued to support all aspects of the state economy, including infrastructure investment, water conservation programs, schools and education, and first responders...." In addition, the Texas oil and natural gas industry in 2019 purchased $220 billion in goods and services, of which 80 percent came from Texas businesses.[64]

In New Mexico, oil production growth on Federal land in the Permian Basin has helped the state's finances and provided the means to expand funding for education and other programs. The New Mexico Oil and Gas Association estimates that $1.2 billion of the state's $6.2 billion budget came from revenue on Federal land, including royalties, bonuses, and other payments.[65] In North Dakota, oil and natural gas taxes provided $18 billion for fiscal years 2008-2018 for the state, accounting for more than 45 percent of total tax revenues.[66]

Crude oil and natural gas production is also a major source of revenue for Wyoming's state and local governments. Given that Wyoming has no state income tax, local and state governments rely on tax revenues from oil, natural gas, and service companies operating in the state to fund many of its essential public services. In 2018, oil and natural gas production contributed $1.39 billion to the state of Wyoming from property taxes, severance taxes, state mineral royalties, and sales and use taxes. These tax revenues were used by the state to support essential public services, including providing $596 million for K-12 education, $510 million to the state's General Fund, and $114 million for public infrastructure, among other uses.[67]

Increased Numbers of Well-paying Domestic Jobs

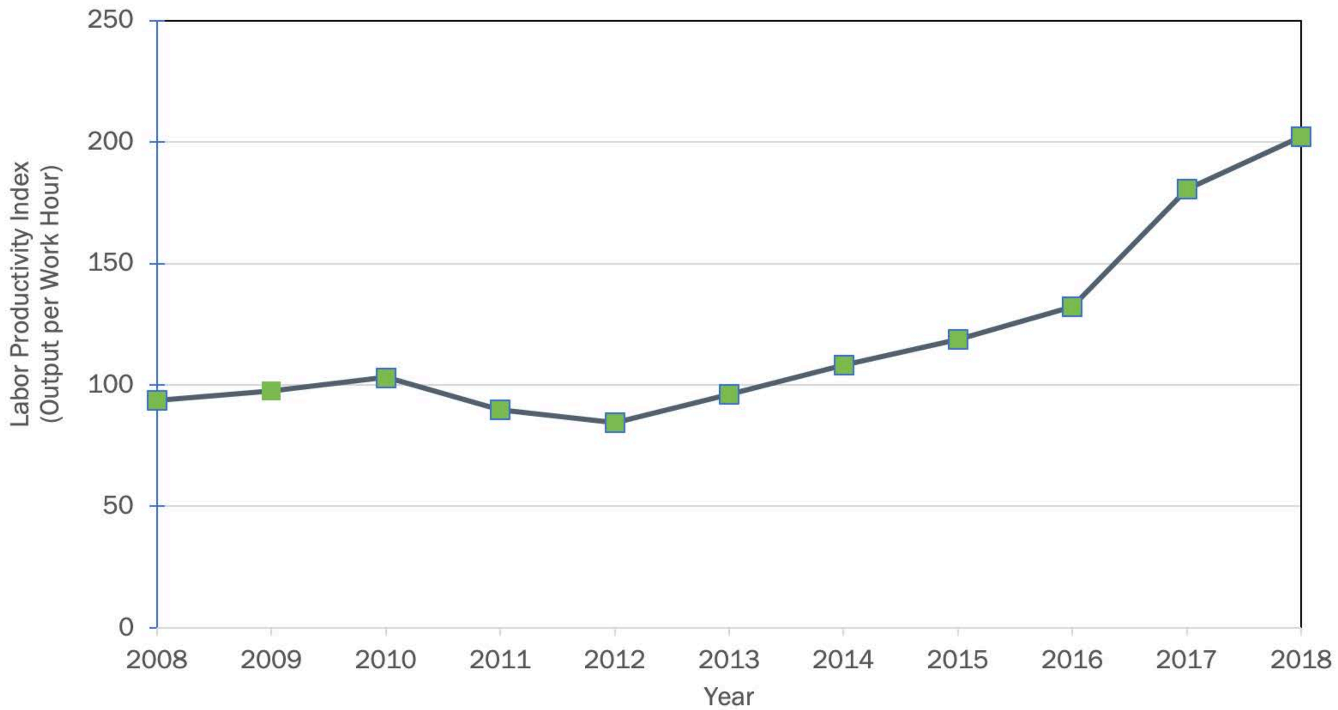
The domestic oil and natural gas extraction industry[68] supports 896,000 jobs (as of the end of 2019), including both direct and indirect jobs.[69] This consists of 158,000 direct jobs[70] and an estimated 738,000 indirect jobs, such as service and supply jobs, as well as induced jobs. The Economic Policy Institute reports that the oil and natural gas extraction industry has one of the highest indirect job employment multipliers, where one direct job leads to an additional 5.43 indirect jobs.[71] **Last year, the average direct job in the oil and natural gas extraction industry had an annual average wage of $112,000, more than double the annual average wage of $51,000 for the private sector.** The non-supervisory direct jobs in this industry, which include oil engineers, wellhead pumpers, roustabouts, and geoscientists, earn an average annual wage of $88,000 – about 70 percent higher than the average annual wage in the private sector.

The development and application of advanced technologies discussed previously in this report and their impact on labor productivity in the oil and natural gas industry are an important foundation for these increasingly productive well-paying jobs. Labor productivity, defined as output per hour worked, has more than doubled in the last decade in the oil and natural gas industry, increasing from an index of 93 in 2008 to an index of 202 in 2018[72] (see Figure 18, next page).

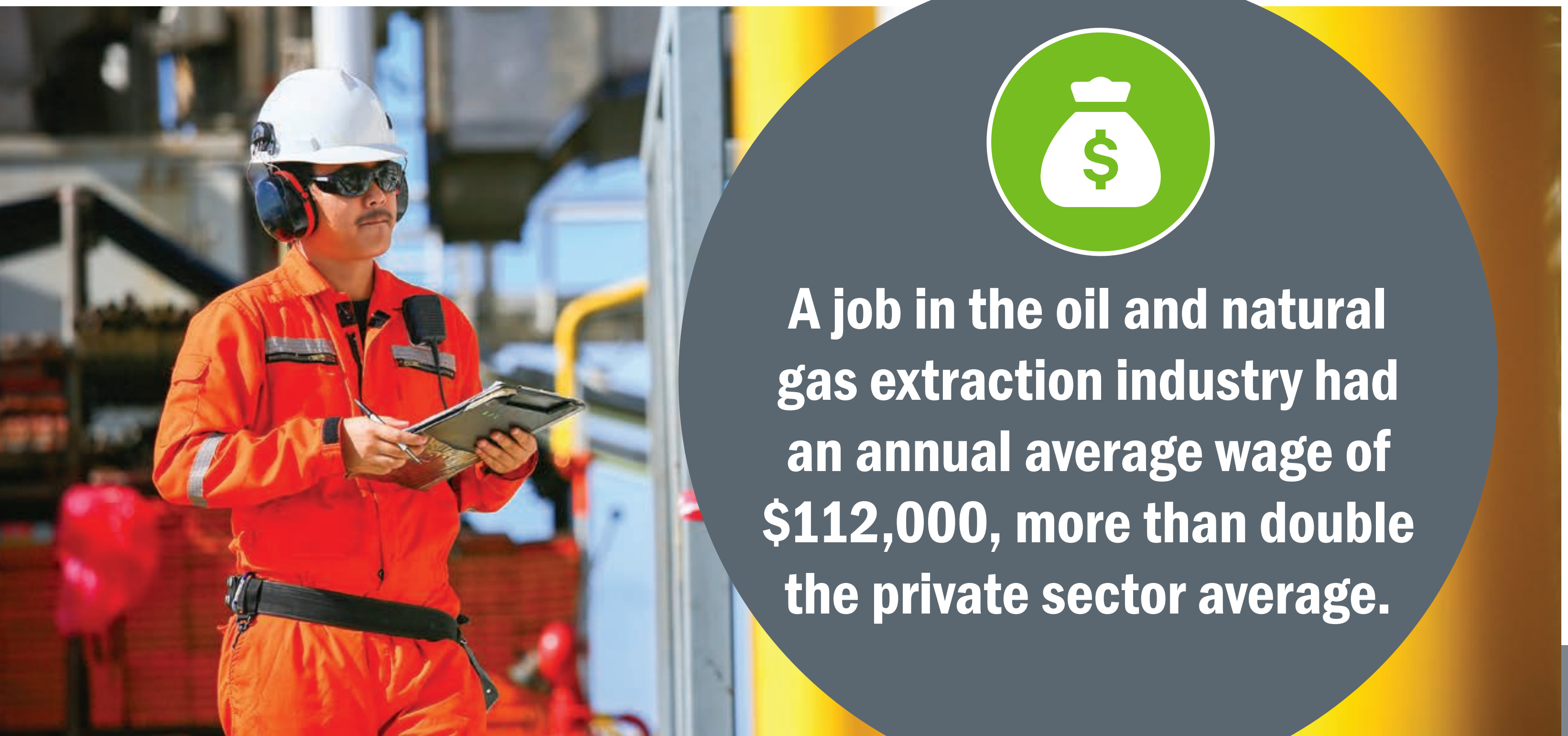
Figure 18

Oil and Natural Gas Extraction Subsector Productivity Improvement 2008-2018[73]

Labor productivity in the oil and natural gas industry has more than doubled in the last decade.



