U.S. DEPARTMENT OF ENERGY

# Flaring and Venting Reduction Research & Development Activities

Report to Congress

August 2021

**United States Department of Energy**
**Washington, DC 20585**

# Message from the Secretary

In response to language in House Report 116-83, Energy and Water Development and Related Appropriations Bill, 2020 (May 23, 2019), the U.S. Department of Energy (DOE) has prepared this Report to Congress on natural gas venting and flaring reduction research and development activities.

DOE is providing this report to the following Members of Congress:

- **The Honorable Kamala D. Harris**
  President of the Senate

- **The Honorable Nancy Pelosi**
  Speaker of the House of Representatives

- **The Honorable Patrick Leahy**
  Chairman, Committee on Appropriations

- **The Honorable Richard C. Shelby**
  Vice Chairman, Senate Committee on Appropriations

- **The Honorable Rosa DeLauro**
  Chairwoman, Senate Committee on Appropriations

- **The Honorable Kay Granger**
  Ranking Member, Senate Committee on Appropriations

- **The Honorable Dianne Feinstein**
  Chair, Senate Subcommittee on Energy and Water Development
  Committee on Appropriations

- **The Honorable John Kennedy**
  Senate Subcommittee on Energy and Water Development
  Committee on Appropriations

- **The Honorable Marcy Kaptur**
  Chairwoman, House Subcommittee on Energy and Water Development, and Related Agencies
  Committee on Appropriations

- **The Honorable Mike Simpson**
  Ranking Member, House Subcommittee on Energy and Water Development,
  and Related Agencies
  Committee on Appropriations

- **The Honorable Joe Manchin**
  Chairman, Senate Committee on Energy and Natural Resources

- **The Honorable John Barrasso**
  Ranking Member, Senate Committee on Energy and Natural Resources

- **The Honorable Frank Pallone, Jr.**
  Chairman, House Committee on Energy and Commerce

- **The Honorable Cathy McMorris Rodgers**
  Ranking Member, House Committee on Energy and Commerce

- **The Honorable Bobby L. Rush**
  Chairman, House Subcommittee on Energy
  Committee on Energy and Commerce

- **The Honorable Fred Upton**
  Ranking Member, House Subcommittee on Energy
  Committee on Energy and Commerce

- **The Honorable Gary Peters**
  Chairman, Senate Committee on Homeland Security and Governmental Affairs

- **The Honorable Rob Portman**
  Ranking Member, Senate Committee on Homeland Security and Governmental Affairs

- **The Honorable Carolyn B. Maloney**
  Chairwoman, House Committee on Oversight and Government Reform

- **The Honorable James Comer**
  Ranking Member, House Committee on Oversight and Government Reform

- **The Honorable Eddie Bernice Johnson**
  Chairwoman, House Committee on Science, Space, and Technology

- **The Honorable Frank Lucas**
  Ranking Member, House Committee on Science, Space, and Technology

- **The Honorable Jack Reed**
  Chairman, Senate Committee on Armed Services

- **The Honorable James Inhofe**
  Ranking Member, Senate Committee on Armed Services

- **The Honorable Angus King**
  Senate Subcommittee on Strategic Forces
  Committee on Armed Services

- **The Honorable Deb Fischer**
  Senate Subcommittee on Strategic Forces
  Committee on Armed Services

- **The Honorable Adam Smith**
  Chairman, House Committee on Armed Services

- **The Honorable Mike Rogers**
  Ranking Member, House Committee on Armed Services

- **The Honorable Jim Cooper**
  Chairman, House Subcommittee on Strategic Forces
  Committee on Armed Services

- **The Honorable Michael Turner**
  Ranking Member, House Subcommittee on Strategic Forces
  Committee on Armed Services

If you have any questions or need additional information, please contact Ms. Katherine Donley, Deputy Director for External Coordination, Office of the Chief Financial Officer, at (202) 586-0176, Mr. Robert Cowin, Deputy Assistant Secretary for Public Engagement or Ms. Elizabeth Noll, Deputy Assistant Secretary for House Affairs, Office of Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

Jennifer Granholm

# Executive Summary

This report identifies technology research and development (R&D) that could lead to substantial reductions in natural gas flaring and venting during oil and gas production from shale and tight formations. Industry, regulators, and the public agree that there is value in applying new technologies and practices for capturing wasted resources and minimizing harmful emissions. Flaring and venting activities represent identifiable point sources of greenhouse gas emissions, specifically carbon dioxide ($CO_2$) and methane ($CH_4$), that contribute to climate change. Methane is of specific concern because of its greater global warming potential than carbon dioxide. The R&D focus of the U.S. Department of Energy's (DOE's) Office of Fossil Energy and Carbon Management (FECM) is to accelerate the development of modular natural gas conversion technologies that will provide additional options for converting gas that would otherwise be flared or vented into value-added products; reducing greenhouse gas emissions in the field.

