U.S. Department of ENERGY | Office of Fossil Energy and Carbon Management

APPENDIX D: ADDENDUM ON ENVIRONMENTAL AND COMMUNITY EFFECTS OF U.S. LNG EXPORTS

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Addendum on Environmental and Community Effects of U.S. LNG Exports Appendix

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FOREWORD

This multi-volume study of U.S. LNG exports serves to provide an updated understanding of the potential effects of U.S. LNG exports on the domestic economy, U.S. households and consumers; communities that live near locations where natural gas is produced or exported; domestic and international energy security, including effects on U.S. trading partners; and the environment and climate. Prior to this study, Department of Energy's (DOE's) most recent economic and environmental analyses of U.S. LNG exports were published in 2018 and 2019, respectively. At that time, U.S. LNG exports were just getting underway and our export capacity was 4 billion cubic feet per day (Bcf/d), less than one-third of what it is today. Since then, our world and the global natural gas sector have changed significantly: the U.S. has become the top global exporter of LNG; Russia has invaded Ukraine and used energy as a weapon to undermine European and global security; the impacts and costs of extreme weather and natural disasters fueled by climate change have increased dramatically; and the pace of the energy transition and technological innovation has itself accelerated.

These developments and others factor into a global energy system that is changing rapidly. The pace of change creates inherent uncertainty in projecting the potential pathways for U.S. LNG through 2050. Accordingly, several considerations should be borne in mind when interpreting this study and its results.

- Given the global scope and timeframe examined in this study, there should be recognition of the inherent uncertainty in conclusions, especially given their size relative to the overall global economy and energy system.
- This study is not intended to serve as a forecast of U.S. LNG exports and impacts. Rather, it is an exercise exploring alternative conditional scenarios of future U.S. LNG exports and examining their implications for global and U.S. energy systems, economic systems, and greenhouse gas (GHG) emissions. This type of scenario analysis is a well-established analytical approach for exploring complex relationships across a range of variables
- The scenarios explored in this study span a range of U.S. LNG export outcomes. Each scenario relies on input assumptions regarding many domestic, international, economic, and non-economic factors, such as future socioeconomic development, technology and resource availability, technological advancement, and institutional change. A full uncertainty analysis encompassing all underlying factors is beyond the scope of this study.
- For the portions of this study that have modeled results, the study does not attach probabilities to any of the scenarios examined.

EXECUTIVE SUMMARY

The production and transportation of natural gas in the U.S., including natural gas for export, has energy, labor/workforce, economic, environmental, social justice, and other implications. Communities of color, including those with Black, Indigenous, and Hispanic populations, as well as rural and low-income communities have historically been disproportionately exposed to the environmental risks, harms, and measurable impacts that arise from fossil fuel development and production activities, while often simultaneously relying on such activities to sustain their livelihoods and economies.

Appendix D, Addendum on Environmental and Community Effects of U.S. LNG Exports, serves as an update to the Addendum to Environmental Review Documents Concerning Exports of Natural Gas from the United States (2014 Addendum) which explored many of these effects, but was prepared and published prior to 2016, when exports of LNG from the lower-48 states first started. Appendix D contains a summary of publicly available peer-reviewed research across the physical and social sciences on the effects of natural gas production, transportation and exports on the environment and on local communities, supplemented in some instances by publicly available NGO and industry materials and news articles.

Consistent with the 2014 Addendum, the environmental and community impacts discussed in Appendix D are those from GHG and other air pollutants, water withdrawal and management, induced seismicity, land use and development, and the effects on communities. This update also considers two topics that were not addressed in the 2014 Addendum: effects on communities from activities associated with natural gas production and transportation, and effects on communities from natural gas exports from LNG facilities. As part of this report, FECM, with support from NETL and other DOE offices, reviewed the literature to identify and discuss many of these key implications for communities including labor, economic, environmental and social considerations.

Key Findings

- **Natural gas production, processing and transportation have environmental impacts, including impacts to water, air, and land.**
  - Natural gas production, processing, and transportation emit pollutants that contribute to global warming, such as CO_2, methane, and nitrous oxides, as well as pollutants that are harmful to human health and can contribute to regional and local air pollution, such as volatile organic compounds (VOCs), nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and particulate matter (PM).
  - Natural gas production from unconventional reservoirs requires large volumes of fresh water (both surface and groundwater) used for hydraulic fracturing, which can reduce local availability of surface and groundwater. Natural gas production also presents risks for surface or groundwater contamination from subsurface migration of fluids, spills on the surface, and management of produced waters following well development. Operators are taking steps to address both water availability and water disposal issues by finding ways to use less fresh water for hydraulic fracturing by recycling flowback and produced water.
  - Both hydraulic fracturing for natural gas production, and the disposal of produced water through underground injection into saltwater disposal wells (SWDs) are linked with induced seismicity in the U.S. Midwest. State regulators have taken steps to mitigate risks by limiting injection when seismicity is detected, and operators are also finding ways to re-use flowback and produced water instead of injecting it in SWDs.

  - Natural gas production, processing and transportation has both short-term and long-term disturbances to land. These land use changes affect plant and wildlife habitat.

- **Natural gas production has impacts on local communities near production, processing, and transportation facilities.**
  - Epidemiologic studies have found increased risks of health problems for people living closer to oil or gas production sites, but these studies are observational and correlational and do not establish causation. Health risks are attributed to exposure to air and water pollutants associated with oil and gas production.
  - Natural gas production tends to increase employment in regions and communities where it occurs, but some evidence indicates that jobs often go to people who either move to the area for the jobs or commute from other areas, rather than to long-term residents.
  - Oil and gas production growth brings new revenues to local governments, but also additional burdens such as increased emergency services and police, additional water and wastewater infrastructure, and potential damage due to increased heavy road usage.
  - Local mineral rights holders receive royalties, though many such recipients are often not local residents.
  - Property prices may rise with increased production, though prices may decline for properties near production facilities or, in some cases, natural gas pipelines.
  - Quality of life impacts include noise, light pollution, increased traffic, crime, and social disruptions due to the cyclical nature of the production industry.
- **Natural gas export activity has effects on local communities near LNG export facilities.**
  - The operation of LNG export facilities releases pollutants that are harmful to human health. Given the recency[1] of U.S. LNG exports from the U.S. Gulf Coast and the other industry co-located in the region,[2] there is a lack of published scientific literature that focuses on the specific observed impacts of LNG export operations or emissions on local public health. However, some local residents have expressed concerns about export operations, including natural gas flaring and other emissions at export facilities.
  - LNG export facilities bring jobs to the regions where they are located, and typically employ thousands of workers during facility construction and a smaller number for permanent operations. They have also provided support for local communities and organizations through grants and partnerships.
  - Although facility operators have made efforts to employ and train local residents for jobs, some community members have expressed concerns that there are limited opportunities for local residents, particularly for higher-wage positions.
  - Some local communities near LNG export facilities on the U.S. Gulf Coast have also expressed concerns about maritime traffic that creates dangers for local boaters and

[1] The first export of U.S. LNG from the lower-48 states was in February 2016. See U.S. Energy Information Administration (EIA), "Growth in domestic natural gas production leads to development of LNG export terminals," 4 March 2016. https://www.eia.gov/todayinenergy/detail.php?id=25232
[2] The Gulf Coast and South-Central region have more than 220 energy-intensive facilities in the region including 62 refineries (46% of U.S.), 67 petrochemical plants (88% of U.S.), and 94 facilities across ammonia, cement, lime, glass, pulp and paper, and bioethanol. U.S. Department of Energy, Office of Fossil Energy and Carbon Management, Gulf Coast and South-Central Regional Report October 29, 2024. https://www.energy.gov/sites/default/files/2024-11/GC%20Regional%20Report_10.29.24.pdf

harms the shrimping, fishing and tourism industries, as well as a perceived lack of benefits for the local tax base due to tax abatements offered by their state governments.

- **The environmental burdens associated with natural gas production, transportation, and export have energy and environmental justice implications**.
    - Multiple studies have found that natural gas production, transportation and export facilities tend to be sited in areas that are disproportionately home to communities of color and low-income communities.
    - Local communities sometimes lack the opportunity or ability to engage in decision-making about natural gas production, transportation, or export. DOE and other federal agencies are taking steps to increase opportunities for substantive engagement.

INTRODUCTION

DOE's Office of Fossil Energy and Carbon Management (FECM) has prepared this update to the 2014 Addendum to Environmental Review Documents Concerning Exports of Natural Gas from the United States (hereafter the 2014 Addendum) (DOE, 2014).[3]

Consistent with the 2014 Addendum, this report, prepared with technical support from the National Energy Technology Laboratory, summarizes key findings from peer-reviewed, scientific literature, as well as publications from industry and non-governmental organizations (NGOs) that are not always peer-reviewed.[4] While the 2014 Addendum focused on environmental impacts of unconventional natural gas production, this report's scope includes natural gas production and additional activities upstream of liquefaction facilities, such as pipeline transportation and wastewater disposal. The geographic focus of this report is the onshore natural gas supply chain in the lower 48 states. DOE has considered environmental impacts associated with projects based in Alaska as part of separate project-specific analyses.[5]

This report also considers two topics that were not addressed in the 2014 Addendum: Effects on communities from activities associated with natural gas production and transportation, and effects on communities from natural gas exports from LNG facilities.[6] As part of this report, FECM and NETL reviewed the literature to identify and discuss many of these key implications for communities including labor, economic, environmental and social considerations. As natural gas is projected to play a significant role during the current energy transition, energy, labor, economic, environmental, and social justice implications are considered within the context of large-scale energy infrastructure planning decisions designed to enable the United States to achieve its goal of net-zero emissions by 2050.

This report is divided into chapters, each focused on a specific topic:

- Greenhouse gases and air pollutants (Chapter 2)
- Water withdrawals and water management (Chapter 3)
- Induced seismicity (Chapter 4)
- Land use and development (Chapter 5)
- Natural gas activity: Effects on communities (Chapter 6)

Chapter 1 presents background information on domestic natural gas production and federal and state regulatory processes related to managing environmental impacts.

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[3] FECM. Addendum to Environmental Review Documents Concerning Exports of Natural Gas from the United States. Available at: https://www.energy.gov/fecm/addendum-environmental-review-documents-concerning-exports-natural-gas-united-states

[4] No opinions regarding, nor endorsement of the literature reviewed in this document, is intended or implied.

[5] For example, DOE published a Supplemental Environmental Impact Statement for the Alaska LNG Project. Additional information is available here: https://www.energy.gov/nepa/doeeis-0512-s1-supplemental-environmental-impact-statement-alaska-lng-project

[6] This report considers only LNG export facilities located in the United States.

CHAPTER 1: BACKGROUND INFORMATION

A. Natural Gas Basics

Natural gas is an odorless gaseous mixture of hydrocarbons, largely made up of methane with varying amounts of natural gas liquids (NGLs) and nonhydrocarbon gases (e.g., carbon dioxide, or CO_2, and water vapor) (Energy Information Administration [EIA], 2023b). Natural gas is the top source of U.S. electricity generation and is also used to produce industrial process steam and heat, and heat residential and commercial spaces.

Natural gas is typically classified as being either conventional or unconventional, depending on the permeability of the geologic formation (reservoir) in which it is found, the production technology used to secure it, and the scale, frequency, and duration of production from the reservoir (EIA, 2023c; and Krieg, 2018). Generally, conventional natural gas refers to natural gas found in highly permeable reservoirs, typically composed of sandstone or limestone, which allows for extraction to be completed in a relatively straightforward manner through the use of vertical drilling. Unconventional natural gas refers to natural gas found in low-permeability reservoirs, generally trapped within the pores (i.e., small, unconnected void spaces) of rocks, which makes extraction more difficult and necessitates the use of advanced drilling (i.e., directional or horizontal drilling) and high volume, multi-stage well stimulation (e.g., hydraulic fracturing) techniques that can be energy intensive (BP, 2017).

Unconventional natural gas production (including associated gas produced from low permeability oil reservoirs) has not only made up for declining conventional natural gas production, but it has also led to higher levels of natural gas supply in the U.S. This increased supply has contributed to an increase in the use of natural gas for power generation, manufacturing, transportation and residential and commercial heating, as well as in the availability of natural gas for export from the U.S (EIA, 2023a).

Today, the majority of natural gas produced domestically is unconventional and found in low-permeability shale rock formations. When such formations are regionally productive and controlled by the same set of geological circumstances, they are termed a “play.” Primary enabling technologies for accessing unconventional natural gas include large volume, multi-stage hydraulic fracturing and long-lateral horizontal drilling. Figure 1 shows the location of established and emerging shale plays within the sedimentary basins of the lower 48 states of the U.S.

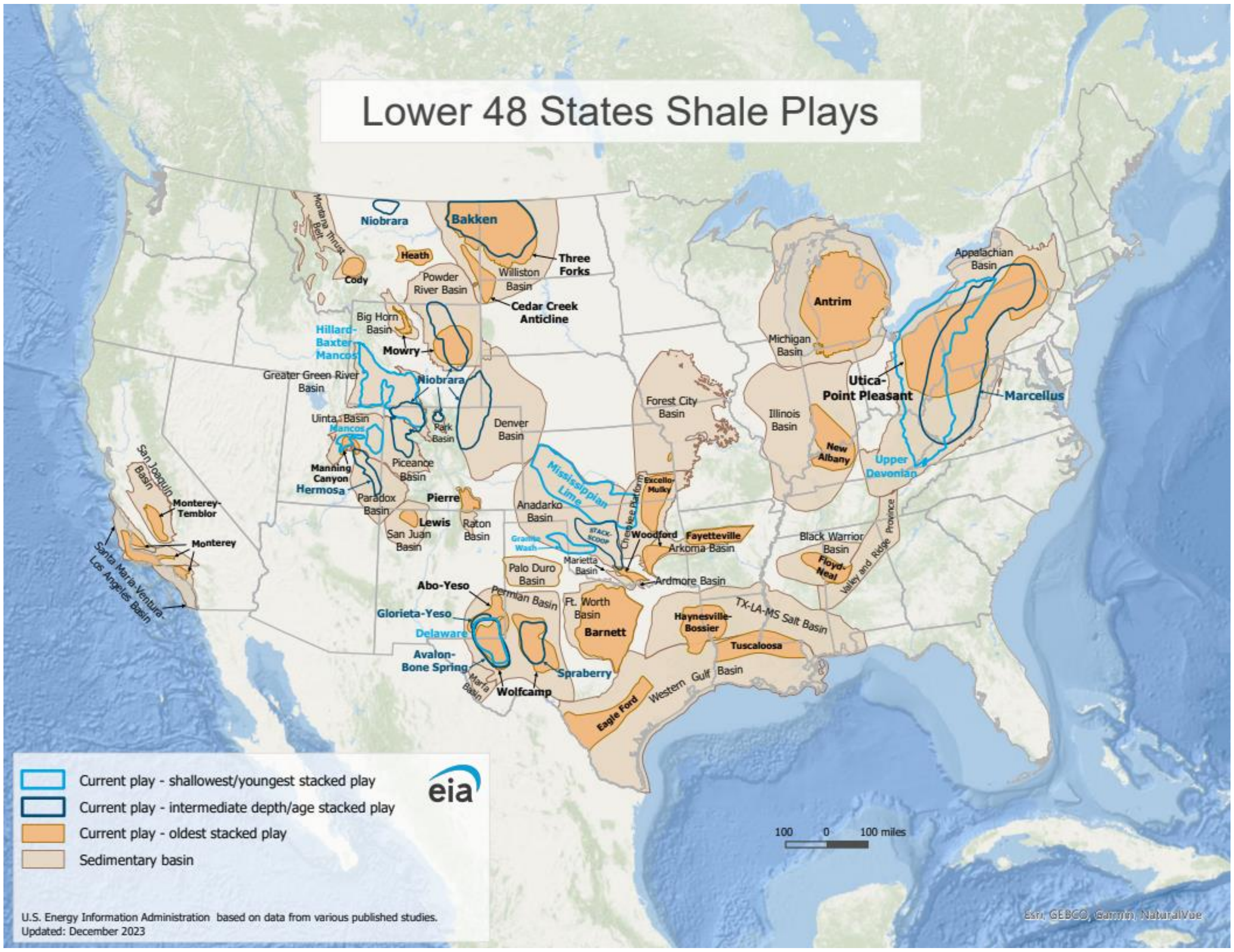


Figure 1. U.S. lower 48 shale plays (EIA 2024a)

B. Liquefied Natural Gas

Liquefied natural gas (LNG) is natural gas that has been cooled to a liquid state (approximately -260° F or -162° C). The volume of natural gas in a liquid state is about 600 times smaller than in a gaseous state at standard conditions of temperature and pressure (Molnar, 2022). Liquefying natural gas is one way to allow its transportation to markets that are far away from production regions (such as overseas), or to locations where pipeline capacity is constrained or unavailable (e.g., New England).

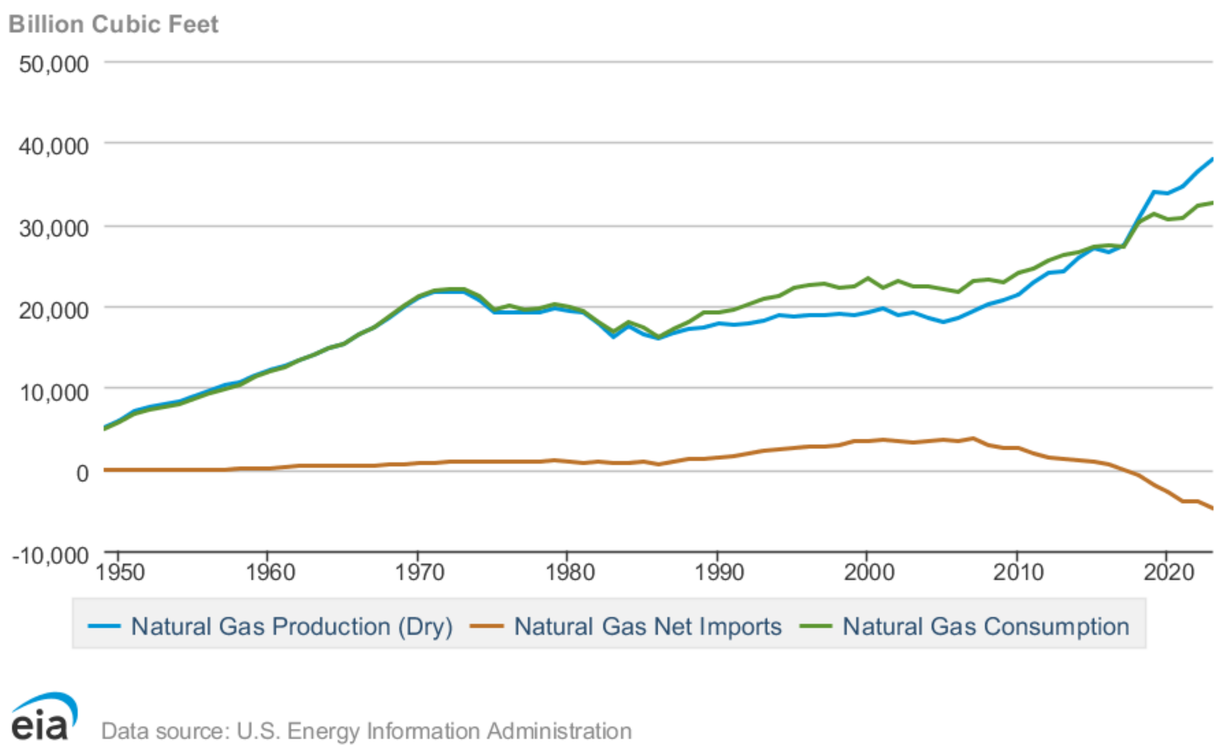
Once in liquid form, natural gas can be shipped to regasification terminals around the world via ocean-going tankers. At regasification terminals, LNG is first returned to its gaseous state and then transported by pipeline to distribution companies, industrial consumers, and power plants. In some cases (over shorter distances), LNG can also be shipped by vacuum-insulated, cryogenic semi-trailers (i.e., tanker trucks), often to end-use facilities, where it is regasified before use on-site (DOE, 2021).

C. U.S. Natural Gas Resources

Annual U.S. production of dry natural gas (natural gas after processing to remove NGLs) was approximately 37.88 trillion cubic feet (Tcf) in 2023 (an average of about 103.78 billion cubic feet [Bcf] per day), increasing approximately five percent over production in 2022 of 35.81 Tcf (an average of about 98.11 Bcf per day) (EIA, 2024c). Except for two instances (2015–2016 and 2019–2020), annual domestic production of dry natural gas has increased every year since 2005 as the application of high-volume, multi-stage hydraulic fracturing combined with horizontal drilling has continued to expand.

Over 60 percent of domestic dry natural gas production in 2022 was supplied by five of the 34 natural gas-producing states in the U.S.[7] States with a larger percentage share of total U.S. dry natural gas production in 2022 included Texas (25.4 percent), Pennsylvania (20.3 percent), Louisiana (11.1 percent), West Virginia (7.4 percent), and Oklahoma (6.8 percent).

Historically, the U.S. consumed almost all the natural gas it produced, and for a period of time was a net importer of natural gas. Advances in technology, including hydraulic fracturing and horizontal drilling, have allowed producers to develop the country's resource of shale gas, and increased production so that the U.S. is now a net exporter of natural gas. In 2023, dry natural gas production in the United States was 104 bcf/day, and about 21 bcf/day was exported by pipeline or as LNG[8]. Figure 2 illustrates historical (1949–2023) U.S. natural gas production, consumption, and net imports (EIA, 2023b).



Source: EIA (2024c)

Figure 2. U.S. natural gas consumption, dry production, and net imports (1949-2023)

[7] Energy Information Administration, Data on Natural Gas Withdrawals and Production. https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_FGW_mmcf_a.htm

[8] Energy Information Administration, Natural Gas Data Natural Gas - U.S. Energy Information Administration (EIA)

D. U.S. Regulatory Framework

Regulatory authorities for oil and gas production in the U.S. vary depending on ownership of the subsurface resources. Owners of onshore oil and gas resources in the U.S. include private citizens or companies, state governments, the federal government, and Indian tribes.[9] In instances known as a "split-estate" arrangement, the surface rights to a property are held by one party, and mineral rights (including to subsurface oil and natural gas) are held by another party.

Most onshore natural gas production in the U.S. takes place on privately held lands, where private entities also own the subsurface mineral rights. Private owners generally lease their mineral rights and land access to companies that produce the gas and pay the owners royalties.

The following sections describe how in general, state agencies, in compliance with federal environmental laws, are responsible for environmental regulation of oil and gas production on private lands or lands owned by state governments. Federal agencies regulate natural gas development on land owned by the federal government and Indian tribes.

Both federal and state entities have regulatory responsibilities for natural gas transportation by pipeline. The Federal Energy Regulatory Commission (FERC) and the Department of Transportation's Pipeline and Hazardous Material Safety Administration (PHMSA) develop and enforce regulations for interstate pipeline safety and operations. PHMSA may authorize state agencies to assume some regulatory or inspection authorities (but not enforcement) for interstate pipelines. States may also assume regulatory, inspection, and enforcement responsibilities for intrastate pipelines (pipelines within one state's borders) if they adopt regulations that are at least as stringent as federal regulations.[10]

1. Regulation on Private Land

Production of oil and gas on privately held lands is regulated by the respective state governments, which issue drilling and other permits and perform inspection and monitoring. There are at least 30 states with oil and gas production on private lands, and each one has its own rules and procedures and division of responsibilities among state agencies. State-specific regulations may include specifications for well spacing and setbacks, directional drilling, casing and tubing, underground injection, permit applications and a range of data reporting, and environmental impact management activities.[11] States develop regulations that fit their specific needs, addressing region-specific factors such as geology, hydrology, climate, topography, industry characteristics, state legal structures, population density, and local economics.