Taking a closer look at Texas, the state boasts 361,000 of these jobs, equal to 40 percent of nationwide oil and natural gas jobs. These jobs in Texas, including roustabouts, field operators, heavy truck drivers, and pretroleum engineers, paid an average annual wage of $132,104 – approximately 130 percent more than the average private sector job in the state.[74] These numbers do not include the significant additional manufacturing jobs that abundant supplies of oil and natural gas have helped create.



A job in the oil and natural gas extraction industry had an annual average wage of $112,000, more than double the private sector average.

Revitalized U.S. Chemical Manufacturing

Increased supplies of affordable shale gas, containing large volumes of ethane and other natural gas liquids, have provided a competitive advantage for chemical manufacturing in the United States, which is projected to create new jobs and supports domestic economic growth. During the past decade, 343 projects involving $203 billion of investment have been completed, placed under construction, or entered into the corporate planning stage. These projects have created or will create: (1) nearly 757,000 permanent new jobs; (2) an annual payroll of $57 billion; and (3) an annual economic output of $289 billion by 2025 (see Figure 19).[75]

Figure 19

Economic Contributions from Chemical Industry Investment in the United States[76]

Abundant quantities of low-cost natural gas have prompted chemical industry investments creating hundreds of thousands of new jobs and billions in economic output.

Economic Contributions from Higher Chemical Industry Output 2010-2025 (Permanent)

	Jobs	Payroll ($Billion)	Output ($Billion)
Direct	76,353	$9.6	$102.3
Indirect	338,729	$29.0	$129.3
Payroll-Induced	341,969	$18.2	$57.8
Total	757,050	$56.8	$289.4

This latest analysis builds on the American Chemistry Council's first report, "Shale Gas, Competitiveness, and New U.S. Chemical Industry Investment – An Analysis of Announced Projects." Released in May 2013, it analyzed the 97 potential projects valued at $72 billion that were announced from 2010 to 2013.

Launching a World-Class Domestic Liquefied Natural Gas Export Industry

The strong growth of natural gas production from the shale gas revolution has led to natural gas supplies that exceed domestic demand. This provided the foundation for building a world-class domestic liquefied natural gas (LNG) export industry. Initial LNG export project efforts converted existing sites and facilities that had been originally constructed to import LNG during periods of domestic under-supply.

Anticipating continued robust natural gas production, **the United States is on track to become the largest global LNG exporter**, increasing exports from six Bcfd at the end of 2019 to an expected 12 Bcfd by the middle of this decade, surpassing both Australia and Qatar.[77] The first wave of LNG liquefaction and export facilities includes two large LNG projects in Louisiana, two in Texas, one in Maryland, and one in Georgia. During 2019, LNG exports created $9.5 billion in revenue and helped to support a positive trade balance.[78]

U.S. LNG export projects have expanded the global availability of natural gas, driving down gas prices around the world while diversifying supplies, particularly in countries like Poland, Lithuania, and other European countries dependent on Russian natural gas pipeline exports (see Figure 20). By supporting the fuel needs of new gas-fired power plants in other countries, U.S. LNG will also help bring energy to some of the one billion people currently living without electricity, helping to lift these people out of poverty.[79]

Figure 20 Global Destinations of U.S. LNG Exports (2016-2019)[80]

U.S. LNG exports have improved energy security for countries across the globe.

A completed multiwell Marcellus Shale well pad in Washington County, Pennsylvania.

Reduced Environmental Footprint from Increased Production of Natural Gas and Lower Impact Extraction Technologies

The availability of abundant, affordable natural gas supplies has led to significant displacement of coal by natural gas as a fuel for electrical power plants. Increased use of natural gas and renewables for power generation has reduced the volumes of carbon dioxide per megawatt hour (MWh) of electricity produced by over 23 percent in the past decade.[81] Abundant supplies of natural gas have also aided the growth of wind and solar power by providing a highly responsive source of backup power when wind and solar energy inputs are interrupted.[82] A recent study published by the National Bureau of Economic Research concluded that renewables and natural gas-powered electrical power are highly complementary and should be jointly installed to meet goals of cutting emissions and ensuring a stable energy supply.[83]

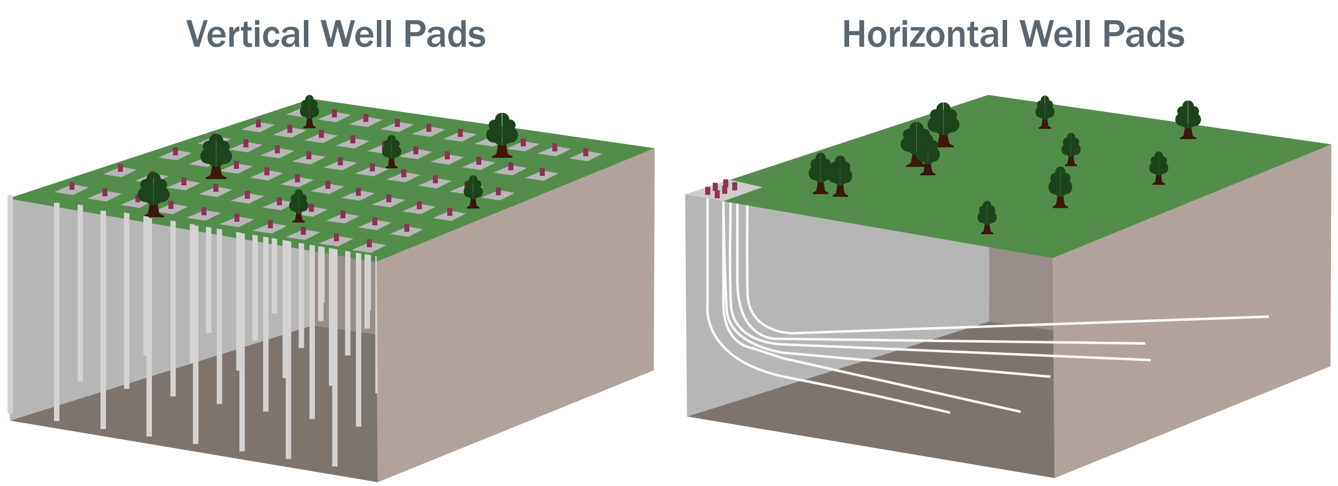
Natural gas liquids also are a significant source of the materials needed to construct lower weight components for fuel-efficient cars, wind turbine blades, solar panels, and energy-efficient materials such as insulation.[84]

In addition, greater use of natural gas for electric power production has led to a 57 percent reduction (per dollar of GDP) in domestic emissions of airborne particles such as soot, resulting in an estimated $17 billion in annual health benefits.[85]

The combination of hydraulic stimulation and horizontal drilling, while enabling the dramatic increase in production of oil and natural gas from shale and other unconventional formations, also has contributed to increased efficiency and resulted in smaller areal footprint per well drilled from drilling location development. For example, what took 64 well pads with 64 vertical wells to access four square miles (40 acres per well) in the early 2000s now can be accessed from a single (slightly larger) well pad with 16 long lateral horizontal wells (see Figure 21). Consolidating wells onto one drilling pad site results in as much as a 90 percent reduction in overall surface presence per well as well as allows for a concurrent reduction in the number of access roads and gathering pipelines needed to service dozens of wells, further reducing the environmental footprint per unit volume of oil or gas produced.[86]

Figure **21** **Multiwell horizontal well pads allow for efficient reservoir drainage with a much smaller surface footprint.**

Consolidating wells onto one drilling pad site results in as much as a 90 percent reduction in overall surface presence per well.