**Natural Gas Flaring and Venting**: Natural gas is a gaseous mixture of hydrocarbon compounds, primarily methane, and non-hydrocarbon gases (e.g., water vapor, carbon dioxide, helium, hydrogen sulfide, and nitrogen). Although flaring is more common than venting, both of these activities routinely occur during oil and natural gas development as part of drilling, production, gathering, processing, and transportation operations. Flaring is the process of combusting natural gas and oxygen at the wellhead using a dedicated flame, which converts methane (and other combustible gases) to carbon dioxide, water, and heat. Combustible gases are flared most often due to emergency relief, overpressure, process upsets, startups, shutdowns, and for other operational safety reasons. Venting refers to the direct release of natural gas and is restricted in certain states. Regulations on venting and flaring practices have to date only been enacted at the state level. Regulations typically impose release restrictions and natural gas capture requirements. Flaring is less harmful from a greenhouse gas perspective because the methane that is vented is a more potent greenhouse gas than the carbon dioxide that results from flaring. Venting and flaring infrastructure vary by location and typically gases are piped to a remote location, usually elevated structures, and released or burned in an open flame in the open air using a specially designed burner tip, auxiliary fuel, steam, or air system.

Over the past two decades and especially during the last five years, flaring has become more common, with the rapid development of unconventional, tight oil and shale gas resources. As crude oil production has outpaced the buildout of gathering and transportation infrastructure to move the natural gas to market, gas associated with oil production, but that is undeliverable to a market, has been increasingly vented or flared. This is a particular challenge in hydrocarbon gas liquids-rich areas, such as the Permian and Williston basins, and the economics of any given oil field situation can dictate that the more valuable oil be produced and the associated gas be flared if gas delivery infrastructure is inadequate.

According to the U.S. Energy Information Administration (EIA), the volume of U.S. natural gas that was reported as vented and flared in 2019 reached the highest average annual level of 1.48

billion cubic feet per day (Bcf/d) since 1961.[1] This represented 1.53 percent of dry natural gas production (approximately 93 Bcf/d), up from 1.26 percent the previous year. North Dakota and Texas accounted for 1.25 Bcf/d or 85 percent of the reported U.S. vented and flared natural gas.[2] If the 2019 volume of vented and flared natural gas could be brought to market, this gas volume equivalent would have a value of greater than $2 billion at the annual average city gate price.[3]

**Market Challenges**: Many oil and natural gas-producing companies in the U.S. continue to implement technology solutions to reduce venting and flaring either voluntarily or in response to regulations. Technological deployment varies across producing regions, and some solutions currently exist to capture gas that would otherwise be waste and convert it into useful products or for onsite use to facilitate production. While there are commercially available technologies for capturing and monetizing flared gas, these options are not employed when market conditions fail to produce a viable economic alternative to lower-cost flaring and venting during routine field production. Commercial alternatives to flaring include compressing the natural gas and trucking it short distances for use as a fuel for oilfield activities, extracting natural gas liquids from the flare gas stream to reduce the flared volume, and converting the gas to electricity using small-scale generators. While concentrated infrastructure and technologies exist to capture and monetize natural gas at various petroleum refineries and chemical plants, a distributed network of technologies and infrastructure are needed to effectively reduce daily venting and flaring volumes as producing regions evolve. These distributed technology alternatives to reduce flared volumes are often not currently cost-competitive, and step-change R&D and infrastructure advancements are needed.

**Research and Development Opportunities:** There could be significant benefit in developing economic alternatives for reducing the volumes of flared gas through the capture of associated gas and conversion to value-added products. These alternatives would benefit from including technologies that are inexpensive to build and operate, and capable of being moved from one well pad to another well pad (i.e., modular). These technologies would be more effective and efficient if they were operationally independent of gathering systems, and capable of turning a range of gas flow rates and chemical compositions into products that have value onsite or at nearby market centers.