Oil and gas producers on private lands must also comply with federal environmental laws and regulations such as the Clean Air Act, the Clean Water Act, the Oil Pollution Prevention Act, the Safe Drinking Water Act, and others. The Environmental Protection Agency (EPA) is the lead agency that administers most of these laws and regulations.[12] Producers may be required to get permits for discharges to water and air directly from EPA, or from a state agency to which EPA

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[9] Offshore oil and gas resources, which will not be considered in this paper, are owned by either state governments or the federal government.

[10] United States Department of Transportation. Federal/State Legislative Authorities. Available at: https://www.phmsa.dot.gov/working-phmsa/state-programs/federalstate-legislative-authorities

[11] The Interstate Oil and Gas Compact Commission shares information about each producing state's oil and gas regulations on this webpage: https://iogcc.ok.gov/state-statutes

[12] These laws and regulations are described in greater detail in subsequent chapters.

has delegated its authority. States may have their own environmental standards, but they must be at least as protective as applicable federal requirements.

Local governments (cities, towns, and counties) may also have regulations affecting oil and gas producers on private lands regarding issues such as zoning, setbacks, road construction, water use, and noise.

Because widespread development of unconventional gas resources began in the mid-2000s, some states have updated their regulations and adopted new rules on topics such as hydraulic fracturing, well construction and integrity, water-sampling, and chemical disclosure, and others that address regional challenges of water availability and induced seismicity. Examples of these updates are highlighted in subsequent chapters.

2. Regulation on Federal Land

The Bureau of Land Management (BLM), which is part of the Department of the Interior, determines who can produce oil and gas on most onshore federal lands. BLM also handles most permitting and environmental regulation on lands held by the U.S. Forest Service and National Park Service. BLM also manages some aspects of oil and gas development for Indian tribes from the Tribal mineral estate.[13] BLM's authority comes from the Mineral Leasing Act.[14]

The U.S. government's onshore subsurface mineral estate includes an area of about 700 million acres from which the sale of oil, gas, and NGLs accounted for approximately 11 percent of all oil and 9 percent of all natural gas produced in the U.S. during fiscal year 2022.[15,16] About 23 million of these 700 million acres were leased to natural gas developers by the end of that year, and about 12.4 million of those acres were producing natural gas in economic quantities (BLM, 2023).

Other owners of federal land, including the U.S. Forest Service and the National Park Service, work with BLM to manage natural gas production on their lands.[17] BLM also manages some aspects of oil and gas production on Tribal land. Depending on the status of the land, some Tribal governments also regulate oil and gas development through tribal codes, ordinances, and constitutions.[18]

On land that it is responsible for, BLM creates land use plans for large areas and conducts competitive lease sales for parcels that are nominated by companies, if it determines that energy development is compatible with the land use plans. BLM then approves a company's Application for Permit to Drill, which includes a drilling plan and surface use plan of operations. This approval requires environmental, geological, archeological, and legal reviews. BLM is also responsible for inspections and enforcement of applicable rules during drilling, operation, reclamation, and abandonment.

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[13] BLM. About the BLM Oil and Gas Program. Available at: https://www.blm.gov/programs/energy-and-minerals/oil-and-gas/about
[14] 30 U.S.C. § 181 et seq
[15] This area is held jointly by the BLM, USFS, and other federal agencies and surface owners.
[16] October 1, 2021, through September 30, 2022
[17] U.S. Forest Service. Federal Oil and Gas Resource Management. Available at: https://www.fs.usda.gov/managing-land/natural-resources/geology/minerals/energy-minerals/oil-gas and National Park Service. Energy & Mineral Development. Available at: https://www.nps.gov/subjects/energyminerals/index.htm
[18] Indian laws, regulations, guidelines, and policies related to oil and gas surface operations (oilandgasbmps.org) http://www.oilandgasbmps.org/laws/tribal/

Companies producing oil and gas on federal lands may still have to apply to the state or locality where the land is located for other permits, such as water use and road construction.

3. Federal Regulation of Natural Gas Imports and Exports

DOE is responsible for authorizing imports and exports of domestically produced natural gas, including LNG, from or to foreign countries under Section 3 of the Natural Gas Act (NGA).[19] Under the NGA, an application to import natural gas or export natural gas to countries that have a free trade agreement (FTA) with the United States requiring national treatment for trade in natural gas, is automatically deemed to be consistent with the public interest and must be granted without modification or delay. For an application to export domestically produced natural gas to countries that have no FTA with the United States but with which trade is not prohibited by U.S. law or policy (non-FTA countries), DOE must grant the application unless it finds that the proposed exportation will not be consistent with the public interest. FECM’s natural gas import–export regulatory program is implemented by the Division of Regulation in the Office of Regulation, Analysis, and Engagement.

Typically, FERC has direct regulatory responsibility over the siting, construction, and operation of onshore LNG export facilities in the U.S. In these cases, FERC leads environmental impact reviews of proposed projects consistent with the National Environmental Policy Act (NEPA), and DOE is typically a cooperating agency as part of these reviews (DOE, 2023). In addition, FERC has established the Office of Public Participation specifically to empower, promote, and support public voices in infrastructure decisions made at FERC (FERC, 2023).

The U.S. Coast Guard leads environmental reviews for the Department of Transportation’s Maritime Administration’s licensing of proposed offshore terminals, guided by requirements in the Deepwater Port Act. Again, DOE is typically a cooperating agency in these reviews. In some limited circumstances, DOE is the lead agency for NEPA reviews related to proposed LNG exports, such as in the case of applications for exports of U.S.-sourced natural gas from export projects proposed for Canada or Mexico.

[19] 15 U.S.C. § 717b. DOE is responsible for considering the environmental impact of its authorizations of natural gas exports. DOE conducts environmental reviews under the National Environmental Policy Act and as part of its public interest review under the Natural Gas Act. Natural Gas Act section 3(a), 15 U.S.C. § 717b(a)

CHAPTER 2: GREENHOUSE GASES AND AIR POLLUTANTS

This chapter provides a characterization of the key sources of emissions from natural gas-related activities upstream of liquefaction facilities and a summary of the latest understanding of the related impacts on air quality and climate. In addition, this section provides an overview of the state and federal regulations that address these emissions.

Key pollutants, which are discussed in further detail later in this section, include:

- Greenhouse gas (GHG) emissions such as CO_2, methane, and nitrous oxides, which directly contribute to global warming. Methane is the primary component of natural gas. It is a short-lived climate pollutant, with a shorter lifespan in the atmosphere than CO_2, but it has a stronger near-term impact (i.e., higher 20-year global warming potential). Methane can also contribute to ground-level ozone (Bessagnet et al., 2024). CO_2 is the most abundant GHG and is emitted when natural gas and other fossil fuels are combusted, or when it is produced along with methane and then released during natural gas processing.
- Non-GHG air pollutants (referred to as air pollutants throughout this document), such as volatile organic compounds (VOCs), nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and particulate matter (PM). These pollutants can contribute to regional and local air pollution, which can damage the environment and impact human health (EPA, 2023a) For example, VOCs can react with other chemicals to form PM and ozone. Some VOCs emitted from natural gas production processes are also hazardous air pollutants (HAPs), including benzene, ethylbenzene, and n-hexane. HAPs are known to cause cancer and other serious health impacts (EPA, 2023b). NO_x can also react with other chemicals to form PM and ozone (EPA, 2024c)

The focus of this chapter is on GHGs and air pollutants from the equipment and processes associated with the production, processing, transport, and delivery of natural gas to a liquefaction facility. This includes equipment and processes to produce and process natural gas extracted along with crude oil and condensate, often referred to as associated gas. When attributing emissions to the natural gas supply chain, it is important to consider the role of coproducts (e.g., oil, condensate). Well sites and processing facilities require additional equipment, including storage tanks and fractionation plants, when handling heavier hydrocarbons such as crude oil. When conducting life cycle analyses, emissions should be assigned to appropriate fuel value chains, as discussed in detail in the forthcoming National Energy Technology Laboratory natural gas life cycle baseline report.[20] For the purposes of this review, impacts from the oil and natural gas sector are characterized generally without attempting to assign them to a specific hydrocarbon value chain to maintain alignment with the environmental impact studies reviewed and referenced within this study.

A. Key Emissions Sources

Emissions of GHGs and air pollutants can vary significantly across different regions and supply chains, depending on the composition of the natural gas, the type of equipment being used to process and transport it, and the number and size of emissions sources. As produced, natural gas contains methane as well as a mixture of smaller amounts of heavier hydrocarbons (e.g., NGLs), and nonhydrocarbon gases (e.g., CO_2 and water vapor). Some fields, such as the Marcellus Shale, produce gas with a higher concentration of methane and require less processing to remove other components. As natural gas is processed to meet pipeline quality specifications,

[20] This is a forthcoming report, we will include a reference and the official title when it is released.

its composition changes to primarily methane for pipeline transport. According to the Inventory of U.S. GHG Emissions and Sinks, methane content ranges from over 78 percent during production to over 93 percent downstream of processing (EPA, 2024a).

Methane emissions are a significant area of focus for researchers and regulators and are the result of venting or leaking (also referred to as fugitive emissions) of natural gas across all segments of the natural gas supply chain. Vented emissions of methane occur through equipment design or operational practices, such as from the periodic bleed of natural gas from pneumatic valve controllers that control fluid flows, levels, and equipment temperatures and from small pneumatic pumps that add chemicals into the flow stream for various purposes. High emission events, referred to as super emitter events or *abnormal* emission *events,* can result in large quantities of natural gas being released to the atmosphere. In addition, fugitive emissions occur from lower volume continuous or intermittent leaks that originate across the underlying gas system infrastructure, for example, from loose connections between pipes, processing vessels, valves and other equipment of various types and vintages.

Depending on the point in the supply chain and the composition of the natural gas, VOCs and other air pollutants may also be emitted. Emissions from tanks and vessels can include the release of VOCs to the atmosphere during normal operations (e.g., when a tank hatch is opened for inspection). Some VOCs emitted from natural gas production processes are also HAPs, including benzene, ethylbenzene, and n-hexane. CO_2 can also be a component of produced natural gas. Thus, when natural gas is vented or when the gas is processed to remove CO_2, the CO_2 present in the natural gas will enter the atmosphere through venting unless it is captured and geologically stored or otherwise utilized. In 2021, about 1.2 percent of CO_2 emissions from petroleum and natural gas systems was estimated to be the result of such non-combustion releases (NPC, 2024).

Incomplete and partially incomplete combustion of the natural gas used to power a compressor (also referred to as combustion slip or methane slip), or from inefficient flaring, is also a source of methane emissions. Natural gas may be flared (i.e., burned or combusted) in response to emergencies, safety tests, maintenance and repairs, or infrastructure constraints. For example, operators sometimes flare natural gas that cannot be economically stored or transported to market, depending on the regulations in the states in which they operate (EIA, 2024d). In addition to emitting CO_2, depending on conditions and composition of the gas, flaring can also result in the release of methane, NO_x, sulfur dioxide (SO_2), CO, and VOCs (Tran et al., 2024). Plant et al (2022) used airborne sampling to measure flare efficiency[21] in three major gas production regions in the U.S. and found that both unlit flares and incomplete combustion contribute to ineffective methane destruction, with flares effectively destroying only 91.1 percent of the methane routed to the flare for combustion (Plant et al., 2022).

Combustion of natural gas and other fuels to power engines and turbines along the natural gas supply chain can result in emissions of CO_2, SO_2, NOx, and PM. Diesel engines used at well sites to power hydraulic fracturing operations are a source of these emissions – as are turbines at compressor stations along natural gas pipelines. About four percent of U.S. CO_2 emissions stem from energy use in the natural gas supply chain (NPC, 2024).

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[21] The flare efficiency is a measure of the effectiveness of the combustion process to fully oxidize the fuel. When inefficiencies occur, unburned fuel, CO, and other products of incomplete combustion (e.g., soot, VOCs, etc.) are emitted into the atmosphere.

According to the EPA National Emissions Inventory (NEI), the natural gas supply chain (such as processes associated with oil and gas production, petroleum refineries, and transportation and storage of petroleum and natural gas) resulted in the emission of about 2.7 million metric tons of VOCs nationally in 2020 (EPA 2024b). In addition, the EPA's Inventory of U.S. GHG Emissions and Sinks estimates that natural gas and petroleum systems emitted 280 $MMTCO_2e$ of methane, about 28 percent of total anthropogenic emissions of methane in the U.S (EPA, 2024a). According to Subpart C of the GHG Reporting Program (GHGRP), total combustion-related emissions from petroleum and natural gas systems contributed over 211 MMT CO_2e in the 2021 reporting period (EPA 2024k).[22]

There are two primary approaches used to estimate methane emissions, top-down (e.g., aerial studies) and bottom-up (e.g., equipment-level inventories) (Rutherford et al., 2021; Alvarez et al., 2018; Balcombe et al., 2016). A top-down approach measures the atmospheric concentrations by using fixed ground monitors, mobile ground monitors, aircraft, and/or satellite monitoring platforms; aggregates the results to estimate total methane emissions; and allocates a portion of these total emissions to each of the different supply chain activities. A bottom-up approach measures (or estimates) GHG emissions directly for each source of emissions, estimates the number of sources, and then aggregates and extrapolates these measurements to estimate emissions for an entire region or process. Both approaches have advantages and disadvantages.

In some cases, top-down approaches report higher emissions from natural gas systems as compared to bottom-up approaches given they can capture more emissions sources by covering an entire area (Rutherford et al., 2021; Alvarez et al., 2018; Balcombe et al., 2016). However, depending on the methodology, these approaches sometimes fail to distinguish between different sectors, which can lead to incorrect attributions of total methane emissions to specific natural gas activities. Alternatively, bottom-up approaches sometimes fail to capture infrequent high emitting events such as malfunctioning or improperly operated equipment. Considerable recent and ongoing research has been devoted to understanding and reconciling the differences between top-down and bottom-up approaches to estimating methane emissions. Example studies include the following:

- The Colorado State University (CSU) Energy Institute's Basin Methane Reconciliation Study—commissioned by NETL, through the Research Partnership to Secure Energy for America (RPSEA) program—was designed to understand, and potentially reconcile, the persistent gap between top-down and bottom-up methane emissions estimates for production regions (CSU 2018; Vaughn et al., 2018).
- In 2019, Environmental Defense Fund launched the Permian Methane Analysis Project (PermianMAP), a first-ever, near real-time CH_4 monitoring initiative in the world's largest oil field (Environmental Defense Fund, 2021; Lyon et al., 2021). Researchers first began collecting aerial CH_4 data in late fall of 2019 and conducted more than 100 flights across the Permian Basin throughout 2020 and 2021.
- To isolate the disagreement between bottom-up inventories such as EPA's GHGI and other studies, Rutherford et al. (2021) reconstructed EPA's GHGI emissions factors, beginning with the underlying datasets, and identified possible sources of disagreement between inventory methods and top-down studies.

[22] Subpart C includes large emission sources from facilities that emit more than 25,000 $MMCO_2e$ per year and therefore may not be representative on a national level and cannot also not be aggregated at the segment level.

In addition, further discussion of the uncertainty of the modeling approaches and underlying data is discussed in the forthcoming National Energy Technology Laboratory natural gas life cycle baseline report.[23]

B. Impacts on Air Quality

Air pollution impacts human health and the environment through a variety of pathways. Some pollutants are released directly into the atmosphere, while other pollutants are formed in the air from chemical reactions. For example, ground-level ozone forms when emissions of NO_x and VOCs react in the presence of sunlight. Scientific studies have linked air pollution and specific pollutants to a variety of health problems and environmental impacts (EPA, 2024c)

Natural gas development has impacts on local air quality due to emissions from activities such as vehicle emissions associated with well pad development and pipeline construction, well drilling and hydraulic fracturing (“fracking”), the venting or flaring of gas during well development, and related fugitive emissions. There are also impacts due to activities at the completed wells to clean and compress produced natural gas and along the pipelines that deliver the gas to market. Depending on the pollutant, people at greater risk for experiencing air pollution-related health effects may include older adults, children and those with heart and respiratory diseases. The range of potential impacts on air quality, by pollutant type, are discussed below. This is a summary of potential air quality impacts of pollutants emitted by the oil and gas industry and is not intended to establish definitive causation with specific aspects of oil and gas operations.

- VOCs are organic chemicals that have a high vapor pressure at room temperature, causing large numbers of molecules to evaporate or sublimate from the liquid or solid form of the compound (commonly referred to as off-gassing) and enter the surrounding air. There are many different VOCs, including both human-made and naturally occurring chemical compounds. VOCs are released throughout the oil and natural gas supply chain through various operations and equipment sources (CRS 2020). Many VOCs are ozone precursors and form ground-level ozone when sunlight is present through reactions with sources of oxygen molecules that occur in the atmosphere including nitrogen oxides (NO_x) and carbon monoxide (CO) (EPA 2024c). In urban settings, air quality is impacted by VOCs through the formation of ground-level ozone pollution and small particulate matter ($PM_{2.5}$) (NOAA 2024).
- CO is a colorless, odorless gas produced by the incomplete combustion of carbon-containing fuels like natural gas (CARB 2024a). CO is a secondary source of emissions (also called an associated source) that can significantly contribute to air pollution (CRS 2020). These emissions originate from operations associated with the combustion of other fossil fuels to power equipment. There is considerable evidence that CO engages in atmospheric chemical reactions leading to the formation of ozone air pollution (CARB 2024a). CO can also be generated through photochemical reactions in the atmosphere involving methane, non-methane hydrocarbons, other VOCs, and organic molecules present in surface waters and soils (CARB 2024a).
- Ground-level ozone (or tropospheric ozone) is not a direct emission from an anthropogenic source, such as burning natural gas. Rather, it is formed by chemical reactions between NO_x and VOCs in the presence of sunlight (EPA 2024c). As discussed further below, methane is also a precursor to ground-level ozone, contributing to air pollution and smog worldwide (Bessagnet et al., 2024). High ozone concentrations have also been observed

[23] This is a forthcoming report, we will include a reference and the official title when it is released.

in cold months, specifically in high-elevation areas in the western U.S. with high levels of local VOCs and NO_x emissions. Notably, ozone can damage sensitive vegetation during the growing season (EPA, 2024c). Ground level ozone is a harmful air pollutant, due to its effects on people and the environment, and it is a central ingredient in "smog" (EPA, 2024c). Direct exposure to ground-level ozone can harm living cells, organs, and various species, including humans, animals, and plants (Zhang et al., 2019).

- HAPs, also referred to as toxic air pollutants or air toxics, are substances known or suspected to cause cancer, other serious health issues such as reproductive effects or birth defects, and to have negative environmental impacts. Many HAPs are also considered VOCs (Tsai 2016). Among the HAPs emitted from oil and gas systems, VOCs constitute the largest group and generally evaporate easily into the air. EPA currently lists 188 pollutants as HAPs (EPA, 2023b). Emissions from a range of processes and operations at oil and natural gas facilities, including natural gas transmission and storage facilities, commonly contain five HAPs: benzene, toluene, ethylbenzene, mixed xylenes (BTEX), and n-hexane (EPA, 2024d). Notably, benzene emissions negatively impact urban air quality and have been of particular concern for communities, and benzene emission reduction programs have shown a positive impact on air quality (Popitanu et al., 2021, Saha et al., 2024).
- Methane is a hydrocarbon and GHG that is a primary component of natural gas (EPA, 2023c) Methane is also a precursor to ground-level ozone, contributing to air pollution and smog worldwide (Bessagnet et al., 2024). A recent study found that methane is responsible for 35% of global harmful ozone and that ozone-related mortalities due to methane emissions will increase by at least 7% by 2050 compared with 2015, even under the strictest reduction scenarios (Bessagnet et al., 2024). Sources of methane include both natural and anthropogenic, with the carbon from methane becoming CO_2 through an atmospheric oxidation process (Mar et al., 2022).[24]
- Nitrogen oxides (NO_x) are a group of highly reactive gasses also known as "oxides of nitrogen." This group includes NO_2, nitrous acid, nitric acid (HNO_3), and nitric oxide (NO). The EPA's National Ambient Air Quality Standards (NAAQS) uses NO_2 as the indicator for the larger group of NO_x. The two most prevalent nitrogen oxides are NO_2 and nitric oxide (NO), and the combination is often referred to as NOx (CARB 2024b). NO_x is emitted at natural gas sites through the combustion of natural gas and diesel during activities such as flaring, driving compressors, and operating engines, drills, heaters, and boilers (CRS 2020). NO_2 and other NO_x compounds react with other chemicals in the air to form both particulate matter and ozone (EPA, 2024e) NO_2 is an important precursor to anthropogenic ozone and plays a crucial role in the formation of various airborne toxic substances including HNO_3, fine particulate matter, peroxyacetyl nitrate, nitrosamines, and nitro-polycyclic aromatic hydrocarbons (nitro-PAHs) (CARB 2024b). NO_2 and other NO_x compounds also interact with water, oxygen and other chemicals in the atmosphere to form acid rain that negatively impacts ecosystems such as lakes and forests (EPA, 2024e)
- Particulate matter (PM), also known as particle pollution, refers to a blend of solid particles and liquid droplets present in the air (EPA, 2024f) During natural gas combustion, PM is emitted. Some PM, like dust, dirt, soot, or smoke, are large or dark enough to be visible to the naked eye, while others are imperceptible. Most PM is formed in the atmosphere through complex chemical reactions involving substances like sulfur dioxide and nitrogen oxides, that are released from power plants, industrial facilities, and automobiles (EPA,

2024f). Fine particles ($PM_{2.5}$) are the central cause of haze, which creates reduced visibility (EPA 2024g) PM can be carried over long distances by the wind before eventually settling on land or water. Potential effects of PM include acidifying lakes and streams, disrupting the nutrient balance in coastal waters and major river basins, depleting soil nutrients, harming sensitive forests and agricultural crops, affecting ecosystem diversity, and contributing to acid rain phenomena (EPA, 2024g).

- SO_2 is a highly reactive gas within the sulfur oxides (SO_x) group that can be released by internal combustion engines used in natural gas activities. Fossil fuel combustion at power plants and other industrial facilities emits the most SO_2 emissions out of all sectors. SO_2 is used as the indicator for the larger group of SO_x. Other SO_x compounds, like sulfur trioxide, are at much lower concentrations in the atmosphere compared to SO_2. SO_x at high concentrations can damage tree and plant foliage, reduce growth, and contribute to acid rain, soil and water acidification, which negatively impacts sensitive ecosystems. Finally, SO_x can interact with atmospheric compounds to form fine particles that diminish visibility, leading to haze (EPA, 2024h, CARB, 2024c).

C. Global Climate Effects

The natural gas sector is one of the largest sources of anthropogenic methane emissions in the U.S (EPA 2024a). Emissions of methane from human activities are responsible for about 30 percent of the rise in global temperatures since the Industrial Revolution (IEA, 2023). The Intergovernmental Panel on Climate Change (IPCC) 2023 Sixth Assessment Report (AR6) Synthesis Report finds that a continued rise in GHGs globally can lead to widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere. Human-caused climate change is already affecting many weather and climate extremes in every region of the globe, which has contributed to widespread adverse impacts and related losses and damages to nature and people, and has disproportionately affected vulnerable communities (IPCC, 2023).