Finally, there are innovative ways that existing oil and natural gas infrastructure can be used for environmentally-friendly applications,[87] even when no longer used for oil and gas natural production. For example, **a joint Federal and industry program converted 532 steel platforms in the offshore Gulf of Mexico that had reached the end of their economic life into artificial reefs.** A typical eight-leg platform provides a home for 12,000 to 14,000 fish and acres of habitat for hundreds of marine species.[88] Researchers report fish densities as much as 30 times higher around active platforms.[89] Other alternative uses of existing offshore structures in offshore waters – such as for carbon capture and storage, and solar and wind energy – also may yield economic benefits and lessen environmental impacts.[90]

Abandoned platforms that are removed from their location and scuttled to form artificial reefs create underwater habitats for hundreds of marine species.

Enhanced Energy Security

As domestic oil and natural gas production rates have risen, U.S. imports of both commodities have fallen. The United States imported about 9.10 million barrels per day (MMb/d) of petroleum in 2019 from about 90 countries, which included 6.8 MMb/d of crude oil and 2.3 MMb/d of noncrude petroleum liquids and refined petroleum products.[91] This was the lowest level of total petroleum imports since 1996. But U.S. exports of petroleum have increased significantly in recent years. In 2019, the United States exported petroleum to about 190 countries. U.S. total petroleum exports averaged about 8.5 MMb/d, which included nearly 3 MMb/d of crude oil, equal to about 35 percent of total petroleum exports. U.S. petroleum net imports in 2019 were the lowest since 1954.

Although most of the natural gas consumed in the United States is produced here, the United States also exports natural gas. Until 2000, the United States exported relatively small volumes of natural gas and mostly by pipeline to Mexico and Canada. Total annual exports have generally increased each year from 2000 through 2019 as increases in U.S. natural gas production contributed to lower natural gas prices and the competitiveness of U.S. natural gas in international markets. In 2019, the United States exported 4.66 trillion cubic feet (Tcf) of natural gas to about 38 countries – the highest volume on record, making the United States a net exporter of natural gas for the third year in a row.[92]

Energy self-reliance makes the United States more secure. The capability to export energy to allies around the world gives the United States an advantage in helping to secure global peace and security.

SECTION 4

OPPORTUNITIES FOR THE FUTURE

Energy from oil and natural gas forms the backbone of our modern economy, powering our factories and communities, heating and cooling our homes, and transporting people and goods. Products made from natural gas liquids are integral to our way of life.

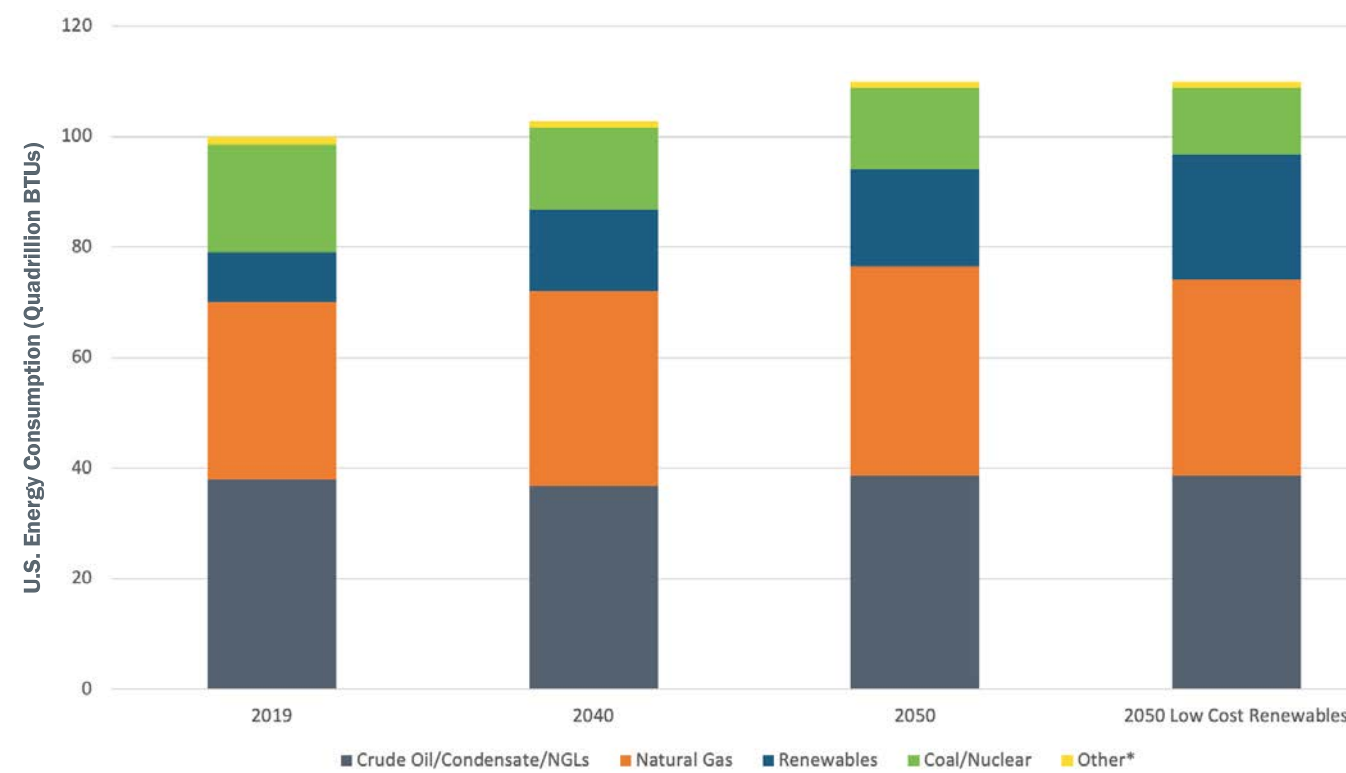
Over the 160-year history of the U.S. oil and natural gas industry, but perhaps most dramatically in the past few decades, innovative technologies have helped increase the amount of economically recoverable oil and natural gas resources available to Americans. These increased supplies of affordable, domestically produced energy have supported steadily improving economic conditions and living standards in the United States as well as the rest of the world.

The fundamental nature of this relationship among energy, technology, and human progress has not changed, despite many short-term ups and downs in the supply/demand balance and accompanying economic disruptions.

Oil and natural gas are the two dominant energy sources in the United States, accounting for two-thirds of the total energy consumed in 2019. Even after accounting for the steady growth of renewables, according to the EIA, oil, natural gas, and natural gas liquids are projected to account for the majority – nearly 70 percent – of domestic energy consumption two decades from now (see Figure 22).[93]

Figure 22 **Estimated Current and Future U.S. Energy Consumption by Source**[94]

Oil, natural gas, and natural gas liquids are projected to account for the majority – nearly 70 percent – of domestic energy consumption for decades to come.



***Other includes methanol, hydrogen, non-biogenic municipal waste.**

As the world transitions toward a lower carbon future, continued oil and natural gas production will remain an integral element of the transition. Natural gas, including associated gas from oil production, will continue to play a key role in the direct de-carbonization of electricity production while also enabling the practical, economic development of low-carbon wind and solar power by providing backup power. Natural gas liquids will continue to play a critical role in producing the materials that will make energy-saving and low-carbon renewable energy technologies feasible. Efforts to recover additional domestic oil resources while simultaneously storing captured carbon dioxide will help launch construction of the nationwide infrastructure buildout that will be needed to safely sequester very large volumes of captured carbon. A seamless transition to a lower carbon future will depend on a steady supply of hydrocarbons to minimize economic disruption.

As the world moves toward a lower carbon future, continued oil and natural gas production will remain an integral part of the transition.

The global economic disruption associated with the 2020 COVID-19 pandemic has highlighted the complicated relationship between our energy supply, society's economic strength, and humanity's physical health. Supplies of oil and natural gas are critical to all of the sectors of society involved in fighting the virus – fueling first responder ambulances, powering hospitals, and providing raw materials for lifesaving drugs and the personal protective equipment needed by caregivers. At the same time, efforts to contain the spread of the virus by shutting down travel and human interactions have led to a drop in global demand for oil and natural gas. Prices have dropped, with concurrent losses in oil and natural gas sector employment and industry bankruptcies that in turn weaken our ability to maintain our oil and natural gas-producing capability and the benefits it provides. The fact that the nationwide shutdown in response to the pandemic in April 2020 resulted in a nearly 50 percent decline in gasoline demand underlines just how closely our modern way of life depends on oil and natural gas.