DOE is focused on accelerating the development of technologies capable of converting natural gas that would otherwise be flared into transportable, value-added products like carbon-free fuels (e.g., hydrogen), chemicals (ammonia), and carbon materials (e.g., solid carbon). DOE envisions successful technologies development through this R&D effort will be integrated into small-scale modular systems that can be transported from one flare site to the next for use during periods when natural gas gathering and sales systems are not yet functional. Such

[1] U.S. Energy Administration, available at: https://www.eia.gov/dnav/ng/hist/n9040us2a.htm
[2] U.S. Energy Information Administration, Natural Gas Gross Withdrawals and Production, available at: https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_FPD_mmcf_a.htm and https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_VGV_mmcf_a.htm
[3] U.S. Energy Information Administration, Natural Gas Prices, available at: https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PG1_DMcf_a.htm

systems might also be employed to develop stranded gas resource accumulations that are not large enough to justify pipeline gathering systems. DOE's Office of Fossil Energy and Carbon Management is specifically targeting two areas where research opportunities have been identified: (1) multifunctional catalysts for methane conversion, and (2) modular conversion equipment designs. The early-stage development and evaluation of multifunctional catalysts can provide the direct conversion of methane to liquid petrochemicals (e.g., methanol, ethanol, ethylene glycol, acetic acid, and other hydrocarbons) that can be easily transported for subsequent incorporation into commercial products. Additional investigation will develop novel equipment and process design concepts for high-selectivity pyrolysis (decomposition through heat), which is integral to the manufacture of high-value carbon products from methane or the mixtures of methane, ethane, propane, and butanes. The second R&D area focuses on the application of process intensification at modular-equipment scales suitable for deployment, and transport between remote locations where gas is most commonly flared. This R&D portfolio will reduce the environmental impacts of flaring and venting, make more efficient use of the Nation's natural resources, and add value to natural gas markets.

# FLARING AND VENTING REDUCTION RESEARCH & DEVELOPMENT ACTIVITIES

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# I. Legislative Language

Explanatory language in H.R. Rep. No. 116-83, Energy and Water Development and Related Agencies Appropriations Bill, 2020 (May 23, 2019), stated:[4] *"The Department is encouraged to explore technologies that curtail methane gas emissions from flaring and venting in shale formations. The Department is directed to provide to the Committee not later than 60 days after enactment of this Act a report on its efforts in this area. The Committee encourages coordination with industry and the Pipeline and Hazardous Materials Safety Administration on methane leak detection technology development*." This Bill was never enacted, the Department is providing this report as a courtesy.

# II. Summary of Flaring and Venting

## *1. Role of Natural Gas for Energy Markets*

The EIA Annual Energy Outlook 2021 (AEO 2021) projects the continued transformation of U.S. power generation into an increasingly natural gas-fueled future.[5] Natural gas used for U.S. electric power generation peaks coincide with relatively low natural gas prices, new natural gas-fired combined-cycle capacity, and coal-fired capacity retirements that drive increases in natural gas-fired generation in the short term. Strong growth in renewables and efficiency improvements in the remaining coal-fired fleet suggest continued amounts of natural gas will be consumed in the electric power sector through 2030. Commercial and residential consumption will additionally remain steady and industrial consumption is projected to increase with growth in the overall economy and the natural gas-weighted industrial production index. The supply of natural gas for this transformation is expected to come from the ongoing development of unconventional natural gas resources (shale gas and tight gas formations) and from associated gas produced along with unconventional oil (tight oil formations). This will be supplemented by a relatively small, and steady, supply from conventional onshore and offshore gas reservoirs.