The U.S. Global Change Research Program (USGCRP) Fifth National Climate Assessment finds that the effects of human-caused climate change are worsening across every region of the U.S. However, rapidly reducing GHG emissions could limit future warming, and deeper cuts in global net GHG emissions are needed, along with accelerated adaptation efforts, to prevent severe climate risks to the U.S. from continuing to grow (USGCRP, 2024). The latest scientific information on the effects of human-caused climate change and how the U.S. is addressing those can be found in the USGCRP Fifth National Climate Assessment Report (USGCRP 2024). Additional information about the life cycle impacts of natural gas is available in the National Energy Technology Laboratory natural gas life cycle baseline report.[25]

D. Regulation

Multiple federal, state, local, Tribal, and territorial efforts to reduce air pollution and greenhouse gases are underway. At the federal level, EPA is the primary regulator of emissions from natural gas operations. In August 2022, the Inflation Reduction Act (IRA) provided new authorities, organized under Section 136 of the Clean Air Act (CAA), to reduce methane emissions from the petroleum and natural gas sector through the creation of the Methane Emissions Reduction Program (MERP).[26] In addition, in December 2023, EPA finalized updates to its New Source Performance Standards (NSPS) to reduce methane and VOCs from new, modified and

[25] This is a forthcoming report, we will include a reference and the official title when it is released.
[26] EPA. Methane Emissions Reduction Program. Available at: https://www.epa.gov/inflation-reduction-act/methane-emissions-reduction-program

reconstructed sources, as well as new Emissions Guidelines which set procedures for states to follow as they develop a State Implementation Plan (SIP) to limit methane from existing sources (EPA, 2024i). Several other agencies and states have also promulgated requirements to reduce emissions from oil and gas operations in response to concerns about local ozone pollution, as well as climate change in the global context. Key regulations, at the state and federal levels, to reduce air and greenhouse gas emissions are discussed further below.

1. Federal Regulation

The Clean Air Act (CAA) requires the EPA to regulate HAP emissions from stationary sources through the National Emission Standards for Hazardous Air Pollutants. The CAA also requires EPA to set NSPS for industrial categories that cause, or significantly contribute to, air pollution that may endanger public health or welfare. EPA is required to review these standards every eight years. Additional Federal regulations include the NAAQS for six "criteria pollutants," which EPA is also required to set under the CAA. The CAA requires EPA to review standards periodically to determine whether changes are warranted.

In December 2023, EPA finalized NSPS to reduce methane and VOC emissions from new, modified, and reconstructed oil and gas sources (referred to as OOOOb). This rule expanded the requirements of the previous two NSPS rulemakings (OOOO and OOOOa) (EPA, 2024i), promulgated in 2012 and 2016, respectively. The final rules package also includes, for the first time, requirements for states to develop plans to limit methane emissions from existing oil and gas sources. EPA detailed the existing source requirements in Emissions Guidelines (OOOOc) that include presumptive standards for states to use as they are developing their SIPs (EPA, 2024i).

In addition, under Congressional direction, the MERP authorized the EPA to develop a Waste Emissions Charge (WEC) for methane (EPA, 2024j). Petroleum and natural gas facilities that emit more than 25,000 metric tons of CO_2 equivalent per year and are required to report under Subpart W of the GHGRP are subject to the WEC provisions. The WEC for methane applies to oil and natural gas facilities that exceed waste emissions thresholds established by Congress through MERP and that are not otherwise exempt from the charge. In April 2024, EPA finalized amendments to Subpart W to allow owners and operators of applicable facilities to submit to the GHGRP empirical emissions data to demonstrate the extent to which a charge is owed under CAA section 136 and to reflect the total methane emissions (and waste emissions) more accurately from applicable facilities (EPA, 2024k).

Beyond EPA, other Federal agencies are taking actions that are expected to reduce methane and air pollutants from oil and gas operations. For example, in March 2024, BLM finalized new regulations to reduce natural gas waste from venting, flaring, and leaks that occur during oil and gas production activities on Federal and Indian leases (BLM, 2024). The new BLM Waste Prevention rule includes requirements such as provisions for investing in technology upgrades (e.g., use of low-bleed pneumatic equipment and vapor recovery for oil storage tanks), maintaining a leak detection and repair program, and minimizing the waste of associated natural gas produced along with oil when oil production is the primary activity and the principal commodity being produced.

Additionally, under the Protecting our Infrastructure of Pipelines and Enhancing Safety Act of 2020, the Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) is developing rules that seek to reduce methane emissions from new and existing gas transmission, distribution, and regulated gas gathering pipelines; underground natural gas storage facilities; and LNG facilities (PHMSA, 2024).

2. State Regulation

Several states have regulations in place aimed at reducing emissions of ozone precursors – NO_x and VOCs - as well as achieving methane and other GHG emissions reductions from oil and natural gas operations (Greif, 2023). While not an exhaustive list, this section includes a brief overview of a sample of State regulations that cover air emissions from oil and gas operations – including recent updates and amendments to expand coverage of VOCs, methane and GHG emissions.

As one example, the state of Colorado has extensive air quality regulations in place and recently finalized new regulations to expand coverage of GHG emissions. In 2022, the Colorado Department of Public Health and Environment (CDPHE) adopted revised and new requirements requiring direct regulation of oil and gas equipment or processes, an upstream GHG intensity program, and midstream GHG emission reduction plans. In 2023, the CDPHE Air Pollution Control Division finalized a new rule that requires GHG intensity targets to reduce the amount of GHGs emitted per unit of production, and to provide flexibility to operators to achieve that reduction. More recently, in April 2024, CDPHE published an Oil and Natural Gas Methane Intensity Verification Protocol, which provides instructions for verifying and reporting methane emissions and calculated GHG intensities required by Regulation 7 (CDPHE, 2024).

In Pennsylvania, the Pennsylvania Department of Environmental Protection (PADEP) published the “Control of VOC Emissions from Unconventional Oil and Natural Gas Sources” and “Control of VOC Emissions from Conventional Oil and Natural Gas Sources” in December of 2022 (PADEP, 2022). These rulemakings provided reasonably available control technology (RACT) requirements and RACT emission limitations for conventional and unconventional oil and natural gas wells and other sources of VOC emissions, such as natural gas-driven continuous bleed pneumatic controllers, compressors, and fugitive components, gathering and boosting stations and natural gas processing plants.

As part of its ozone attainment initiative, and as mandated under the New Mexico Air Quality Control Act, the New Mexico Environment Department (NMED) is also developing a draft rule to establish emissions standards for VOCs and NOx for oil and gas upstream and midstream (production and processing) and focusing on sources located in areas of the state where ozone concentrations are exceeding 95 percent of the national ambient air quality standard (NMED, 2024).

CHAPTER 3: WATER WITHDRAWALS AND WATER MANAGEMENT

The primary water-related effects associated with natural gas production from unconventional reservoirs in the U.S. are: 1) large volumes of fresh water (both surface and groundwater) used for hydraulic fracturing and 2) potential for surface or groundwater contamination from subsurface migration of fluids, spills on the surface, and management of produced waters following well development (i.e., fluids that return to the surface through the wellbore), including chemicals used during well completion and production operations. Water withdrawals for natural gas development can impact local watersheds, through changes in both availability and quality of water sources. Produced water has the potential to introduce pollutants to surface or groundwater, if not managed properly.

A. Water Withdrawals for Hydraulic Fracturing

Since 2014, oil and natural gas producers have used a combination of large volume, multi-stage hydraulic fracturing and horizontal drilling for most new natural gas wells in the U.S (EIA, 2018). Hydraulic fracturing is the process of pumping water mixed with sand (or other "proppants") and chemical additives underground through a wellbore at a pressure sufficient to cause a target rock formation to break (i.e., fracture) and to hold (or "prop") such fractures open to extract hydrocarbons previously trapped there (U.S. Geological Survey [USGS], 2019).[27] As the rock is fractured, natural gas that would have otherwise remained trapped is able to flow into a wellbore and rise to the surface (USGS, 2019). Water is the main component of the fluids used for hydraulic fracturing, generally making up 90 to 97 percent of the fluid by volume (EPA, 2016).

Developers generally use some combination of fresh or brackish water from surface and groundwater sources, flowback water, and/or produced water.[28] Fracturing flow back water is water that has been returned to the surface after being previously injected for hydraulic fracturing (Depending on the produced water quality, it may require treatment using a range of technologies before re-use in hydraulic fracturing). The amount of water used to hydraulically fracture a well varies depending on the region, the geology, the depth, thickness and extent of the shale formation, the technology used, the length of the horizontal well, operator preferences, availability of nearby water supplies, and regulatory requirements.

Even considering these variations, researchers have found that the average total volume of water (including both fresh and brackish surface or groundwater or recycled produced water) used for hydraulic fracturing on a per well basis has increased over time. An EPA study on the effects of hydraulic fracturing on drinking water supplies, which was published in 2016, found that in the 2011-2013 timeframe, the median volume of water used, per well, for hydraulic fracturing was approximately 1.5 million gallons (5.7 million liters) (EPA, 2016). In its 2019 Produced Water Report, the Groundwater Protection Council (GWPC), an association of state ground water regulatory agencies, estimated that the average multi-stage hydraulic fracturing of a single horizontal shale gas well could use an average of about 12 million gallons of water (GWPC, 2019).

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[27] The specific types of chemical additives used, and the proportions of each, depend on the type of rock formation that is being fractured and the design of the hydraulic fracturing treatment. Additives function as friction reducers, biocides, oxygen scavengers, fluid stabilizers, and mineralogically active acids, all of which are necessary to optimize production. The chemical composition of these fluids and the purposes of the additives are described in more detail later in this chapter.

[28] Flowback water is hydraulic fracturing fluid that returns the surface. Produced water is naturally occurring water that is extracted from the rock formation. See https://www.americangeosciences.org/critical-issues/faq/what-produced-water

In 2023, the *New York Times* used FracFocus[29] data to estimate that while in 2012, the average hydraulically fractured well used less than 5 million gallons of water, by 2023, the average well used over 16 million gallons and that some wells used up to 40 million gallons (Tabuchi and Migliozzi, 2023).[30]

The increasing lateral length of horizontal wells is the main reason that the amount of water required to fracture a well has risen (GWPC, 2023b). EIA also reported that the average footage of wells drilled more than doubled from 7,300 feet per well to 15,200 feet per well between 2010 and 2021 (EIA, 2022).[31]

Water consumption for hydraulic fracturing has been described as relatively minor compared with other industrial water uses in different regions and over different time periods (Kondash et al 2018, 2017). However, large withdrawals of water from local surface and groundwater sources can be locally significant. Large withdrawals of water for natural gas well completion operations also can occur over a very short period of time, rather than over many months as is more typical for other users (such as agriculture), which can result in entire water bodies briefly going dry. A 2020 literature review found that researchers have paid relatively little attention to the potential impacts of large volumes of water withdrawals from groundwater and surface water resources for hydraulic fracturing. Although there are many articles in the scholarly literature describing potential impacts—such as reduced volumes of water in rivers and streams, regional water shortages, competition over water resources, reduced quantities of water for human use, and erosion of habitat—few studies have quantified these effects (Saha and Quinn, 2020).

EPA's 2016 study on impacts of hydraulic fracturing on drinking water sources found several examples of local impacts on drinking water quantity in areas with increased hydraulic fracturing activity. These examples included an instance in 2011 where drinking water wells located within the Haynesville Shale play area in Louisiana were running out of water, and an instance in 2009 where groundwater levels in an area in Texas dropped by 100 feet to 200 feet. EPA's report also cited studies in the Upper Colorado and Susquehanna River basins that found minimal impacts on drinking water resources from hydraulic fracturing withdrawals (EPA, 2016).

Additional work in this area includes work by Brien, et al (2023), who found that groundwater withdrawals from the Eagle Ford Shale in Texas between 2011 and 2020 caused water levels in nearby wells to decrease by 20 meters. Unruh et al (2021) studied the Haynesville Shale and the Tuscaloosa Marine Shale in Louisiana and found that, based on historic and future projected hydraulic fracturing scenarios, while demands on surface water resources places only low stress on most nearby watersheds, they do make groundwater resources vulnerable.

Increasing demand for water for hydraulic fracturing has incentivized operators to seek supplemental sources of water and alternatives to local freshwater supplies. Producers are

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[29] FracFocus is a national registry for operators to report the chemicals they use in hydraulic fracturing operations. It is managed by the Groundwater Protection Council. Operators may, but do not always, include the volume of water used for hydraulic fracturing in the data that they submit, and they do not have the option of indicating the source of the water used.

[30] For context, according to the U.S. Geological Survey, in 2015 water use in the United States was estimated to be about 322 billion gallons per day. https://www.usgs.gov/special-topics/water-science-school/science/total-water-use-united-states

[31] According to EIA, the total number of crude oil and natural gas wells fell by 66 percent between 2010-2021, but as the average footage of wells that were drilled increased, wells became more productive, and during that time period crude oil production more than doubled, and natural gas production increased 55% (EIA, 2022)

increasingly prioritizing the use of brackish surface or groundwater, treated produced water, and municipal wastewater effluent (GWPC, 2023a). For example, in 2023, about 50 percent of the water used for hydraulic fracturing in the Permian Basin was recycled produced water (Norton, 2024).

B. Management of Potential Surface and Groundwater Contamination

Producers must take care to properly manage and dispose of both hydraulic fracturing fluid flowback and produced water to avoid contamination of surface and ground water. As oil and gas wells are sometimes located near drinking water wells (although at significantly different depths), the potential for contamination is often an issue of concern to local residents.

Although hydraulic fracturing fluid that flows back after fracturing consists overwhelmingly of water, it also includes chemicals such as acids, biocides, viscosity breakers, clay stabilizers, corrosion inhibitors, polymer crosslinkers, friction reducers, gelling agents, iron precipitation controllers, emulsion breakers, pH-adjusting agents, scale inhibitors, and surfactants.[32] Many of these chemicals are toxic to humans and ecosystems (Abraham et al., 2023; Wollin et al., 2020; Elliott et al., 2016; and EPA, 2016). Produced water characteristics vary by formation and depth but generally include suspended solids, oils and grease, salts, dissolved organic compounds, metal ions, dissolved gases, microorganisms, chemical additives from past fluid injection operations, and sometimes naturally occurring radioactive materials (GWPC, 2023a; and Amakiri et al., 2022).

One difficulty that researchers have encountered in assessing the impacts of natural gas production on surface and groundwater is that there are few places where baseline environmental monitoring occurred before production activities began (Brantley et al., 2018; Mauter et al., 2014; and Soeder et al., 2014)

There are three major water contamination concerns around natural gas development: 1) the upward migration of fluids (injected hydraulic fracturing fluids, stray hydrocarbons) into groundwater aquifers; 2) surface spills of oil and gas production fluids, including produced water; and 3) the discharge of inadequately treated produced water to surface water sources.

1. Subsurface Migration of Fluids

Many studies have focused on understanding the risks associated with the subsurface migration of fluids injected into or produced from unconventional oil and gas wells. Most of these studies have focused on either fracturing fluid migration or stray gas (i.e., methane) migration.

Migration of fracturing fluid from the deep subsurface into shallow groundwater is very rare. To date, it has only been documented in a few locations, such as Pavilion, Wyoming, where the hydraulic fracturing process was mismanaged (DiGiulio and Jackson 2016). Several numerical modeling studies have shown that low formation permeabilities and capillary imbibition[33] of injected water into partially saturated shales act to sequester most hydraulic fracturing fluid within the subsurface (Birdsell et al., 2015).

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[32] The specific chemicals used are too numerous to list here, but can be found at fracfocus.org/explore/chemical-names-and-cas-registry-numbers.

[33] Capillary imbibition refers to the “capillary-driven invasion of wetting fluid to minimize the free energy of the multiphase system,” such as “plant roots taking up water, reservoir rocks absorbing brine and a tissue paper wiping stains.” Jianchao et al 2022.

Gas migration along wellbores with casing cement integrity issues, from the producing formation upwards into groundwater aquifers, is a greater concern than fracturing fluid contamination, but also still somewhat rare. Well integrity issues can include inadequate length of surface casing, poor cement integrity, and leaks in production casing and wellhead seals. Methane is non-toxic and commonly present in shallow groundwater, from natural sources. However, methane migrating at higher concentrations from an oil or gas well can pose an explosion or asphyxiation hazard if degassed in a confined space (Penn State Extension, 2022). Methane also induces a reduction-oxidation (redox) effect that mobilizes arsenic in groundwater and can lead to the formation of harmful compounds (Glodowska et al., 2020).

In regions with natural gas production, it can be difficult to determine whether stray gas in water supplies is caused by gas production activities or other sources such as landfills, coal beds, abandoned oil and gas wells, leaking gas pipelines, leaking gas storage formations or microbial gas generated naturally in shallow aquifers (Soeder et al., 2014).

Some researchers have established causal links between incidents of methane migration and surface and groundwater quality in the Marcellus Shale region (Abdalla et al., 2016; Brantley et al., 2018; and Llewelyn et al., 2015). Another study in Colorado found that well integrity issues, not high-volume hydraulic fracturing, were responsible for the small number of incidents of stray gas contamination of water wells from oil and gas production (Sherwood et al., 2016).

2. Surface Spills

Wastewater spills appear to pose more of a risk than subsurface migration pathways from oil and gas development.

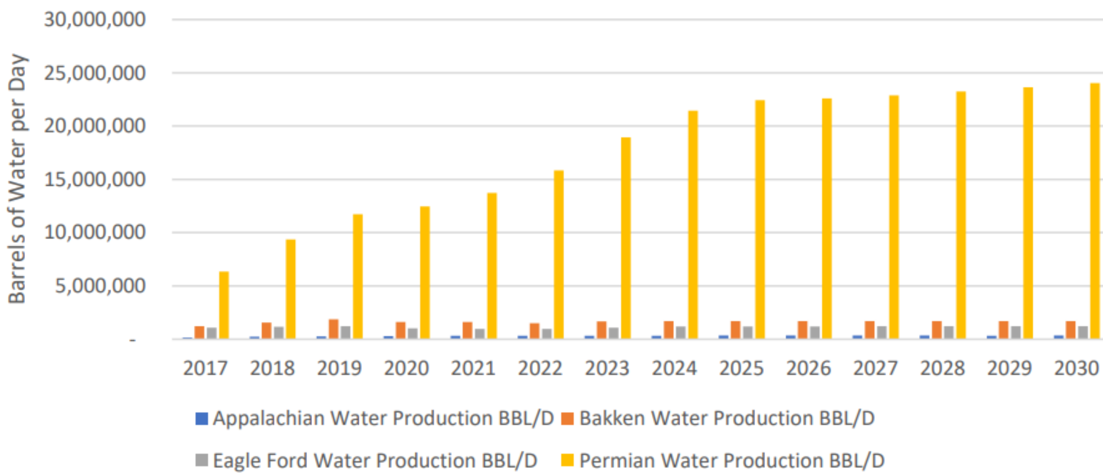
State authorities require that operators report spills of fracturing fluid, chemicals or produced water. Although federal law sets minimum standards for reporting under the Clean Water Act and CERCLA, states have different reporting requirements that make comparisons of spill frequency and spill impacts among states difficult. However, leaks and spills are regular occurrences in natural gas production areas. State databases for spills in Colorado, New Mexico, North Dakota, and Pennsylvania between 2005 and 2014 show 6,622 reported spills of chemicals, waste materials or oil and gas associated with unconventional oil and gas wells (Maloney et al., 2016). From 2005-2014, in Colorado, New Mexico, North Dakota, and Pennsylvania from 2 to 16 percent of wells reported a spill (Patterson et al., 2017). Data from the state of New Mexico show that between 2000 and 2023, the state had records of over 10,000 produced water spills, totaling about 1.4 billion barrels of wastewater (Kashani et al 2024).

Most leaks and spills are accidental. The greatest risk for contamination of surface waters is from uncontrolled releases during hydraulic fracturing, leaking or overflowing water storage impoundments, inadequate wastewater treatment prior to discharge, or release of fluids during transport and disposal (Soeder et al., 2014). One study estimated that about 50 percent of spills in oil and gas operations are related to fluid storage and moving of fluids in pipelines (Patterson et al., 2017).

Intentional illegal dumping of produced water and other wastes also occurs. Although the volume dumped appears to be small compared to the volume of wastewater that is properly handled, dumped water and wastes can be harmful to the environment. Kashani et al (2024) studied 39 illegal dumps of produced water, totaling about 4,000 barrels, in just one two-week period in southeastern New Mexico in 2017. These dumps caused significant changes in soil chemistry and microbial community structure, most likely due to the high salinity of the produced water.

3. Management of Wastewater (Produced Water)

Figure 3 from the GWPC shows there is significant variance among producing regions as to the amount of produced water generated from oil and gas production, both historically and projected into the future. Producers in the Permian Basin of Texas and New Mexico (the largest oil and gas producing basin in the U.S.) generate produced water volumes that can be an order of magnitude higher than producers in the Appalachian Basin, Bakken, or Eagle Ford play areas, and these volumes are projected to rise through 2030 as oil and gas production continues to increase (GWPC, 2023a).



Source: GWPC, 2023a

Figure 3. Produced Water by Basin, barrel per day (BBL/D)

By 2022, produced water generation across the Permian Basin averaged 15.8 million bpd (GWPC, 2023a). However, produced water volumes in other basins including the Appalachian, Bakken and Eagle Ford basins were only small fractions of this total – for example, in the Appalachian basin, produced water totaled about 0.33 million bpd in 2023 (Bennett, 2023).

There are a finite number of options for managing produced water: (1) underground injection (i.e., disposal) into saltwater disposal wells (SWDs), (2) treatment and recycling for re-use in hydraulic fracturing, (3) desalination for beneficial reuse outside oil and gas applications (e.g., irrigation, industrial use, etc.), or (4) discharge (limited to low-salinity brines only) and / or evaporation (limited volumes in certain climates) (Drouven et al., 2023; and GWPC, 2023a). When produced water cannot be economically recycled or reused, it is typically disposed of in SWDs in areas where such wells are available. In terms of absolute volumes, the industry currently relies heavily on underground injection into SWDs as a means of managing produced water (especially in the Permian Basin). These disposal activities are seen as possible contributors to the induced seismicity experienced in several plays (as discussed in Chapter 4).

Produced water is sometimes stored at the well-pad in tanks or pits before being treated and disposed of or recycled, but generally the fluids are transported off-site via trucks or dedicated water pipelines immediately after they are produced. Over the past decade, midstream water management companies have emerged to treat, transport, and recycle produced water. Today, these companies manage large water networks that are transporting millions of barrels of produced water daily via hundreds of miles of pipeline infrastructure – which has eliminated millions of truckloads of water from roadways (Dunkel, 2023; and GWPC, 2023a).

The major challenges to beneficial reuse of produced water (i.e., for applications outside of the oil and gas industry) is the lack of state regulatory frameworks governing such activities, the need for desalination of the high salinity water and managing the associated products and wastes that are generated. Although the most common water desalination technology is reverse osmosis (RO), the concentration of total dissolved solids in produced water is usually too high for that technology. Thermal and membrane-based desalination processes could potentially be used, but both the capital and the energy costs are higher than for RO processes (GWPC, 2023a).

As an alternative to desalination, operators have increasingly been pursuing treating and reusing produced water for use in hydraulic fracturing. This approach varies by region in terms of the volumes processed and the technologies employed. In Pennsylvania, for example, over 80 percent of water produced from fractured wells has consistently been recycled for subsequent hydraulic fracturing purposes (GWPC, 2023a). In the Permian Basin, water consultancy Deep Blue estimates that in 2023, about 50 percent of the water used for hydraulic fracturing was treated produced water, and that by 2030 this number will exceed 80 percent as recycling capacity increases to over 6 million barrels per day (Norton, 2024).

