Advancing Systems and Technologies to Produce Cleaner Fuels

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Quadrennial Technology Review 2015

Chapter 7: Advancing Systems and Technologies to Produce Cleaner Fuels

Supplemental Information

Oil and Gas Technologies

Subsurface Science, Technology, and Engineering

U.S. DEPARTMENT OF ENERGY

Quadrennial Technology Review 2015

Oil and Gas Technologies

Chapter 7: Advancing Systems and Technologies to Produce Cleaner Fuels

Oil and Gas in the Energy Economy of the United States

Fossil fuel resources account for 82% of total U.S. primary energy use because they are abundant, have a relatively low cost of production, and have a high energy density—enabling easy transport and storage. The infrastructure built over decades to supply fossil fuels is the world's largest enterprise with the largest market capitalization. Of fossil fuels, oil and natural gas make up 63% of energy usage.[1] Across the energy economy, the source and mix of fuels used across these sectors is changing, particularly the rapid increase in natural gas production from unconventional resources for electricity generation and the rapid increase in domestic production of shale oil.

While oil and gas fuels are essential for the United States' and the global economy, they also pose challenges:

- Economic: They must be delivered to users and the markets at competitive prices that encourage economic growth. High fuel prices and/or price volatility can impede this progress.
- Security: They must be available to the nation in a reliable, continuous way that supports national security and economic needs. Disruption of international fuel supply lines presents a serious geopolitical risk.
- Environment: They must be supplied and used in ways that have minimal environmental impacts on local, national, and global ecosystems and enables their sustainability. Waste streams from production, such as produced water, and from use, such as CO_2 emissions, are causing serious problems in many locations across the globe.

Oil and gas (O&G) have advantages and disadvantages with respect to these challenges. Since these needs are vital to the national interest, it is essential to demonstrate improvement across all three dimensions and maintain a robust set of options for rapidly changing conditions.

In the near- to mid-term, multiple technological pathways need to be explored to serve as bridges to a low carbon future. Particular focus should be given to interim technologies that help alleviate greenhouse gas (GHG) challenges while minimizing embedded infrastructure changes that would inhibit the transition to sustainable solutions. Fuel sources, such as natural gas, if utilized properly, could help enable this transition.

While fossil fuels have advantages from an economic and security perspective, they are the largest emitters of greenhouse gases, chiefly carbon dioxide (CO_2) and methane (CH_4), which are the primary contributors to global warming. Potential impacts on water systems are also a growing concern. This has led to increased investment, development, and commercialization of fuels and technology systems that would reduce climate, water, and/or other impacts.

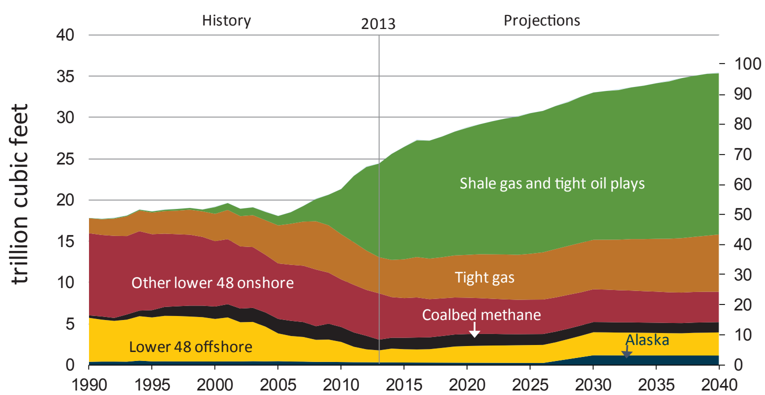
This supplemental material considers the technology needed to ensure prudent development of O&G resources. The primary research needs for O&G are related to resource extraction. Current technology is reviewed and key R&D opportunities are identified that could help resolve sector challenges. This supplemental material examines R&D opportunities associated with these transitions and their attendant challenges with specific technology assessments where sectors of unconventional oil and gas, CO_2-enhanced oil recovery (EOR), offshore oil spill prevention, gas hydrates, and infrastructure are addressed.

Renaissance of U.S. Oil and Gas Production

The United States will, for the foreseeable future, continue to rely heavily upon oil and natural gas to support its economy, national security, and energy security. Until recently, U.S. oil production was in decline. Oil imports contributed more than half of domestic oil consumption. Natural gas investment was moving towards expensive terminals to import natural gas. Today the situation has reversed—the United States is the world's largest producer of oil and natural gas, is exporting more refined products, and is on the path toward exporting crude oil[2] and liquefied natural gas (LNG).[3] For LNG, consumers are concerned about prices. A study funded by the Department of Energy (DOE) indicates that the increased export of natural gas can lead to increased domestic natural gas prices commensurate with the rapidity with which exports expand.[4] Figure 1 demonstrates historic shale gas production and future production potential.[5]

Figure 1 Shale Resources Remain the Dominant Source of U.S. Natural Gas Production Growth

Credit: U.S. Energy Information Administration

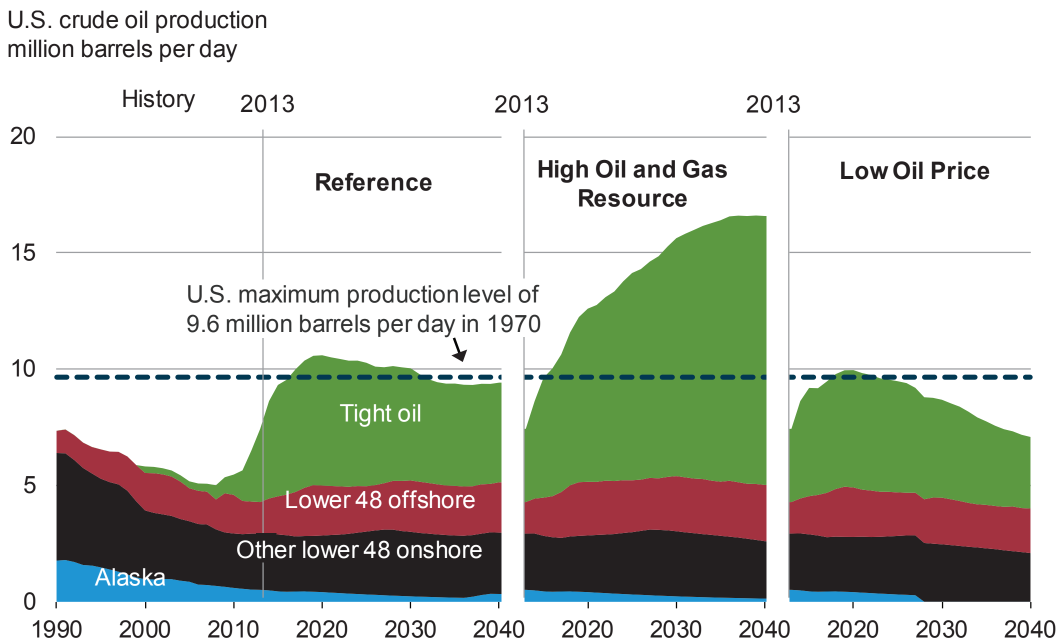


These considerable changes result primarily from new technology developments in hydraulic fracturing and horizontal drilling that have allowed industry to produce oil and gas from low permeability formations including shale and "tight" formations, often called "unconventional resources". These advances were generated in part by DOE technological investments in the early 1980s,[6] and in part by industry's continued development and application of those technologies. Together with increased work in rock mechanics and the understanding of fracture development and propagation to enhance production, these technological advances have driven the rapid increase in production from unconventional resources. Figure 2 shows the projected growth from tight oil production.[7]

Concurrent with these technological advances has been the drive to increase the effort to address environmental issues associated with oil and gas production. Public concerns over potential environmental impacts have been heightened by the *BP Deepwater Horizon* incident offshore,[8] and by hydraulic fracturing onshore and the rapid development of shale oil and gas fields in many parts of the United States. Government mandates to increase safety and environmental stewardship have advanced safety regulations and practices, promoted development of safety cultures, and developed accident mitigation technologies. In addition, industry has responded with the development of new and revised standards and practices that help address environmental and safety concerns. For example, industry has created the Center for Offshore Safety, which focuses on promoting the highest level of safety in offshore operations and has developed a system for auditing and sharing lessons learned from the implementation of offshore safety and environmental management systems.

Figure 2 Expected Gains in Tight Oil Production Drive Projected Growth in Total U.S. Crude Oil Production

Credit: U.S. Energy Information Administration



Recent Technology Advancements

In 2011, the National Petroleum Council reported that the resource base for technically recoverable oil and gas was 2.3 quadrillion cubic feet of natural gas,[9] and 167 billion barrels of oil.[10] Advanced technology can help make that resource economically recoverable in an environmentally prudent way.

Progress in technology development over the last five to ten years, both offshore and onshore, has been focused in several distinct areas:

- Sophisticated data acquisition, processing, and visualization applied across the sector, from exploration to field maintenance and safe final plugging of wells.
- Water conservation and protection, chiefly through treatments enabling water reuse, as well as use of brines and non-potable water in oil and gas applications.
- Materials science, especially in cements and metals used for wellbore isolation and integrity.
- Technologies to increase reservoir recovery factors, in particular via stimulation.
- Combining increased oil and gas recovery with carbon sequestration in a technique known as CO_2 Enhanced Oil Recovery (CO_2 EOR), a nascent opportunity for building experience with carbon sequestration, but one with promise.
- Oil spill prevention technology for operations in deep- and ultra-deepwater.
- R&D for operations in extreme environments, especially the Arctic, which contain significant oil and gas resources in environmentally sensitive areas.

Overall the most profound technical developments have been in the field of drilling and completions, including horizontal drilling, extension, and hydraulic fracturing.

It is clear that technology development has played a role in advancing hydrocarbon recovery and reducing environmental impact at the surface and in the subsurface. Discussed below are on- and offshore well construction, enhanced oil recovery and natural gas hydrates as a prelude to emerging research opportunities and specific technology assessments that address oil and gas challenges.

Onshore Well Construction: Drilling, Completion, and Stimulation. Technologies are being developed that will result in the need for fewer wells overall with far less impact on the surface and subsurface environments. Advances include reducing the drilling footprint through the use of drilling pads that allow multiple wells to be drilled from a single pad location.[11] Pad drilling can also enable rigs to be moved using railed systems. Reduced well pad sites for drilling, hydraulic fracturing and production reduces wildlife habitat fragmentation and reduces the amount of truck traffic and air pollution associated with transportation and resource development.[12] More recent technology has led to "walking rigs" that can travel from pad to pad under their own power.[13] New technologies provide more precise information about the subsurface location of oil and gas zones. Of key significance are technologies that allow operators to steer wells more precisely and with greater control.[14] Advances in the chemical formulations that make up drilling fluids have enabled use of less-toxic additives.[15]

There have also been technological advances in well completion and stimulation. Hydraulic fracturing of a single well at various points along the horizontal length in shale formations can dramatically increase initial production of new wells.[16] Advances in fracturing fluid technology plus technologies to treat flowback and produced water may enable production companies to recycle and/or re-use the same water for hydraulic fracturing and other operations depending on technology, transportation, and economic factors.[17] These and other technologies can increase production while reducing environmental impacts.[18]

Offshore Well Construction and Operations. Drilling challenges in deep and ultra-deepwater are different from those onshore; the lower strength of these geologic formations can increase the risk of loss of well control. That is, the increased hydrostatic head of the mud due to the water depth added to the hydrostatic head of the mud due to the formation means that when drilling, the forces in the drilling column are very close to the fracture pressure of the geologic formation. Technologies such as dual gradient drilling reduce this challenge, allowing for more controlled—and safer—drilling.