Both the EIA and independent experts forecast that the primary contributors to U.S. natural gas supply through 2050 will be the Appalachian Basin (primarily the Marcellus Shale) and associated gas from Lower-48 tight oil plays (primarily the Permian, Bakken and Eagle Ford plays).[6] This will be supplemented by steady production from other onshore Lower-48 gas plays. The AEO 2021 Reference case, which assumes current laws and regulations through 2050, projects domestic crude oil production to return to 2019 levels by 2023 and then remain near 13 million to 14 million barrels per day (b/d) through 2050. Domestic natural gas

[4] H.R. Rep. No. 116-63, at 105 (2019), available at: https://www.congress.gov/congressional-report/116th-congress/house-report/83/1

[5] U.S. Energy Information Administration, Annual Energy Outlook 2021 (with projections to 2050), available at: https://www.eia.gov/outlooks/aeo/pdf/AEO_Narrative_2021.pdf

[6] U.S. Energy Information Administration, Annual Energy Outlook 2021 (with projections to 2050), available at: https://www.eia.gov/outlooks/aeo/pdf/AEO_Narrative_2021.pdf

production in the Reference case also returns to pre-pandemic levels starting in 2022 at 34.0 trillion cubic feet (Tcf) per year and 93 billion cubic feet (Bcf) per day of dry gas production. This level of production is projected to supply U.S. demand and support increased levels of liquefied natural gas (LNG) exports from U.S. terminals. The EIA expects LNG exports to more than double between 2020 and 2029 in the reference case.[7]

The U.S. continues to be an integral part of global oil markets and a significant source of supply, despite uncertainty surrounding post-pandemic expectations for oil and natural gas demand. The U.S. remained the world's top producer of petroleum and natural gas hydrocarbons in 2019, reaching a record high.[8] The U.S. has been the world's top producer of natural gas since 2009, when U.S. natural gas production surpassed that of Russia, and the world's top producer of petroleum hydrocarbons since 2013, when U.S. production exceeded that of Saudi Arabia.[9] In 2020, U.S. petroleum and natural gas output totaled 66.9 quadrillion British thermal units (quads), which was more than both Russia's 45.5 quads and Saudi Arabia's 26.5 quads of petroleum and natural gas production. Petroleum and natural gas production fell in all three countries in 2020 following a rapid decline in demand during the novel coronavirus disease (COVID-19) pandemic and the consequent crude oil price declines, particularly in the first quarter of 2020.[10]

The U.S. energy-related $CO_2$ emissions from fossil fuels are historically tied to economic output. The U.S. gross domestic product (GDP) is forecasted to have fallen more than 5 percent in 2020 as a result of the COVID-19 pandemic. In 2020, as the country responded to the pandemic, $CO_2$ emissions from energy consumption in the United States fell to the lowest level since 1983. The 4.6 billion metric tons (Bmt) of $CO_2$ emitted in 2020 was an 11% decrease from 2019, the largest annual decrease on record. Much of the drop in $CO_2$ emissions relates to estimated impacts of the travel restrictions and general economic activity slowdown associated with the efforts to mitigate the spread of the COVID-19 virus. Independent of the effects of the pandemic, a decline in 2020 energy-related emissions is forecasted to be generally consistent with the trend of lower U.S. $CO_2$ emissions since their peak in 2007.[11]

Energy-related $CO_2$ emissions include emissions from the consumption of petroleum, coal, natural gas, and municipal solid waste, as well as some forms of geothermal power generation. Industrial processes, such as cement manufacture, also contribute to $CO_2$ emissions. In 2020, U.S. petroleum consumption accounted for 2.0 Bmt of energy-related $CO_2$ emissions, or about 45 percent of the U.S. total (about 77 percent of petroleum $CO_2$ emissions occurred in the transportation sector). In 2020, U.S. natural gas consumption accounted for 1.7 Bmt of $CO_2$

[7] U.S. Energy Information Administration, Annual Energy Outlook 2021 (with projections to 2050), pages 21, 22, 23, available at: https://www.eia.gov/outlooks/aeo/

[8] International - U.S. Energy Information Administration

[9] U.S. Energy Information Administration, EIA United States Energy Profile, available at: https://www.eia.gov/international/rankings/country/USA

[10] U.S. Energy Information Administration, United States continued to lead global petroleum and natural gas production in 2020, available at: https://www.eia.gov/todayinenergy/detail.php?id=48756