Concerns about induced seismicity from SWDs, combined with the increasing need for fresh water in arid regions, have inspired several initiatives for the surface-level management of produced water, including for beneficial reuse. DOE sponsors several initiatives, including the National Alliance for Water Innovation and the Produced Water Optimization Initiative, or Project PARETO (Drouven, 2022). Texas, New Mexico and Colorado are each home to consortia studying produced water reuse (GWPC, 2023a).

C. Potential Community Effects

The impacts on water quality, quantity, and infrastructure are concentrated closest to natural gas production operations, although there is the potential for more dispersed impacts as a result of wastewater disposal. Impacts to water quality and quantity may also be more acute and/or accelerated in areas already experiencing water scarcity (Black et al., 2021; and EPA, 2016) and in places already experiencing water contamination (Kondash et al., 2018). Researchers and NGOs also note the potential for long-lasting impacts and extended cleanup operations resulting from water contamination, as well as the relative lack of research and “potential for surprising and unwelcome links” between natural gas production operations and water resources (Willow and Wylie, 2014) (more wide-ranging impacts are also covered in Chapter 5 on Land Use Development).

As described in previous sections, natural gas production activities can impact drinking water resources under some circumstances. When such contamination impacts drinking water supplies, it may raise the risk of public health effects (EPA, 2012; EPA, 2016; and Yost et al., 2016). However, while adverse health effects have been associated *generally* with natural gas development, no studies have concretely linked such health impacts to water contamination specifically (Deziel et al., 2020).

Both scholarly research and reports by NGOs show community concern about potential impacts on water quality and quantity, with some variation by region. Concerns include depletion of water resources, particularly for rural communities in arid and semi-arid regions and those that rely on well water; contamination of fresh surface or groundwater, particularly in places like Pennsylvania that have already experienced drinking water contamination due to mining or natural methane migration; environmental degradation due to spills or leaks of fracturing chemicals into water systems; and fears that developers will not be sufficiently regulated or held accountable for any impacts that occur (Black et al., 2021; Brasier et al., 2021; Kroepsch, 2019; Neville et al., 2017; Willow and Wylie, 2014; and Wrenn et al., 2016).

In response to these and other concerns, water monitoring and mapping projects comprise a subset of citizen science projects documenting the impacts of hydraulic fracturing (Penningroth et al., 2013; and Wylie and Albright, 2014). Additionally, while wastewater may present economic growth opportunities as a source for treatment for beneficial use or mineral recovery operations, wastewater can be challenging to treat, manage, and transport, and may not be perceived by some as safe for reuse even after treatment (NASEM, 2017). Reinjection of wastewater also raises concerns about induced seismicity (detailed in Chapter 5).

D. Regulatory Framework

There are a number of statutes and regulations related to water use and management in oil and gas operations. These include federal requirements to review the potential impacts of proposed actions as well as requirements for setbacks and limitations that may be established under state laws.

1. Key Federal Statutes and Regulations

The National Environmental Policy Act (NEPA)[34] requires the analysis of potential environmental impacts of proposed federal actions, such as approvals for hydrocarbon exploration and production on federal lands.

Commonly known as Superfund, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)[35] created a tax on the chemical and petroleum industries and provided broad Federal authority to respond directly to releases or threatened releases of hazardous substances that may endanger public health or the environment. Natural gas releases do not require notification under CERCLA, but other hazardous substances may be released in reportable quantities during natural gas production.

The Clean Water Act (CWA)[36] makes it unlawful to discharge any pollutant from a point source into navigable waters, unless a National Pollutant Discharge Elimination System (NPDES) permit is obtained. Stormwater runoff containing sediment that could cause a water-quality violation requires a permit under CWA decisions. Beneficial uses of surface waters are protected under Section 303 of the CWA.

The CWA effluent guidelines program sets national standards for industrial wastewater discharge to surface waters and municipal sewage treatment plants based on the performance of treatment and control technologies.[37] Effluent guidelines for onshore oil and natural gas extraction facilities prohibit the discharge of pollutants into surface waters, although some permit exceptions may allow for discharge under unique conditions.[38] In 2016, the EPA promulgated pretreatment standards for the Oil and Gas Extraction Category (40 CFR Part 435) under the Onshore

[34] 42 U.S.C. §§ 4321 et seq
[35] 42 U.S.C. §§9601-9675
[36] 33 U.S.C §§ 1251 et seq.
[37] EPA. Effluent Guidelines. Available at: https://www.epa.gov/eg
[38] 40 CFR Part 435.

Subcategory (Subpart C). The standard prohibits discharge of wastewater pollutants from onshore unconventional oil and natural gas extraction facilities to publicly owned water treatment works (POTWs).[39]

The Emergency Planning and Community Right-to-Know Act[40] obligates industry to report on the storage, use, and release of certain chemicals to federal, state, tribal, territorial, and /or local governments. It also requires these reports to be used to prepare and protect communities from potential risks.

The Oil Pollution Act[41] identifies spill prevention requirements, reporting obligations, and response planning (measures that will be implemented in the case of release of oil or other hazardous substances).

The Resource Conservation and Recovery Act (RCRA)[42] establishes the framework for a national system of solid and hazardous waste control. The Solid Waste Disposal Act Amendments of 1980 temporarily exempted drilling fluid, produced water, and other wastes associated with the exploration, development, and production of crude oil, natural gas, and geothermal energy from regulation under Subtitle C of RCRA until further study of the associated risks had been completed.[43] In 1988, EPA issued a final determination that maintained the exemption from Subtitle C of RCRA.[44]

The Spill Prevention Control and Countermeasure (SPCC) rule,[45] Section 311(j)(1)(C) of the Clean Water Act, provides a robust framework to help facilities prevent a discharge of oil into navigable waters or adjoining shorelines. By requiring covered facilities to develop and implement an SPCC Plan, operators are well positioned to prevent, respond to, and control potential spills and the environmental harm they could cause.

The Safe Drinking Water Act (SDWA)[46] includes provisions to prevent injection wells from contaminating underground sources of drinking water. EPA regulates the construction, operation, permitting, and closure of injection wells used to place fluids underground for storage or disposal through its Underground Injection Control (UIC) program. The UIC program consists of six classes of injection wells. EPA has approved UIC primacy programs for multiple well classes in 31 states and three territories, in which the Agency grants delegated authority to a state, territory or tribe to administer the program according to federal standards. Multiple well classes generally include Class I, II, III, IV, and V. EPA retains direct implementation authority for Class II wells in Florida and Idaho. Seven states and two tribes have approved primacy programs for Class II wells

[39] 40 CFR Part 435 Subpart C. The term "Publicly Owned Treatment Works or POTW" means a treatment works as defined by section 212 of the Act, which is owned by a State or municipality (as defined by section 502(4) of the Act). This definition includes any devices and systems used in the storage, treatment, recycling and reclamation of municipal sewage or industrial wastes of a liquid nature. It also includes sewers, pipes and other conveyances only if they convey wastewater to a POTW Treatment Plant. The term also means the municipality as defined in section 502(4) of the Act, which has jurisdiction over the Indirect Discharges to and the discharges from such a treatment works. 40 CFR 403.3(q).
[40] 42 USC Ch. 116
[41] 33 U.S.C. ch. 40 § 2701
[42] 42 U.S.C. §§ 6901 et seq
[43] Solid Waste Disposal Act Amendments of 1980 (Pub. L. 96-482), 42 U.S.C. 6982 (1980)
[44] Regulatory Determination for Oil and Gas and Geothermal Exploration, Development and Production Wastes, 53 FR 25447 (Jul 6, 1988).
[45] 40 CFR part 112
[46] 42 U.S.C. §300f et seq

only. Louisiana, North Dakota, and Wyoming, are the only states with primacy for all well classes (I, II, III, IV, V, and VI). EPA implements the Class VI program in all other states, territories, and tribes. Additionally, EPA directly implements the full UIC program in eight states, two territories, the District of Columbia, and all Indian tribes (except for class II wells on Navajo and Fort Peck).[47]

The Energy Policy Act of 2005[48] excludes hydraulic fracturing (except when diesel fuels are used) for oil, natural gas, or geothermal production from regulation under the UIC program. This statutory language caused some regulators and some within the regulated community to raise questions about the applicability of UIC permitting practices.[49] As a result of these developments, EPA developed revised UIC Class II permitting guidance specific to oil and natural gas hydraulic fracturing activities using diesel fuels (EPA, 2024m). Although this guidance was developed specifically for hydraulic fracturing operations where diesel fuels are used to enhance well stimulation, many of the recommended practices are consistent with best practices for hydraulic fracturing in general. For example, similar regulatory language can be found in state mandates as well as model guidelines for hydraulic fracturing developed by industry and stakeholder organizations. Where EPA is the permitting authority, the federal guidance outlines for permit writers 1) the existing Class II requirements for diesel fuels used in hydraulic fracturing, and 2) technical recommendations for consistently and effectively permitting those wells (EPA, 2024n).

2. State and Tribal Regulation

State regulation related to water use and management varies widely by state, and each has different reporting requirements for spills, and different setbacks for streams and drinking water wells (Maloney et al., 2016). State regulators in oil and gas producing states have taken a variety of actions to meet the challenges of water acquisition and management for oil and gas operations. Some of these actions that relate to induced seismicity resulting from wastewater injection are described in Chapter 4 of this report. Many states also require operators to disclose the chemicals used in hydraulic fracturing through the FracFocus database.[50] More information on state actions regarding produced water can be found in the Groundwater Protection Council's 2023 Produced Water Update, including actions in some states to define and require best practices for wastewater management, create new rules for injection wells and beneficial reuse, and conduct research (GWPC, 2023a).

Lastly, under Section 401 of the CWA, states and authorized Tribes are empowered to either grant, reject, or waive certification of proposed oil and gas projects with federal licenses or permits that they find may lead to incidents resulting in discharges into waters of the U.S. states and authorized Tribal governments (EPA, 2023e).

[47] EPA. Primary Enforcement Authority for the Underground Injection Control Program. Available at: https://www.epa.gov/uic/primary-enforcement-authority-underground-injection-control-program-0

[48] 119 Stat. 594

[49] EPA. Providing Regulatory Clarity and Protections Against Known Risks. Available at: https://www.epa.gov/uog/providing-regulatory-clarity-and-protections-against-known-risks

[50] FracFocus.org reports that 27 states now allow or require companies to report this data.

CHAPTER 4: INDUCED SEISMICITY

Seismicity refers to vibrations of mechanical energy that pass through the earth, in a manner similar to the way that sound waves travel through the atmosphere. The seismic activity of a region is defined by the frequency, type, and magnitude of all seismic events (e.g., earthquakes or tremors) experienced over a period of time. The term “induced seismicity” refers to seismic events precipitated by human activities – in contrast to natural events, including earthquakes, which arise from tectonic and magmatic forces.

There is potential for induced seismicity to arise from various large-scale engineering activities, such as mining, geothermal energy production, underground injection disposal operations, and oil and gas fluid production and injection operations. Seismic vibration can be triggered by the increased underground pressure and stress created by injecting fluids into geologic formations. Activities associated with oil and gas production, including injecting produced water and wastewater into saltwater disposal wells (SWDs) for disposal and high-pressure injection of working fluid to induce hydraulic fracturing, have been linked to induced seismicity in various geologic settings and jurisdictions around the world (Skoumal, Brudzinski, and Currie, 2015; Schultz et al., 2020; Skoumal et al., 2020; USGS, 2022; and USGS, 2023a-2023g).

A. Understanding of Induced Seismicity

Underground injection is the practice of pumping produced water and wastewater deep underground into highly permeable, porous subsurface rock formations where it can be permanently stored, and it is one of the most commonly used methods of managing produced water. Researchers have found extensive spatial and temporal (i.e., location and timing) correlations between induced seismicity and the disposal of produced water through underground injection into SWDs, including in Texas, Oklahoma, Kansas, Colorado, Arkansas, and Ohio. Researchers have also found spatial and temporal correlations between induced seismicity and hydraulic fracturing. In some oil and gas producing regions, such as the Bakken in North Dakota and the Marcellus in the eastern U.S., there has been relatively little observed seismic activity associated with oil and gas production activities observed (Van der Baan and Calixto, 2017).

The U.S. Geological Survey (USGS) has not found any documented example linking injection operations to triggering of major earthquakes, but the possibility of one occurring cannot be ruled out (USGS, 2023e). Some examples of earthquakes of magnitude 4.0 and above triggered by oil and gas activities in the U.S. are described later in this chapter. The largest earthquake in the U.S. known to have been induced by wastewater disposal occurred in Pawnee, Oklahoma, in 2016, and was magnitude 5.8 event (Moschetti et al., 2019). In 2019, a magnitude 6.0 earthquake that was linked to wastewater disposal occurred in China (Lei et al., 2019). However, most seismic events associated with wastewater injection or hydraulic fracturing have been at a magnitude of

3.0 or lower,[51] which is not large enough to cause damage to surface structures. According to the USGS, earthquakes under magnitude 4.0 or 5.0 usually do not cause damage.[52]

In general, the maximum seismic event magnitude that a fault can produce is correlated to its surface area (Hanks, 1977; Scholz, 2002; and Zoback and Gorelick, 2012). There is not yet a consensus on the maximum possible magnitude of an induced earthquake but work in the area suggests that it is “regional tectonics, rather than operational constraints of injection, that control the maximum magnitude of induced seismic events” (Van der Elst et al., 2016; and Kroll and Cochran, 2021). Regulators in oil and gas producing states where induced seismicity has occurred have taken actions to reduce the risks of triggering larger earthquakes by creating or revising requirements for seismic monitoring; working with local academic and research entities to establish seismic monitoring networks; creating rules governing SWD well location (with respect to known faults) and operation (with respect to injection pressures and rates), and regulating hydraulic fracturing (GWPC, 2023a).

1. Physical Mechanisms Leading to Induced Seismicity

The fundamental physical and geological mechanisms that give rise to induced seismicity from fluid injection associated with oil and gas operations are generally understood. When earthquakes are induced by fluid injection, the primary mechanism is the increase in fluid pressure in the pore space of reservoir rocks that changes the normal stress on an associated fault and increases the probability of the fault slipping (i.e., seismic activity) (National Research Council (NRC), 2013; and GWPC, 2023). A secondary contributing mechanism is deformation of the rock matrix related to poroelastic stresses associated with fluid injection. These stresses propagate much farther than direct pore-fluid pressure and lead to fault slip. With either of these mechanisms, slippage can occur during injection or even after operations cease (Boyet et al., 2023). *In-situ* field tests have shown that aseismic slip (fault slip without detectible seismic waves) can lead to stress changes that may then lead to induced earthquakes and to further altering subsurface stress and triggering additional earthquakes (Bhattacharya and Viesca, 2019).

While faults in sedimentary basin rock layers contribute to induced seismicity associated with fluid injection, the potential for migration of injected fluid downward into critically stressed faults in the crystalline basement rock that underlies the sedimentary basins is generally considered to present a greater hazard for potentially inducing seismicity. Due to tectonic driving forces, many faults in the earth's brittle upper crust are understood to exist in or near a critically stressed state (Zoback and Townend, 2001; and Zoback et al., 2002). Even small changes in stress or pore pressure, such as those which arise from subsurface fluid injection, have the potential to induce slip on these critically stressed faults (Zoback and Gorelick, 2012). Proximity of produced water disposal wells or hydraulic fracturing to the crystalline basement increases the likelihood of induced seismicity (Skoumal et al 2018b; and Weingarten et al., 2015). Scanlon et al. (2018) suggested

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[51] In general, earthquakes are measured in terms of their magnitude and intensity. The magnitude of an earthquake is a number characterizing its relative size (maximum motion) as measured by a seismograph. Every earthquake has single magnitude, expressed on a logarithmic scale as a whole number and decimal fraction (so each number on the scale represents an earthquake 10 time stronger – e.g., a “5” is 10 times stronger than a “4”). While several definitions for magnitude scale exist, the Moment Magnitude Scale (Mw) is now commonly used because it takes into account all types of seismic wave generated by an earthquake (USGS 2023c, 2023d). Earthquake intensity is a measure of the severity of an earthquake at a specified location based on observable impacts to people and their environment.
[52] See U.S. Geological Survey: “At what magnitude does damage begin to occur in an earthquake”. Available at: https://www.usgs.gov/faqs/what-magnitude-does-damage-begin-occur-earthquake

that lower levels of seismicity in some producing regions (such as the Bakken) are likely related to shallower disposal of produced water (well above the crystalline basement) and lower rates of produced water injection.[53] Other papers on this subject that provide more general descriptions of hydraulic fracturing include Schultz et al (2020), Eyre et al (2019), Bhattacharya and Viesca (2019), Sone and Zoback (2013a and 2013b), Guglielmi et al (2023), Jin et al (2023), and Li et al (2022).

An area of active investigation is the development of numerical models that can capture mechanisms of coupled fluid flow and geomechanical subsurface behavior in simulations, and the application of these models to reliably forecast induced seismicity at real sites with complex geometries, uncertainties with respect to the location and properties of faults, the state of in-situ stress, and subsurface rock properties (Yeo et al., 2020; Hager et al., 2021; and Kroll and Cochran, 2021). Increasingly, hybrid machine learning approaches are being developed and applied that use physics-informed numerical modeling together with field data interrogation to gain deeper insights into mechanisms and to improve forecasting and management of induced seismicity.

2. Characterizing Induced Seismic Hazard

One important aspect of managing seismic risk is the detection of faults that are sufficiently large to generate seismicity levels of concern. Fault detection is typically accomplished using two- or three-dimensional (2D or 3D) active-source seismic data that are interpreted in combination with other geologic characterization data. Larger, more concerning faults can be reliably detected before injection operations through active-source seismic surveys, but it may be more difficult to detect smaller faults and faults that are oriented such that they do not create a detectable reflection response. Smaller faults that are more difficult to detect using active-source seismic surveys may be detected during injection operations using passive seismic monitoring techniques.

Passive seismic monitoring refers to the acquisition, processing, and interpretation of continuous waveform data collected by seismic monitoring arrays that are capable of measuring small-magnitude seismic events that may be imperceptible to humans. To detect the smallest events, relatively dense arrays of highly sensitive instruments are deployed either in permanent or temporary campaigns that supplement traditional seismic networks which are designed to routinely detect larger, concerning tectonic earthquakes at the local, regional, national, and global scales. In response to the increased incidence of induced seismicity observed in some regions of the U.S., and recognizing that sparse networks of seismic monitoring instruments are inadequate to reliably detect or locate small earthquakes, several entities (e.g., USGS, state geological surveys, national laboratories, universities, and oil and gas operators) have worked to expand and improve seismic networks to better characterize induced seismicity at sites and in regions of active or potential future injection operations.

Empirical observations of seismic activity demonstrate a power-law relationship between the number of observed events and their magnitudes. This means that enhancing the ability to detect smaller magnitude events will produce an order of magnitude increase in the number of detected events. Collecting larger catalogs of seismic events is useful to gain a better understanding of site

[53] Similarly, CO_2 injection into the Mt. Simon reservoir in Illinois was moved to a shallower horizon at the Decatur ICCS project, but it is still associated with seismic activity, albeit at lower rates than deeper injection (Williams-Stroud et al 2020).

characteristics and behavior, but also presents a technical challenge to gain value from large volumes of data. The advent of machine learning offers new opportunities to interpret large catalogs of seismic data to discern valuable seismic signal from noise, detect and confidently locate seismic events, determine the source mechanisms of those seismic events, analyze clusters of seismic events to understand their spatiotemporal relationships and gain insight into dimensions, orientation, and complexity of faults and fractures, and to forecast induced seismicity at a site.

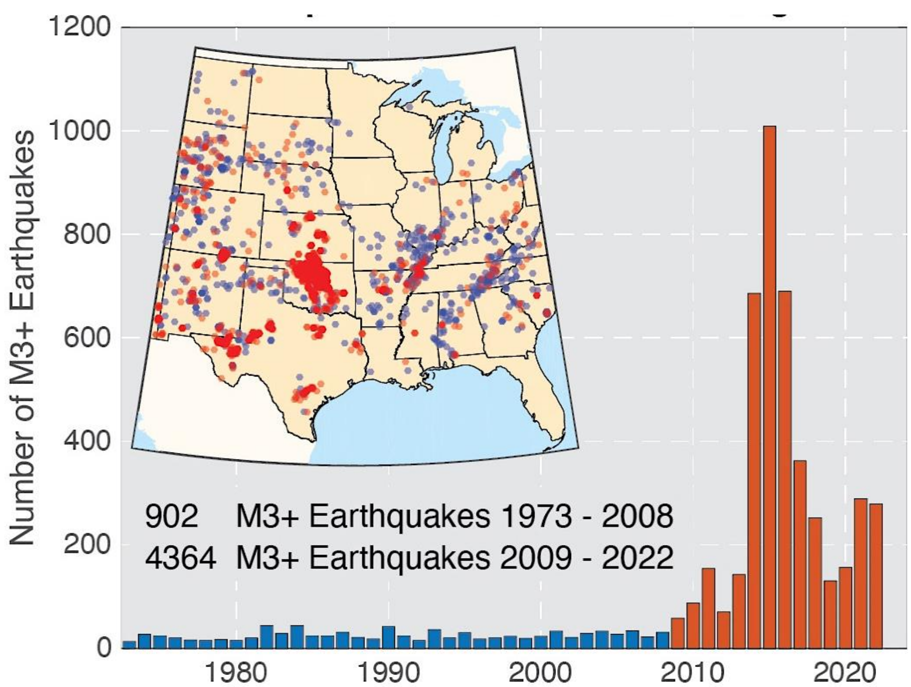
B. Seismic activity in the US associated with produced water injection and/or hydraulic fracturing

Field data now strongly supports that there are direct causal relationships between large volume produced water injection or hydraulic fracturing operations and seismic activity. Since the 1960s, researchers have observed strong spatial and temporal correlations between fluid injection and induced seismicity (SEER, 2021; and GWPC, 2023b). Operators and state regulators in oil and gas producing regions also accept this relationship and have cooperated on mitigation measures.

Researchers have focused on produced water injection as the source of most induced seismicity in oil and gas producing areas in the U.S. Researchers have also found spatial and temporal correlations between hydraulic fracturing and seismic activity, although in the U.S., seismicity caused by produced water injection is much more frequent. Cases of spatial/temporal correlation between seismicity and hydraulic fracturing in locations around the world including Poland, Alberta, British Columbia, and the United Kingdom, as well as some locations in the U.S., are summarized by López-Camino et al (2018) and Schultz et al (2020).

According to the USGS, the number of earthquakes in the central and eastern U.S. increased dramatically beginning in 2009. Although approximately 25 earthquakes of magnitude 3.0 or larger occurred in these regions between 1973 and 2008, starting in 2009 the yearly number of earthquakes of magnitude 3.0 or larger began to increase. By 2013, at least 100 earthquakes of magnitude 3.0 were occurring annually (USGS, 2022). Most of the earthquakes were between magnitudes 3.0 and 4.0, which made them large enough for people to feel, but not to cause damage. However, starting in 2011, earthquakes over magnitude 5.0 also occurred.

Figure 4 presents the annual number of seismic events with a magnitude of 3.0 or larger occurring in the central and eastern areas of the U.S. recorded by the National Earthquake Information Center from 1973–2022.