Much technology development has focused on oil spill prevention and mitigation. The Macondo incident focused attention on over-pressured zones and the integrity of the entire well construction system during the drilling process, particularly on the components of the system such as casing, cement, and the seal that must be established between the rock and the well.[19] Progress has been made in expandable casing,[20] a technology that helps ensure integrity of the wellbore while allowing the well to maintain a larger diameter for a longer interval. This has been accompanied by advances in metallurgy and cement chemistry, resulting in downhole tubulars with lower fatigue and failure rates in the case of metallurgy,[21] and wellbores with enhanced integrity due to advances in cementing technology.[22]

Substantial research has been conducted, and is ongoing, for foamed cement[23] in applications where low density fluids and sealing materials are required, and for alternatives to traditional cement. Integrity monitoring of downhole tubulars and cement in real time through the placement of downhole temperature and pressure sensors has been introduced in an attempt to identify and mitigate potential failure.

As in the onshore sector, advances in logging-while-drilling and measurement-while-drilling,[24] including measurements at the drill bit, allow for greater precision in steering deviated and lateral wells, while identifying the potential for unexpected pressure anomalies.

Technological advances with regard to metallurgical options and analysis of fatigue and failure in metal components, especially with application to drilling risers (which connect the well to the drillship) are ongoing.[25] Existing metal properties are being examined[26] and new alloys are being studied and developed. Advances in remote inspection capabilities using remotely operated vehicles and autonomous underwater vehicles are being made.[27]

Blowout preventer (BOP) design has been reexamined and new technology developed for BOP control systems and sealing and cutting rams. In order to promptly contain the spill at or near the wellhead after a blowout or other loss of well control, industry has invested significant resources in subsea spill containment capabilities.[28]

Considerable progress has been made in subsea processing technologies, allowing processing of produced fluids at the seafloor to be sent from the field to gathering pipeline systems via subsea pumping systems. Saltwater and the metal corrosion it causes is another challenge unique to offshore production. Inspection of Gulf of Mexico facilities, especially older ones, is important for continuation of safe operations offshore. New technologies and analytical algorithms have been developed to allow subsea inspection of offshore facilities to identify failed or at-risk structural components.[29]

Enhanced Oil Recovery (Including CO_2-EOR and the ROZ). Improved oil recovery (IOR) and enhanced oil recovery (EOR) are technical strategies used to increase the amount of oil and/or gas recovered from a particular deposit. In the past, these terms have had more precise definitions but now the terms are used more generally to indicate any technical activity that can increase the ultimate recovery from oil and gas reservoirs. These technologies generally include the injection of water, steam, gas, chemicals, microbes or other techniques to address some particular barrier in the reservoir that is preventing greater recovery of hydrocarbons. Each has its strengths and all have increased costs that affect project economics.

The potential application for carbon dioxide enhanced oil recovery (CO_2-EOR) has gained interest because of the potential for sequestering CO_2 while improving recovery of hydrocarbons. In two common approaches, CO_2, either naturally occurring or captured from industrial and/or generation processes (anthropogenic CO_2), is injected into oil bearing formations, either alternating with water (water-alternating-gas or WAG) or as a continuous flood in the reservoir. CO_2-EOR has a lower carbon footprint compared to other EOR/IOR technologies such as the use of steam, a comparison which should be more fully characterized in future analytical work. Currently, CO_2-EOR accounts for about 300,000 barrels or almost 4% of U.S. daily production of crude oil.[30] Currently, the vast majority of CO_2-EOR is performed with natural CO_2, but projects using anthropogenic CO_2 sources, while nascent—comprising about nineteen projects (in evaluating, defining, executing and operating life cycle stages) in the U.S.—are increasing (e.g., with installations at Kemper County Energy Facility (Mississippi), Petra Nova CCS Project (Texas), and Weyburn-Midale Project (Canada, but sourced with CO_2 from the U.S.).[31] CO_2 EOR technology at the field scale has been performed for over 40 years, with the first installation at SACROC field in the Permian Basin of Texas in 1972.[32] It's important to note that CO_2 EOR and other CCUS projects that offer co-benefits should be fostered if the aim is to help launch promising CO_2 capture technologies or to promote the security and permanence of CO_2 stored.

Natural Gas Hydrates. The Bureau of Ocean Energy Management (BOEM) assessment identified ~20,000 tcf of resource-grade gas hydrates in the United States' Outer Continental Shelf.[33] This estimate is an order of magnitude more gas than the entire United States' non-hydrate technically recoverable natural gas resource base.[34] Although a DOE-USGS-BOEM-Industry drilling program in 2009 confirmed gas hydrate resource occurrence and exploration approaches,[35] these represent the only wells to validate the BOEM hydrate resource estimate. Despite the large resource, gas hydrates are far from a viable option for meeting potential domestic energy supply needs in the mid-term.

Safety and environmental risks from gas hydrate production are comparable to those in all oil and gas production. Well control risks are more limited because of the shallow, low-pressure setting of gas hydrate reservoirs. Reservoir subsidence and resultant instability in overburden and at the seafloor is a risk that may be most relevant to gas hydrate production, particularly in marine applications, given the shallow and generally unconsolidated nature of most potential gas hydrate reservoirs.

More information on natural gas hydrates is provided in the Quadrennial Technology Review Technology Assessment 7C-*Gas Hydrates Research and Development*.

Emerging Research Opportunities

Large strides in technology, safety, and environmental practices have been made, yet a set of persistent and emerging challenges remain that point to a set of research opportunities for which there is a potential federal role (Table 1). Some are important to address in the near-term, in part because of the driving needs of policy makers, regulators, and other public stakeholders. Others are less so, but reflect important opportunities to either dramatically improve environmental performance or to dramatically increase resource availability.

Table 1 Emerging Issues Around Hydrocarbon Production. Near term, medium term, and long term refer to potential outcomes with substantial impacts within the time frame.

Key research opportunities	Near term (2–5 years)	Medium term (5–10 years)	Long term (>10 years)
Environmentally sustainable drilling and completion technologies and methodologies [36]	✓		
Unconventional oil and gas environmental challenges	✓	✓	
Offshore and Arctic oil spill prevention	✓	✓	
Gas hydrates characterization			✓

In recognition of these emerging challenges, many groups in industry, government, and academia have highlighted potential R&D efforts, including Federal Advisory Groups such as the National Petroleum Council, the Secretary of Energy Advisory Board, and the National Academy of Sciences; environmental organizations such as the Environmental Defense Fund, Natural Resources Defense Council, and World Resources Institute; and state governments. The oil and gas industry is engaged in significant but often proprietary R&D efforts as well.

Themes to Address R&D Challenges

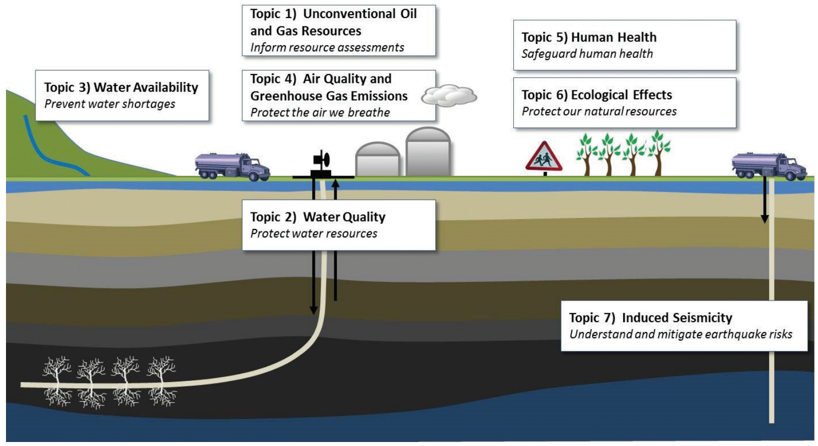
The challenges described above can be grouped and divided into the four themes: environmentally sound drilling and completions; other environmental challenges for unconventional oil and gas; emerging research needs for offshore safety and spill prevention; and gas hydrates (assessment, and safe and effective production). These are discussed below.

Environmentally Sound Drilling and Completions.

- **"Golden Rules" or Best Practices**. The International Energy Agency recently published a set of principles or "Golden Rules" applicable to operations in Unconventional Oil and Gas (UOG).[37] These practices include measurement, disclosure, and engagement with stakeholders; prudent choice of drilling locations; proper well construction designed to protect the environment from wellbore fluids; prudent use of water resources; protection of air quality; and cognizance of the cumulative impacts of UOG development (Figure 3).[38] The American Petroleum Institute (API) also publishes standards outlining best practices for all significant activities associated with conventional and unconventional oil and gas development.[39] Analysis and research are needed to understand the costs and potential benefits associated with wide-spread deployment of these practices, and how much they could be improved to reduce risk to the environment in terms of CH_4 leakage, water quality and quantity, truck traffic, and the subsurface footprint.

Figure 3 Emerging Issues of UOG Development

Credit: Federal Multiagency Collaboration on Unconventional Oil and Gas Research: A Strategy for Research and Development, July 2014



- **Protection of Natural Waters (Groundwater).** Protection of groundwater encompasses a range of biological, chemical, and physical systems for both surface (lakes and streams, as well as near-shore oceans) and subsurface waters (aquifers). The Environmental Protection Agency (EPA) is currently in the process of completing a national study on the impacts of hydraulic fracturing on groundwater resources. In addition, the U.S. Geological Service has conducted various studies of the potential impacts at site specific and basin specific locations.[40] Public concern regarding UOG development is related to potential water quality impacts on ecosystems and human well-being. Research needs in this area include improved quantitative evaluations of contaminant pathways in water resources that can be used to assess potential human and ecological health effects. Research is also needed to quantify understanding of water quality impacts over the entire cycle of UOG operations (site preparation, water acquisition, drilling, completion and fracturing, production, wastewater disposal,[41] pipeline construction and site closure), and how these impacts may vary over time and space and may be attributed to differences in UOG operations.

- **Efficient and Reduced Use of Water.** Generally, water is used in the drilling, completion, and hydraulic fracturing of oil and gas wells. Sometimes, large volumes of water are produced with the oil and gas. Key challenges include understanding the true impacts of water withdrawn from surface and groundwater systems, and water produced during the active phase of a UOG operation. Produced and flowback wastewaters are important because instead of injection as wastewater,[42] they can potentially be reused in hydraulic fracturing, thereby reducing total freshwater withdrawals. They may also be treated and returned to the environment, potentially reducing demands on the local water budget. Water that is co-produced with the oil and natural gas has a range of quality from relatively clean water to a high brine concentration because of the geological setting in which it exists. Several companies experience produced water of such a quality that it requires only limited treatment before it can be reused to hydraulically fracture other wells or to use it in other production operations activities.

  Research questions relate to how UOG activities may impact both the quantity and availability of water required for hydraulic fracturing, and to a better understanding of the possible impacts of ground and surface water withdrawals on drinking water resources. Research challenges and opportunities exist in a number of areas, including alternative water sources, reducing the volume of water used during hydraulic fracturing, technologies and approaches for beneficial treatments of produced water, and low- to zero-water hydraulic fracturing techniques. Another opportunity for research is the use of brackish and other non-potable water for drilling, hydraulic fracturing, and other operations. The mapping of brackish water sources is one area that could be expanded. In addition, there is the possibility of using municipal waste waters and acid mine drainage waters.