The resiliency of the U.S. energy industry has been proven through a multitude of commodity price fluctuations over many decades. American crude oil and natural gas prices have varied 100 percent or more above and below their average price over the past two decades alone (see Figure 23). Often, it has been during the times of economic stress that paradigm-shifting technologies have been developed and deployed.

Figure 23

U.S. Crude Oil and Natural Gas Prices 1997-2020[95]

Major variations in oil and natural gas prices often lead to the development of new technologies.

Continued production of affordable supplies of oil and natural gas will remain an essential element of future progress in our nation's economic health and America's living standards. And a key factor in assuring economic access to secure, affordable, domestic supplies of oil and natural gas has been, and will continue to be, innovation in oil and natural gas extraction technology.

Continued production of affordable supplies of oil and natural gas is an essential element of future progress in our nation's economic health and living standards.

Opportunities for continued oil and natural gas sector technology innovation in the face of reduced demand and falling prices are plentiful.

- Applying lower cost horizontal drilling methods and other novel approaches to increase recovery from mature conventional fields that still contain significant volumes of residual oil and natural gas and are faithfully maintained by thousands of small businesses.
- Cost effectively capturing and utilizing anthropogenic carbon dioxide for EOR from both conventional and tight oil reservoirs.
- Lowering the cost of production both onshore and offshore through innovative use of remote sensing, artificial intelligence and robotics, data analytics, and machine learning.
- Developing cost-effective ways to produce as-yet-undeveloped resources such as methane hydrates that could supply the world with a lower-carbon energy source for generations.

All of these opportunities require sustained investment in research and development to continuously further scientific understanding and technological innovation.

Investments made over recent decades enabled the United States to become a world leader in oil and natural gas production, which has yielded many societal benefits – related to both economics and convenience. Sustained investment in research and development is critical for theUnited States to maintain its leadership and technological competitiveness in global energy markets.

Oil and natural gas will continue to play an important role in the nation's future energy supply. As Americans rise to meet new challenges, technological innovation will remain a cornerstone for our country to sustain the domestic energy supply that is so vital to providing our energy security and supporting our quality of life.

GLOSSARY

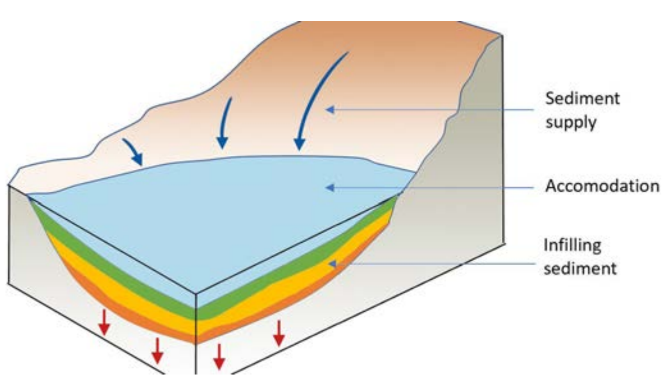
ANADARKO BASIN – A sedimentary basin centered in the western part of Oklahoma and the Texas Panhandle, extending into southwestern Kansas and southeastern Colorado.

ANTRIM SHALE – A productive natural gas-bearing formation of Devonian age (see geologic time scale) located in the Michigan Basin, a geologic basin centered on the Lower Peninsula of Michigan. It is a source of natural gas in the northern part of the basin. The Antrim is a brown/black, organic-rich shale, ranging from 60 to 220 feet thick.[96]

APPALACHIAN BASIN – The Appalachian Basin is a geologic basin containing sedimentary rocks of Early Cambrian through Early Permian age. From north to south, the Appalachian Basin crosses New York, Pennsylvania, eastern Ohio, West Virginia, western Maryland, eastern Kentucky, western Virginia, eastern Tennessee, northwestern Georgia, and northeastern Alabama. The Marcellus Shale formation is a Devonian-aged organic shale deposited in the Appalachian Basin that is a prolific producer of natural gas and natural gas liquids.

ASSOCIATED GAS – Natural gas found in association with petroleum, either dissolved in the oil or as a free "gas cap" located above the oil level within the reservoir. The dissolved gas is separated from the oil at the surface and sold separately. Sometimes associated gas is burned (flared) at the surface if economics do not support its capture and sale.

BASIN – A low area in the Earth's crust, typically created by large scale movements of the crust, in which sediments accumulate. Sedimentary basins range in size from as small as hundreds of meters to as large as portions of ocean basins. Oil- and natural gas-bearing rocks are often made up of sediments deposited in ancient basins formed millions of years ago.[97]



BAKKEN SHALE – An oil- and natural gas-bearing formation of Late Devonian to Early Mississippian age located within the Williston Basin, underlying parts of Montana, North Dakota, Saskatchewan, and Manitoba.

BARNETT SHALE – An oil- and natural gas-bearing formation of the Early Mississippian age located in Fort Worth Basin of Texas. The Barnett Shale play was discovered by Mitchell Energy in 1981.[98]

CANA-WOODFORD SHALE – A liquids-rich part of the Woodford Shale formation named after Canadian County, Oklahoma, although the formation underlies several counties in the western half of the state. Also known as the Anadarko-Woodford. The Woodford Shale is mostly Late Devonian in age with the uppermost part Early Mississippian in age. The Woodford covers virtually the entire state of Oklahoma and is more geologically complex than other Devonian black shales found in North America.[99]

CARBON CAPTURE, UTILIZATION, AND STORAGE (CCUS) – The practice of capturing carbon dioxide from an industrial process (e.g., coal combustion or ethanol production) and either utilizing it for another commercial purpose (e.g., carbon dioxide enhanced oil recovery) or injecting it deep underground into depleted oil reservoirs or salt water aquifers where it can be permanently stored.

CARBON DIOXIDE ENHANCED OIL RECOVERY (CO_2-EOR) – Carbon dioxide is miscible with crude oil – that is, it mixes with it in all proportions without an interfacial contact (for example, with oil and water). If carbon dioxide is injected under high pressure into an oil reservoir where there is residual oil remaining behind after production, this miscibility enables the carbon dioxide to essentially dissolve the oil and, when followed by injected water, displace the accumulated oil droplets towards a producing well. This process enhances the overall recovery of oil from the reservoir that would otherwise be considered depleted.

CARBONATE ROCKS (DOLOMITE AND LIMESTONE) – A class of sedimentary rocks composed primarily of carbonate minerals. The two major types are limestone, which is composed of calcite or aragonite (different crystal forms of $CaCO_3$) and dolomite, which is composed of mineral dolomite ($CaMg(CO_3)_2$).

CLASS II WATER INJECTION WELLS – A well classification of the U.S. Environmental Protection Agency (EPA) for wells that are used only to inject fluids associated with oil and natural gas production. Class II injected fluids are primarily brines (saltwater) that are brought to the surface while producing oil and natural gas. It is estimated that over two billion gallons of fluids are injected in the United States every day in Class II wells. Most Class II wells are in Texas, California, Oklahoma, and Kansas. The number varies from year to year based on fluctuations in oil and natural gas production. Approximately 180,000 Class II wells are in operation in the United States.[100]

COALBED METHANE (CBM) – Coal, being the product of organic material that has been compressed over geologic time, includes methane molecules that are either adsorbed onto the surface of the coal matrix or held within the fractures of the coal seam. When the pressure is reduced in a coal seam by mining or by withdrawal of the water in the fractures via a well, the methane released is called coalbed methane. Deeply buried, un-mineable coal seams have been tapped to produce this natural gas in parts of the United States.