[11] U.S. Energy Information Administration, After 2020 decline, EIA expects energy-related $CO_2$ emissions to increase in 2021 and 2022, available at: https://www.eia.gov/todayinenergy/detail.php?id=46537#

emissions, or about 36 percent of the total—its largest share on record. U.S. consumption of natural gas averaged 83.3 Bcf/d in 2020. In 2020, about 38 percent of $CO_2$ emissions from natural gas occurred in the electric power sector, and 32 percent were in the industrial sector.[12] In 2019, Petroleum and other liquid fuels were the largest single source of energy-related $CO_2$ emissions in the U.S., accounting for 46 percent of the 2019 total or 2.4 Bmt. Natural gas production was the second–largest source of $CO_2$ (includes flaring of natural gas from wellhead), and contributed approximately 1.1 Bmt in 2019. In total, the U.S. energy-related $CO_2$ emissions totaled greater than 5.1 Bmt in 2019.[13] Economic growth and the lessening of pandemic-related restrictions will result in more energy consumption and associated $CO_2$ emissions. The EIA expects total energy-related $CO_2$ emissions to increase to 4.8 Bmt in 2021 and 4.9 Bmt in 2022. While $CO_2$ accounts for more than 80 percent of U.S. emissions, many other different greenhouse gases are also emitted. Methane, nitrous oxide, and other gases with high global warming potential account for the other nearly 20 percent of the total.

According to a recent assessment, flaring and venting waste 8 percent of global natural gas production annually, and contribute 6 percent of global greenhouse gas emissions and disperse a range of other harmful pollutants.[14] The Greenhouse Gas Inventory of the U.S. Environmental Protection Agency (EPA) makes an estimate of flaring's contribution to $CO_2$ emissions. The estimate for 2018 totaled 32.8 million metric tons of $CO_2$.[15] The International Energy Agency (IEA) prepares estimates of $CO_2$ emissions from natural gas flaring around the world. IEA's latest estimate published in June 2020 shows that flaring in North America (both U.S. and Canada) resulted in 36.7 million metric tons of $CO_2$ emissions in 2018, consistent with the EPA's estimate.[16] An alternative calculation method would be to convert EIA's estimate of gas vented and flared to $CO_2$ emissions. As mentioned above, per the EIA data, the volume of U.S. natural gas vented and flared in 2019 was 1.48 billion Bcf/d or 540 Bcf.[17] Flaring one Bcf of methane produces roughly 54,900 metric tons of carbon dioxide.[18] Accordingly, assuming 100 percent of the gas estimated to have been vented and flared in 2019 was flared at 100 percent efficiency, a total of 29.65 million metric tons of $CO_2$ emissions would have resulted. These estimates of U.S. $CO_2$ emissions associated with flaring, on the order of 30 million metric tons per year, are a relatively small fraction of the total energy-related $CO_2$ emissions noted above. Nevertheless,

[12] U.S. Energy Information Administration, In 2020, the United States produced the least CO2 emissions from energy in nearly 40 years, available at: https://www.eia.gov/todayinenergy/detail.php?id=48856

[13] U.S. Energy Information Administration, U.S. Economic Assumptions and Energy-Related Carbon Dioxide Emissions, available at: https://www.eia.gov/outlooks/steo/report/renew_co2.php?src=Environment-b1

[14] Calel, Raphael and Mahdavi, Paasha, *The unintended consequences of antiflaring policies—and measures for mitigation*, Proceedings of the National Academy of the United States (PNAS), June 9, 2020, available at: Opinion: The unintended consequences of antiflaring policies—and measures for mitigation

[15] U.S. Environmental Protection Agency, Greenhouse Gas Inventory, Annex 3.5: Methodology for Estimating $CH_4$, $CO_2$, and $N_2O$ Emissions from Petroleum Systems, available at: https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2018-ghg

[16] International Energy Agency, Flaring Emissions, June 2020, available at: https://www.iea.org/reports/flaring-emissions

[17] U.S. Energy Information Administration, 2020, Natural gas venting and flaring in North Dakota and Texas increased in 2019, December 8, 2020.

[18] U.S. Environmental Protection Agency, Greenhouse Gases Equivalencies Calculator - Calculations and References

the amount of $CO_2$ emitted by flaring has increased dramatically with increases in associated gas flaring due to tight oil development.

## *2. Flaring and Venting Background*

Natural gas is a gaseous mixture of hydrocarbon compounds, primarily methane, along with ethane, propane, butane and non-hydrocarbon gases (e.g., water vapor, carbon dioxide, helium, hydrogen sulfide, and nitrogen). Natural gas flaring is the controlled combustion of such volatile hydrocarbons. Venting is the direct release of natural gas into the atmosphere, typically in small amounts. While flaring is more common than venting, both of these activities routinely occur during oil and natural gas development as part of drilling, production, gathering, processing, and transportation operations. Flaring and venting activities represent both the loss of a valuable natural resource and a source of environmental impact. The reasons behind flaring and venting may be related to maintaining safety, economics, operational expediency, or a combination of all three.