Energy-Water Crosscut Research: Induced Seismicity

Understanding the true impacts of water used and produced during UOG operations is a key challenge, including with respect to induced seismicity. This is important because a small fraction of the estimated 151,000 wastewater injection wells permitted in the United States have documented incidents of felt seismic events resulting from injection activities. A significant increase in these seismic events has been observed in central Oklahoma that is inconsistent with any natural processes; this increase is likely the result of wastewater injection associated with a rapid growth in oil and gas production.

R&D opportunities include reducing water use in UOG activities such as developing treatment technologies for wastewater reuse or recycle. Understanding physical subsurface conditions and mitigation strategies that affect seismic events related to wastewater injection are very important.

DOE has established the Water-Energy Technology Team to identify and pursue cross-cutting technology, data, modeling, analysis, and policy evaluation relevant to the issues that crosscut energy production and water availability, use, treatment, and reuse or release. (See http://www.energy.gov/water-energy-tech-team.)

- **Non-Water Stimulation.** Several hydraulic fracturing methods that have been investigated in the past decades use little or no water and some have been adopted into commercial practice. According to data contained in the *FracFocus* database, 609 stimulations were performed using compressed gases in the 2011-2012 timeframe (less than 2-3% of the hydraulic fracturing in the United States and 20-30% of the hydraulic fracturing performed in Canada). Even though nitrogen and carbon dioxide based stimulation methods have been available since the 1970's, they still represent a niche share of the market. Non-water hydraulic fracturing fluids and techniques include: nitrogen-based foam; CO_2-based foam; CO_2-sand fracturing; straight nitrogen or straight CO_2 based fracturing; gelled liquefied petroleum gas (LPG) fracturing; and, LNG fracturing. Each has strengths, weaknesses, and costs. Continued R&D into improving the environmental performance and cost of these techniques could yield major environmental benefits.

Other Environmental Challenges for Unconventional Oil and Gas.

- **Induced Seismicity**. During 2014, Oklahoma surpassed Alaska and California in the number of annual earthquakes. Geophysicists have long known about the potential for human activity, from petroleum extraction to water reservoir impoundments and fluid injection into the subsurface, to cause seismic activity. Changes in fluid volume and pore pressure through fluid injection can and have induced seismic events. Consequently, the three stages of the UOG life cycle that could potentially cause such events are: (1) during the disposal of UOG produced and flowback wastewater via deep injection wells; (2) long-term extraction of oil and gas; and, (3) large stage hydraulic fracturing. Induced seismicity can also occur during other activities, such as enhanced geothermal recovery and carbon dioxide storage. There is a need for more data and analysis to relate UOG operations to induced seismic events, to connect these events to specific operational parameters and geologic conditions, and to develop and assess possible mitigation options for use by technical and/or regulatory decision makers in an attempt to minimize seismic risks.[43]

- **Flaring of Associated Natural Gas**. Some tight oil production tends to be gas-rich. This gas is flared when it cannot be economically captured and used (often due to lack of infrastructure). As a result, North Dakota has been flaring 30% or more of all the gas produced in the state. In comparison, the national average for gas flaring is less than 1% of marketed production. Flaring of associated gas from oil production is often allowed so that oil production can start, subsequent revenues can flow, associated taxes and fees can be paid, and prospective gas volumes can be estimated. Where appropriate, gas infrastructure–gathering lines, processing plants, and compressors–can be planned and eventually built. New technologies that could use and convert into useful products methane that might otherwise be flared remain an important technology challenge and R&D need. Regional issues need to be further identified (flare gas volumes/compositions, potential technologies to generate Compressed Natural Gas (CNG), LNG, or electricity, etc.). In addition, associated logistical issues of where to market the CNG, LNG, or electricity, etc., can be problematic.
- **Truck Traffic and Alternatives**. UOG development sometimes occurs near communities previously unfamiliar with oil and gas operations. UOG operations involve the transport of equipment, fluids, and other materials, usually by trucks, resulting in significant truck traffic increases in communities where developmental activities occur. The largest contributor to this increased truck traffic is from transporting fracturing fluids to fields and produced water to disposal sites. Associated with increased truck traffic is increased noise, dust, and air emissions from the trucks. Close community engagement is key to helping address community concerns. Best practices should be implemented, for example, the API Bulletin 100-3 Community Engagement Guidelines.[44] Further, research is needed to develop alternative methods of transporting fluids, developing technologies that use less or no water, and pollution and noise mitigation technologies.
- **Control of Methane Leaks**. Methane leakage during the production, distribution, and use of natural gas has the potential to undermine and possibly even reverse the GHG advantage that natural gas has over coal or oil.[45] This is because CH_4 is a potent GHG. CH_4's lifetime in the atmosphere is much shorter than carbon dioxide (CO_2), but CH_4 traps more radiation than CO_2. The comparative impact of CH_4 on climate change is over 20 times greater than CO_2 over a 100-year period[46] and about 86 times greater over a 20-year period.[47] The EPA's national Greenhouse Gas Inventory estimates that in 2012 CH_4 contributed roughly 10 percent of gross GHG emissions (on a $C0_2$-equivalent basis) from U.S.

Subsurface Crosscut Research

Use of the subsurface is important to many activities, including production of oil and gas, extraction of minerals, energy storage, disposition of civilian and defense waste streams, and remediation of sites contaminated from past endeavors, with a common need to understand such issues as wellbore integrity and subsurface stress. DOE has established a crosscutting science and technology team—Subsurface Technology and Engineering Research (SubTER)—that includes the DOE offices involved in subsurface activities that are aligned with energy production/extraction, subsurface storage of energy and CO_2, subsurface waste disposal, and environmental remediation. (See http://www.energy.gov/subsurface-technology-and-engineering-rdd-crosscut and QTR Chapter 7 Supplemental Information: Subsurface Science, Technology, and Engineering.

anthropogenic sources, nearly one quarter of which were emitted by natural gas systems.[48] In 2012, EPA promulgated rules for reducing VOC emissions from oil and gas production and processing facilities and these rules were identified by EPA to have the co-benefit of reducing methane emissions. As of January 1, 2015, these rules were fully effective, and emissions reductions are expected to continue for hydraulically fractured natural gas wells, pneumatic devices, compressors, and storage tanks.[49] Although the forgoing can reduce methane leakage substantially, for the LNG and CNG transportation sector, there could be concerns that inadequate infrastructure investments may impact efforts to reduce GHG emissions for transportation fuels. In addition, although the natural gas resource base is large, natural gas demand increases could be significant for new base load power to replace old coal plants, resulting in more natural gas demand than is anticipated. R&D to resolve these emissions sources with unambiguous and reconciled data is needed. Beyond that, technology is needed to reduce CH_4 leaks associated with pipelines and compressors in the midstream infrastructure, and to increase the operational efficiency of natural gas infrastructure as a whole. Research needs include: improved pipeline inspection technologies; external monitoring technologies, and real-time leak detection, including sensors; "live" pipeline repair technologies; improved gas compression and compressor controls, and response time to changing demand profiles; and gas storage alternatives.

- **Reducing Subsurface Footprint**. Near and long-term, cumulative environmental impacts of UOG development are dependent largely on the nature and pace of the development process and the geologic and geographic setting where development occurs. At present, industry is striving to improve the low recovery efficiencies that are typical of UOG development by employing increasingly intensive activities, including more closely-spaced wells, stacked wells, and more fracture stages per well-bore. Research is required that will lead to technological solutions that enable a prudent balance of maximum recovery efficiency with minimum development intensity. These include fit-for-purpose simulation tools, novel stimulation technologies (e.g., energetic stimulation materials), and improved process control systems. Such technology will need to be based on an improved scientific understanding of the fundamental nature of UOG reservoirs as well as the processes that govern the storage, release, and flow of hydrocarbons in response to alternative stimulation designs and approaches.

Emerging Research Needs for Offshore Safety and Spill Prevention. The offshore environment can be characterized by geologic, meteorologic, oceanographic, and hydrologic uncertainties that require better understanding to reduce the risk to the environment during oil and gas resource development. In the Gulf of Mexico, water depths of greater than 1,000 feet create substantial logistical and operational challenges. In the Arctic, extreme cold creates surface ice and other logistical issues (e.g., oil flow). Spill prevention is of paramount importance, and technologies are needed that ensure well control. A more detailed understanding of the geologic environment where hydrocarbons exist could prevent hazards from leading to failures. Technologies and processes that protect the environment during the drilling and completion of wells and the umbilicals and systems that bring the production to the surface could minimize potential environmental damage.

Increased reliability of subsea systems could reduce both cost and environmental risks. For example, improved protection of the environment at and below the seafloor during drilling and completion could be improved with novel designs and materials for wellbore integrity, comprehensive knowledge of wellbore intervention and remediation technologies (pre- and post-abandonment), and the advancement of the capabilities for human interface with sophisticated technology and monitoring systems. Challenges associated with surface systems and umbilicals include large scale system designs and technology to improve safety and long-term durability, and to increase automation in support of decision-making.

As discussed in the recent National Petroleum Council Study, *Arctic Potential,*[50] spill prevention is especially important in avoiding dealing with spill response in Arctic waters. Research priorities are similar to those offshore in the Gulf of Mexico except that surface temperatures and the presence of ice require enhancements to surface systems and equipment in order to address drilling and production in extreme environments. According to the National Petroleum Council, technologies have been developed and are available that can offer superior protection with shorter implementation time than a relief well. These technologies include subsea isolation devices and capping stacks. Furthermore, there have been advances in oil spill response techniques designed for operations in ice.[51] In addition, recent API standards and standards-related research have been focused on presenting the most current proven engineering practices for offshore safety in the areas of prevention, mitigation, and response. For example, current research efforts include applications for high-pressure high-temperature equipment design and verification, blow-out preventer shearing ram capabilities, and models for predicting met-ocean (wind, wave, and current) conditions that would result in improved offshore operating safety.[52]

Gas Hydrates: Assessment, and Safe and Effective Production. Gas hydrate is a material very much tied to its environment— it requires very specific conditions to form and remain stable. Pressure, temperature, and availability of sufficient quantities of water and CH_4 are the primary factors controlling gas hydrate formation and stability, although geochemistry and the type of sediment also play a part. In high pressure and low temperature conditions, free methane gas and water will form and sustain solid gas hydrate. Gas hydrates can be found in pipelines, in the subsurface, and on the seafloor.[53]

Science and technology advancement on three fronts would be needed to assess, and to safely and effectively produce methane hydrates. First, the United States' resource must be more fully characterized and confirmed. While the assessment of gas hydrate onshore Alaska is relatively advanced, the bulk of the resource lies offshore.

Second, production approaches must be demonstrated over sufficient timeframes to generate reliable estimates of gas/water production. Multiple long-term tests would identify and provide insight into potential production issues (such as sand production, seal integrity, and others). While depressurization will be the base technology for commercial applications, the optimal use of chemical, mechanical, and thermal stimulation could affect site-specific production levels significantly. Initial field experiments are likely to occur in the Arctic, with lessons learned subsequently implemented in the deep waters of the Gulf of Mexico. Commercial applications will also likely leverage drilling approaches tailored to the shallow depths at which gas hydrate occurs.

Third, concerns regarding gas hydrate's potential response to ongoing climate change must be addressed through continued integration of gas hydrate science into ocean processes and global climate models. Gas hydrate geohazard issues, especially on shallow arctic shelves, are an area of increasing concern.