COMBINED HEAT AND POWER (CHP) – CHP is an energy efficient technology that generates electricity and captures the heat that would otherwise be wasted to provide useful thermal energy—such as steam or hot water—that can be used for space heating, cooling, domestic hot water, and industrial processes. CHP can be located at an individual building or a utility but is typically located at facilities where there is a need for both electricity and thermal energy. By capturing and using heat that would otherwise be wasted, and by avoiding distribution losses, CHP can achieve efficiencies of over 80 percent, compared to 50 percent for conventional electricity generation and an on-site boiler.[101]

COMPOSITIONAL RESERVOIR MODELING – Reservoir modeling (or reservoir simulation) involves the use of mathematical models to predict the flow of fluids (typically, oil, water, and natural gas) through porous media. A compositional reservoir model calculates the pressure-volume-temperature (PVT) properties of oil and natural gas phases within the reservoir as production takes place, using equations of state. Compositional modeling can be important when simulating carbon dioxide-enhanced oil recovery (CO_2-EOR) floods or the production of reservoirs containing very volatile crude oils or condensates.

CONDENSATE – A lighter (low density) liquid hydrocarbon often found in association with natural gas. Its existence as a liquid or gas phase depends on temperature and pressure conditions. Condensate often exists as a gas in the reservoir but condenses into a liquid as it is produced up the well and into surface production equipment. Mainly composed of propane, butane, and pentane mixed with some higher carbon hydrocarbon fractions, condensate is typically much lighter in color than crude oil. Pictured below from left to right: Crude Oil, Condensate, Light Condensate, and Refined Fuel placed on Shale Reservoir Rock.

CONVENTIONAL OIL – Oil produced from conventional reservoirs rather than "unconventional" reservoirs. Conventional reservoir rocks are typically porous and permeable sandstones, conglomerates, limestones, or dolomites into which hydrocarbons have migrated from much finer grained "source" rocks where the oil and gas was formed over geologic time.

CORE AREA – The core area of a shale gas or shale oil play is the area of the play where wells produce the highest return on capital employed. These are the wells with highest initial production rates and highest estimated ultimate recoveries due to a combination of the best geology and the best initial price per acre and royalty terms. Shale formations vary in thickness, depth, organic content, and mineralogy across the play. The core of the play occurs where the confluence of these different parameters is optimal and offers the best development economics.

DEEP COAL SEAMS – Coal formations that are too deep to mine but remain sources of coalbed methane that can be recovered via wells.

DEEPWATER – Generally considered to be marine waters that are greater than 1,000 feet in depth. Ultradeep waters are between 7,000 and 12,000 feet in depth.

EAGLEFORD SHALE – An oil- and natural gas-bearing formation deposited during the Late Cretaceous Period over much of south-central Texas. The productive area is about 50 miles wide by 400 miles long, and the formation is on average 250 feet thick and buried between 4,000 and 12,000 feet below the surface, reaching from the Mexican border into east Texas. The Eagle Ford is predominantly composed of organic-rich marine shales with interbedded thin limestone layers.[102]

ELECTRIC SUBMERSIBLE PUMP (ESP) – An oil well pumping device that includes a hermetically sealed electric motor coupled to a fluid pump. The assembly is submerged in the fluid to be pumped at the bottom of the well's production tubing and is powered from the surface via an electric conduit. When operating, the pump moves the fluids entering the wellbore up the tubing. Electrical submersible pumps are well suited to wide range of flow rates.

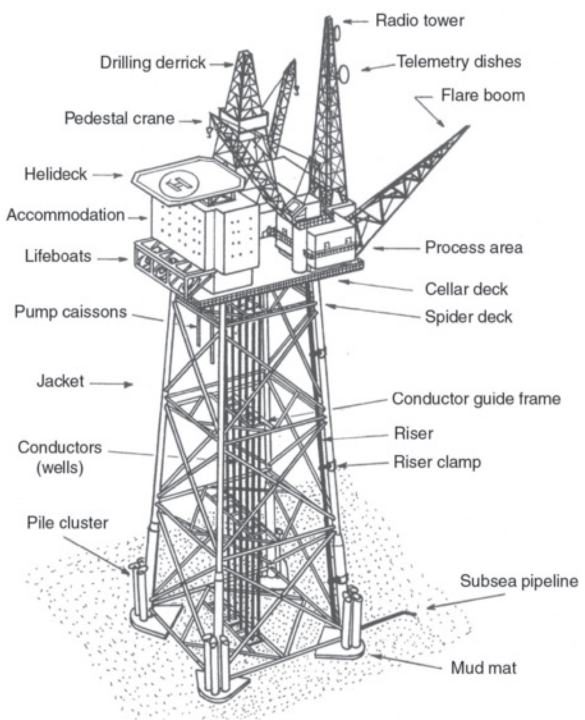
ELECTRONIC DIGITAL TWIN – A digital version of a physical system that forms the basis for simulation software that models the system's behavior under different scenarios. Such digital twins can be used to test the outcomes of variations in operating practices or safety protocols without having to make changes to the physical system.

EXPECTED OR ESTIMATED ULTIMATE RECOVERY (EUR) – An estimate of the volume of oil or natural gas that can be expected to be produced from a well over its lifetime, based on certain economic and operating assumptions. Estimates of EUR can be made by modeling the well's behavior or using simpler mathematical tools to extrapolate production behavior based on analog wells.

EXPECTED ULTIMATE GAS RECOVERY (EUG) – See Expected or Estimated Ultimate Recovery (EUR).

FAYETTEVILLE SHALE – An oil- and natural gas-bearing formation of Mississippian age composed of black, organic-rich shale and located within the Arkoma Basin of northern Arkansas and Oklahoma. It is named for the city of Fayetteville, Arkansas.

FIXED-TO-THE-SEAFLOOR PLATFORM – A fixed platform that consists of a set of welded tubular steel legs (called a "jacket"), deck or decks, and surface facilities. The jacket and decks make up the foundation for the surface facilities that can include a drilling rig, well heads, producing equipment, and living accommodations. Piles driven into the seafloor secure the jacket legs in place. The water depth at the intended location dictates the required height of the platform, which is typically constructed on shore and moved to the location on a barge.[103]



FLOATING PLATFORM – Offshore structures designed to drill, produce, and perhaps process and temporarily store crude oil and natural gas in deepwater locations. Tension leg platforms and spar platforms (tethered to the seafloor with mooring lines rather than vertical tension leg cables) are two types. Floating drilling platforms or drill ships are used to drill wells that may ultimately be produced via subsea wellheads.

FLOW CAPACITY– The product of permeability (in millidarcies or mD) and reservoir interval thickness, measured in mD-feet (or mD-meters). A completion interval in a thick reservoir with low permeability could have a flow capacity similar to that of a completion interval in a thin reservoir with a high permeability.

FLOWBACK WATER – Flowback water is a mixture of fracturing fluid and formation water that flows back once a well has been put on production following a hydraulic fracturing treatment. This water includes chemical additives, formation sediment, and typically high concentrations of inorganic salts and other contaminants. Post-fracturing flowback can continue for days or weeks with the volumes declining with time. Ideally, flowback water is captured and recycled in subsequent fracturing treatments on other wells, eliminating the need for immediate disposal in deep water disposal wells.

GEOLOGIC TIME SCALE – A system of chronological dating that relates geological strata (stratigraphy) to time. It is used by geologists, paleontologists, and other Earth scientists to describe the timing and relationships of events that have occurred during Earth's history. The scale is divided up into four eons, the most recent of which is divided up into eras, periods, and epochs. The periods are often subdivided into early, middle, and late (progressively younger) sections.[104]

Eon	Era	Period		Epoch
Phanerozoic	Cenozoic	Quaternary		Holocene
				Pleistocene
		Neogene		Pliocene
				Miocene
		Paleogene		Oligocene
				Eocene
				Paleocene
	Mesozoic	Cretaceous		~
		Jurassic		~
		Triassic		~
	Paleozoic	Permian		~
		Carboniferous	Pennsylvanian	~
			Mississippian	~
		Devonian		~
		Silurian		~
		Ordovician		~
		Cambrian		~
Proterozoic	~	~		~
Archean	~	~		~
Hadean	~	~		~

Younger ↑ ↓ Older

Today
11.8 Thousand years ago (Ka)
66 Million years ago (Ma)
252 Ma
541 Ma
2.5 Ga
4.0 Ga
4.54 Ga
2.5 Billion years ago (Ga)

GRAVITY STABLE CARBON DIOXIDE FLOOD – A tertiary flood where carbon dioxide is injected into the top of a steeply dipping reservoir and allowed to expand downward as injection continues, relying on the difference in density between the lighter carbon dioxide on top and the heavier residual oil layer below to keep the flood front stable as oil is produced from the bottom of the oil zone. This method is considered to be particularly well suited for the steeply dipping, high permeability sandstone reservoirs found around salt dome structures in the offshore Gulf of Mexico, where residual oil remains to be recovered after primary depletion.