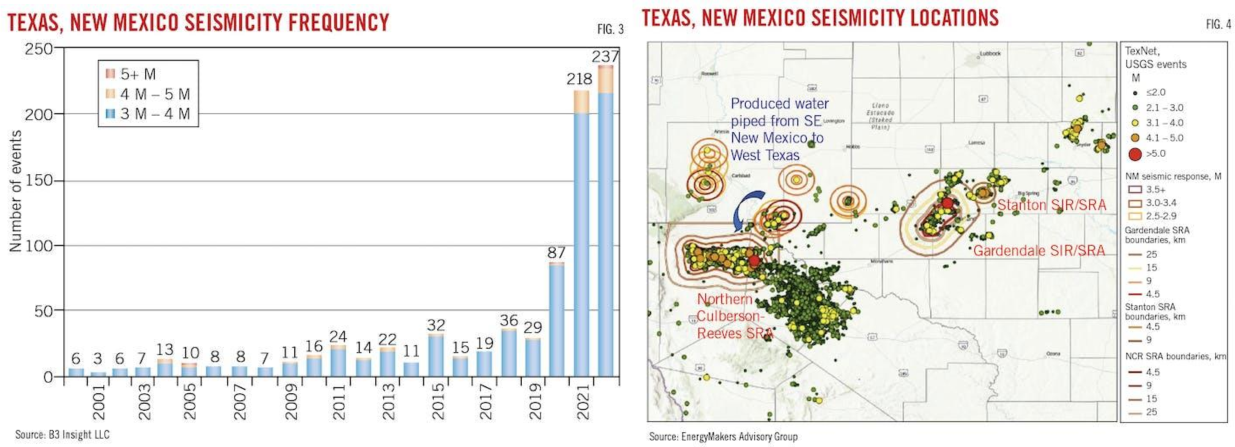
Source: USGS (2022)

Figure 4. Earthquakes in the Central and Eastern United States 1973–2022

Researchers have attributed many of these earthquakes, which occurred in areas with high levels of oil and gas production, to associated activities, including produced water injection and hydraulic fracturing. The following sections discuss induced seismicity that has occurred in several oil and gas producing basins in the U.S.

1. Induced Seismicity in the Permian Basin – Texas and New Mexico

The Permian Basin in Texas and New Mexico is the top oil-producing region in the U.S., and the second highest gas-producing region, averaging 6.2 million barrels of oil per day in June 2024, and 25.4 billion cubic feet of gas per day (EIA, 2024b). Researchers have associated oil and gas activities with seismic events in the Permian Basin for decades (Lund Snee, 2018). But over the past two to three years higher numbers of earthquakes have been observed, many at magnitude 3.0 or higher. Procyk (2023) reported that seismicity rates have greatly increased in New Mexico and Texas from 29 seismic events with magnitude greater than 3.0 in 2019, to 218 events in 2021, and 237 events in 2022. This is shown in Figure 5 below.



Source: Procyk, 2023

Figure 5. Frequency and locations of seismic events in Texas and New Mexico

Researchers have published several papers on seismicity associated with wastewater injection over the past decade in the Permian Basin. As oil and gas production increased dramatically in this area during this time, volumes of produced water also increased. By mid-2023, produced water generation across the Permian basin averaged 18.9 million barrels per day – orders of magnitude higher than in any other U.S. oil and gas producing basin (Bennett, 2023).

More than 2,000 earthquakes of magnitude 2.0+ have occurred in the Permian Basin since 2017, and most of these events, including a 5.0 magnitude earthquake that occurred in March 2020, were induced by wastewater disposal (Skoumal and Trugman, 2021). Several studies have concluded that most earthquakes in the Delaware Basin (a sub-basin of the Permian, with a relatively large amount of earthquake activity) from 2009-2018 were associated with produced water disposal, with a small fraction associated with hydraulic fracturing (Skoumal et al., 2020; and Grigoratos et al., 2022).

Satellite data has shown increases in surface deformation (including both uplift and subsidence) between 2015 and 2021 related to oil and gas production, wastewater injection, and hydraulic fracturing in the Delaware Basin These factors produce ongoing induced seismicity, but may also compromise well integrity, and thus may pose a potential risk for groundwater Hennings et al., 2023).

A more recent study that focused on the Midland Basin, another sub-basin of the Permian, found that current wastewater injection had reactivated a newly discovered fault zone, potentially significantly increasing the frequency and intensity of earthquakes in the region (Huang et al., 2024).

The Texas Railroad Commission (RRC), which regulates oil and gas operations in Texas, has taken several actions to mitigate seismicity risks over the past several years, including issuing guidelines for injection wells that include initial seismic reviews and the reporting of additional seismic information, if RCC staff deem it necessary (GWPC, 2023a). Its *Response Plan to Seismic Events in Texas*[54] delineates Seismic Response Areas (SRAs), within which the RRC can require actions for operators that could include reducing injected volumes or even suspending

[54] RRC (January 2022). Response Plan to Seismic Events in Texas. Available at: https://www.rrc.texas.gov/media/buhgzt0o/2022-01-31_seismic_response_sog_final.pdf

operations. In addition, in 2015, the Texas Legislature established the TexNet Seismic Monitoring Program, which is run by the Bureau of Economic Geology at the University of Texas at Austin. In 2017, TexNet began seismic monitoring operations with its newly installed state-wide seismic monitoring network.

New Mexico's regulator, the Energy, Minerals, and Natural Resources Department, Oil Conservation Division, has also implemented requirements for injection well operators to provide seismic data and has established seismic response protocols that require operators to act when seismic events of magnitude 3.0 or greater occur near injection wells.

Chapter 3 of this report described trends in water management practices, particularly in the Permian Basin. As noted in that chapter, operators in the Permian Basin are moving toward treating and reusing produced water for new hydraulic fracturing activity, instead of injecting wastewater into SWDs, and considering options for treating water for reuse outside of oil and gas operations (such as irrigation or livestock watering).

2. Induced Seismicity in Other U.S. Regions

Although the Permian Basin is currently experiencing the most noticeable induced seismicity related to oil and gas development, other plays and basins in the U.S. have experienced seismicity as well. The regions described here are the Eagle Ford shale play in Texas, the Utica and Marcellus shale plays in Pennsylvania and Ohio, the Anadarko and Arkoma basins in Oklahoma, and the Fayetteville shale play in Arkansas. Although the Bakken shale play in North Dakota encompasses a large producing region, there has been little seismic activity associated with oil and gas production activities observed there (Van der Baan and Calixto, 2017).

a. Eagle Ford Shale Play in the Western Gulf Basin of Texas

Production in the Eagle Ford shale play in southeastern Texas averaged 1.1 million barrels of oil per day and 7.3 billion cubic feet of gas per day in June 2024 (EIA, 2024b). As in other regions, seismicity levels increased in this region along with oil and gas activities in the 2010s including both wastewater disposal and hydraulic fracturing (Acevedo et al 2022; and Frohlich and Brunt, 2013). By 2018, the seismicity rate in the Eagle Ford play was 33 times higher than in previous years. Researchers using spatial and temporal correlation techniques were able to attribute a number of events to hydraulic fracturing, rather than wastewater disposal, including the magnitude 4.0 event in 2018 -- the largest earthquake induced by hydraulic fracturing in the U.S (Fasola et al., 2019) The rate of seismicity began to decrease in the Eagle Ford as well completions and hydraulic fracturing operations decreased between 2019 and 2020 (McKeighan et al., 2022; and Fasola and Brudzinski, 2023).

b. Utica and Marcellus Shales in the Appalachian Basin

The Appalachian Basin, which includes the Marcellus and Point Pleasant Utica shale plays, extends from New York to Kentucky, and is the largest gas producing region in the U.S., averaging 35.8 billion cubic feet of gas per day in June 2024 (EIA, 2024b). Researchers have observed induced seismicity connected to produced water disposal and hydraulic fracturing in this region, but it has not been as prevalent as in other oil and gas producing regions (Skroumal et al., 2018a; and Schultz et al., 2020).

Oil and gas and environmental regulators in Ohio and Pennsylvania have taken actions to manage risks of induced seismicity. The Ohio Department of Natural Resources, which oversees the permitting of injection wells and hydraulic fracturing activities, imposes site-specific conditions on operators, requires that operators monitor injection pressure and volume, and uses a traffic light (red/yellow/green) system for seismic events that requires operators to pause or cease operations depending on the magnitude of seismic activity detected in the area. Pennsylvania's Department of Environmental Protection employs a similar system (GWPC, 2023b).

c. Anadarko Basin of Oklahoma

Production in the Anadarko Basin in Oklahoma averaged 383,000 barrels of oil per day in June 2024, and 6.5 billion cubic feet of gas (EIA, 2024b). Between about 2008 and 2015, central and eastern Oklahoma experienced dramatic increases in seismic activity (SEER, 2021; USGS, 2023a; Schultz et al., 2020; and Ellsworth, W. L., 2013). In 2016, a series of larger earthquakes that included one of magnitude 5.8 was observed in Pawnee, Oklahoma (SEER, 2021). Researchers attributed this increase to the disposal of large volumes of produced water (SEER, 2021; Haffener et al., 2018; Ellsworth, W. L., 2013; Scanlon et al., 2018; Keranen et al., 2014; Rubinstein and Mahani, 2015; Krupnick and Echarte, 2017c; and USGS, 2023a).

Earthquake frequency began to decrease in 2016 as the Oklahoma Corporation Commission (the state regulator) implemented new regulations and protocols to help reduce the occurrence of induced events (Skinner, 2018; and SEER, 2021). These new protocols included seismic analyses prior to permitting, monitoring and pausing operations when seismicity is detected, and prohibited installation of new wells in certain formations that were thought to be particularly prone to seismic events (GWPC, 2023b). By mid-2018 the rate of earthquakes fell by 80 percent (Langenbruch et al., 2018).

d. Fayetteville Shale in Arkansas

Natural gas producers began actively developing the Fayetteville Shale in Arkansas in 2004. After the first SWDs became active in 2009, earthquake activity started to increase. In 2010 and 2011, thousands of earthquakes occurred on the previously unmapped Guy-Greenbrier fault (an event referred to as the Guy Earthquake Swarm). The Guy Earthquake Swarm led to concerns that even larger earthquakes could potentially occur in the area, and after investigation by the Arkansas Oil and Gas Commission, several operators of SWDs shut down their wells either voluntarily or after being ordered to do so. The Commission also prohibited SWDs near the fault and established rules for other SWDs in the Fayetteville Shale. Seismic activity along the fault soon ceased, and researchers have since built a strong case for the activation of the Guy-Greenbrier Fault by wastewater disposal (Horton et al., 2023; Horton, S., 2012; Ogwari, P.O., Horton, S.P., and Ausbrooks, S.M., 2016; Ogwari and Horton, 2016; and Park, Y. et al., 2020).

Other locations in the Fayetteville Shale have continued to experience seismic activity, but not at the level of the Guy Earthquake Swarm. Some of this seismicity has been linked to hydraulic fracturing (Horton et al., 2023). Natural gas production in the Fayetteville Shale has declined over the past decade and there has been little new drilling activity since 2016.

C. State Government Management of Induced Seismicity

There are no federal laws that directly address induced seismicity resulting from oil and natural gas development or produced/wastewater disposal operations. However, the SDWA, which prevents the injection of liquid waste into underground drinking water sources through the UIC program, addresses this indirectly, as EPA rules for certain well classes require evaluation of seismic risk.[55] EPA Region III, which directly implements the UIC program in Pennsylvania and Virginia, evaluates induced seismicity risk factors when considering permit applications for Class II wells.[70]

As described in the section above, when earthquakes can be linked to wastewater injection, some regulators respond by ordering operators to cease or limit either injection rates and/or volumes in nearby wells (EPA UIC National Technical Workgroup, 2015). Many regulators also require that new injection wells avoid areas near known and/or active faults. Similar procedures have been applied to hydraulic fracturing operations in some states. That is, when earthquakes are detected, operations are either modified or suspended (American Geosciences Institute, 2017). Some states use a traffic light system (red/yellow/green) which prescribes specific actions to be taken by operators depending on earthquake magnitude and proximity to an injection well or hydraulic fracturing operation (GWPC, 2023b).

In Texas and New Mexico, state agencies have established SRAs so that they can ask operators to reduce produced water injection in specific areas where seismic activity has increased. Although participation is voluntary, GWPC notes that most operators have agreed to cooperate to avoid more stringent regulatory actions. Consequently, in Texas, operators have curtailed injection of about 300,000 barrels of water per day. These programs encourage operators to find other ways to manage produced water, such as treatment for beneficial reuse or hydraulic fracturing (GWPC, 2023a).

D. Potential Community Effects

Most seismic events associated with wastewater injection or hydraulic fracturing have been magnitude 3.0 or lower; however, the largest earthquake known to have been induced by wastewater disposal was magnitude 5.8 (Moschetti et al., 2019). USGS determines the “significance” of an individual seismic event based on its magnitude, and the effects of the shaking on people and the natural and built environment (including economic loss impacts) (USGS, 2023f). While seismic events that damage structures are generally higher than magnitude 4.0 (USGS, 2023g), lower magnitude events can still be felt.

Potential impacts associated with induced seismicity can include physical damage, social and mental health disturbances (including consequences of communities perceiving an increased seismic risk), nuisance effects, economic disruption, and the effects of secondary environmental hazards such as landslides and soil liquefaction (Templeton et al., 2021). The extent to which communities are impacted by induced seismicity varies as a function of multiple factors, such as the resilience of the building and infrastructure stock and the regional population’s previous exposure to and tolerance of seismicity (induced and/or natural, minor and/or major shaking).

Much of the literature on social considerations and impacts, public health impacts, and energy justice dimensions of hydraulic fracturing and wastewater disposal has focused on health impacts and/or adopted a more holistic approach, with a limited focus on induced seismicity beyond acknowledging a potentially rising level of risk. Following the initial correlation of hydraulic fracturing operations and induced seismicity in locations that had not previously seen significant seismic activity (Keranen et al., 2014), there was a sudden increase in interest across social science and environmental justice venues, environmental news reporting, and reports and analysis from environmental organizations and NGOs. This discourse largely acknowledged the

[55]Congressional Research Service. Earthquakes Induced by Underground Fluid Injection and the Federal Role in Mitigation. R47386. Available at: https://crsreports.congress.gov/product/pdf/R/R47386

overall low risk of hydraulic fracturing-related operations producing seismic activity that posed a significant risk to infrastructure and human health. However, it also expressed shared concerns about potential future impacts if the severity and/or frequency of induced seismic activity were to increase in ways that could not be predicted at the time, particularly for communities and infrastructure predating nearby fracturing and wastewater injection operations (Ladd, 2018; NRC, 2013; and NRC, 2014). Similarly, some called for attention to the significant social, political, and environmental “instability” that induced seismicity generated for communities and their trust in institutions more broadly, regardless of whether specific seismic events could be directly attributed to hydraulic fracturing and/or wastewater injection operations (Reddy, 2020; and Willow and Wiley, 2014).

More recent analyses published in academic and grey literature[56] document several trends, such as heightened concerns about hydraulic fracturing and wastewater disposal operations occurring near recently active seismic faults (e.g., wastewater injection wells in California have been a focus of NGO reports); emerging insurance and emergency management needs related to the shifting risk landscape of newly seismically active areas (Mix and Raynes, 2018); and declining home values owing to perceived seismic risk (Black et al., 2021; Cheung et al., 2018; Ferreira et al., 2018; and Burnett and Mothorpe, 2021). Public perceptions of and support for/opposition to operations that may induce seismicity remain a focus (e.g., Boudet et al., 2014; Campbell et al., 2020; and Evensen, 2018a), including perceptions of regulatory inaction, insufficiency, and/or latency leading to an erosion of institutional trust (Evensen, 2018b; Mix and Raynes, 2018; and Ritchie et al., 2021); and the importance of transparent data sharing among operators/industry, researchers, regulators, and communities; acknowledgment of lived experience; and documentation of impacts for sound decision making, regulation, and accountability (NASEM, 2018; Wylie and Albright, 2014; and Wylie, 2018).

Good management practices (which cannot be developed without transparency and data sharing) can substantially reduce, but will likely not fully eliminate, seismic hazards (Rathnaweera et al., 2020; and White and Foxall, 2016). Effective management requires careful site selection and characterization, sensitive seismic monitoring to detect problematic seismicity before it negatively impacts operations or surrounding communities, and risk-based mitigation planning (White and Foxall, 2016; and Templeton et al., 2021). Stakeholder support is also an essential component of any oil and gas project and successful management of induced seismicity risk requires a deliberate process of broad-based, proactive, and participatory stakeholder engagement (Willow and Wiley, 2014; Reddy, 2020; and Templeton et al., 2021).

[56] I.e., information produced by government agencies or the private sector that is not typically published by commercial publishers.

CHAPTER 5: LAND USE AND DEVELOPMENT

The natural gas supply chain impacts the land in areas where natural gas is produced, processed, and stored, as well as areas through which it is transported. Land disturbances can be short-term (e.g., temporary access roads and rights-of-way for construction) or long-term (e.g., well pads and pipelines that are in place for decades). As natural gas production activities expand in an area, each new component contributes to a cumulative impact on the land.

This chapter addresses impacts on land and land-based ecosystems, including plant and animal species, but not the impact of land use changes on human populations, or the impacts of traffic, noise, or light pollution on human populations, which are addressed in Chapter 6.

A. Natural Gas Upstream and Midstream Operational Footprint

Energy development, including natural gas development, has been a leading cause of land use change in the U.S (Trainor et al., 2016). Different types of energy development have different direct impacts and landscape impacts, where landscape impacts refer to the total area required when accounting for land between elements of physical energy infrastructure (e.g., space between wind turbines or between wells and other oil and gas infrastructure).

The landscape impact of natural gas extends beyond the site of production where the well pad is located, related equipment is stored, and storage tanks and disposal ponds are situated. It includes the space between wells, and additionally includes land dedicated to:

- gathering pipelines (commonly buried), which move gas between well sites, compressor units, and metering stations;
- natural gas transmission pipelines (commonly buried), which move gas between states;
- access roads for well drilling, completion (both temporary), and production activities, as well as pipeline construction and maintenance;
- construction rights of way for pipelines;
- natural gas compressor stations;
- natural gas processing plants;
- highways and railroads used for transportation; and
- water or waste treatment and disposal facilities.

Preparing a wellsite can take several months and involves clearing land; building necessary access roads; constructing and installing infrastructure for water delivery and storage and wastewater management and disposal, as well as electricity generation or delivery; digging and lining mud pits to prevent contamination of water below the surface; digging reserve pits to store and eventually dispose of drill cuttings; and drilling the well itself. A well site generally requires several acres, but there is enough variation by basin and operator, and over time, that it is not possible to provide an average number of acres for existing well sites throughout the country.[57]

In some areas, operators have moved towards drilling multiple wells from a single pad. Although the amount of land required for a multi-well pad might be larger than for a single well pad, the total number of well pads required to develop a formation is reduced. In the Piceance Basin in Colorado, the average number of wells per pad had risen to 9.1 by 2016 (Martinez and Preston, 2016). As of the first half of 2021, a quarter of the well pads in the Midland Basin and Delaware

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[57] Studies that include estimates of well site footprints in different regions at different times include Allison and Mandler (2018), Preston and Kim (2016), Slonecker and Milheim (2015), and Martinez and Preston (2018).

Basin (sub-basins of the Permian Basin) contained at least nine wells (AJOT, 2021). As of 2023, the average number of wells per pad was two in the Haynesville Shale and six in the Marcellus (GWPC, 2023b). GWPC also reported that some operators, particularly in the Permian Basin, were drilling as many as 24 wells to 40 wells on "super pads."

As drilling and completion equipment are moved off of the location and production begins at a well pad, significant portions of the well site are typically remediated, but supporting infrastructure such as well site fluid handling equipment, produced fluid storage tanks, gathering pipelines and access roads remain in place as long as the well is active.

Although the total number of well pads may be reduced by drilling multiple wells per pad, supporting infrastructure also requires land. In the Marcellus and Utica shales in Pennsylvania and Ohio, researchers have found that construction of pipeline right of ways, particularly for gathering pipelines, was the largest cause of surface impacts (Donnelly et al., 2017).

B. Footprint per Unit of Production

Horizontal drilling allows operators to drill more wells from a single pad and to access more of the productive reservoir volume per wellbore, reducing the total land footprint required for well pads although not necessarily for roads, pipelines or other infrastructure (GWPC, 2023b; DOE, 2016; and Soeder et al., 2014). Researchers used machine learning, remote sensing, and geographic information systems to obtain spatially explicit information on the land required to support natural gas production in the Western Interconnection, which encompasses the entire Western U.S.[58] Researchers found that in the area studied, the co-location of directional wells on fewer well pads significantly reduced land use requirements per unit of production (Dai et al., 2023). Similarly, researchers have found that in West Virginia, unconventional oil and gas wells drilled between 2009 and 2012 caused land disturbances five times greater – at well sites – than conventional oil and gas wells; however, unconventional wells produced 28 times more energy per hectare of land disturbed (Gruchecky et al., 2022).

C. Habitat Fragmentation

A review of existing literature found that there is ample evidence that oil and gas production and transportation activities contribute to habitat loss and degradation for plants and animals (Deziel et al., 2022). In particular, the development and siting of drilling sites for natural gas production can temporarily disrupt the habitat of both plant and animal species through the clearing and reconfiguration of the land area occupied by well pads, pipelines, and roads. In forested areas, the landscape fragmentation that results from pipeline and well development creates open corridors and edge habitat (where one type of habitat is adjacent to another) which can be detrimental to wildlife that rely on core forest habitat. In forests and grasslands, invasive species can enter and reduce native ground cover, which can also be detrimental to birds and other wildlife (Caldwell et al., 2022; Langlois, Drohan, and Brittingham, 2017; Jones et al., 2015; Kargbo et al., 2010; and Barlow et al., 2017).

[58] The Western Interconnection is one of the four major electric system networks in North America, and spans more than 1.8 million square miles in all or part of 14 states, the Canadian provinces of British Columbia and Alberta, and the northern portion of Baja California in Mexico. https://www.wecc.org/epubs/StateOfTheInterconnection/Pages/The-Western-Interconnection.aspx

D. Effects of Noise, Light and Activity on Local Wildlife Habitat

Noise, light and human activity associated with natural gas production and transportation can also be detrimental to local wildlife populations (Deziel et al., 2022). For example, compressor stations located along natural gas pipelines can generate significant noise that reduces local wildlife populations (Bayne et al., 2008).

Outdoor nighttime lighting, which may be necessary at an active well site, can also have consequences for wildlife populations. It affects nighttime behavior and habits of terrestrial (Bennie et al., 2015) and marine (Davies et al., 2013) wildlife populations, particularly for species that use sunlight or moonlight for guidance. It also disrupts natural sleep and reproductive cycles, geographical orientation, and predator-prey relationships (Longcore and Rich, 2004). Other effects of light pollution include changes in bird singing behavior (Miller, 2006), insect pollination (MacGregor et al., 2015), and fish biological rhythms (Brüning et al., 2015). These impacts have led to ecosystem-wide changes in biodiversity and growing disparities between entire taxonomic groups (Davies et al., 2013).

Chalfoun (2021) reviewed recent literature on wildlife responses to oil and natural gas development in their habitats and found a diversity of wildlife responses, more than half of which were neutral. Negative responses were the second most common, occurring in more than one quarter of studies, and positive responses the least common, occurring in less than twenty percent. The authors concluded that, while the level of knowledge on wildlife responses to oil and gas development has improved, gaps remain.