BP Deepwater Horizon Oil Spill

On April 20, 2010, the Macondo well located about 50 miles from New Orleans in over 5,000 feet of water with a pay depth of over 18,000 feet subsea blew out, costing the lives of 11 men and spilling over 4 million* barrels of crude oil into the Gulf of Mexico. The root causes identified by a Presidential commission were associated with zonal isolation during cementing and the failure to create a competent barrier to uncontrolled flow. Other risk factors contributing to this disaster were associated with well monitoring equipment on the Deepwater Horizon, including data displays, and the lack of attentiveness to the risk resulting from deviation from the original designs for well construction.

* No. 10-2771 and No. 10-4536, Findings of Fact and Conclusions of Law, Phase Two Trial at 43-44 (E.D.L.A. Jan 15., 2015), http://www2.epa.gov/sites/production/files/2015-01/documents/phase2ruling.pdf

There is currently little or no domestic industry investment in this area, either on a proprietary basis, or in collaboration with government. Effective collaboration between federal and state research, international research programs, and government agencies would improve any future research in this area.

To summarize the themes, the oil and gas sector has undergone significant changes due, in large part, to advanced technologies. Oil and gas are relatively low cost, and represent a large, secure domestic resource. However, in order to ensure prudent development of the U.S. oil and gas resource base both onshore and offshore, technological advances are still needed to address the remaining challenges.

For UOG, this includes improving water and air quality, reducing the surface and subsurface footprint, and addressing induced seismicity. For water, the concern is protecting groundwater, reducing the amount of water used in UOG development, and efficient use of water, and non-water stimulation. For induced seismicity, we need to understand the specific relationship between seismic events and UOG operations– is it always related to the disposal of wastewater? Is it related to the size of the hydraulic fracturing treatment? Can faults be identified before they move? We need to understand these relationships and their mechanisms in order to predict and mitigate induced seismicity. Another important challenge is the intensity of development of UOG. The low recovery factor from these wells is leading to more frequent and more intensive stimulation. Understanding the scale and nature of UOG formations could help reduce this intensity which in turn could lead to a number of environmental benefits such as fewer wells, reduced water, reduced truck traffic, and improved air quality.

Moving to the offshore, the challenges are basically associated with the complexity of dealing with deep water and deep formations in the Gulf of Mexico, and surface temperatures and ice in the Arctic. The technology opportunity space for oil spill prevention in the Gulf of Mexico (GOM) includes understanding the geologic hazards in the subsurface before the drilling program is designed, and then being able to handle any anomalies during drilling. This intersection of the natural system with the engineered systems is the point of highest risk in oil and gas development. This risk is exacerbated when drilling through thousands of feet of water into pay zones that can be miles deep and located over 100 miles from shore. Once the well is in production the risk continues. The umbilicals and the surface systems are subject to hurricanes on the surface, and to currents and corrosion subsea. Finally, many of the subsea and seafloor systems are automated, so reliability of the components is critical. Arctic development has significant challenges due to low temperatures, ice, and remoteness of the location. The recent NPC study advises of the need "to validate technologies for improved well control…"

For future supply from gas hydrates the issues focus on two main questions: How to commercially produce certain hydrate deposits, and identifying the conditions for stability of non-commercial hydrate deposits. The technology space is framed by three key thrusts: (1) characterization of the resource; (2) production approaches, for commercial deposits; and (3) for non-commercial deposits, conditions of hydrate stability.

The oil and gas section below also discusses delivery infrastructure and the need to reduce fugitive methane emissions. Opportunities include: understanding the volume of emissions, improved monitoring and leak detection, and increased operational efficiency.

Technology can help overcome some of the shortcomings associated with oil and gas during the transition to a low carbon economy.

Addressing Oil and Gas Challenges Through Specific Technology Assessments

Unconventional Oil and Gas Resources

Given the increasing reliance on unconventional oil and gas (UOG) resources[54] optimizing the public good of the nation's UOG endowment will require safe, efficient, and environmentally-responsible UOG exploration and production systems.[55] While science-based regulation and adherence to best practices can contribute significantly to achieving this goal, continued science and technology advance is a prerequisite to development that optimally-balances the maximization of the national energy and security and economic benefits of UOG development with minimization of any negative environmental impacts.

Five broad UOG topical areas are recognized within the Federal Multiagency Collaboration on Unconventional Oil and Gas Research:[56]

1. Resource recovery
2. Water quality protection
3. Water availability
4. Air quality protection
5. Induced seismicity

The multiagency collaboration also includes topic areas on ecosystem impacts and implications for human health.

Today, increased pad drilling and extended-reach horizontal wells are reducing the land impacts of drilling. Integration of "green completions", increased recycling of flow-back and produced water, and improved disposal protocols are similarly reducing negative impacts to air and water. However, significant issues remain. Going forward, alternatives to water as the base fluid for fracture stimulation hold promise to relieve future burdens on water availability and on water handling and disposal. Clarification of the cumulative air quality impacts of UOG development is also needed, as well as confident determination in the nature and source of emissions so that corrective actions can be taken. The integrity of wellbores, particularly after the production life of the well has passed and in the context of dense populations of horizontal wells, is unclear and improved methods for evaluation and remediation of wells are needed. While risks of subsurface fluid migration enabling contamination of shallow aquifers is likely very low in most settings, the role of legacy wellbores as enabling pathways remains uncertain. Modular, rapid, flexible, and large volume produced water treatment technologies will be needed, as is the information and insight required to manage wastewater disposal in a manner that eliminates the risk of induced seismicity that can be damaging. Further, although UOG production is commercial in many regions, a large portion of the resource remains unviable with existing technologies. Many of the engineering paradigms that have historically guided oil and gas reservoir and field management simply do not apply in the new context of nano-porous reservoirs. The fundamental science required to enable a practical understanding of the reservoir and its response to stimulation is tenuous and therefore the potential for more efficient and less impactful recovery from alternative means is unrealized.

UOG development has clearly provided substantial benefits to the nation; nonetheless, current approaches are not yet achieving an optimal balance of high resource utilization and low environmental impact. The UOG resource in the U.S. and the scale of future development that it can support (including the number and pace of wells to be drilled), remain highly uncertain, making assessment of cumulative benefits and impacts unclear. In the current environment of high industry activity levels, high public awareness, and strongly divergent views on the impacts of development, there is need for objective science to inform sound policy, and accelerated delivery of technological options that enable the most prudent use of natural resources. While efforts in basic science and outreach are critical, acceleration of the development of advanced technologies can provide solutions that enable the simultaneous achievement of the resource conservation and environmental impact reduction goals. These are outcomes that are difficult to achieve solely via regulation or application of best practices.

Conventional oil and gas resources are those in which oil and gas can be economically produced given natural reservoir conditions. In other words, the hydrocarbons are housed at high concentrations in reservoirs of sufficient porosity and permeability such that natural subsurface pressure can drive the hydrocarbon into wells and to the surface at rates that result in profitable (commercial) production. In contrast, UOG resources are those that, in their pre-development state, are trapped in rocks that cannot be produced economically without the use of well stimulation to augment reservoir quality.[57,58] While coal-bed methane, shale gas, fractured reservoirs, tight oil, oil shales, tight gas, and gas hydrates are all considered unconventional resources; this supplemental material focuses primarily on those that have experienced rapid escalation in production in recent years (shale gas, tight oil, and tight gas) due to the widespread and effective use of hydraulic fracturing (HF).

Factors Affecting UOG Recovery and the Federal Role

UOG reservoirs commonly extend across large regions and therefore represent extremely large in-place resources. However, even with the application of advanced technologies, UOG reservoirs typically exhibit a low recovery factor (RF; the ratio of produced gas to total gas residing in-place). Production is highly sensitive to the nature and effectiveness of the interaction between the stimulation process and variable reservoir conditions. The consideration of impacts from UOG development must focus not only on near-term implications of individual processes but on cumulative impacts across the UOG lifecycle over long time frames.[59]

R&D Drivers and Federal Role. UOG development is occurring at a high rate in many regions of the country and is substantially contributing to increased national energy security and local and regional economic development. The motivations for federally-funded R&D associated with UOG development include enabling objective science, resource conservation, and environmental protection.

- *Enabling objective science* refers to the need to base policies, including regulations, on the latest and most reliable scientific information, and, with that foundation foster public confidence. As this assessment documents, there remain many key unknowns and uncertainties related to UOG development, most notably with respect to environmental implications to water quality, water availability, air quality, and induced seismicity. Public sector science organizations have reported that gaining access to the sites of UOG operations for the purpose of evaluating potential impacts[60] is a high priority in the advance of science and technology in the public good.
- *Resource conservation* refers to the maximization of a range of public economic and energy security benefits obtained from optimal and efficient (non-wasteful) development of a natural resource. At present, the low recovery efficiencies inherent in UOG development practices leave substantial resource quantities in the ground. Even a modest increase in recovery efficiency (for example from 10% recovery to 15% recovery) could expand by 50% the economic benefits associated with the nation's UOG endowment.
- *Environmental Protection* refers to the federal role in funding research to mitigate negative externalities of oil and natural gas development activities. With regard to UOG resources, the potential environmental impacts are broad, including risks to soil, water, air, and climate, as well as those impacts associated with induced seismicity.[61]

Stakeholders in UOG R&D and Technology Areas, Challenges, and Research Needs and Opportunities. Key stakeholders with strong interest in research and development as it relates to UOG development include, but are not necessarily limited to: the public, policy-makers and permitting entities, oil and gas producing companies, academia and national laboratories, technology providers, non-governmental organizations, and federal agencies.

The primary R&D needs identified include technologies to enable resource extraction in a manner that minimizes environmental impact as well as technologies that can improve the efficiency of unconventional oil and gas development to the extent that vast stores of public resources are used appropriately. R&D in improved development efficiency specifically targets those opportunities to enable gas recovery from fewer and less impactful wells. Opportunities exist to provide a fuller understanding of the basic petrophysical nature of UOG reservoirs as well as the fundamental geomechanics of their stimulation so that both the reach of individual wells and the production efficiency (the ratio of produced resource to resource existing in-place) of the resource can be maximized. In addition, science and technology to document, mitigate, and avoid (where feasible) the negative environmental impacts of UOG development on air quality, surface and groundwater quality and availability, climate, induced seismicity, and ecosystems should be pursued.