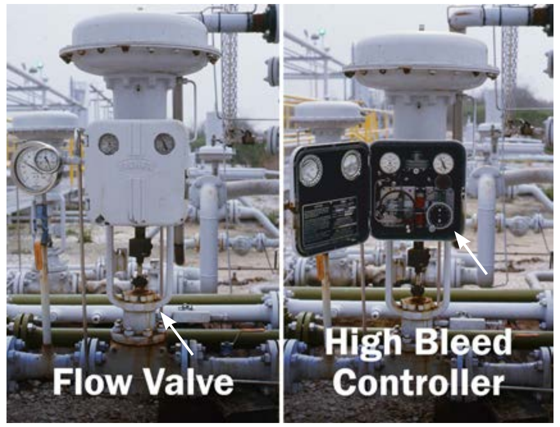
GREEN COMPLETIONS – A well completion process where any natural gas produced following hydraulic fracturing is not vented or flared but separated from the flowback fluids using temporary skid or trailer mounted equipment, dehydrated and sent to a sales pipeline. Liquid hydrocarbons may be collected and sold. Produced water is stored in water tanks or in a reserve impoundment for later treatment or disposal. Care is taken to minimize any emissions of methane to the atmosphere during the well completion process.

GREENHOUSE GAS (GHG) – A gas that absorbs and emits radiant energy within the thermal infrared range. Greenhouse gases cause the greenhouse effect on planets. The primary greenhouse gases in Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, and ozone.[105]

HAYNESVILLE SHALE – A prolific natural gas-bearing formation of the Jurassic Period that underlies southwestern Arkansas, northwest Louisiana, and east Texas. It averages about 200 to 300 feet in thickness, lies at depths of 10,500 to 14,000 feet below the land's surface, and produces dry gas (little liquid). The Haynesville "shale" is a geologically heterogeneous mudstone with varying amounts of clay and carbonate material both vertically and horizontally.[106]

HENRY HUB PRICE – Natural gas produced at a particular location is typically priced based on the differential to the price at a specific reference location, with the differential based on regional market conditions, transport costs, and available transmission capacity between locations. The reference location chosen by the industry for this purpose is a gas distribution hub on the pipeline system in Erath, Louisiana that interconnects with more than a dozen pipelines, called the Henry Hub. This level of interconnection allows natural gas shippers and marketers access to pipelines serving markets across the Unites States. Wellhead prices are closely related to the Henry Hub price, so it serves as a reference price for U.S. natural gas.

HIGH-BLEED PNEUMATIC CONTROLLERS – Valves within the piping associated with a well or with related oil and natural gas production equipment are typically opened and closed using a pneumatic system that relies on pressurized natural gas diverted from the production system. The valves are operated by a controller that routinely releases (bleeds) small volumes of the gas. Modern alternative “low bleed” devices, designed to release less gas, are gradually replacing vintage equipment known as “high bleed” devices.



HORIZONTAL DRILLING AND HORIZONTAL LATERALS – A horizontal well is a directionally drilled oil or natural gas well at an angle of at least 80 degrees to a vertical wellbore. After the well has been deviated from vertical via a bend in the wellbore of a specific radius, the horizontal portion of the wellbore is referred to as the horizontal lateral. Some modern shale wells have laterals as long as 20,000 feet at depths of 10,000 feet.

HYDRAULIC FRACTURING – An oil and natural gas well stimulation process that typically involves injecting water, sand, and chemicals under high pressure into a rock formation via a wellbore. This process is intended to fracture the rock formation, creating and extending new fractures in the rock as well as increasing the size, extent, and connectivity of existing fractures. The sand (proppant) props open the created fracture after pressure is released. The technique is used in low-permeability rocks like tight sandstone, shale, and some coal beds to increase oil and gas flow to a well.

HYDROCARBONS – Organic compounds made up of hydrogen and carbon atoms. The simplest hydrocarbons are methane (CH_4), ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), pentane (C_5H_{12}), and hexane (C_6H_{14}). Natural gas is mostly methane but also includes amounts of these other compounds as well. Crude oil contains more complex hydrocarbons containing many more carbon and hydrogen atoms combined into complicated structures and longer chains of molecules that include other atoms.

INDUCED SEISMICITY – Typically minor seismic events and tremors that are caused by human activity that alters the stresses and strains on the Earth’s crust. Most induced seismicity is of a low magnitude, undetectable by humans. Recently, the pumping of large volumes of fracturing flowback water produced from shale gas and shale oil wells into deep water disposal wells has led to an observable increase in induced seismicity related to disposal wells in Oklahoma and Texas.

LIQUEFIED NATURAL GAS (LNG) – Natural gas that has been cleaned, dried, and compressed into a liquid phase and that is kept under pressure at low temperature. LNG is a concentrated form of natural gas that can be transported as a liquid in trucks, pipelines, or large ships and then re-gasified and placed into a pipeline for distribution to consumers.

LOGGING-WHILE-DRILLING (LWD) – A process whereby sensing equipment (logging tools) are integrated into the bottom end of a drilling string (drill pipe and drill bit) such that they can be used to make geophysical measurements of the surrounding rock formations while the well is being drilled. The information is transmitted up the drill string through a variety of methods in real time or nearly real time. This method permits the driller to adjust how the well is drilled, for example, to make certain that the most productive zone of a rock formation is penetrated when drilling horizontally. LWD, while expensive, makes it unnecessary to pull the drill string out of the hole at intervals to run wireline logging tools.

LONG STROKE PUMPING UNITS – A type of oil well pumping unit that applies long pump strokes—more than 35 feet—that allow more time for fluids to enter the pump intake before being lifted to surface. This requires fewer strokes per barrel produced, increasing equipment life and resulting in fewer downhole equipment failures.

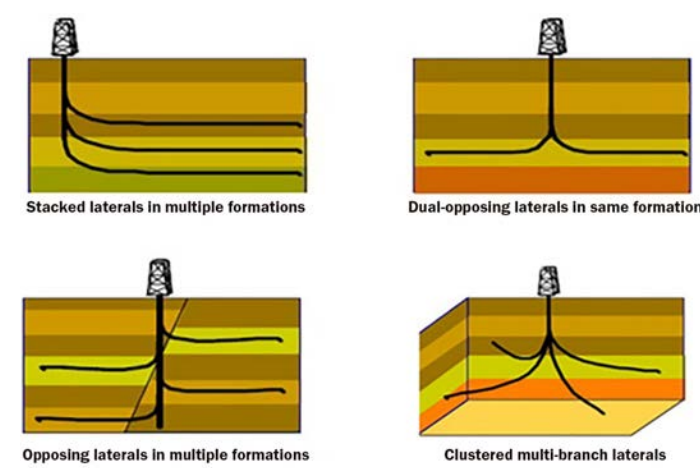
MARCELLUS SHALE – A prolific natural gas producing formation of Middle Devonian age found in the eastern United States’ Appalachian Basin. Named for an outcrop near the village of Marcellus, New York, the Marcellus consists predominantly of black organic shale and a few limestone beds. It stretches from upstate New York down through Pennsylvania to West Virginia and west to parts of Ohio. Most of the Marcellus’ development and a majority of the natural gas and natural gas liquids production to date has taken place in Pennsylvania, primarily in the southwestern and northeastern portions of the state.

MEASUREMENT-WHILE-DRILLING (MWD) – Measurement while drilling (MWD) is similar to logging-while-drilling (LWD), but MWD refers to directional-drilling measurements made to ensure the smooth operation of the drilling operation, while LWD refers to measurements of the characteristics of the geological formation being penetrated that are made while drilling is underway.

MOBILITY CONTROL – A condition during enhanced oil recovery (EOR) processes whereby the mobility of the injectant (e.g., carbon dioxide) is reduced relative to that of the oil, leading to a stable displacement of the oil by the injectant (i.e., less fingering of a high mobility injectant through the oil zone). Commonly the materials used to reduce injectant mobility are soluble polymers that increase viscosity. Carbon dioxide mobility can be reduced by the addition of polymer or surfactant-based foams.