Options for mitigating habitat fragmentation and other detrimental effects to wildlife include requiring buffers or setbacks, fewer but larger well pads to reduce well density, placement of infrastructure on already-degraded land, and controls on emissions, noise, and light (Deziel, 2022). Many operators already utilize such practices. Requiring pipelines and other infrastructure to co-locate with existing infrastructure is widely accepted as an effective mitigation strategy to reduce surface impacts (Bearer et al., 2012; and Racicot et al., 2014). Abrahams et al. (2015) found that requiring pipelines to follow existing roads would prevent further fragmentation in core forested regions while allowing full extraction of the shale resource.

E. Regulation

Under the National Environmental Policy Act (NEPA),[59] federal agencies are required to analyze the potential impacts of proposed actions, such as approvals for exploration and production of natural gas on federal lands. NEPA analyses can include land use-related impacts.

The Endangered Species Act (ESA)[60] provides a program for the conservation of threatened and endangered plants and animals and the habitats in which they are found. The ESA prohibits federal agencies from taking any action that is likely to jeopardize the continued existence of any endangered or threatened species (listed species), or result in the destruction or adverse modification of such species' designated critical habitat (ESA Section 7); prohibits the taking[61] of a listed species (ESA Section 9); and allows the U.S. Fish and Wildlife Service and National Marine Fisheries Service to issue a permit, accompanied by an approved habitat conservation

[59] 42 U.S.C. §§ 4321 et seq

[60] 16 U.S.C. §1531 et seq (1973)

[61] In the Endangered Species Act, the term "take" means to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct (U.S. Fish and Wildlife Service, https://www.fws.gov/laws/endangered-species-act/section-3)

plan, that allows for the incidental, non-purposeful "take" of a listed species under their jurisdictions (ESA Section 10).

In addition, state and local requirements associated with infrastructure development may include measures to reduce or mitigate related impacts.

CHAPTER 6: NATURAL GAS ACTIVITY: EFFECTS ON COMMUNITIES

Previous chapters in this document described the environmental impacts of activities in the upstream and midstream portions of the natural gas supply chain, including natural gas production and transmission.

Section A of this chapter introduces foundational concepts, policies, federal initiatives, and approaches relevant to social and economic considerations and impacts, including environmental, workforce, and energy justice considerations, of natural gas development, production, and transportation. Sections B and C describe the areas of interest and/or concern among different stakeholders living near upstream, midstream, and natural gas export activities. Section D summarizes literature on the effects of upstream and midstream natural gas production and transportation activities—including construction, drilling, completion, processing, and transportation by pipeline—on local communities, including workforce and economic effects.[62] Section E summarizes the effects of natural gas export activity on communities located near LNG export facilities, as well as these communities' concerns related to engagement and environmental justice and initiatives by federal agencies to address them.[63]

Sources of information for these descriptions are drawn from publicly available peer-reviewed papers across the physical and social sciences, as well as from publicly available NGO and industry materials and news articles. Many of these sources also reflect, summarize, and cite community members' lived experiences. "Community" is defined in a manner consistent with both Executive Orders 14008 and 14096 and the cited sources as including both geographically determined communities (e.g., communities adjacent to specific facilities or operations) and geographically dispersed communities that share common lived experiences (e.g., Indigenous communities, frontline communities,). Additionally, and following the definition of "environmental justice" included in Executive Order 14096, community impacts are considered both singularly and cumulatively.[64]

Currently, many similar terms are used by researchers, public agencies (including federal agencies like DOE), NGOs, and communities to categorize a community with environmental justice concerns, including underserved community, disadvantaged community, environmental justice community, energy justice community, fenceline community, and others.[65]

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[62] It should be noted that most scientific literature assessing the effects of oil and natural gas development on communities does not attempt to differentiate between the effects of activity related to oil production and natural gas production, or populations near oil producing wells or gas producing wells.
[63] This report does not address the local environmental impacts of LNG export facilities, which are addressed in FERC environmental reviews.
[64] Executive Order 13985, On Advancing Racial Equity and Support for Underserved Communities Through the Federal Government (January 20, 2021), https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/20/executive-order-advancing-racial-equity-and-support-for-underserved-communities-through-the-federal-government/, and Executive Order 14008, Tackling the Climate Crisis at Home and Abroad (January 27, 2021), https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/
[65] Executive Order 14096 describes "communities with environmental justice concerns" as those which "face entrenched disparities that are often the legacy of racial discrimination and segregation, redlining, exclusionary zoning, and other discriminatory land use decisions or patterns. These decisions and patterns may include the placement of polluting industries, hazardous waste sites, and landfills in locations that cause cumulative impacts to the public health of communities and the routing of highways

This chapter covers specific effects on local communities that are not addressed in the previous chapters, including upon physical and mental health, jobs, economies, and quality of life (traffic, noise, light, social disruptions, etc.). Some of these effects (including cumulative impacts) have been documented as correlated with natural gas development and export, but they cannot be directly attributed to a single cause covered in the previous chapters for various reasons, including data availability and sample size. Analyses and qualitative information beyond those contained in previous chapters are included for two reasons: 1) because they represent the lived experiences of communities, often in their members' own words; and 2) subject matter experts (including social scientists) draw on these data and information and have found the correlations to be significant according to their methodological standards.

The environmental impacts of natural gas development on air, water, and land, as well as induced seismicity, are detailed in their respective chapters above. However, much of the existing research on community impacts of natural gas development operates within a sociological or economic framework, adopting a place-centered approach and documenting trends and patterns in reported effects on physical and mental health, property and land values, local perceptions, and/or lifeways (Malin et al., 2019; and Haggerty et al., 2018). With increased attention on unconventional gas production as part of the energy transition, social scientists are increasingly calling for longitudinal studies of changing perspectives and cumulative impacts "as the lived experience with extraction and regulation progress[es]," including cycles of boom and bust (Evensen, 2018a).

A. Community Impacts and Environmental Justice

The production and transportation of natural gas in the U.S., including natural gas for export, has energy, labor/workforce, economic, environmental, social justice, and other implications. Communities of color, including those with Black, Indigenous, and Hispanic populations, as well as rural and low-income communities have historically been disproportionately exposed to the environmental risks, harms, and measurable impacts that arise from fossil fuel development and production activities, while often simultaneously relying on such activities to sustain their livelihoods and economies (NASEM, 2023).

1. Environmental and Energy Justice

The environmental justice movement in the United States is often associated with movements focused on civil rights, labor rights, and Indigenous sovereignty (Pellow, 2018; Harrison, 2019). While Title VI of the Civil Rights Act (1964) codified protection from discrimination on the basis of race, color, religion, sex, or national origin in programs receiving federal funding, "environmental justice" itself was not recognized in federal policy until 1994 in Executive Order 12898: Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations

and other transportation corridors in ways that divide neighborhoods….Such communities are found in geographic locations that have a significant proportion of people who have low incomes or are otherwise adversely affected by persistent poverty or inequality. Such communities are also found in places with a significant proportion of people of color, including individuals who are Black, Latino, Indigenous and Native American, Asian American, Native Hawaiian, and Pacific Islander. Communities with environmental justice concerns also include geographically dispersed and mobile populations, such as migrant farmworkers." Within this broad definition, "fenceline community" is a common colloquial term meaning EJ communities that are physically adjacent to (i.e., on the "fenceline" of) polluting industries and sites.

(Executive Order 12898).[66] Executive Order 12898 directed federal agencies to identify and address "disproportionately high and adverse human health or environmental effects of its programs, policies, and activities on minority populations and low-income populations." In 2023, Executive Order 14096: Revitalizing our Nation's Commitment to Environmental Justice for All[67] formalized the federal government definition of environmental justice (EJ) as:

Just treatment and meaningful involvement of all people, regardless of income, race, color, national origin, Tribal affiliation, or disability, in agency decision-making and other Federal activities that affect human health and the environment so that people: (i) are fully protected from disproportionate and adverse human health and environmental effects (including risks) and hazards, including those related to climate change, the cumulative impacts of environmental and other burdens, and the legacy of racism or other structural or systemic barriers; and (ii) have equitable access to a healthy, sustainable, and resilient environment in which to live, play, work, learn, grow, worship, and engage in cultural and subsistence practices.

Other recent Executive Orders have expanded and refined this directive to include climate justice, racial equity, sustainability, and energy communities, including Executive Order 13985: Advancing Racial Equity and Support for Underserved Communities Through the Federal Government (2021), and Executive Order 14008: Tackling the Climate Crisis at Home and Abroad (2021).[68]

The Department of Energy defines "Energy justice" as "the goal of achieving equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those disproportionately harmed by the energy system."[69] This concept applies the basic principles of civil rights and environmental justice to the energy sector. It centers the concerns of communities, particularly communities that have been exposed to pollution and climate change risks and impacts, in decision-making.

B. Summary of stakeholder group concerns

Including community impacts, including cumulative impacts, in decision making about natural gas activity may require balancing conflicting stakeholder priorities. For example, the onset of natural gas development in an area may create jobs for skilled workers, and revenues for mineral rights owners, but also increase traffic and air pollution that affects community members that do not receive those economic benefits. Table 1, developed by DOE, describes the stakeholder groups that may have a stake in the development, transportation, and export of natural gas in the U.S.,

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[66] Executive Order 12898: Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations (1994) https://www.archives.gov/files/federal-register/executive-orders/pdf/12898.pdf

[67] Executive Order 14096: Revitalizing our Nation's Commitment to Environmental Justice for All (2023) https://www.federalregister.gov/documents/2023/04/26/2023-08955/revitalizing-our-nations-commitment-to-environmental-justice-for-all

[68] Executive Order 13985, On Advancing Racial Equity and Support for Underserved Communities Through the Federal Government (January 20, 2021), https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/20/executive-order-advancing-racial-equity-and-support-for-underserved-communities-through-the-federal-government/, and Executive Order 14008, Tackling the Climate Crisis at Home and Abroad (January 27, 2021), https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/

[69] U.S. Department of Energy, "How Energy Justice, Presidential Initiatives, and Executive Orders Shape Equity at DOE." 22 January 2022. https://www.energy.gov/justice/articles/how-energy-justice-presidential-initiatives-and-executive-orders-shape-equity-doe . DOE's definition is taken from the Initiative for Energy Justice, https://iejusa.org/.

including general interests, priorities, and potential concerns as described in this and previous chapters.

Table 1. Stakeholder concerns about natural gas development and export

Stakeholder group	General areas of interest and/or concern	Example interests and/or concerns
State officials	Economic impact, Governance	Maximizing tax revenue from gas production (severance, income, property, and other taxes or royalties) for state budgets; Ensuring compliance with regulations
Local officials	Economic impact, Social Disruption, Governance, Infrastructure Impacts	Maximizing tax revenue and supporting needed municipal services; Managing impacts on and maintenance for local infrastructure; Increasing jobs and maintaining/enhancing quality of life
Labor	Economic impact, Equity	Increasing and protecting well-paid jobs and careers, worker protections
NGOs (community, social justice, environmental)	Health, Economic Impact, Environment, Equity, Environmental Justice, Governance	Increasing transparency and sharing of information on potential health and environmental impacts; Building and maintaining trust and accountability with community members; Avoiding and addressing any health impacts for community members (including mental health); Avoiding and addressing any impacts to air and water quality; Increasing well-paid jobs and workplace protections; Ensuring that jobs go to priority workers (e.g., members of local EJ communities); Supporting needed municipal services; Minimizing impacts on and maintenance of local infrastructure; Minimizing social disruption and enhancing quality of life
Developer(s)	Economic impact, Environment, Governance	Maximizing profits; Adhering to applicable municipal, state, and federal regulations for engagement, permitting, GHG emissions, water and air quality; Building and maintaining social license to operate
Mineral rights owners[70]	Economic impact, Governance	Maximizing royalties from natural gas production; In the cases where the mineral rights owner is also the surface rights owner, minimizing and mitigating impacts to surface location
Tribes	Environment, Health, Environmental Justice, Equity, Economic impact, Governance	Increasing transparency and sharing of information on potential health and environmental impacts data; Building and maintaining trust and accountability with Tribal members; Avoiding and addressing any health impacts for Tribal members (including mental health); Avoiding and addressing any impacts to air and water quality, habitat, species, and natural and cultural resources; Increasing well-paid jobs and workplace protections; Ensuring that jobs go to

[70] Mineral rights owners may be the developers themselves or may be separate entities receiving royalties from the developers. They may not be residents of local communities.

		priority workers (e.g., Tribal members); Maximizing profits from mineral rights and oil and gas reserves; Minimizing social disruption and enhancing quality of life; Recognizing Tribal rights and sovereignty, including informed consent and self-determination
Community members near natural gas activity	Environment, Health, Economic impact, Governance	Increasing transparency and sharing of information on potential impacts data; Building and maintaining trust and accountability with community members; Avoiding and addressing any health impacts for community members (including mental health); Avoiding and addressing any impacts to air and water quality; Ensuring that jobs go to priority workers (e.g., local residents); Supporting needed municipal services; Impacts on and maintenance for local infrastructure, including any new access roads or infrastructure; Minimizing social disruption and enhancing quality of life, including potential effects on traffic, air and noise pollution; Maximizing economic benefits like increased property values and tax revenue and increased revenue for local businesses and municipal services; Reducing negative impacts to other local land uses like agriculture; Coastal erosion; Minimizing negative impacts on local housing market
Schools, Colleges, Universities	Economic Impact, Workforce	Maximizing tax revenue and supporting needed educational services; Providing training/educational preparation for new jobs

C. Characterization of Communities Near Upstream, Midstream, and Export Facilities

1. Populations Living Near Upstream and Midstream Activities

Almost 18 million people in the United States live within about 1 mile (1,600 meters) of a producing oil or natural gas well, according to a 2017 estimate (Czolowski et al., 2017).[71] Researchers have characterized the populations living near such wells as disproportionately low income and/or communities of color, meaning that these populations may be disproportionately exposed to any positive or negative effects associated with upstream oil and gas development (Gonzalez et al., 2023; Proville et al., 2022; Zwicki, 2019; and Haggerty et al., 2018). Low-income residents and people of color in California, Oklahoma, Texas, and Colorado are more likely to live near producing wells (Gonzalez et al 2023, Proville et al., 2022; and Zwicki et al., 2019). In Colorado, there is a larger proportion of low value homes near producing oil and gas wells (McKenzie, 2016). In New Mexico, Native American populations are more likely to live in proximity to producing wells. In Appalachia, the people living near producing wells tend to be white with low incomes and high unemployment (Proville et al., 2022; and Ogneva-Himmelberger and Huang, 2015). Residents of neighborhoods around the country that have historically experienced redlining[72] are also more likely to live near producing wells (Gonzalez et al., 2023). Additionally, in the Eagle Ford Shale region in Texas, Hispanic residents have been found to be more exposed to natural gas flaring than non-Hispanic white residents, and more likely to live in proximity to a wastewater disposal well (Johnston et al., 2020; and Johnston et al., 2016).

Although there is no published estimate of the number of people who live close to a natural gas pipeline, the number is likely to be much higher than those for oil or natural gas wells, as the U.S. natural gas pipeline network includes about 297,693 miles of onshore transmission pipelines and 105,889 miles of gathering pipelines.[73] There is some evidence suggesting that counties with residents who have higher levels of social vulnerability have more natural gas gathering and transmission pipelines (Emanuel et al., 2021, 2020).

2. Populations Living Near LNG Export Facilities

As with upstream and midstream natural gas development, natural gas export facilities also tend to be sited in areas that are disproportionately home to historically communities of color and low-income communities. A 2024 study by the Robert D. Bullard Center for Environmental and Climate

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[71] The Czolowlski paper further estimated that of these people, about 45% live in proximity to one or more oil wells, 31% to one or more wet gas wells and 55% to one or more dry gas wells, with some people living near more than one kind of well. The paper defined the type of well by the gas-to-liquid ratio of production. The number of wells analyzed in the study was 808,485 oil and gas wells across 30 states that were actively producing or newly drilled as of 2014.

[72] Redlining is the practice of denying a creditworthy applicant a loan for housing in a certain neighborhood even though the applicant may otherwise be eligible for the loan. The term refers to the presumed practice of mortgage lenders of drawing red lines around portions of a map to indicate areas or neighborhoods in which they do not want to make loans (Federal Reserve, "Federal Fair Lending Regulations and Statutes," https://www.federalreserve.gov/boarddocs/supmanual/cch/fair_lend_fhact.pdf

[73] Annual Report Mileage for Natural Gas Transmission & Gathering Systems, https://www.phmsa.dot.gov/data-and-statistics/pipeline/annual-report-mileage-natural-gas-transmission-gathering-systems. Data as of 2023. Gathering pipeline systems gather raw natural gas from production wells. Transmission pipeline systems transport natural gas longer distances from gathering, processing or storage facilities to processing or storage facilities, large volume customers, or distribution systems. These numbers do not include distribution lines that transport natural gas to consumers.

Justice found that for several LNG export facilities on the Gulf Coast, the percentages of Black Americans, Hispanic Americans, and lower-income populations living within three miles of the facilities were much higher than their population shares in their respective states or the nation as a whole.[74]

One analysis using EJScreen[75] to identify environmental burdens for communities near LNG facilities in the Gulf Coast found that "five of the six communities near ... selected LNG facilities have environmental pollution burdens greater than the 75th percentile in relation to their respective states, the nation as a whole, or both. Four communities have pollution burdens above the 90th percentile" (Saha et al., 2024). Additionally, the same analysis used the CDC PLACES[76] mapping tool to identify community health disparities near LNG locations in Louisiana, including disproportionately high rates of adult cancer, asthma, and obesity (Saha et al., 2024).[77] On environmental burdens more broadly, researchers and communities also note that the Gulf South region has already seen intensive development for agriculture; canal building, wetland drainage, and otherwise directing water flow; and urbanization; which has reduced residents' access to ecosystem services (particularly for resource-dependent communities like those relying on fisheries or tourism, as noted below) and increased their exposure to hazards like hurricanes, flooding, erosion, land subsidence, and excessive heat (Saha et al., 2024).

D. Characterization of Effects on Communities - Upstream and Midstream

Previous chapters in this document described the potential effects on the environment of activities in the upstream and midstream portions of the natural gas supply chain, including natural gas production and transmission. This section characterizes effects on communities near upstream and midstream facilities, including health effects (drawing on information reviewed in previous

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[74] Robin Saha et al., "Liquefying the Gulf Coast: A Cumulative Impact Assessment of LNG Buildout in Louisiana and Texas," 2024. Page xxiii. "Living within 3 miles of Freeport LNG in Texas and Plaquemines LNG in Louisiana are much higher percentages of Black Americans than the percentages of Black Americans in the states where these sites are located (23.1% versus 12.1%, and 71.7% versus 31.9%, respectively). Both LNG sites also have much higher percentages of Black Americans than the national average (12.6%). Corpus Christi LNG and Freeport Pretreatment Facility, both in Texas, have slightly higher percentages of Hispanic Americans than the state, whereas Freeport LNG and Rio Grande LNG, also in Texas, have much higher percentages of Hispanic Americans (62.8% and 85.7, respectively) than both the state (39.8%) and the nation (18.4%). Rio Grande LNG, Freeport LNG, and Plaquemines LNG have higher percentages of lower-income populations than do their respective states, as does Plaquemines LNG in relation to the nation."

[75] "EJSCREEN is an environmental justice screening and mapping tool that utilizes standard and nationally-consistent data to highlight places that may have higher environmental burdens and vulnerable populations. The tool offers a variety of powerful data and mapping capabilities that enable users to access environmental and demographic information, at high geographic resolution, across the entire country; displayed in color-coded maps and standard data reports. These maps and reports show how a selected location compares to the rest of the nation, EPA region or state. The tool also combines environmental and demographic indicators to create EJ indexes." (EPA, Frequent Questions about Environmental Justice Screening and Mapping Tool (EJSCREEN), https://19january2017snapshot.epa.gov/ejscreen/frequent-questions-about-ejscreen_.html - q1)

[76] CDC PLACES, used by the Center for Disease Control and Prevention, "provides model-based, population-level analysis and community estimates of health measures to all counties, places (incorporated and census designated places), census tracts, and ZIP Code Tabulation Areas (ZCTAs) across the United States." https://www.cdc.gov/places/index.html

[77] It should be noted that this analysis shows a correlation between the location of LNG export facilities and pre-existing environmental stressors for adjacent communities but does not attribute the pollution burdens or health disparities to the LNG facilities themselves.

chapters), economic effects, quality-of-life impacts, and social disruption. It should be noted that there is significantly more scientific literature available about effects on communities near upstream facilities (well sites, etc.) than there is for communities near pipelines.

1. Health Effects

As described in Chapter 2, natural gas production and processing emits air pollutants that are harmful to human health, including methane, volatile organic compounds (VOCs), particulate matter (PM), and nitrogen oxides, as well as hazardous air pollutants (HAPs) (EPA, 2023a, 2023b, 2023c, 2024g, 2024h). Natural gas transmission facilities, particularly compressor stations located along natural gas pipelines, emit pollutants including VOCs, nitrogen dioxide, and PM (Davis et al., 2023). VOCs and nitrogen oxides are precursors to ozone, and multiple studies have found that exposure to ozone can have adverse health effects, including increased mortality. Exposure to PM and HAPs can also lead to adverse health effects (EPA, 2023a, 2023b, 2023d, 2024h, 2024i). Chapter 3 described how natural gas development activities may also cause contamination of surface or ground water used as drinking water by local communities.

Epidemiologic studies that rely on proximity-based models that compare the health of people living closer to oil or gas production sites to people who live farther away consistently find that living closer to an oil or gas[78] production site is associated with increased risks of health problems (Deziel et al., 2022). Most of these studies have attributed these elevated risks to exposure to air and water pollutants. However, these studies are observational and correlational and cannot definitively establish causation. Health researchers have also pointed out that they do not have the methodological tools to consider the cumulative impact from multiple industrial sources of pollutants for some communities (Johnston and Cushing, 2020).

Nevertheless, these studies have found increased incidence of adverse pregnancy outcomes, cancer, heart disease, hospitalizations, asthma, liver damage, immunodeficiency, neurological symptoms, and other health problems among populations living near oil and gas production (Aker 2024; Deziel et al., 2022; Apergis et al., 2021; Denham et al., 2021; McAlexander et al., 2020; and Bamber et al., 2019). People who reside near oil and gas production facilities also report health symptoms at a higher rate than residents further away (Johnston et al., 2021; Blinn et al., 2020; and Elliott et al., 2018).

Proximity to oil and gas production is correlated with increased mortality in local communities (Li et al., 2022; and Apergis et al., 2021). Adverse pregnancy outcomes associated with residential proximity to oil and gas production activity include higher risks of preterm birth and congenital abnormalities (Gaughan et al., 2023; Willis et al., 2023; Willis et al., 2021; Hill and Ma, 2022; Tran et al., 2021; and Gonzalez et al. 2020). Living close to flaring at a production site has also been associated with preterm births (Cushing et al., 2020).

There is more limited research on the health effects on populations living in proximity to natural gas transportation facilities, such as pipelines and compressor stations. One study found that higher levels of total VOCs were reported around compressor stations, and that these emissions were associated with greater age-adjusted mortality (Hendryx and Luo 2020). Another study found that in homes within two kilometers of a compressor station in Ohio, indoor benzene levels and levels of other VOCs exceeded state standards (Martin et al., 2021).

[78] These studies generally do not make a distinction between populations living near oil or gas production sites, or both.