Subsurface Challenges. The environmental impact of UOG development is dependent largely on the nature of the development process and the geologic and geographic setting where the development occurs. Assessing the location and potential size of different UOG resources around the country, the evolution in development processes, and the nature of subsurface physical processes is a requirement for understanding the potential scale and impacts of development. These same factors are critical as well in assessing recovery efficiency, where the current state of the art and R&D drivers include:

- *Fundamental Science*: Despite the significant growth in the production of UOG resources, much has yet to be learned about their basic physical structure and behavior. In contrast to conventional reservoirs, in UOG settings, neither the *in situ* nature of hydrocarbon occurrence nor the resultant flow properties of the stimulated reservoir are well known, and neither lends itself to ready diagnosis from standard analyses of log, core, or production data.[62,63]
- *Resource Assessment/Characterization*: In conventional reservoirs, the most basic resource calculation—the volume of in-place resources—can be determined using a relatively simple calculation. In contrast, such calculations are complex in UOG reservoirs, because well log data do not as readily reveal reliable estimates of porosity or saturation, among other complications. Similarly for calculation of technically-recoverable resource (TRR – that subset of the volume of the in-place resource that is practically available for production with today's recovery technology, without regard to economic cost) is subject to great uncertainty. For UOG resources, most groups that conduct assessments obtain TRR from observed well performance and do not attempt to estimate in-place resources. In shale reservoirs, however, observed well performance is often not indicative of reservoir potential due to the strong reliance of production on what technology is applied and how well matched it might be with the particular geology found in any specific well. Further, even where technology is uniformly applied, the nature of technology as it is applied to UOG resources evolves rapidly, meaning that any well is, at best, a snapshot of potential TRR at that particular point in time (or point in the development of technology). Further, development typically proceeds from resource sweet-spots to more challenging areas, meaning early wells may not be fully indicative of larger regions. As a result, published assessments of resources in UOG plays have a limited "shelf life" and are prone to substantial revision as new data is obtained (e.g., as illustrated by evolution of Marcellus Shale resource estimates).[64,65] Such substantial revisions, both positive and negative, should be expected, as the first substantive drilling information from emerging basins becomes available and many key factors, such as recovery factors, the potential areal variability in well performance, the impact of sustained low prices, development practices, and the potential impact of future technology, become better understood.
- *Improved Recovery Efficiency*: There is limited information available on UOG recovery efficiencies. Much of it is anecdotal, suggesting that recovery efficiency is typically quite low—values of 10% or less are commonly cited for liquid-rich shales and 25-35% for gas rich shales.[66] In conventional resource development, increased areal recovery efficiency is often enabled through secondary recovery and infill drilling. However, due to complexities of the impact of injected water, unpredictable stimulated rock volume (SRV) geometry, complex induced variations in pressure, etc., concepts for infill drilling, secondary recovery, and even re-stimulation of primary UOG wells are very poorly developed.[67] As a result, there is a great motivation to properly/optimally stimulate[68] and space the primary wells.[69] The goal of these efforts is to produce a more predictable and controllable SRV so that wells can more effectively drain a given reservoir volume.[70] Therefore, ongoing efforts to assess and improve the recovery factor focus on four primary challenges:
    - How can effective re-stimulation and other approaches for enhanced (secondary and tertiary) hydrocarbon recovery[71] be made?

- What is the extent that recovery is occurring within the SRV?
- How can stimulation to produce more uniform and pervasive SRV be performed?
- From a field development standpoint, to what extent do the highly-irregular SRVs from numerous wells interact to fill the available reservoir area, and how can more predictable and expansive SRVs be developed so that a given area can be effectively drained with fewer wells?

Future R&D challenges and opportunities can provide material benefits resources in the subsurface. Current UOG development can be improved significantly from advanced scientific understanding of the thermodynamic, petrophysical, chemical, and geomechanical nature of UOG reservoirs and the interaction between such reservoirs and stimulation practice. Given the current scale of both UOG resources and UOG development activity, the benefits of advanced science and technology that allow greater resource recovery from fewer wells could be substantial. The primary R&D challenges include:

- Understanding the nano-scale structure of UOG reservoirs, and the nature of hydrocarbon storage, release, and flow.
- Improving extraction efficiency from current low levels to reduce the incidence of stranded/unproduced resources and the related lost economic and energy security benefits.
- Understanding the continued likely growth in recoverable resource volumes with technology advance, and accurately assessing the potential nature, scale, and rate (intensity) of future development.
- Mitigation of future development intensity, in terms of significant reduction in the number of wells required to drain a given area, via more effective creation and control of the SRV.

Water Quality Impacts. UOG development can impact water resources at many stages throughout the UOG life cycle, including site construction, drilling, completion, production, and wastewater management.[72] The science of assessing impacts includes identification and measurement of changes in water quality (such as flow rates, temperature, turbidity, etc., as well as occurrence of chemical or biological contaminants), and various experimental and modeling activities designed to understand geochemical reactions between rocks and injected fluids, the potential release and migration of pollutants through surface water and groundwater, and ultimately to attribute contaminants to specific sources. R&D challenges and opportunities include the following:

- Enhanced Wellbore Integrity: Opportunities for research to reduce the risks of poor wellbore integrity should focus primarily on gaining a common understanding of the various manifestations of well integrity loss and the causes of each. Technological solutions could include:
  - New cement formulations that maximize the chances of good isolation across a range of pressure, temperature, and wellbore fluid conditions;
  - Advanced technology for cement bond evaluation (at installation and monitoring over time); and
  - Advanced materials for casing and cements for long-term durability in a range of geologic environments.
- Effective Produced Water Treatment and Management: Given the increasing scale of development, perhaps the best solutions to the issue of environmental impacts associated with produced water handling begin with those approaches that reduce produced water volumes.
- Reduced Risk of Groundwater Contamination: Opportunities for research to further reduce the potential for groundwater contamination related to UOG development include:
  - Gathering information to more accurately characterize shallow potable water aquifers in UOG play areas (e.g., depth, thickness, pressure, salinity, pre-development methane content, etc.);
  - Determining play-specific best practices for surface hole drilling operations;
  - Conducting field experiments that characterize and quantify the risk of unintended subsurface migration of drilling and completion fluids under a variety of scenarios; and

- Developing, testing, and demonstrating novel, cost-effective techniques for locating legacy wells.

Water Availability Impacts. In this area, R&D challenges and opportunities include:

- Alternative water sources: Primary needs in enabling the accelerated use of acid mine drainage and/or brackish water as an alternative for freshwater in HF operations will require the comprehensive development and testing of technologies that reduce the treatment cost and demonstrate a broad applicability in a range of geologic and operational settings.
- Less-water-intensive hydraulic fracturing:
  - Collection, analysis, and dissemination of data sets that relate completion design to production performance;
  - New technologies and analytical approaches that support the optimal placement of hydraulic fracturing treatments based on reservoir characterization (lithology, saturation, natural fracturing, etc.) along horizontal wellbores;
  - New technologies that enable greater control of placement, nature, and extent of induced fractures;
  - Improved imaging of the distribution and nature of induced-fractures;
  - Collection, analysis, and dissemination of data sets that enable the performance of alternative fracture fluids to be assessed; and
  - New formulations for CO_2-based and other foams that improve technical performance.
- Waterless Stimulation: The establishment of effective, waterless stimulation could have a major transformational impact on the environmental profile of UOG development, particularly in those areas where water resources are already stretched.

Air Quality Impacts. The expanded utilization of natural gas is often considered to have strong net positive impact on air quality, particularly where it serves as a replacement fuel for other, less-clean sources, although the issues are complex.[73] UOG development, from mining through gas gathering and distribution, has the potential to release an array of pollutants with implications for greenhouse gas/climate issues[74,75,76] and for human health.[77]

R&D challenges and opportunities focus on efforts to understand and mitigate the impact of UOG development on air quality: measurement and attribution to accurately measure emissions of various pollutants and determine their sources and mitigation to provide technological approaches to reduce air quality impacts.

A high priority should continue to be placed on accurately characterizing the national and regional emissions footprint of UOG development as it is currently being conducted. Resolution of the discrepancies between top-down and bottom-up methodologies will be critical to achieving a consensus on this issue.

Technological solutions to address both fugitive and non-fugitive emissions associated with UOG, include more durable components related to gas handling and compression, non-venting pneumatic controllers, and procedures for lifting fluid in mature gas wells without venting. Also needed are distributed and effective technologies and procedures to improve leak detection and repair and solutions for associated gas in areas lacking gas gathering infrastructure are needed to eliminate venting and flaring.

Induced Seismicity Impacts. Any injection or withdrawal of fluids from the subsurface has the potential to alter local stress conditions. Therefore, three aspects of the UOG development—well stimulation via hydraulic fracturing (injection), hydrocarbon and formation water production (withdrawal), and waste water disposal via deep wells (injection)—have the potential to induce seismic events.[78] R&D challenges and opportunities include:

- Analysis and Attribution: Protocols for distinguishing injection-induced events from natural events are unclear and may be highly variable from location to location. Additional studies that collect comprehensive data to enable correlations between causes and effects will be required within each basin where UOG activities are ongoing.

- Prediction and Mitigation: Seismicity monitoring guides the management of wastewater injection, and improved protocols for the evaluation of local conditions and the setting of thresholds need to be developed, based on improved statistics-based attribution and analysis capability. There is a need for modeling of changes in stress from wastewater injection and to determine the viability of developing reliable and actionable, physics-based prediction capabilities.

Offshore Oil Spill Prevention

The global oil and natural gas industry has responded to growth in international energy demand by developing new technologies for finding and producing oil and natural gas from deposits that are increasingly more technically challenging to develop, including those in the deeper water areas along continental shelves. The offshore area is a complex, challenging environment characterized by meteorological, oceanographic, and hydrologic unknowns that require increased effort to reduce development risk. For these reasons, ensuring this valuable national resource is developed in a safe and sustainable way is a crucial research and technology development effort.

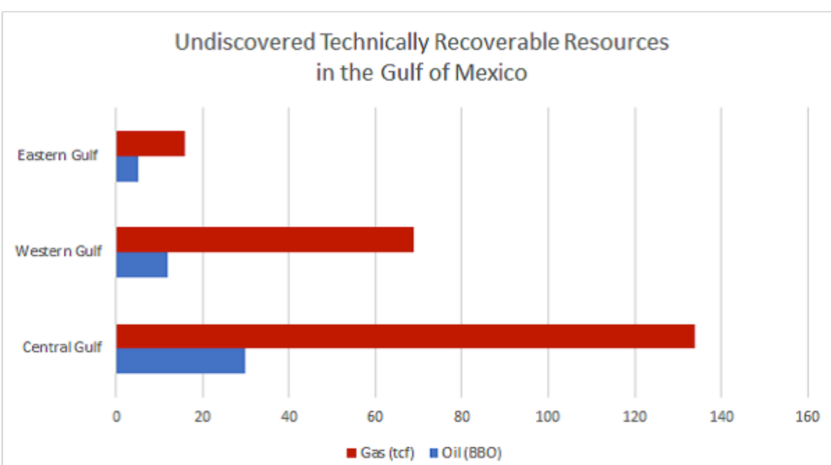
Offshore oil and natural gas resources, primarily from the Gulf of Mexico, have played a significant role in U.S. energy supplies for decades. As worldwide oil and natural gas demand grows, offshore resources will necessarily remain a key contributor to America's supply of oil for the foreseeable future. Federal offshore areas contain over 15 percent (about 5.1 billion barrels) of total proved domestic crude oil reserves.[79]

Gulf of Mexico

The Gulf of Mexico (GOM) is one of the most important locations of U.S. offshore resource production. The Department of Interior (DOI)'s Bureau of Ocean Energy Management (BOEM) estimates the undiscovered technically recoverable resources in the: Central Gulf are more than 30 billion barrels of oil (Bbo) and nearly 134 trillion cubic feet (tcf) of natural gas; for the Western Gulf estimates are more than 12 Bbo and 69 tcf of natural gas; and for the Eastern Gulf estimates are over 5 Bbo and 16 tcf of natural gas[80] (Figure 4).

Figure 4 Technically Recoverable Reserves in the Gulf of Mexico.

Credit: BOEM, Assessment of Undiscovered Technically Recoverable Resources on the Nation's Outer Continental Shelf. Bureau of Ocean Energy Management, 2001. http://www.boem.gov/2011-National-Assessment-Factsheet/



While many challenges are applicable both onshore and offshore, the relatively remote location, the surface environment, and the necessity of placing equipment hundreds of feet below sea level, means special technology solutions are necessary for the offshore environment. The existence of the key challenges, and the importance of solving them, was brought to the attention of many people with the *BP Deepwater Horizon* incident.