DOE's FECM launched an effort in 2019 to compile natural gas venting and flaring regulations implemented by oil- and gas-producing States. The purposes behind this effort were to determine the current state of regulatory requirements; inform DOE leadership and program offices, States, industry, and other stakeholders; and engage with all interested parties on FECM's research portfolio and potential technology options available to economically capture and use natural gas. FECM compiled and publicly released a comprehensive report, a regulatory database with hyperlinks to each State regulation, 32-State fact sheets, and a Federal Offshore Gulf of Mexico fact sheet with information on flaring and venting regulations.[19]

Domestically, flaring is becoming more prevalent with the rapid development of unconventional, tight oil and shale gas resources over the past two decades. Unconventional development has brought online hydrocarbon resources that vary in characteristics and proportions of natural gas, natural gas liquids (NGL) and crude oil. While each producing region flares gas for various reasons, the lack of direct market access for the gas is the most common reason for ongoing flaring of associated gas. Economics can dictate that the more valuable oil be produced and the associated gas flared to facilitate production if gas delivery infrastructure is inadequate. Of specific concern is the increase in flaring in hydrocarbon gas liquids-rich plays like the Permian Basin and the Williston Basin, where there is not enough gas gathering and transportation infrastructure for the captured gas to be brought to market.

Many companies have implemented technology solutions to routine venting—voluntarily or in response to regulations; although, ongoing venting and equipment leaks are identifiable sources of emissions. In many cases, the equipment that is the source of recurrent venting are being replaced by more modern, less emitting devices. Technologies also currently exist to

[19] U.S. Department of Energy, Office of Fossil Energy, State-Level Natural Gas Flaring and Venting Regulations, available at: https://www.energy.gov/fe/state-level-natural-gas-flaring-and-venting-regulations

capture gas that would otherwise be flared and convert it into useful products, or to use it onsite to facilitate production. Opportunities exist to increase the prevalence of these technological solutions and improve economical uses, ultimately benefiting domestic and international gas consumers. Currently available commercial alternatives to flaring include: compressing the natural gas and trucking it short distances for use as a fuel for oil field activities; extracting natural gas liquids from the flare gas stream to reduce the flared volume (a partial solution); converting the gas-to-electric power using small-scale generators, and small-scale gas-to-methanol or gas-to-liquids conversion plants. These alternatives are often not cost-competitive and different solutions or step-change improvements to these alternatives would be needed to make them cost-competitive.

## 3. *Flaring and Venting Domestic Landscape*

From 2018 to 2020, the annualized price of natural gas at Henry Hub declined to an average of $2.03 per million British Thermal Units (MMBtu) from just above $3.15/MMBtu.[20] Near-term prices are anticipated to increase in response to winter demand and economic rebound in travel and trade. Given such (generally) low prices, the overall costs to transport associated gas to market can be too high to make sales profitable, especially in areas where oversupply is widespread, leaving increased flaring the only economical option for maintaining oil production. As a result of the increase in flaring, regulations on flaring continue to tighten, making it more difficult to flare large volumes of natural gas.[21] In this environment, many operators are actively seeking ways to reduce flaring.

The EIA's AEO 2020 reported that the annual volume of gas flared and vented was 538 Bcf. The flared gas represented approximately 1.53 percent of the almost 34 Tcf of total dry natural gas produced.[22] Dry natural gas is the natural gas that remains after the liquefiable hydrocarbon portion, and any volumes of nonhydrocarbon gases (where they occur in sufficient quantity to render the gas unmarketable), have been removed. Two states annually accounted for 85 percent of domestic flaring and venting—Texas totaled 251 Bcf and North Dakota totaled 205 Bcf. These totals are 10 to 20 times the volumes reported by other States, reflecting the much higher level of unconventional oil and natural gas production in these two States.[23]

The AEO 2020 data reported the volumes of gas flared reached levels of between 225 and 285 Bcf per year in the mid-1990s. After dropping to less than half that during the early 2000s, reported flared volumes rose to levels between about 200 and 500 Bcf per year during the