MULTI-STAGE HYDRAULIC FRACTURING – Hydraulic fracturing process that involves repeated pumping of fracturing fluid and proppant into successive perforated intervals along a wellbore. The process typically begins at the “toe” or farthest extent of the horizontal lateral and continues in stages along the lateral back towards the vertical portion of the wellbore. Once each interval, or stage, is adequately fractured, pumps are shut down and the process is repeated. The number of stages depends on the lateral length of the well, but 20 or more stages is not uncommon. Completing the planned stages can take three to four days. Then flow-testing and production equipment is installed.

MULTILATERAL DRILLING – A type of horizontal drilling where several horizontal wellbore branches radiate from the main vertical borehole. There are several categories of multi-lateral wells based on how the wells are drilled, cased, and cemented. Multilateral technology has advanced in recent years and has seen application in producing heavy oil.[107]



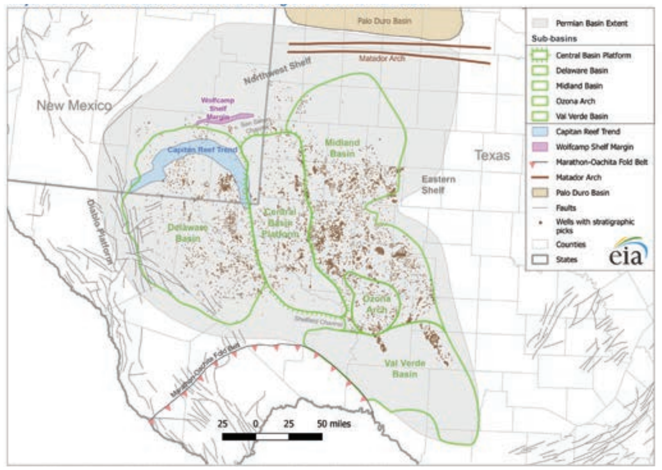
NATURAL GAS LIQUIDS – Natural gas liquids (NGLs) are hydrocarbons—in the same family of molecules as natural gas and crude oil, composed exclusively of carbon and hydrogen, with few carbon atoms. Ethane (two carbon atoms), propane (three), butane (four), isobutene (four), and pentane (five) are all NGLs. They are often found and produced along with natural gas (methane, which has only one carbon atom), and are often in a gaseous state in the reservoir but are separated as liquids from the methane at the surface.

NET ENERGY BASIS – While the United States imports crude oil, liquefied natural gas, pipeline natural gas, natural gas liquids, and refined petroleum products, it also exports each of them. When all energy imports and exports are accounted for, if the United States exports more than it imports, it can be considered to be energy independent on a net energy basis (exports minus imports is a positive value).

ORGANIC-RICH SHALES – Organic-rich sedimentary rocks contain significant amounts (>3 percent) of organic carbon. Black shale is one example where organic material is disseminated throughout a fine-grained rock imparting a uniform dark color. These organic-rich sedimentary rocks may act as source rocks which generate hydrocarbons that migrate and accumulate in other sedimentary “reservoir” rocks, or they may be produced themselves via a combination of horizontal drilling and hydraulic fracturing.

PERMEABILITY (FLOW CAPACITY) – A measure of the ability of a porous material (e.g., a rock) to allow fluids to pass through it. The permeability of a rock is related to its porosity (percentage of its volume that is open pore space filled with fluids), and to the size and shapes of the pores in the medium and their degree of connectedness. Flow capacity is the product of a reservoir rock’s permeability and the reservoir interval thickness.

PERMIAN BASIN – A large sedimentary basin located in western Texas and southeastern New Mexico. It is one of the world's thickest deposits of rocks from the Permian geologic period. The Permian Basin includes several component basins: the Midland Basin, Delaware Basin, and Val Verde Basin. There are several tight oil formations that are currently being developed with horizontal drilling and large volume hydraulic fracturing. This has led to a dramatic resurgence in oil and natural gas production in a producing area that has been prolific for many decades.[108]



PLAY – An area in which hydrocarbon accumulations or prospective accumulations that are controlled by the same set of geological circumstances occur. For example, the shale gas plays in the United States, named after the productive formation, include the Barnett, Eagle Ford, Fayetteville, Haynesville, Marcellus, and Woodford, among others.

PORE THROAT – Within a sedimentary rock made up of mineral grains with pores between them, the small pore space at the point where two grains meet, which connects two larger pore volumes. The number, size, and distribution of the pore throats control the flow and capillary-pressure characteristics of the rock.

PRESSURE DEPLETION – One of several mechanisms by which fluids are produced from oil and gas reservoirs. When fluids (gas, oil or water) are removed through a well from a bounded reservoir that is initially under pressure due to its depth, the average pressure in the reservoir drops. As the pressure declines with continued production the energy available to move the fluids out of the reservoir quickly declines as well, leaving significant volumes of the fluids in place. Water influx in cases where a large water saturated portion of the reservoir (an aquifer) underlies the oil or gas saturated portion counters this effect in reservoirs, helping to maintain pressure. Likewise, the presence of a gas cap above the oil layer can slow pressure depletion.

PRODUCED WATER – Naturally occurring water that comes out of the ground along with oil and natural gas. Most oil- and natural gas-bearing rocks also contain water. When the oil or natural gas is extracted from these rocks, a portion of the water comes out too. Produced water often contains salts and minerals and is considered a brine.

PROPPANT – A solid material, typically sand (treated sand or man-made ceramic material), designed to keep an induced hydraulic fracture open (to "prop" it open) during and following a hydraulic fracturing treatment.

RELATIVE PERMEABILITY – When multiple fluids are flowing through a porous rock such as an oil reservoir at the same time (e.g., oil and water), the permeability of the rock to a given phase is dependent on the saturation of that phase as the flow of each phase is inhibited by the presence of the other phases. The relative permeability is the ratio of the permeability of a given phase to the absolute permeability of the rock, and changes as a function of the phase's saturation.

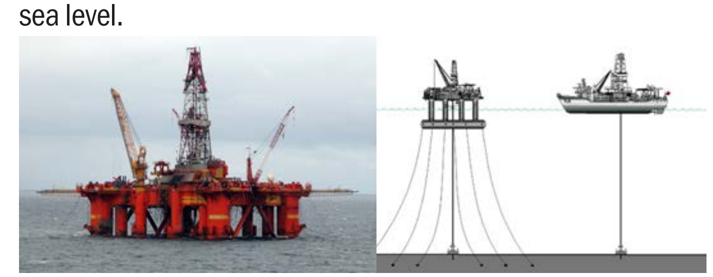
REDUCED EMISSIONS COMPLETIONS (REC) – See green completions.

RESIDUAL OIL ZONES (ROZ) – Areas of immobile oil located below the oil-water contact of a conventional oil reservoir. The oil saturation in this zone is lower than that in the productive interval above the oil water contact, but because of the large volumes of rock involved, contain substantial volumes of oil. Some ROZ oil saturations are similar to reservoirs that have been water-flooded and thus may be candidates for carbon dioxide flooding.

SACROC UNIT OF THE KELLY SNYDER FIELD – Scurry Area Canyon Reef Operators Committee (SACROC) is an oil production unit that comprises one of the largest and oldest United States oilfields employing carbon dioxide flooding. Discovered in 1948, the SACROC unit of the Kelly Snyder field is located in the Permian Basin of Texas. Currently, Kinder Morgan owns about 97 percent of the working interest in SACROC and has expanded the development of the carbon dioxide project initiated by previous owners and increased production over the last several years.[109]

SECTION 45Q TAX CREDITS – Section 45Q of the United States Tax Code provides a tax credit on a per-ton basis for anthropogenic carbon dioxide that is sequestered. The credit was originally enacted by Congress in 2008 to incentivize the reduction of carbon dioxide emissions and support enhanced oil recovery. The Bipartisan Budget Act of 2018 modified the credit, expanding its application and making its benefits available to more taxpayers. The Section 45Q tax credit is designed to increase to $35 per metric ton for enhanced oil recovery (EOR) and $50 per metric ton for geologic storage by 2026.[110]

SEMI-SUBMERSIBLE PLATFORM – A marine vessel used as an offshore drilling and production platform. They have good stability, better than drill ships, due to ballasted, watertight pontoons located below the ocean surface and wave action. Structural columns connect the pontoons and operating deck, which can be located high above the sea level.



SHALE GAS – Common term for natural gas produced from unconventional reservoir rocks, primarily low permeability shales but also formations that include non-shale intervals. The application of horizontal drilling and high volume, multi-stage hydraulic fracturing permitted economic production rates to be realized from these previously non-producible rocks, launching the rapid growth in shale gas production with increasing volumes of shale gas entering the market from plays like the Barnett Shale, Marcellus Shale, Fayetteville Shale, Haynesville Shale, and others.