Arctic

The Arctic Region is another potentially significant area for oil and gas development. It holds an estimated 90 billion barrels of the world's undiscovered conventional oil resources and about 30% of its undiscovered natural gas resources, according to the United States Geological Survey (USGS). However, it is technically challenging and costly to develop in the Arctic environment. Many of the same challenges and advances in technology for offshore Gulf of Mexico are applicable to the Arctic. However, the complex Arctic environment poses additional challenges for development.

As the National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling stated in its January 2011 final report:

> "The Alaskan Arctic is characterized by extreme cold, extended seasons of darkness, hurricane-strength storms, and pervasive fog—all affecting access and working conditions. The Chukchi and Beaufort Seas are covered by varying forms of ice for eight to nine months a year. These conditions limit exploratory drilling and many other activities to the summer months. The icy conditions during the rest of the year pose severe challenges for oil and gas operations and scientific research; and oil spill response efforts are complicated year-round by the remote location and the presence of ice, at all phases of exploration and possible production."

Offshore Research and Technology Opportunities

Four key areas of activity in the deepwater Gulf of Mexico illustrate the range of research and technology challenges and opportunities in the offshore environment. These four areas include: (1) Walker Ridge, (2) Keathley Canyon, (3) Alaminos Canyon, and (4) Eastern Gulf/ Independence Hub. These areas are good examples of the range of technical challenges in offshore oil and gas production. The technology challenges associated with all four areas include higher drilling costs and challenging economics.

The key research and technology challenges for spill prevention can be divided into four major areas (Figure 5):

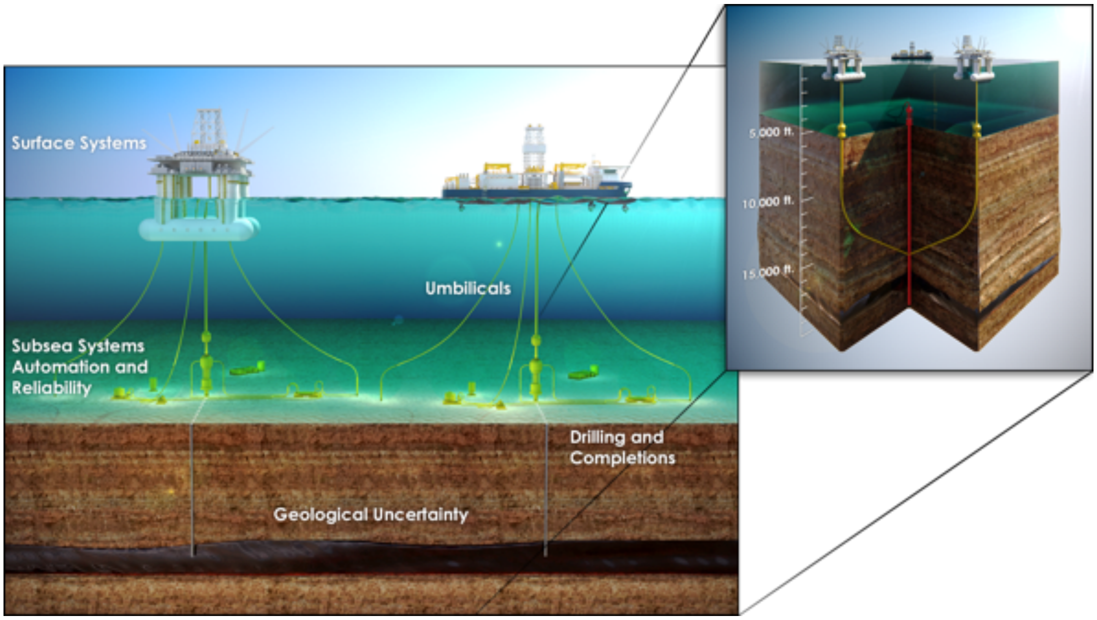
- The **geologic environment** needs to be characterized with high quality data and modeled accurately to allow industry to recognize and respond to geologic hazards earlier. This capability reduces the risk associated with encountering these hazards.
- **Drilling and completion equipment**, including well materials, best practices, sensors, and other technologies used in drilling and completing an offshore well need to be optimized to reduce the risk of drilling in complex conditions. Improving these capabilities can quantify and reduce the drilling and completions risks, and increase the long-term reliability of the well.
- **Subsea equipment** must be able to reliably handle seafloor conditions, operate independently, have high resolution, and be monitored and repaired quickly. Improvements in the performance and inspection of this equipment can help operators identify and respond to damage, corrosion, and other issues.
- **Equipment at the surface** needs to be able to withstand challenging conditions, including hurricane force winds, currents, and waves, and fires or explosions. Offshore facilities and systems need to be designed so that they can handle these conditions and minimize the impacts of any worst-case incidents.

R&D Drivers, Challenges and Opportunities. There are several trends in the area of geologic characterization that reinforce the necessity of research in this area in order to increase safety and prevent offshore oil spills.

The primary goal is to develop technologies that help decrease risk and mitigate "precursors" to future incidents through timely identification. In the area of geologic uncertainty, these technologies would include all pre-drill characterization studies and remote sensing technologies in addition to high-resolution, real-time sensing technologies during drilling.

Figure 5 Offshore challenges include surface systems, subsea systems, geologic uncertainty, and drilling and well construction.

Credit: NETL



Next generation seismic receivers (fiber optic and micro-electro-mechanical systems sensors), in limited prototype demonstrations, have shown the ability to detect very faint seismic signals at frequencies of one and possibly up to two orders of magnitude greater than current systems. The emphasis in this area, as opposed to drilling and completions, is next generation sensors and downhole measuring systems that provide direct measurement of geology/hydrology versus today's sensors/systems that rely on interpretation of indirect responses, such as the use of resistivity to identify saturation and more permeable zones. If these sensors could provide discrete, instantaneous measurements and could enable detection of trace amounts of hydrocarbon before an overpressured zone is encountered, a possible kick could be avoided.

Offshore Drilling and Completions Operations. Drilling and completions include the challenges associated with how people work and interact with technology—especially advanced technology—in safe operations (human factors and human-machine interface), as well as enhanced blowout preventer technologies. This reflects the need to assess risks associated with innovative drilling and completions technologies and methods and the need to reduce the risk of drilling in particularly complex conditions. In addition, this area highlights the need to improve the ability to collect and communicate data while drilling, which can provide the operator with early indications of possible issues.

The Offshore Drilling and Completion Operations research area addresses the human machine interface, which involves improved decision making by advanced downhole sensing technologies and advanced surface readout and integration systems as well as improved operational methodologies based on improved understanding of equipment and materials (such as cement and other critical barriers). Ancillary research includes such topics as early kick detection, BOP technologies, and best practices to maximize the effectiveness of researched areas/topics.

Some of the most recent technology developments are as follows:

- High-speed downhole data transmission—wired pipe
- Logging While Drilling (replacing wireline logging)

- Best practices for use of cement offshore
- Feasibility of Offshore Reverse Circulation Cementing for safer operations
- Managed Pressure Drilling design and analytical tools to identify overpressure zones
- Intelligent Production System for Ultra-Deepwater with Short Hop Wireless Power and Wireless Data Transfer that brings downhole information to the surface instantaneously using information gathered along the drill pipe

More specifically, there are a number of nascent technologies that have both economic and risk reduction benefits for offshore drilling and completion operations. Since it is best to have industry participation for field demonstrations in any drilling/completion technologies, DOE is looking for cost effective investments in the dual benefit of these technologies, which provides an opportunity for it to lead offshore operational risk reduction through rapid deployment of these "common interest" technologies.

The area of sensor development is a significant part of these technologies. Essentially all downhole sensors used in drilling take indirect measurement of the subsurface environment. For example: resistivity can be used to calculate an estimate of water saturation, and sonic travel time can be used to calculate formation density/integrity. The problem with these systems is that many things affect resistivity and sonic travel time; hence, interpretation is required and often takes time, and time is costly, especially for deep water rigs. Interpretation is also open to error, especially if the tools are not properly calibrated before each use.

Alternatively, geochemical sensors have recently been developed that can provide direct readings of low levels of geochemicals that enter the wellbore. These sensors appear to have the ability to not only detect hydrocarbons in a stream, but also to differentiate the components (methane, ethane, propane, etc.) and their relative percentages. They could also be used to differentiate between sand and shale for better understanding of changes in geology.

Surface Systems and Umbilicals. Umbilicals connect the surface facilities to the subsea system, transferring power, communication, and more. In this topic area, key needs for risk reduction include analysis of cumulative fatigue in the wellbore system so as to inform design and maintenance of equipment and facilities. As industry moves into more challenging conditions, and as climate conditions change, the capability of offshore systems to deal with extreme conditions will likely need to increase.

These projects reduce the risk of future spills due to previously unanticipated extreme conditions. The term "wellbore stability" recognizes that the wellbore in offshore operations now includes an engineered system from the ocean floor, supported by the drilling platform, which undergoes continual stresses and corrosion during drilling. In order to ensure wellbore integrity throughout the well, analysis of cumulative fatigue in that system must be accounted for in design and maintenance. In the area of surface systems and umbilicals, major trends are:

- Rapid development in battery technology, especially for long subsea tiebacks;
- Use of smaller vessels and lighter-weight materials and composite materials;
- Cybersecurity; and
- Making umbilicals (power, control, chemistry) lighter and cheaper in order to develop enabling technologies that are safe, reliable, and cost-effective.

The Surface System and Umbilicals research areas include:

- Platforms. More stable platform designs; ignition source design impact studies for safer facility designs; improved meteorologic and oceanographic metocean 100-year design criteria; improved loop current and hurricane forecasting; lighter/stronger riser materials for reliability in 10,000-12,000 foot water depths; and, riser inspection technologies and standards/best practices.

- Cement, umbilicals, and risers. This is especially true for "mega" research projects and large-scale projects as well as collaborating on dry tree research, EOR/IOR, and all safety and health related topics.
- Surface systems. Materials research and related improvements in technology can transcend all sectors of oil and gas.

Subsea Systems Reliability and Automation. This area includes subjects such as analysis and improvement of the reliability of components within complex production systems operating autonomously on the ocean floor). The purpose of these systems is reducing the risk of spills (by identifying issues earlier, with greater accuracy, and a faster response time) and lessening the environmental impact at the time of a possible failure.

The identified drivers and trends point to the necessity of continued research and development in the area of subsea systems reliability and automation. A few trends mirror those identified in other research areas.

Recent low oil prices are impacting the subsea sector, including:

- Forcing consolidation of the services support industry, which reinforces less industry investment.
- Increasing the role of sensors and automation.
- Aging of the infrastructure, including brownfields. There is a lack of information on current state, and any increased threat from aged pipelines/umbilicals.
- Increasing interest in high-integrity pressure protection systems, which were developed for protection of subsea pipelines after valve installation.

The Subsea Systems Reliability and Automated Safety Systems research area recognizes that the current trend for offshore development is subsea completions. The risk of significant undetected subsea oil and gas leaks increases with each mile of pipeline and umbilical connection that is made. This research area includes advanced equipment packaging; improved sensor and system reliability for ROV maintenance and intervention; ROV interface standardization; and advance flow assurance understanding, especially under high pressure, high temperature conditions.

CONCLUSION

Current fuel use trends put the world on the path towards a dramatic rise in average global temperature. The cleaner fuels R&D portfolio can help stave off that threat while increasing economic competitiveness and energy independence. Each fuel has strengths and shortcomings, and the fuel system must meet several challenging needs: economic prosperity requires low cost fuels; energy security requires stable, abundant domestic resources; meeting environmental goals requires reduction of greenhouse gas emissions and other externalities. This supplemental material explores options to address each of these challenges in oil and gas.