[20] U.S. Energy Information Administration, Henry Hub Natural Gas Spot Price, available at: https://www.eia.gov/dnav/ng/hist/rngwhhdA.htm
[21] Railroad Commission of Texas. RRC Regulation of Flaring and Venting, available at: https://www.tceq.texas.gov/assets/public/assistance/sblga/oil-gas/RRC-Flare-Vent-Program-Presentation.pdf
[22] U.S. Energy Information Administration, AEO 2020, available at: https://www.eia.gov/outlooks/aeo/pdf/AEO2020%20Full%20Report.pdf
[23] U.S. Energy Information Administration, Natural Gas Gross Withdrawals and Production, available at: www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_VGV_mmcf_a.htm

2011-2018 time period as both oil and natural gas production levels increased significantly.[24] The increase in flaring correlates with growing production in the same time frame due to low gas prices and increased gas use in the utility sector. By 2019, U.S. total gross natural gas production reached a record of 112 Bcf per day or about 40.9 Tcf per year.[25] Thus, in both 2018 and 2019 vented and flared gas represented about 1.3 percent of gross natural gas production.

Currently, the largest volumes of associated flared natural gas are due to a lack of available pipeline infrastructure, such as in the Bakken shale play in North Dakota and across a number of tight oil plays in the Permian Basin, underlying Texas and New Mexico. The primary reasons for this situation are economics and unavailability of local pipeline gathering and distribution systems to take oil and natural gas to refineries, chemical plants and other markets.

Estimates show flaring in Texas averaged between 0.80 and 0.90 Bcf/d through the last quarter of 2018 and the last quarter of 2019.[26] The Railroad Commission of Texas (TRRC) projects that new pipeline systems will result in flaring reductions of approximately 0.050 Bcf/d to 0.20 Bcf/d, over 12 to 18 months beginning February 2020.[27] These gains could be offset by the drilling of additional new wells that will increase the need to add new flares. Total gross flaring volumes in Texas could increase as produced oil volumes increase, although current declines in new-well production relative to COVID-19 related demand destruction indicate at least a short to mid-term reduction.

Market assessment of production activity in Texas highlights that 2020 flaring volumes are down significantly from 2019 volumes (<0.40 Bcf/d) due to impact of shut ins and reduced activity in response to global supply-demand imbalance. As various sectors of the economy are recovering at variable rates, demand for oil and natural gas will influence prices. Within the Permian Basin, drops in flaring intensity are temporary and flaring is expected to continue to increase at a yearly average of about 0.46 Bcf/d by 2025 when oil prices are above $60 per barrel.[28] Oil price is a key driver of projected drilling activity and accompanying U.S. crude oil production rates. In the Reference case, the EIA projects that the Brent crude oil price increases (in real dollar terms) from its 2020 average of $42/barrel to $73/barrel by 2030 and to $95/barrel by 2050.[29]

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[24] U.S. Energy Information Administration, U.S. Natural Gas Vented and Flared, available at: www.eia.gov/dnav/ng/hist/n9040us2a.htm

[25] U.S. Energy Information Administration, U.S. Dry Natural Gas Production, available at: https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_FGW_mmcf_a.htm

[26] Oilfield Technology, Rystad Energy: Permian Gas Flaring Declining, April 7, 2020, *available at:* www.oilfieldtechnology.com/special-reports/07042020/rystad-energy-permian-gas-flaring-declining

[27] Railroad Commission of Texas, Research and Statistics, available at: https://www.rrc.state.tx.us/oil-gas/research-and-statistics/

[28] Texas Permian Natural Gas Flaring Forecast to Increase as Activity Returns, NGI's Sale Daily, February 2, 2021, available at: https://www.naturalgasintel.com/wp-content/uploads/2021/02/sd20210202.pdf

[29] U.S. Energy Information Administration, Annual Energy Outlook 2021, available at https://www.eia.gov/outlooks/aeo/production/sub-topic-01.php

While on a percentage of production basis, flaring is small, one day's worth of Permian Basin level of flaring alone (~0.85 Bcf/d) is equivalent to generating 117,000 megawatt-hours (MWh) from a natural gas combined cycle power plant, capable of powering 10,700 homes for a year. Greater than three million homes could be powered for a year with the power that could be produced with a year's worth of Permian gas flaring at this rate. Flaring this gas results in greater than 17 million metric tons per year of $CO_2$ emissions.[30]