SOURCE ROCKS – Organic rich sedimentary rocks from which hydrocarbons have been generated or are capable of being generated.

SPRABERRY FORMATION – The Spraberry Trend is a large oilfield in the Permian Basin of West Texas, within the Midland Basin. All the Spraberry Trend oilfields produce from a single enormous sedimentary unit known as the Spraberry Sand, which consists of a complex mixture of fine-grained sandstone, mudstone, and siltstone, all of Permian age. The sands are interbedded with shales. Unlike many of the oil-bearing rocks of west Texas, very low porosity and permeability make economic oil recovery difficult.

STACK/SCOOP – STACK: Sooner Trend (oilfield), Anadarko (basin), Canadian and Kingfisher (counties). SCOOP: South Central Oklahoma Oil Province.

STEAM METHANE REFORMING (SMR) – A process during which high-temperature steam is used to produce hydrogen from a methane source, such as natural gas. In SMR, the methane reacts with steam at atmospheric pressure in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide. Then, in what is termed the "water-gas shift reaction," the carbon monoxide and steam are reacted using a catalyst to produce carbon dioxide and more hydrogen. In a final process step the carbon dioxide and other impurities are removed from the gas stream, leaving essentially pure hydrogen.

STEP-OUT DRILLING – A well drilled at a later time over undeveloped portions of a partially developed continuous play.

STEERABLE DRILLING SYSTEM – A drilling technology that employs the use of specialized downhole equipment programmed by a directional driller who transmits commands using surface equipment (typically using either pressure fluctuations in the mud column or variations in the drill string rotation) which the tool responds to, gradually steering into the desired direction. The driller's commands are based on data transmitted to the surface from Measurement-While-Drilling (MWD) tools within the drill string near the bit. Some systems use movable pads on the outside of the tool which press against the well bore thereby causing the bit to press on the opposite side causing a direction change, and some cause the direction of the bit to change relative to the rest of the tool by bending the main shaft running through it.

SUBSEA FACTORY – A collection of subsea oil and gas producing equipment, located on the seafloor, that substitutes for the production equipment normally located on a producing platform and permits the fluids produced from subsea wells to be processed and the separated oil and gas moved through pipelines to shallower water platforms or to land.

SUBSEA WELL – A well where all the producing wellhead equipment is located on the seabed. The subsea well's equipment includes the valves, pressure control and sensing equipment, and flowlines that control the flow of fluids from the well to a fixed or floating production platform.

TENSION-LEG PLATFORM – A vertically moored floating structure used for offshore production of oil or natural gas, particularly suited for water depths greater than 1,000 feet and less than about 4,900 feet. A buoyant hull supports the platform's topsides, offsetting its weight. Clusters of massive cables from the tension legs secure the structure to the seabed. The tension leg system allows for some horizontal movement from waves, but does not permit vertical movement, making it particularly stable.

TIGHT GAS SANDS (TGS) – Low-permeability sandstone reservoirs that produce mainly dry natural gas. Many low-permeability sandstone gas plays were developed using closely spaced vertical wells that were hydraulically fractured using large volume treatments, before the more recent growth in development of shale gas plays. The Muddy Sandstone/J Sandstone reservoirs of the Wattenberg Gas Field in the Denver Basin of Colorado, and the reservoirs of the Mesaverde Group in the Piceance Basin of Colorado, are examples of tight gas sands.

TIGHT OIL – Common term for oil produced from unconventional reservoir rocks, primarily low permeability shales but also formations that include non-shale intervals like low permeability carbonates and sandstones. The application of horizontal drilling and high volume, multi-stage hydraulic fracturing permitted economic production rates to be realized from these previously non-producible rocks, launching the rapid growth in tight oil production with increasing volumes of oil entering the market from plays like the Permian Basin Wolfcamp, Bakken Shale, Eagle Ford Shale, and others.

ULTRADEEP WATERS – Generally considered to be marine waters that are between 7,000 and 12,000 feet in depth. Deepwater is generally considered to be greater than 1,000 feet in depth.

UNCONVENTIONAL OIL – See tight oil.

UTICA SHALE – An oil- and natural gas-bearing formation of Upper Ordovician age, located in the Appalachian Basin. It underlies much of the northeastern United States and adjacent parts of Canada, is gas productive in Quebec and is becoming a major oil and natural gas producer in the eastern part of Ohio. The prospective Utica area extends into Pennsylvania and West Virginia but the Ohio portion appears to be richer in oil, condensate, and natural gas liquids based on drilling to date.

VARIABLE SPEED DRIVE (VSD) – A variable speed drive (also called variable frequency drive) can be used to run electrically powered oil well pumping equipment. VSDs allow for infinite control over a pumping unit's speed, allowing the motor to run with higher levels of efficiency. Mechanical wear on equipment is also reduced by more consistent, optimum operation.

VENTING – Purposeful release of natural gas to the atmosphere from oil and natural gas production or processing equipment for operational, maintenance, or safety reasons.

WASTE HEAT TO POWER (WHP) – The recovery of waste heat generated from industrial processes for use in generating electrical power without combustion and thus without emissions. Energy-intensive industrial processes—such as those occurring at refineries, steel mills, glass furnaces, and cement kilns—all release hot exhaust gases and waste streams that can be harnessed to generate electricity.[111]

WATER CUT – The ratio of the volume of water produced compared to the total volume of liquids (oil and water) produced from an oil well. Oil wells in mature fields with water floods produce at very high water cuts.

WELL STIMULATION – The process of stimulating flow from an oil- or natural gas-bearing formation by increasing the permeability from the reservoir into the wellbore. The most common way of doing this is through hydraulic fracturing.

WELL COMPLETION – The multi-stage process of cementing the final string of casing in a well, perforating the casing and stimulating the well (if necessary), and running the appropriate tubing and packers into the casing so that a well is prepared for production or "completed."

WOLFCAMP SHALE – An oil- and natural gas-bearing formation located in all parts of the Greater Permian Basin that consists of at least four main intervals (Wolfcamp "benches" A, B, C, and D). The Wolfcamp is a geologically complex unit consisting mostly of organic-rich shale and clay-rich carbonate intervals. Depth, thickness, and lithology vary significantly across the basin.[112]

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[12] In the early 1980s, the newly created Energy Research and Development Administration (ERDA), subsequently folded into the Department of Energy (DOE), launched RD&D efforts on Enhanced Oil Recovery and Enhanced Recovery of Unconventional Gas. A series of studies and roadmaps provided the analytic foundation and research pathways for pursuing technologies that would unlock these resources, considered at the time to be speculative by many. The foundation for DOE's research program for unconventional gas was the three-volume report,"Enhanced Recovery of Unconventional Gas: Volumes I, II and III" (1978). (See, for example, https://www.osti.gov/biblio/6827170).

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[14] Much of the initial definition and testing of domestic shales was based on the research and test wells supported by U.S. DOE's and the Gas Research Institute's (GRI) RD&D programs during the 1980s and 1990s.

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[17] Advanced Resources International database, 2020, based on data from U.S. Energy Information Administration, natural gas production data (https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_FGW_mmcf_a.htm) and other sources.

[18] "Blue" carbon involves the use of steam methane reforming (SMR) to release the hydrogen atom from the carbon atoms and then storing (or utilizing) the released carbon.

[19] The scientific unit of measurement for size is meters, where one meter equals 1.09 yard or 3.28 feet. Progressively small units are millimeters (mm), equal to one thousandth of a meter, micrometers (μm), a million times smaller than a meter, and nanometers (nm), a billion times smaller than a meter. For reference, the size (diameter) of a human hair range from 17,000 to 187,000 nanometers (nm).

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[26]A digital twin is a complete 360-degree replica of a physical asset such as pipelines, gathering systems, heat exchangers, turbines, pumps, compressors, or entire plants, created digitally within a software system that enables modeling of process and control and monitoring of equipment health. It can help optimize production, detect equipment problems before failures occur, and uncover new opportunities for process improvement, while reducing unplanned downtime. (Offshore Magazine, 2019, "Digital twin strategy improves offshore oil and gas production, April 1, https://www.offshore-mag.com/production/article/16763951/digital-twin-strategy-improves-offshore-oil-and-gasproduction, accessed 7/27/2020).

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