Until recently, domestic oil and natural gas production was in decline but due to technology advances in hydraulic fracturing among others, the U.S. is now the world's largest producer of these fuels. While oil and gas are low cost, have good economics, are abundant, and support national security, they have a poor carbon footprint and other environmental issues. The QTR identifies many opportunities for federal R&D to support the future of fuels in the United States. Each fuel type in the U.S. will pose tradeoffs—cost, performance, infrastructure, security, climate impact, and others—across different timeframes.

Endnotes

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Acronyms

CO_2	Carbon Dioxide
DOE	United States Department of Energy
DOI	United States Department of Interior
EIA	Energy Information Administration
EPA	United States Environmental Protection Agency
FE	Fossil Energy
GHG	Greenhouse Gas
HF	Hydraulic Fracturing
LNG	Liquefied Nitrogen Gas
LPG	Liquefied Petroleum Gas
N	Nitrogen
NETL	National Energy Technology Laboratory
NGL	Natural Gas Liquids
QTR	Quadrennial Technical Review
R&D	Research and Development
RPSEA	Research Partnership to Secure Energy for America
SRV	Stimulated Rock Volume
tcf	Trillion Cubic Feet
tcf/y	Trillion Cubic Feet Per Year
TRR	Technically Recoverable Resources
TX	Texas
UK	United Kingdom

UOG	Unconventional Oil and Gas
U.S.	United States
USGS	United States Geological Survey
VOC	Volatile Organic Compound

Glossary

Alaska North Slope	The Alaska North Slope is the region of the U.S. state of Alaska located on the northern slope of the Brooks Range along the coast of two marginal seas of the Arctic Ocean, the Chukchi Sea being on the western side of Point Barrow, and the Beaufort Sea on the eastern. The North Slope contains more than a dozen of the 100 largest oil fields in the United States and several of the 100 largest natural gas fields. Most of Alaska's oil production takes place on the North Slope.
Anthropogenic	Made or generated by a human or caused by human activity. The term is used in the context of global climate change to refer to gaseous emissions that are the result of human activities, as well as other potentially climate-altering activities, such as deforestation.
Aquifer	A body of rock whose fluid saturation, porosity and permeability permit production of groundwater.
Arctic Region	All U.S. and foreign territory north of the Arctic Circle and all U.S. territory north and west of the boundary formed by the Porcupine, Yukon, and Kuskokwim Rivers; all contiguous seas, including the Arctic Ocean and the Beaufort, Bering, and Chuckhi Seas, and the Aleutian Chain. [The Aleutian chain boundary is demarcated by the 'Contiguous zone limit of 24-nautical miles.] [As defined by the Arctic Research and Policy Act]
Arctic Shelves	Continental shelves at high latitudes.
Basin	A depression in the crust of the Earth, caused by plate tectonic activity and subsidence, in which sediments accumulate. Sedimentary basins vary from bowl-shaped to elongated troughs. Basins can be bounded by faults. Rift basins are commonly symmetrical; basins along continental margins tend to be asymmetrical. If rich hydrocarbon source rocks occur in combination with appropriate depth and duration of burial, then a petroleum system can develop within the basin. Most basins contain some amount of shale, thus providing opportunities for shale gas exploration and production.

Blowout	An uncontrolled flow of formation fluids from the wellbore or into lower pressured subsurface zones (underground blowout). Uncontrolled flows cannot be contained using previously installed barriers and require specialized services for intervention. A blowout may consist of water, oil, gas or a mixture of these. Blowouts may occur during all types of well activities and are not limited to drilling operations. In some circumstances, it is possible that the well will bridge over, or seal itself with rock fragments from collapsing formations downhole.[81]
Blowout Preventer (BOP)	A large valve at the top of a well that may be closed if the drilling crew loses control of formation fluids. By closing this valve, the drilling crew usually regains control of the reservoir, and procedures can then be initiated to increase the mud density until it is possible to open the BOP and retain pressure control of the formation. BOPs come in a variety of styles, sizes and pressure ratings. Some can effectively close over an open wellbore, some are designed to seal around tubular components in the well (drillpipe, casing or tubing) and others are fitted with hardened steel shearing surfaces that can actually cut through drillpipe. Since BOPs are critically important to the safety of the crew, the rig and the wellbore itself, BOPs are inspected, tested, and refurbished at regular intervals determined by a combination of risk assessment, local practice, well type and legal requirements.[81]
Brownfield	An oil or gas accumulation that has matured to a production plateau or even progressed to a stage of declining production. Operating companies seek to extend the economic producing life of the field using cost-effective, low-risk technologies. Stimulation or refracturing operations, completing additional zones, and installing artificial lift equipment are a few technologies commonly applied in brownfields before any drilling options are attempted. [81]
Chemical Injection	A general term for injection processes that use special chemical solutions to improve oil recovery, remove formation damage, clean blocked perforations or formation layers, reduce or inhibit corrosion, upgrade crude oil, or address crude oil flow-assurance issues. With respect to gas hydrates, chemical injection is a potential production mechanism whereby destabilizing chemical inhibitors are placed in contact with the hydrate deposit matrix to liberate methane gas.

CO_2 and Nitrogen Injection	**CO_2 Injection** - An enhanced oil recovery method in which carbon dioxide (CO_2) is injected into a reservoir to increase production by reducing oil viscosity and providing miscible or partially miscible displacement of the oil. **Nitrogen Injection** - A process whereby nitrogen gas is injected into an oil reservoir to increase the oil recovery factor. Below the minimum miscibility pressure (MMP), this is an immiscible process in which recovery is increased by oil swelling, viscosity reduction and limited crude-oil vaporization. Above the MMP, nitrogen injection is a miscible vaporizing drive. Miscibility of nitrogen can be achieved only with light oils that are at high pressures; therefore, the miscible method is suitable only in deep reservoirs.
Conventional Oil and Gas	Crude oil and natural gas that is produced by a well drilled into a geologic formation in which the reservoir and fluid characteristics permit the oil and natural gas to readily flow to the wellbore.
Coring	The process of taking a cylindrical sample of geologic formation, usually reservoir rock, taken during or after drilling a well.
Crude Oil	A mixture of hydrocarbons that exists in liquid phase in natural underground reservoirs and remains liquid at atmospheric pressure after passing through surface separating facilities.[82]
Deepwater	Exploration activity located in offshore areas where water depths exceed approximately 600 feet [200 m].
Deepwater Horizon	A member of Transocean's fleet of offshore drilling rigs; The $560-million-dollar semisubmersible rig, under lease to BP, which was working on BP's 18,000-foot-deep Macondo well when it blew out and escaping methane gas exploded.[83]
Depressurization	The pressure of fluids within the pores of a reservoir is usually hydrostatic pressure, or the pressure exerted by a column of water from the formation's depth to sea level. Depressurization is a production mechanism through which an oil or gas reservoir is produced through the differential pressure that drives fluids from the reservoir into the wellbore.
Drilling	The act of boring a hole (1) to determine whether minerals are present in commercially recoverable quantities and (2) to accomplish production of the minerals (including drilling to inject fluids). Exploratory drilling is done to locate probable mineral deposits or to establish the nature of geological structures; such wells may not be capable of production if minerals are discovered. Developmental drilling is done to delineate the boundaries of a known mineral deposit to enhance the productive capacity of the producing mineral property. Directional drilling involves the purposeful deviation of a wellbore from the vertical to reach a specific subsurface target or targets. Note: this definition is focused on minerals.

Faults	A fracture along which the blocks of crust on either side have moved relative to one another parallel to the fracture.[84]
Flow Assurance	The design, strategies, and principles for ensuring that there is uninterrupted hydrocarbon production flowing from the reservoir to the point of sale. Impediments to hydrocarbon flow in wellbores and flowlines include many phenomena, including the spontaneous formation of solid gas hydrates.
Flowback Water	Water that is produced back from a well immediately after a hydraulic fracturing treatment. Such water can be salty after picking up ionic constituents from the reservoir rock and fluids, and will also contain additives pumped along with the fracturing treatment. As such, it must be captured, handled carefully, and treated or disposed of properly to prevent environmental impacts. The share of injected water that returns immediately as flowback water can vary based on the size of the treatment and the character of the reservoir.
Fracture	A crack or surface of breakage within rock not related to foliation or cleavage in metamorphic rock along which there has been no movement. A fracture along which there has been displacement is a fault. When walls of a fracture have moved only normal to each other, the fracture is called a joint. Fractures can enhance permeability of rocks greatly by connecting pores together, and for that reason, fractures are induced mechanically in some reservoirs in order to boost hydrocarbon flow. Fractures may also be referred to as natural fractures to distinguish them from fractures induced as part of a reservoir stimulation or drilling operation. In some shale reservoirs, natural fractures improve production by enhancing effective permeability. In other cases, natural fractures can complicate reservoir stimulation.
Free Gas	The gaseous phase present in a reservoir or other contained area. Gas may be found either dissolved in reservoir fluids or as free gas that tends to form a gas cap beneath the top seal on the reservoir trap. Both free gas and dissolved gas play important roles in the reservoir-drive mechanism.
Fugitive Emissions	Unintended leaks of natural gas or volatile organic compounds during the production, processing, transmission, and/or transportation of fossil fuels.
Gas Flux	The rate of gas flow at a specific location compared to background emission measurements.
Gas Hydrate Geohazard	A hazard associated with gas hydrate formation or decomposition, whether generated by natural or industrial processes. Induced gas hydrate destabilization can negatively impact the mechanical stability of the host sediments.

Gas Hydrate Reservoirs	Deposits of methane hydrates which exist due to the temperature and pressure conditions suitable for the formation and stability of gas hydrate. These environments are: 1) sediment and sedimentary rock units below Arctic permafrost; 2) sedimentary deposits along continental margins; 3) deep-water sediments of inland lakes and seas; and, 4) under Antarctic ice. With the exception of the Antarctic deposits, methane hydrate accumulations are not very deep below Earth's surface; in most instances within a few hundred meters of the sediment surface. In these environments methane hydrate occurs in the sediment as layers, nodules, and inter-granular cements.
Gas Hydrates	Solid, crystalline, ice-like substances composed of water, methane, and usually a small amount of other gases, with the gases being trapped in the interstices of a water-ice lattice. They form beneath permafrost and within deep ocean sediments under conditions of moderately high pressure and at temperatures near the freezing point of water.
Geochemical	A process related to the study of the chemistry of the Earth and within solid bodies of the solar system, including the distribution, circulation, and abundance of elements (and their ions and isotopes), molecules, minerals, rocks, and fluids.
Geohazard	Features including faults and pressure differentials that may result in an unexpected influx into the wellbore.
Geomechanical	The geologic specialty that deals with understanding the strength and physical stability of rocks and sediments.
Geomechanics	The geologic specialty that deals with understanding how rocks, stresses, pressures, and temperatures interact. This understanding is used to solve oilfield problems, such as optimizing hydraulic fracturing treatments of shale reservoirs. Geomechanics specialists typically work with experts in geophysics, geology, petrophysics, reservoir engineering, drilling engineering, and rock physics to solve geomechanical problems and address production challenges in shale reservoirs.[81]
Global Carbon Cycling	The process by which carbon moves between rocks, oceans, and the atmosphere over various time-scales.
Green Completions	Well completion processes that minimize the potential for environmental impacts. These often relate to the hydraulic fracturing process in particular and generally involve the use of systems that contain the injected and flowback fluids within a closed system, preventing emissions of gases or liquids that might contaminate the air, groundwater, or soil near a well location. Such systems may also include gas flaring equipment designed to minimize emissions. This can also refer to the use of non-toxic fluids in the completion process.