Researchers have also found associations between the onset of oil or natural gas development in a new area and mental health issues for the local populations, including depression, stress, and anxiety (Grier, 2024; and Casey et al., 2018). Some residents near new development in rural areas have reported stress or grief about changes to both the physical landscape and overall "sense of place" caused by industrial development (Caretta et al., 2021; and Hirsch et al., 2017). Residents who feel that they do not have information about environmental or health risks, or that their local or state officials are not listening to them, can also experience stress and anxiety related to socio-economic change and feelings of powerlessness (Malin, 2020; Fisher et al., 2018; and Kroepsch, 2019). These mental health and psychosocial impacts vary by economic position, with those benefitting financially (through mineral rights ownership or access to jobs) reporting higher quality of life perceptions (Fernando and Cooley, 2016).

2. Economic Effects

Economic effects for upstream communities include employment, multiplier effects, revenues for local governments in areas that host infrastructure, the potential for royalties from natural gas production, and impacts on housing and real estate values.

a. Employment: National and Regional

According to the 2024 U.S. Energy and Employment Report, the natural gas sector employed 268,170 workers in 2023, up 5,283 from the 262,886 employed in 2022 (2%). Most natural gas workers in the United States (92%) worked in onshore natural gas. The largest number of natural gas workers were in the mining and extraction industry (155,726 workers, or 58.1%). Mining and extraction employment in natural gas remained flat year-over-year (U.S. Department of Energy, 2024) A 2024 paper from the National Association of Manufacturers estimated that in 2023 employment in exploration, production and processing of natural gas specifically for LNG exports totaled 16,560 workers, employment in pipeline transportation for LNG exports totaled 4,060 workers, and LNG export facilities themselves employed 5,310 workers, for a total of 25,930 LNG export-related jobs in the U.S.[79] (National Association of Manufacturers, 2024).

Several studies have characterized the employment impacts of increasing oil and gas production throughout the U.S. A 2017 study found that changes in oil and gas rig counts had significant effects on employment during the 2000s, with each additional rig resulting in the creation of 31 jobs immediately and 315 in the long run (Agerton et al., 2017). A review paper found that multiple studies show evidence of local wage and employment gains during periods of growth in oil and gas development (Krupnick and Echarte, 2017a).

In addition, oil and gas activities have a "multiplier effect" where one direct job leads to additional jobs. A 2019 study by the Economic Policy Institute estimated that one direct job producing oil and gas leads to an additional 5.43 indirect jobs (Bivens, 2019). The paper cited above from the National Association of Manufacturers used a multiplier of 8.6 to estimate that indirect effects of LNG exports on employment in 2023 totaled 86,410 jobs, and "induced" employment totaled 110,120 jobs.[80] (NAM, 2024)

Researchers have found that natural gas production tends to increase employment in regions and communities where it occurs. One study found that throughout the U.S., every million dollars of

[79] The paper said that it used data from the Energy Information Administration, the Bureau of Labor Statistics, and the IMPLAN modeling system.
[80] The paper characterizes "induced" effects as employment induced by changes in spending from households as income increases or decreases due to the changes in production.

new oil and gas production output in a county is associated with an $80,000 increase in a county's total wage income, and 0.85 new jobs within the county in that year. The study also found that wage and employment impacts grow with distance, and that within a 100-mile radius, each million dollars in new production is associated with wage increases of $257,000 and 2.13 jobs (Feyrer et al., 2017). Increases in oil and gas employment in a state have been shown to increase the probability of employment and increase the average annual earnings in all sectors (Winters et al 2019). A higher number of wells drilled in a county, compared to counties with fewer wells, has also been linked to increased employment (Maniloff and Mastromonaco, 2017). A 2022 study focused on Ohio and Pennsylvania found that counties where shale gas production took place in the 2005-2018 timeframe had higher job growth and wages than in counties without production (Sapci, 2022). Multiple studies have also found that oil and gas development has had significant positive impacts on employment and wages in the Permian basin (Wang, 2018).

There is some evidence suggesting that local residents do not always benefit from the availability of new jobs in natural gas production sites near their homes. Multiple studies focused on different regions have found that although employment may increase in an area with new natural gas production, these new jobs often go to people who either move to the area for the jobs or commute from other areas, rather than to long-term residents of those areas (Gershenson et al., 2024; Gittings and Roach, 2020; Kim and Johnson, 2020; Suchyta and Kelsey, 2018; Clough and Bell, 2016; Wrenn et al., 2015; and Wilson, 2016).

b. Public Finance

Local oil and gas production growth can bring new revenues to local governments from property taxes, sales taxes, and local shares of state severance taxes or state and federal leases (depending on state laws). Local governments must also manage new costs, including potential road damage from heavy truck traffic, increased demands for emergency services and police, and the need for new water and wastewater infrastructure. Despite the additional costs and volatility in revenues, most local governments in oil and gas producing regions have experienced net fiscal benefits (Newell and Raimi, 2018). In addition, some state governments, including Colorado, North Dakota, Louisiana, and Pennsylvania, have allocated severance tax funds (or increased such funding) to localities that need to spend more on services due to oil and gas development (Rabe and Hampton, 2015).

c. Royalties from Natural Gas Production

Local mineral rights owners can gain economic benefits through royalty payments from producers who lease their land for natural gas development. These benefits accrue only to mineral rights owners, and not to renters of homes on land that is also leased for development or to residents who only hold surface rights.

Researchers have limited ability to assess whether royalties in any particular region tend to accrue to mineral rights owners living in that region, due to limited data availability about mineral rights ownership in county land ownership files. However, some research suggests that the owners of mineral rights in a region are often not local residents. In Pennsylvania counties with the most drilling activity, one study found that ownership of the land was concentrated in a small share of residents and in owners from outside the county (Kelsey et al., 2012). While ownership patterns for the surface estate, per se, do not show which landowners retain mineral rights, another study found that fewer than 10 percent of residents in counties with 90 or more wells reported receiving royalties (Hardy and Kelsey, 2015). And in one city in Texas' Barnett shale region, non-local mineral owners owned the majority of mineral rights and received at least 68 percent of the value of development (Fry et al., 2015).

The benefit that a mineral rights owner receives also depends on the terms that are negotiated with the producer, which may advantage better-informed or higher-educated mineral rights owners (Hardy and Kelsey, 2015). Researchers found that in Texas, Hispanic and Black mineral rights owners receive lower royalty rates, longer primary terms, and fewer beneficial landowner concessions in their negotiated contracts (Timmins and Vissing, 2021).

d. Housing and Real Estate Values

The onset of natural gas production in a region can affect housing costs and property values. Housing costs may increase during a boom period, as new workers arrive and need housing. For example, the boom in the Bakken shale region of North Dakota and the resulting extreme housing shortage was widely covered in the press in the early 2010s.[81] Research highlighted the unique precarity of renters, who were vulnerable to eviction as higher paid oil and gas workers arrived, and also lacked property owners' ability to profit from resources located on their land (Gershenson et al., 2024; and Jackson, 2015).

Property values are also affected by the onset of oil and gas production in a region. Researchers have found that property values increased in Oklahoma as shale gas production increased (Apergis, 2019) as well as in the Barnett shale region in Texas (Weber et al. 2014).

But property values may also decline for homes in close proximity to natural gas production sites, as they are viewed as less desirable. Malin et al (2023) found that the tendency in states to favor mineral rights owners' rights to lease their property for development, over the rights of other landowners, can create uncompensated losses for neighboring landowners who either do not own their own mineral rights, or do not support development. Researchers have found evidence of this throughout the U.S (Krupnick and Echarte, 2017b), including in West Virginia (Keeler and Stephens, 2020), Pennsylvania (Gopalakrishnan and Klaiber, 2014), and Colorado (Boslett et al., 2019; and Bennett and Loomis, 2015). In addition, there is some evidence that a property that relies on groundwater instead of piped water and is in proximity to a production site loses more of its value (Muehlenbachs et al., 2015; and Krupnick and Echarte, 2017b). Another study found that homes in New York state within three miles of an announced natural gas transmission pipeline declined in value (Boslett and Hill, 2019).

3. Quality of life impacts

Natural gas development and transportation can bring noise, nighttime lighting, and additional traffic to local communities which can have adverse effects for local residents.

a. Noise

Natural gas production and transportation activities can produce high levels of noise. Some of these activities are temporary or intermittent and include construction and preparation of access roads and well sites and well pads; production and completion of wells including drilling and hydraulic fracturing; and traffic noise during construction and operations (Hays et al., 2017). Research suggests that noise levels during these activities can exceed guidelines for residential exposure, sometimes around the clock during periods of intense activity (Allshouse et al., 2019;

[81] For example: Kris Hudson, 4 April 2013. Oil-Boom Byproduct: Unaffordable Housing, Wall Street Journal. Available at: https://www.wsj.com/articles/SB10001424127887324883604578396491794558304

Richburg and Slagley, 2019; and Blair et al., 2018). The operation of compressor stations that move gas through pipelines produces continuous noise, audible to households located in the vicinity (Boyle et al., 2018).

There are a range of potential health risks from chronic exposure to high levels of noise including hypertension, endocrine disruption, cognitive impairment, cardiovascular disease, diabetes, and poor birth outcomes (Hays et al., 2017). High local noise levels have also been associated with reduced property values (Farooqi et al., 2022).

b. Light Pollution

In the U.S., the unconventional natural gas production boom has significantly increased light pollution in rural areas (Boslett et al., 2021). Natural gas production sites often require continuous lighting through the day and night to ensure worker safety during site preparation, drilling, completion, and maintenance activities. Although these activities may be limited in time, new access roads and compressor stations for natural gas pipelines often require permanent nighttime lighting. Natural gas flaring also produces nighttime light that may last for lengthy periods of time.

Most research on the impacts of light pollution on public health has not focused on any particular source. However, there is some research speculating that light pollution associated with shale development may induce psychosocial stress (Fisher et al., 2017) and sleep and mental health issues (Casey et al., 2018).

c. Traffic

The onset of natural gas development and transportation can increase traffic, particularly truck traffic, in rural areas that may not have well developed road networks, or roads that were designed to carry high numbers of trucks with heavy loads. Trucks are required for trips to well sites to bring construction materials, drilling equipment, pipe, and when hydraulic fracturing is performed, to bring chemicals, proppants, and large volumes of water if there is no water pipeline connection. The water needed for hydraulic fracturing may account for 20 to 80 percent of the trucks needed for the development of a well, but both the percentage and the actual number depends on many factors, including the number of wells per pad, well depth, region, geologic formation, and whether trucks or pipelines are used to transport water for hydraulic fracturing (Tsapikis, 2020). The total number of truck trips required during initial operations can be in the hundreds or even the thousands depending on these factors. Hundreds or thousands of additional truck trips may be required over the lifetime of a single well, which can be 5 to 20 years, for further well stimulation (additional hydraulic fracturing) and other construction and maintenance activities (Goodman et al., 2016). In the Permian basin in Texas, traffic volumes on key highways rose 10-fold as production activities increased between 2009 and 2019 (Collins, 2021)

Increased traffic on unpaved rural roads in areas with heavy oil and gas development can produce high levels of dust, which is harmful to human, animal, and plant health (Kahn and Strand 2018, Tong 2023) Local farmers may be affected as dust from traffic on unpaved roads is associated with loss of agricultural plant yield and livestock health problems (Aleadelat and Ksaibati, 2017, McCrea, 1984) Increased road dust from vehicle traffic supporting oil and gas development was a particularly acute problem in North Dakota during the Bakken oil boom in the early 2010s, and farmers raised concerns about stunted crops, damaged pasture, and sick livestock (Gedafa et al., 2016, Heglund et al., 2014).

Excessive use of rural roads that were not designed for heavy truck traffic can lead to increased need for maintenance. Often the roads most impacted by traffic associated with natural gas production are local and county roads that are usually not maintained by federal or state governments. This leaves counties and townships with the burden of maintenance and repair (Dundon et al., 2018). In addition, several studies have found an association between increased traffic, particularly industrial truck traffic from oil and natural gas development, and an increased risk of motor vehicle crashes and fatalities (Collins, 2021; Xu and Xu, 2020; Muehlenbachs et al., 2021; and Graham et al., 2015).

4. Social Disruptions

Researchers have also noted disruptions in sense of place and social identity associated with hydraulic fracturing and natural gas development that can influence and compound perceptions of environmental and health impacts (Sangaramoorthy et al., 2016).

a. Boom-bust Cycle of Resource Development

Researchers report that communities can experience harms due to the boom-bust cycle that is a characteristic of natural resource development. The cycle begins with a natural gas discovery and production, which brings a boom of investment, jobs and tax revenue to local communities, but may then eventually evolve into a bust as resource production declines or prices fall, and workers and contractors leave for other jobs, property values decline, unemployment and poverty increases, and government revenues decline (Schafft et al., 2017; Arnold et al., 2022; Gershenson et al., 2024; and Klasic et al., 2022). This follows the pattern identified by researchers in the oil boom-and-bust cycle of the 1970s and 1980s, in which post-bust communities face predictable challenges around community development and degraded relationships between social entities and stakeholders (Jacobsen and Parker, 2014; and Fernando and Cooley, 2016).

Researchers note that, despite their value, the historical focus on this boom-and-bust cycle within the literature does perpetuate some trends that may make systematic documentation of community effects challenging -- for example, focusing on remote rural communities over urban ones, assuming that a spatially concentrated resource will follow a clear linear boom and bust, and ending a study before longer-term impacts can be studied (Kroepsch, 2019; and Walsh et al., 2020). Furthermore, researchers also note that with changes in resource extraction techniques enabling more and more intensive natural gas development closer to where people live and work (as well as driving demand for housing closer to energy development) in places like Colorado (Kroepsch, 2019), continued case studies and other locally specific research are needed to better understand how natural gas development does and does not follow the cycles characteristic of other resource development. Social impacts of oil and gas exploration and development are shaped by interactions with locally-specific economic cycles, geology, technologies deployed, and other factors. As such, both social impacts and perceptions of those social impacts can vary significantly across different locations and communities (Haggerty et al., 2018).

b. Crime

Multiple studies focused on communities in the U.S. have found that the onset of a boom in natural gas development is associated with increased rates of crime, both nonviolent and violent, likely due to the influx of young men to work on natural gas projects (Shaw, 2024; Stretesky and Grimmer, 2020; and Shakya and Sohag, 2021). Natural gas development booms have been identified as likely contributing factors for 9 to 16 of the top 23 “hot spots” (identified based on the highest rate of cases in the country) for the crisis of missing and murdered Indigenous women (Joseph, 2021).

E. Characterization of Effects on Communities – Exporting LNG

The first part of this chapter described the potential effects of activities in the upstream and midstream portions of the natural gas supply chain, including natural gas production and transmission, on local communities. This section characterizes effects on communities located near where export-related activities occur.[82]

As described above, there is a wide body of published scientific literature regarding the effects of natural gas production and transportation on local communities. However, there is significantly less published scientific literature regarding the effects of LNG exports on local communities in or around the geographic area where the LNG exports occur, given that the U.S. only began exporting LNG from the lower-48 states in 2016. This portion of the chapter relies on published scientific literature, where available, to describe effects on communities, but also makes use of publications and testimony directly from local residents, community organizations, and non-profit organizations.

Since DOE issued the Environmental Addendum in 2014, the rapid growth in natural gas production and LNG exports has led to a buildout of associated facilities and infrastructure that has left a substantial footprint in the U.S. Gulf Coast region, from which most U.S. LNG exports occur. This physical footprint is expected to grow in the near to medium term based on natural gas export capacity under construction.

Most existing and proposed LNG export facilities in the U.S. are sited on the Gulf Coast in Texas and Louisiana, some in very close proximity to one another (See Figure 6 and Figure 7). Accordingly, this section focuses on this region.[83] Six areas are highlighted:

- Cameron Parish and Calcasieu Parish in Louisiana are home to three operational facilities (Sabine Pass, Cameron, and Calcasieu Pass); two other facilities that have been authorized for non-FTA exports but are not yet under construction after reaching a final investment decision (FID) (Lake Charles and Driftwood,); and three that have pending applications seeking authorization to export to non-FTA countries (CP2, Commonwealth, and Magnolia).
- In the Port Arthur area on the Texas-Louisiana border, there are two LNG facilities (Golden Pass and Port Arthur) that are currently under construction after reaching FID.
- In Freeport, Texas, the Freeport LNG facility is operational.
- In Corpus Christi, Texas, the Corpus Christi LNG facility is operational and has an expansion under construction.
- In Plaquemines Parish, near New Orleans, there is one facility that is under construction (Plaquemines) and one that has a pending application to export to non-FTA countries (Gulfstream).
- In Brownsville, Texas, there is one facility that is under construction (Rio Grande) and one that has been authorized for exports to non-FTA countries but has not reached FID and is not under construction (Texas LNG).

[82] As noted previously, this chapter does not address the local environmental impacts of LNG export facilities, which are addressed in FERC environmental reviews.
[83] Locations of existing and proposed LNG liquefaction facilities outside the Gulf Coast include Maryland, Georgia, and Alaska.

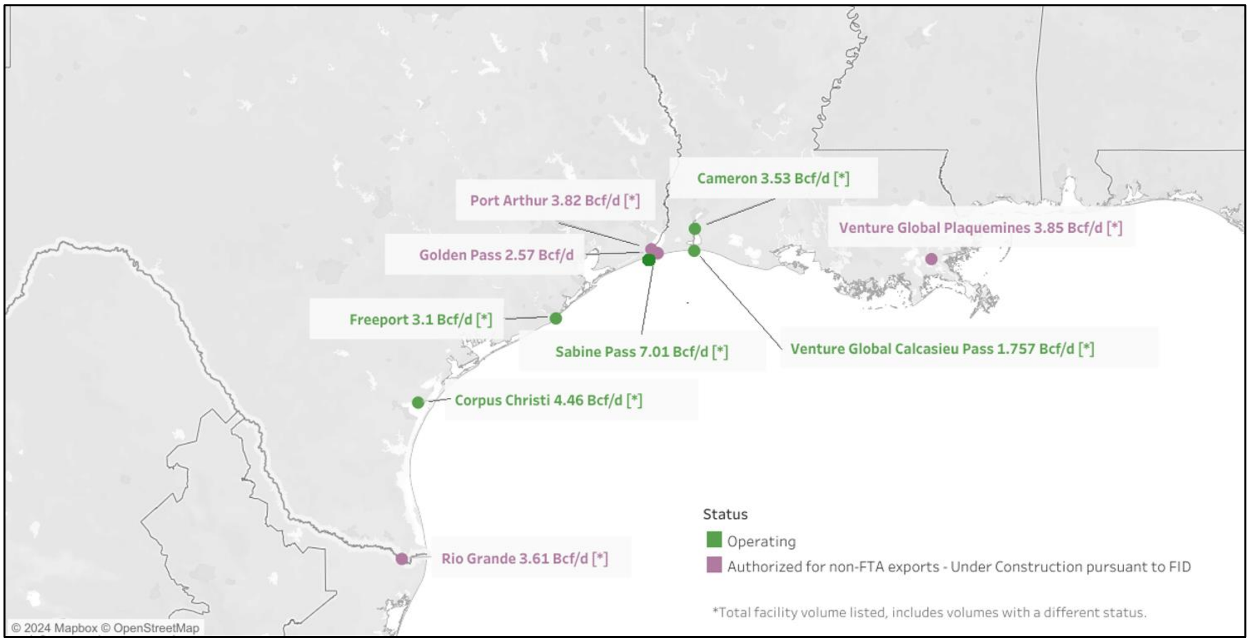

Figure 6. U.S. LNG Export Facilities on the Gulf Coast: Existing and Under Construction (August 2024)

Figure 6 shows the location of LNG export facilities on the U.S. Gulf Coast that are operating or under construction after reaching FID. Figure 7 includes the operating and under construction facilities; facilities that have been authorized for exports to non-FTA countries but are not yet under construction; and planned facilities that are awaiting authorization for exports to non-FTA countries.

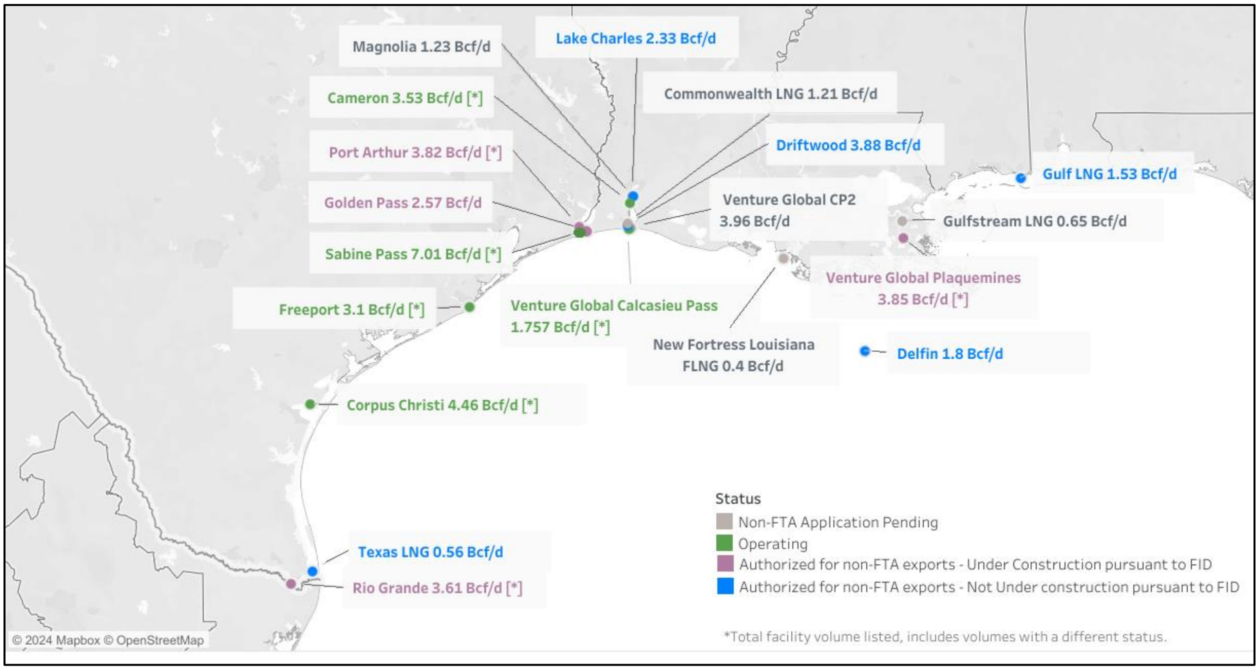

Figure 7. U.S. LNG Export Facilities on the Gulf Coast: Existing, Under Construction, Authorized for exports to Non-FTA countries, and Non-FTA Application Pending (as of August 2024)

Source for both figures: U.S. Department of Energy. Liquefaction capacities, billion cubic feet/day (Bcf/d)

Public Health and Quality of Life

a. Health: Legacy Impacts from Other Industries vs Impacts from LNG Exports

The Port Arthur area, Cameron and Calcasieu Parishes, and Corpus Christi, where existing and proposed LNG export facilities are located, are also major centers for refining and petrochemicals. Refining and petrochemical facilities release pollutants that are harmful to human health including VOCs (volatile organic compounds) and particulate matter (Ragothaman and Anderson, 2017), and researchers have found that residents from fenceline communities experience both higher rates of nonmalignant respiratory symptoms (Chang et al., 2020) and leukemia (Jephcote et al., 2020). In Louisiana, researchers found that residents of south Louisiana are experiencing an upward trend in industrial emissions and concentrations of particulate matter and have suggested that this contributed to increased COVID-19 death rates among some parishes in south Louisiana (Terrell and James, 2022). The concentration of industries in these areas has left a legacy of pollution and public health implications. This has impacted many residents and local community groups impression of the potential health effects of existing and proposed LNG export facilities, regardless of the emissions profiles of these industries.

b. Potential Health Impacts on Local Communities from the Export of LNG

The operation of LNG export facilities also releases pollutants that are harmful to human health, mostly from venting or flaring in order to burn away excess natural gas. For example, the Center for Biological Diversity has listed the major pollutants from LNG export operations that it identifies as affecting human health as diesel exhaust, particulate matter, nitrogen oxides, sulfur oxides, ozone, carbon monoxide, heavy metals like mercury, dioxins, and volatile organic compounds (Parker et al., 2024). State regulators determine the limits for such emissions when they issue emissions permits.