Greenhouse Gas	Those gases, such as water vapor, carbon dioxide, nitrous oxide, methane, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride, that are transparent to solar (short-wave) radiation but significantly opaque to some portions of the spectrum of long-wave (infrared) radiation, thus reducing the loss of long-wave radiant energy from the Earth. The net effect is a trapping of absorbed radiation and a tendency to warm the planet's surface.
Horizontal Well	A well that is purposefully deviated from the vertical to a horizontal or nearly horizontal trajectory upon reaching the target formation. Such wells are designed to maximize the length of wellbore exposed within a producing formation and are often hydraulically fractured at multiple locations along the horizontal lateral section.
Hydraulic Fracturing	Fracturing of rock at depth with fluid pressure. Hydraulic fracturing at depth may be accomplished by pumping water into a well at very high pressures. Under natural conditions, vapor pressure may rise high enough to cause fracturing in a process known as hydrothermal brecciation.[82]
Hydrocarbons	An organic chemical compound of hydrogen and carbon in the gaseous, liquid, or solid phase. The molecular structure of hydrocarbon compounds varies from the simplest (methane, a constituent of natural gas) to the very heavy and very complex oils.
Hydrologic Cycle	The water cycle describes the continuous movement of water on, above, and below the surface of the Earth.
In Situ	Latin for "in its original place." In the original location or position, such as a large outcrop that has not been disturbed by faults or landslides. Tests can be performed in situ in a reservoir to determine its pressure and temperature and fluid properties.
Infill Drilling	The addition of wells in a field that decreases average well spacing. This practice both accelerates expected recovery and increases estimated ultimate recovery in heterogeneous reservoirs by improving the continuity between injectors and producers. As well spacing is decreased, the shifting well patterns alter the formation-fluid flow paths and increase production from areas where greater hydrocarbon saturations exist.
Kick	A flow of formation fluids into the wellbore during drilling operations. The kick is physically caused by the pressure in the wellbore being less than that of the formation fluids, thus causing flow.[81]

Kick Detection	The process of identifying when a well being drilled for hydrocarbon or other subsurface purposes is taking on a "kick" from hydrocarbon, gas, or water from the surrounding strata. Currently, most subsurface drilling operations rely upon mud returns to the rig floor to identify a kick. [National Energy Technology Laboratory]
Liquefied Natural Gas (LNG)	Natural gas (primarily methane) that has been liquefied by reducing its temperature to -260 degrees Fahrenheit at atmospheric pressure.
Liquefied Petroleum Gas	A group of hydrocarbon gases, primarily propane, normal butane, and isobutane, derived from crude oil refining or natural gas processing. These gases may be marketed individually or mixed. They can be liquefied through pressurization (without requiring cryogenic refrigeration) for convenience of transportation or storage. Excludes ethane and olefins.
Lithology	The macroscopic nature of the mineral content, grain size, texture and color of rocks.
Logging	The process of lowering instruments into an oil and gas well and recording rock and fluid properties using measurement of various physical parameters.
Methane Hydrate	An occurrence of hydrocarbon in which molecules of methane are trapped in ice molecules. More generally, hydrates are compounds in which gas molecules are trapped within a crystal structure. Hydrates form in permafrost zones and in deep water.
MetOcean	METeorological and OCEANographic
Modeling	The use of mathematical representations of physical processes to simulate modifications to those processes to better understand how to achieve desired outcomes. Examples include reservoir production modeling to understand how to optimally develop an oil or gas reservoir, and hydraulic fracturing modeling to understand how to optimize the design of a hydraulic fracture stimulation. Modeling can include an economic analysis component that optimizes based on certain economic objectives.
Numerical Modeling	A rendering of a model of a reservoir or field in entirely numerical formats. Numerical models, once built, may be used to perform many mathematical operations, including calculations of available reserves and simulations of the behavior of the reservoir.
Organic Carbon	Naturally-occurring organic carbon forms are derived from the decomposition of plants and animals as well as those organic carbon forms derived from the soil's parent material/geology.
Oxidize	To chemically transform a substance by combining it with oxygen.

Pad Drilling	A process whereby multiple oil or gas wells are drilled directionally from a single drilling "pad" or flat area constructed to permit the set up and operation of drilling and well completion equipment during the drilling process, and surface production equipment during the producing phase. The pad may consist of compacted earth, gravel, plastic mats, or ice (in arctic locations). This process can serve to reduce the overall surface impact or "footprint" of field development in environmentally fragile ecosystems or in densely populated areas.
Permafrost	The permanently frozen subsoil that lies below the upper layer (the upper several inches to feet) of soil in arctic regions.
Petrophysical	Two definitions: (1) A process or procedure used to interpret petrophysical (usually wireline log or core) data. Usually representing a set of equations, algorithms or other mathematical processes, petrophysical models often have multiple routines. For example, a deterministic model might include routines that calculate the volume, total porosity, effective porosity, water saturation, and permeability. Often, the model is calibrated using core, production, test and other data sets. Although many software packages contain ready-built petrophysical models or component routines that can be called upon, many log-analysis problems are unique and require that "built to purpose" models be constructed. Construction of new petrophysical models is normally driven by the data available and the nature of the problem to be solved. (2) Rock types that have been classified according to their petrophysical properties, especially properties that pertain to fluid behavior within the rock, such as porosity, capillary pressure, permeabilities, irreducible saturations or saturations. Petrophysical rock types are often calibrated from core and dynamic data, but are usually calculated from wireline logs, where possible, because the wireline logs are generally the only measurements that are available for all wells at all depths. Electrofacies approaches are often used to determine rock types from logs.
Petrophysics	The study of the properties (physical, electrical, and mechanical) and the rock/fluid interactions of petroleum systems. [Society of Petroleum Engineers]
Play	A set of known or postulated oil and gas accumulations sharing similar geologic, geographic, and temporal properties, such as source rock, migration pathway, timing, trapping mechanism, and hydrocarbon type. A play differs from an assessment unit; an assessment unit can include one or more plays
Precursors	A state (event, data point, etc.) that precedes a potential drilling and/or production incident that could result in an oil spill or loss of life. [QTR-2015: Offshore Technology Assessment]

Proppant Sized particles mixed with fracturing fluid to hold fractures open after a hydraulic fracturing treatment has been pumped. In addition to naturally occurring sand grains, man-made or specially engineered proppants, such as resin-coated sand or high-strength ceramic materials like sintered bauxite, may also be used. Proppant materials are carefully sorted for size and sphericity to provide an efficient conduit for production of fluid from the reservoir to the wellbore.

Prudent Development Development of a natural resource by parties acting with or showing care and thought for the future. This care can relate to immediate and future safety, environmental impact, fiduciary responsibility to shareholders, or a combination of all three.

Relief Well A well drilled to intersect a well that has experienced a blow-out as a method to obtain control of the fluid flow.

Remote Sensing The process of measuring, observing, or analyzing features of the Earth from a distance. Satellite photography and radar are techniques commonly used for remote sensing. Many geophysicists do not consider seismic methods to be remote sensing because although seismic methods sense the subsurface remotely, the sources and receivers are in contact with the Earth.[81]

Reservoir A porous and permeable underground formation containing an individual and separate natural accumulation of producible hydrocarbons (crude oil and/or natural gas) which is confined by impermeable rock or water barriers and is characterized by a single natural pressure system.

Seismic Data Data relating to an earth vibration caused by an external source. Data from seismic surveys generally is obtained using surface receivers to record the reflection of vibrations from subsurface rock layers induced by explosions at the surface. Borehole seismic data is data measured with receivers, sources or both in a well, such as a vertical seismic profile (VSP), crosswell seismic data or single-well imaging. By directly measuring the acoustic velocity of each formation encountered in a well, the well logs and borehole seismic data can be correlated to surface seismic data more easily. Borehole seismic data, including both S- and P-waves, can be gathered in a cased or open hole.

Sequestration The permanent isolation of some substance from a protected portion of the environment. Typically used in relation to the storage of carbon dioxide injected for permanent storage into underground geologic reservoirs, such as oil and natural gas fields, saline aquifers, or abandoned coal mines.

Shale Gas	Natural gas produced from wells that are completed in shale formations. Shale is a fine-grained, sedimentary rock composed of mud from flakes of clay minerals and tiny fragments (silt-sized particles) of other materials. The shale acts as both the source and the reservoir for the natural gas.
Shale Oil	Shale oil is a subset of tight oil. (See definition of tight oil).
State Lands	Lands under jurisdiction of one of the 50 states, including adjacent outer continental shelf areas, or the District of Columbia.
Stratigraphic Unit	A layer of sediment or sedimentary rock, or stratum.
Thermal Stimulation	Injection processes that introduce heat into a reservoir as a method of thermal recovery performed to restore or enhance the productivity of a well and create a highly conductive flow path between the reservoir and the wellbore.
Tight Gas	Gas produced from a relatively impermeable reservoir rock. Hydrocarbon production from tight reservoirs can be difficult without stimulation operations. Stimulation of tight formations can result in increased production from formations that previously might have been abandoned or been produced uneconomically. The term is generally used for reservoirs other than shales.
Tight Oil	Oil produced from petroleum-bearing formations with low permeability such as the Eagle Ford, the Bakken, and other formations that must be hydraulically fractured to produce oil at commercial rates. Shale oil is a subset of tight oil.
Ultra-Deepwater	A water depth of greater than 5,000 feet [QTR-2015: Offshore Technology Assessment]
Umbilicals	The connective medium between surface installations and subsea developments that transfer power, chemicals, communications, and more.
Unconventional Oil and Gas	An umbrella term for oil and natural gas that is produced by means that do not meet the criteria for conventional production. See Conventional oil and natural gas production. Note: What has qualified as "unconventional" at any particular time is a complex interactive function of resource characteristics, the available exploration and production technologies, the current economic environment, and the scale, frequency, and duration of production from the resource. Perceptions of these factors inevitably change over time and they often differ among users of the term.

Upstream	”Upstream” refers to the exploration, production, and field processing phases of the oil and natural gas commercial exploitation process. In the case of natural gas, this phase is followed by gas gathering and centralized natural gas processing, gas transportation and storage, and natural gas distribution phases. In the case of crude oil, it is followed by gathering transportation, refining and refined product distribution phases. The gathering and transportation phases are sometimes referred to as “midstream” and the distribution and refining portions referred to as “downstream.” When focused on unconventional resources, it would be “upstream unconventional oil and gas development.”
Venting	The release of natural gas to the ocean or atmosphere.
Wellbore Integrity	The condition of a wellbore that relates to its ability to maintain its stability during drilling (i.e., not allow the hole walls to cave in) and after the well has been cased and cemented, its ability to prevent the flow of fluids between permeable formations behind the casing. This requires a competent sheath of the appropriate type of cement that has been properly placed into the annulus and allowed to set under the proper conditions.
Wellbore Integrity/Stability	The ability of well materials (cement, metals, etc.) to ensure wellbore control and maintain zonal isolation between the wellbore and the surrounding formations.
Well Stimulation	A treatment performed to restore or enhance the productivity of a well. Stimulation treatments fall into two main groups, hydraulic fracturing treatments and matrix treatments. Fracturing treatments are performed above the fracture pressure of the reservoir formation and create a highly conductive flow path between the reservoir and the wellbore. Matrix treatments are performed below the reservoir fracture pressure and generally are designed to restore the natural permeability of the reservoir following damage to the near-wellbore area. Stimulation in shale gas reservoirs typically takes the form of hydraulic fracturing treatments.