DOE has not been able to identify any published scientific literature that focuses on the specific observed impacts of LNG export operations or emissions on local public health. However, environmental and community groups have expressed concerns about the potential public health impact of LNG exporters exceeding their permitted emissions levels (Saha et al., 2024; and Sierra Club et al., 2024).

In Louisiana, some residents and community organizations have complained (as reported in the media and collected by NGOs and/or in lawsuits) about excessive natural gas flaring and emissions at export facilities. The complaints allege that LNG facilities are exceeding their air emissions permits. In certain instances, State regulators have also noted emissions violations. For example, in June 2023, the Louisiana Department of Environmental Quality (LDEQ) sent an LNG exporter a compliance order that listed numerous incidents when the facility exceeded its permitted levels of emissions, including 139 volatile organic compound (VOC) infractions and 47 hazardous air pollutant (HAP)/toxic air pollutant (TAP) emissions incidences (LDEQ, 2023). Some community groups have also raised concerns that in March 2023, that exporter requested that LDEQ raise its permitted emissions levels for VOCs and other compounds, and to increase its annual flaring limit from 60 hours to 500 hours (Stewart, 2023).

Some local residents in Texas have also raised concerns about an LNG export facility exceeding its permitted limits for pollutant emissions, and they have challenged that export facility's application to the Texas Commission on Environmental Quality (TCEQ) to raise its emissions limits (Croom and Volcovici, 2022).

A community group in Port Arthur sued TCEQ to demand that it apply a stricter standard for the air permit for another LNG export project, and a federal court agreed that TCEQ should vacate the permit and start proceedings to develop a new one (Williams, 2023).

c. Community Concerns about Emergency Situations

Some national organizations and local community representatives near LNG export facilities have expressed concerns about the risks of explosions and other dangerous situations, limited information from facility operators about emergency plans, and poor communication during emergencies (Sierra Club, 2022b; and Sierra Club et al., 2024). For example, local residents near one LNG facility, which experienced an explosion, fire and shutdown in 2022, have expressed concerns that potentially dangerous facility conditions have not been addressed, and that the facility has not been open with the community about potential future hazards (Saha et al., 2024)[84].

d. Community Concerns about Maritime Traffic

Community residents near LNG facilities have also raised concerns about the impact of LNG traffic on local waterways. In Corpus Christi, Texas, multiple incidents involving marine traffic related to the operation of the Corpus Christi LNG export facility have been documented in local media.[85] In a letter to the Coast Guard opposing a decision to allow an increase in LNG carrier

[84] No injuries or fatalities occurred either at the side or outside the fenceline, according to FERC (June 2022). Freeport LNG Incident. Available at: https://www.ferc.gov/industries-data/resources/project-directory/freeport-lng-incident-june-2022

[85] For example: Blenkey, Nick (2023). Excessive speed seen in expensive ASD tug grounding. Available at: https://www.marinelog.com/news/excessive-speed-seen-in-expensive-asd-tug-grounding/, MarineLink (2022). Engine Issues Led To Tanker Striking Dock In Corpus. Available at: https://www.marinelink.com/news/engine-issues-led-tanker-striking-dock-495402, and Maritime Shipping News (2022). Tanker engine problem led to $7.55m hit on loading dock. Available at: https://news.maritime-network.com/2022/05/18/tanker-engine-problem-led-to-7-55m-hit-on-loading-dock/.

ships in the Corpus Christi Ship Channel, they cite both environmental and safety issues (Nye, 2024).

2. Local Employment

LNG export facility operators and construction contractors typically employ thousands of workers during facility construction, but the facilities themselves have a much smaller staff of employees when operational.[86] For example, Cheniere's Sabine Pass LNG export facility, the largest export facility in the U.S., employs about 950 personnel, and its Corpus Christi LNG export facility employs 750 people.[87] Cameron LNG employs 265 staff at its facility in Louisiana.[88]

LNG export facility operators have made efforts to hire local residents. For example, Cheniere has a partnership with two community colleges in Lake Charles, Louisiana, and Corpus Christi, Texas, and the company has sponsored apprenticeships that had led to 36 direct hires as of 2022. Cheniere has described other community college and high school recruitment efforts and donations as well.[89] Golden Pass LNG funds students at a local state college in their process technology programs.[90] NextDecade, developer of the Rio Grande LNG project, has announced that its project expects to have approximately 5,000 jobs during peak construction and 350 operations jobs to 400 operations jobs once the project is completed, and it has also committed to hiring at least 35 percent of their workforce locally.[91] Other LNG exporters have made similar efforts to train and recruit local residents for employment at their facilities.[92]

However, some community residents and organizations have expressed concerns that LNG export facilities do not make enough of an effort to employ local residents and that they usually hire people from outside the area for the most high-paying jobs. A 2024 letter summarizing the experiences of residents and community-based organizations around the Gulf Coast of Texas and Louisiana alleged that "[m]ost companies hire out-of-state workers for project construction or recruit skilled people from other parts of the state to help. Local folks get jobs cleaning offices, working security, and driving trucks, all jobs that pay sub-poverty wages" (Sierra Club et al., 2024). DOE was not able to identify published data regarding these assertions.

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[86] In June 2024, the five LNG plants under development in Texas and Louisiana were employing more than 20,000 workers. Reuters (24 June, 2024). Rising US Labor Costs Threaten to Derail New LNG Projects. Available at: https://www.reuters.com/business/energy/rising-us-labor-costs-threaten-derail-new-lng-projects-2024-06-24/

[87] Cheniere. Sabine Pass Liquefaction. Available at: https://www.cheniere.com/where-we-work/sabine-pass ; Cheniere. Corpus Christi Liquefaction. Available at: https://www.cheniere.com/where-we-work/ccl

[88] Cameron LNG. More jobs, more prosperity. Available at: https://cameronlng.com/lng-facility/economic-impact/

[89] Cheniere. 2023 Corporate Responsibility Report. *Community Investments*. Available at: https://www.cheniere.com/pdf/2023-CR-Report.pdf

[90] Golden Pass LNG. Opportunity Roadmap. Available at: https://www.goldenpasslng.com/work-with-us/opportunity-roadmap

[91] Rio Grande LNG. Commitment to the Community & the Environment. Available at: https://nextdecadelng.wpenginepowered.com/wp-content/uploads/2024/08/RGLNG-One-Pager-ENG-SPA.pdf

[92] Examples at: Port Arthur LNG (2023). Education Partner Spotlight – Lamar Stare Collage Port Arthur. Available at: https://portarthurlng.com/education-partner-spotlight-lamar-state-college-port-arthur/; FreePort LNG. Community. Available at: https://freeportlng.com/scir-2023/community

3. Effects on Public Finances

Some members of communities near LNG export facilities have raised concerns about tax abatements offered by their state governments for LNG facilities, claiming that the abatements limit the benefit that the projects bring locally and do not offset the harms cause by the project, let alone providing a net benefit. For example, in 2024, the Sierra Club and several local Gulf Coast organizations wrote a letter to DOE saying that "In Texas and Louisiana, LNG companies are regularly exempt from up to 80% of state and local taxes" (Sierra Club et al., 2024). In these states, six LNG projects have received over $100 billion in tax abatements from state and local governments (Saha, 2024).[93] LNG facility operators and supporters note that the companies have made substantial contributions to local charities and institutes of higher education.[94]

4. Effects on Other Industries

a. Shrimping and Fishing Industries

The Gulf Coast has long-established shrimping and fishing industries, and shrimping is particularly important for Texas and Louisiana. In recent years, fishermen have been struggling with the effects of climate change, hurricanes, and particularly with low-cost imported shrimp (Chavez, 2023; and Villareal, 2023). In 2022, the crab and shrimp harvests in Cameron and Calcasieu Parishes totaled approximately $5 million and nearly $2.5 million, respectively, relatively small shares of the state total of $223 million (Louisiana State University, 2022).

These parishes are the home of three operational LNG export facilities (Sabine Pass, Cameron and Calcasieu Pass), and some local fishermen blame LNG export-related activity for harming their operations. Fishermen cite the size of the LNG tankers, which they say causes erosion and silt buildup along the riverbanks and necessitates routine dredging; requirements that fishing boats stay clear of LNG tankers, which limits their time on the water; and in the case of the Calcasieu Pass terminal, the company's shutdown of many local boat launches (Cunningham, 2024). One fisherman in Cameron Parish said that his boat is diverted about three times per week by LNG tankers, costing him significant revenue (Drane, 2023). Some crab fishermen also describe LNG tankers creating giant wakes that suck crab traps out into deeper water where they cannot be retrieved (Kelleher, 2023).

The Louisiana Shrimp Task Force—an advisory group that makes recommendations to the Louisiana Wildlife and Fisheries Commission and includes representatives from the shrimp industry and related state agencies—published a letter in 2023 calling on FERC, DOE, and state agencies to stop the permitting of additional LNG exports in southwestern Louisiana. The group asserted that the fishing and shrimping industry in Cameron Parish is threatened by construction, ship traffic, reduced access to boat launches, and the filling in of local wetlands (Louisiana Shrimp Task Force, 2023).

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[93] The report lists the following projects and local tax abatement amounts: Cameron LNG: $3 billion; Cheniere Energy: $3 billion; Venture Global: $1.86 billion; Sabine Pass LNG: $126.5 billion; Corpus Christi LNG: $147 million; Freeport LNG: $178 million (Saha, 2024)

[94] For example: Cameron LNG's 2022 Community Impact Report describes several local grants and partnerships, see https://cameronlng.com/wp-content/uploads/2023/01/2022-Community-Impact-Report_FINAL.pdf; Cheniere LNG has a charitable foundation, see https://www.cheniere.com/where-we-work/our-communities.

b. Tourism Industry

In 2024, Sierra Club and local community organizations on the Gulf Coast asserted in a letter that LNG export activity has reduced tourism in the area by ruining local beaches with dredged materials and creating noxious odors that "overwhelm" the region (Sierra Club et al., 2024). Community leaders near the tourist destination of South Padre Island in Texas have passed resolutions against the two proposed LNG export facilities in Brownsville over concerns about the impact on tourism (Gallucci, 2024).

F. Equity and Environmental Justice

In recent years, social science research on energy development has intersected with social science research on environmental justice and the social impacts of science and technology to focus on topics like cumulative impacts, risk, and citizen science (in which community members participate in data collection and other research processes) (Malin et al 2019). Two key concepts, the distribution of impacts, and participation in decision-making, are described below.

1. Distribution of Impacts

A chief concern that some NGOs and some local community members often raise about natural gas activity, and energy production and transportation activity in general, is that the harms and risks associated with the energy lifecycle (in this case the natural gas lifecycle) fall disproportionately on low-income communities, and communities of color, including those with Black, Native American, and Hispanic populations. As noted in section 6.C.1, multiple studies have found evidence that populations living in proximity to upstream and midstream oil and gas activity tend to be members of groups that have been underserved and overburdened. Section 6.C.2 describes how, for several LNG export facilities on the Gulf Coast, the percentages of Black Americans, Hispanic Americans, and lower-income populations living within 3 miles of facilities were much higher than their population shares in their respective states or the nation as a whole, and that most of the communities near some "LNG export facilities have greater existing environmental pollution burdens than other places in their states" (Saha, 2024).

2. Participation in Decision Making

Researchers and NGOs have also investigated what they describe as procedural justice concerns, which refers to meaningful participation in the processes and decision-making around energy development, distribution, and governance (Heffron and McCauley, 2017). Some of these concerns have been documented in natural gas development specifically, and some of which may be inferred from trends in energy development in the United States more broadly (Malin et al 2019; and Saha et al., 2024). When communities do not have the opportunity to participate in this decision-making, it can lead to or further perpetuate community distrust and disengagement and increase the potential for additional harms.

Whether community participation is equitable, meaningful, and productive depends on a number of factors. First, actions taken by individuals and institutions can (sometimes inadvertently) facilitate or prevent building trust. Second, participants' personal experiences with and perceptions of energy industries shape how they approach participation (Mayer, 2016). Third, the broader regulatory, economic, social, and political contexts generally give developers more power and resources than community members (Malin et al., 2019).

Additionally, researchers note that the complex scientific, legal, and regulatory environment in which natural gas development operates—including the highly technical nature of decision making—can make it more difficult for community members to engage and easier for landowners and local residents to be isolated, uninformed, or misinformed (Willow and Wylie, 2014; and Yoder, 2024). For example, in a Texas case study, areas that were more Black, Hispanic, or spoke limited English (referring to the number of "limited English-speaking households" in U.S. Census data) were less likely to have protective clauses in leases that addressed environmental and health effects (Timmins and Vissing 2015; and Black et al., 2021). Another study found that local farmers may benefit from natural gas leases in the short term, but in the long-term, are at a disadvantage with regard to negotiating and enforcing lease terms, in addition to the environmental effects detailed in previous chapters (Malin and DeMaster, 2016).Researchers also highlight case studies at multiple scales, such as local residents developing citizen science efforts to ensure understandable and trustworthy data monitoring (Wylie, 2018), and a potentially broad loss of public trust related to reporting and regulatory processes for hydraulic fracturing chemicals, which may be perceived as opaque and/or disjointed (Underhill, 2023).

Information and transparency gaps may also diminish communities' abilities to participate in decision making: first, by requiring communities to "prove" harm they have experienced via authoritative technical expertise and information to which they may not have equitable access; and second, by making it more difficult for research studies to examine whether causal links exist between specific natural gas development technologies and practices and health and environmental effects, thus further perpetuating the persistent gaps in data availability.

Considering these and other inequities shaping the engagement process, researchers have noted that a lack of significant opposition to natural gas development should not be assumed to constitute consent, but its absence could instead indicate a lack of resources and other conditions required for engagement (Eaton and Kinchy, 2016).

3. Community Engagement in Decision Making on Natural Gas Production and Transportation

Researchers have found that public engagement in decision making regarding natural gas activities can vary widely. Opportunities for communities to engage with Federal, state and local decision-making authorities depend greatly on the location of the development (Federal or private land[95]), and in the case of private land, on the state or locality where it occurs.

a. Public Engagement Regarding Natural Gas Production on Private Lands

As described in Chapter 1, most oil and gas development activity occurs on private lands in the U.S., where developers negotiate directly with the owner of the mineral rights (who is usually, but not always, the owner of the surface rights) about leasing their land for development. When developers seek permits from state and local governments to drill wells and initiate other activity on the leased land, state and local laws and regulations determine whether and how local communities are notified and if they have an opportunity to raise objections or have other meaningful input.

In some areas, states or local governments require notifying or consulting with nearby landowners and communities before drilling and other permits are issued. For example, regulations adopted in 2021 require that the Colorado Energy and Carbon Management Commission (CECMC) solicit

[95] States also lease state-owned land for oil and gas development, but for simplicity that will not be addressed in this report.

public comments before approving oil and gas development plans.[96] In 2023, CECMC also began a series of listening sessions with disproportionately affected communities in different parts of the state to discuss the cumulative impacts of oil and gas development.[97] In North Dakota, the public may participate in monthly hearings that determine the number of wells that can be drilled in a given area.[98] In Montana, developers must give public notice whenever they wish to drill a well outside of existing fields, and a public hearing may be held, if there are objections.[99] In Pennsylvania, applicants for many kinds of environmental permits, including those related to oil and gas activities, must notify local communities before the Department of Environmental Protection will consider their applications (Hess, 2024). However, in some states, the public may not have an opportunity for formal input into well permitting decisions by the state, and there may not be a notification process for local communities (Bastian, 2017).

In many states, local governments, including towns, cities, and counties, have jurisdiction over some aspects of natural gas production on private lands, including zoning and setback rules, road and utility permitting, noise levels, and more. But, for oil and gas development on private lands, the state is the primary regulator, and by both statute and tradition, state governments often view their primary roles as maximizing production in order to benefit from tax revenue and job growth (Wiseman, 2020). In some states, recently passed laws explicitly pre-empt local control over many aspects of upstream activity. On the other hand, in 2019, Colorado enacted legislation that gave more authority over upstream oil and gas development to local communities, but this is an exception to the trend (Wiseman, 2020; and Righetti et al., 2020).

b. Public Engagement Regarding Natural Gas Activities on Federally Owned Land

As described in Chapter 1, BLM manages most of the oil and gas development that occurs on federally owned land. There are opportunities for public engagement at several steps in the process.

Far in advance of any oil and gas leasing, BLM develops a Resource Management Plan (RMP) for public lands in a large area and identifies which areas are appropriate for oil and gas development. When BLM develops a draft RMP and draft Environmental Impact Statement (EIS) for the areas under consideration, the public has 90 days to comment. After public comments are considered, and a proposed RMP and final EIS are released, affected stakeholders have another 30 days to file protests before the RMP is made final.

The public has another chance for input when BLM posts a notice of a Lease Sale for parcels that it has identified for oil and gas leasing. Members of the public have a 30-day period to comment on the leasing of specific parcels.

The public has a fourth opportunity for input when a developer that has acquired a lease submits to BLM its Application for Permit to Drill. If BLM decides that an Environmental Assessment (EA) or EIS is need, these are posted for public comment for another 30-day period.

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[96] CECMC (2021). Permitting Process. 300 Series. Available at: https://ecmc.state.co.us/documents/reg/Rules/LATEST/300 Series - Permitting Process.pdf
[97] CECMC. Listening Sessions with Disproportionately Impacted Communities. Available at: https://ecmc.state.co.us/documents/media/ECMC_DI_Listening_Session.pdf
[98] North Dakota State Government. Underground Injection Control Program Frequently Asked Questions. Available at: https://www.dmr.nd.gov/oilgas/permitting.asp - mr11
[99] The Montana Department of Natural Resources & Conservation. For Current or New Operators. Available at: https://dnrc.mt.gov/BOGC/current-new-operators

Developers of natural gas on federal land also need to apply for state and local permits for different activities, and the public has engagement opportunities as described in the previous section.

The federal government, through the Federal Energy Regulatory Commission (FERC), has almost all authority over the siting and construction of interstate natural gas transmission pipelines. Communities have an opportunity for input at several points in the process, including when FERC issues a Notice of Application and conducts scoping to determine environmental issues; when FERC issues a draft EIS or an EA; or after an order is issued, when FERC can be asked to rehear the case or to refer to a FERC administrative law judge. FERC orders are also appealable to the federal Court of Appeals.[100]

c. Public Engagement Regarding LNG Export Facility Construction and Operation

The existing federal processes for permitting LNG exports and export facilities have also received some criticism from local communities. For example, some researchers and communities have noted that spatial analysis tools developed by the federal government to help identify communities of concern (e.g., the EPA's EJScreen, the White House Council on Environmental Quality's Climate and Economic Justice Screening Tool or CEJST, the CDC's Environmental Justice Index, etc.) are recommended but not required in reviews conducted by FERC (Saha et al., 2024). Researchers have also noted additional gaps or discrepancies between federal agencies regarding how communities of color are categorized, how community benefits are determined or assumed, whether and how cumulative impacts are considered, and overall guidelines on the use of spatial analysis tools to address environmental justice concerns in review and permitting processes (Rozansky, 2022; and Saha et al., 2024). Taken together, and considering already existing environmental, health, and economic burdens, researchers and communities suggest that these gaps and discrepancies can contribute to a review process in which potential burdens are under-recognized and potential benefits are over-counted (Rozansky, 2022; and Saha et al., 2024).

More broadly, some community members have also raised concerns about a perceived lack of transparency from both government and industry actors, and insufficient opportunities for public comment and engagement (Renaud, 2023; Sierra Club 2022a; and We Act, 2022). Some Tribal communities specifically have noted concerns about a perceived lack of consultation and potential destruction of culturally significant sites (Sierra Club, 2022a).

Communities and NGOs have also reported concerns about what they perceive as a lack of information on potential environmental impacts of LNG export facilities, calling for additional research beyond what is included in existing environmental impact reviews (Saha et al., 2024; and van Heerden, 2022). Others have called for DOE to perform a programmatic EIS, which would include a cumulative environmental and climate justice analysis (Sierra Club et al., 2024a).

d. Facilitating Meaningful Community Engagement in Decision Making

Researchers note that the complexity of the decision making and regulatory landscape – including whether developers are required to conduct broader public engagement at all – can be at odds with community engagement best practices and introduce additional complications for understanding societal considerations and impacts and potential energy futures (Neville, 2017).

[100] FERC. Application Process. Available at: https://www.ferc.gov/media/application-process

Some researchers have suggested that decision makers follow documented best practices to support meaningful engagement and procedural justice, such as empowering communities through agreements like community benefits plans and consent-based siting processes (Elmallah, 2022; Wang and Lo, 2021; and Williams and Doyon, 2019). Additionally, some researchers suggest establishing clear goals to use intentional, routine community engagement to: 1) identify all those who may be impacted by, have a right to, and/or see themselves as having a stake in the process and outcomes; 2) better understand the priorities and concerns of affected communities; 3) build relationships based on trust and accountability; and 4) ensure that the greatest benefits accrue to the communities who have been and/or will be most impacted, including creating ownership stake opportunities for communities where possible (Hogan et al., 2022; Mayer, 2016; and NASEM, 2023).

e. Federal Government Initiatives to Improve Engagement

While DOE does not have a regulatory role in siting natural gas infrastructure, DOE recognizes the need to engage more substantively and consistently, and the Department has launched several initiatives to build and maintain connectivity with communities impacted by energy development and production.

For example, DOE's Office of Energy Justice and Equity led the "Energy Justice to the People Roadshow" in 2023 to engage communities about resources they could receive from DOE programs. Then, in 2024, the Department launched the Regional Energy Democracy Initiative (REDI) in 2024 to provide technical assistance and capacity building to help communities meaningfully engage in the design and implementation of Community Benefits Plans (CBPs) associated with DOE funded projects in the U.S. Gulf South region of Texas and Louisiana. Both efforts focused on communities that face high environmental and socioeconomic burdens, and which are also poised to receive significant federal investments through the Bipartisan Infrastructure Law (BIL) and Inflation Reduction Act (IRA) to help advance clean energy goals and address those burdens. In 2024, DOE's Office of Energy Jobs launched the Community Workforce Readiness Accelerator to "create and scale effective, inclusive workforce development strategies aimed at forging pathways for local workers, underrepresented populations, and disadvantaged communities (including justice-involved people, youth, and women)." More broadly, DOE has incorporated CBPs as a requirement for nearly all applications for funding and loan opportunities funded by the BIL and IRA, and those CPBs include clear, specific, and trackable commitments to communities, which then become part of the award agreement after negotiation.

Outside of DOE, FERC's Office of Public Participation (OPP) conducts direct outreach and education to assist community members, Tribal governments and members, small businesses, and others with FERC proceedings, including responding to requests for technical assistance. Recognizing that federal government processes can be challenging and often seem impenetrable, OPP is designed to provide guidance and instruction on how to "intervene, comment, file motions, or seek rehearing."

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