In the Bakken Shale of North Dakota's Williston Basin, about 20 percent of the roughly 85 Bcf per month, or 0.56 Bcf/d, will continue to be flared until pipeline infrastructure that is currently under construction is completed. One day's worth of this flaring would be capable of powering 7,000 homes for a year. About 2.6 million homes could be powered for a year. Flaring this gas further results greater than 11 million metric tons per year of $CO_2$ emissions.[31]

Every oil- and gas-producing State has in place regulations to limit or prevent the "waste" of gas resources. Flaring limits vary from State to State, and no national set of standards currently exists. In the states with a large number of permitted gas flares, planned increases in natural gas processing and pipeline takeaway capacity may reduce the volume of flaring over the next five years. In both Texas and North Dakota, gas processing and gas pipeline capacity are being expanded to handle the increased volumes of associated gas being produced. While planned increases in processing and pipeline capacities will reduce flared volumes, these actions will be insufficient to eliminate flaring and venting, and additional reduction alternatives would be required to further reduce flaring and venting.

In the short term, flaring percentages have the potential to vary in both Texas and North Dakota as oil prices fluctuate, drilling rig activity changes, and compliance requirements are reevaluated. Historically, flaring volumes typically correlate one-to-one with new oil well production. As evidence of the dramatic recent changes to market conditions; while the overall amount of gas produced in Texas declined by 13 percent from June 2019 to May 2020, the portion of produced gas that was flared dropped much more sharply by 79 percent during that same period—an unprecedented market decoupling. In August 2020, the TRRC approved a draft change to tighten its existing rules to reduce the flaring of methane.[32]

## *4. Issues and Market Conditions*

Upstream natural gas flaring and venting includes flaring for operational and safety reasons, flaring for economic reasons, and venting for operational reasons. Flaring for operational and safety reasons is generally short term. Venting for operational reasons generally includes small

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[30] U.S. Energy Information Administration, available at: https://www.eia.gov/tools/faqs/faq.php?id=77&t=11

[31] Bradley, David. Natural Gas Flaring Bug Hits Oil Hotspots in Bakken, Permian, available at: https://www.naturalgasintel.com/texas-north-dakota-lead-u-s-to-record-1-28-bcf-d-venting-flaring-in-2018/

[32] World Oil, Texas Regulators Update Rules to Limit Gas Flaring, August 5, 2020, available *at:* https://www.worldoil.com/news/2020/8/5/texas-oil-regulators-update-rules-to-limit-gas-flaring

volumes (or else it would be captured and flared as a safety hazard). Less frequently, venting is may be required for safety reasons. The flaring of relatively large volumes of gas associated with oil production, either temporarily or long term, is the area that has generated the most concern among stakeholders and is a primary focus of this report.

Some venting is avoidable and could be reduced or prevented with off-the-shelf technology (e.g., by installing low-bleed controllers, vapor recovery units, or improved compressor seals) or the application of better maintenance and best management practice programs. In some cases, these options are economic and may result in the increase in gas sales volumes. In other cases, unless required by regulations or corporate objectives determine such to be worthwhile; the required capital investment in venting solutions may be uneconomic or a marginally economic undertaking, and subsequently venting mitigation may not be implemented.

Flaring of associated gas for extended periods may be necessary if a well is being drilled in a new area that lacks natural gas pipeline take-away capacity. In some cases, several wells may be drilled and begin a period of extended oil production before a company determines from the test data that an investment in associated gas processing facilities and pipelines will meet economic standards. When long-term volumes, pressures, and rates of associated gas production prove to be sustainable at levels that can economically justify installation of new gas gathering infrastructure or expansion of existing infrastructure, only then will those investments be made and the flaring discontinued. If the economics cannot justify the investment, associated gas flaring may continue as long as it is not prohibited by State or Federal regulations.

To address flaring in the field, DOE has undertaken market and technology evaluations to understand the composition of flare units across major producing regions. This approach provides DOE with tailorable solutions that optimize technology deployment and the promulgation of best industry practices. Important metrics to track include: total annual flared volume, total annual $CO_2$ emissions, the number of leases that flare, the estimated number of operators, and chemical characterization of the produced hydrocarbons. Analysis of this data yields estimates for the distribution of flare units, average chemical composition of natural gas, operational days and locations across the well development lifecycle, and producing information for each individual flare.

DOE analysis across the Bakken play in North Dakota and the Eagle Ford and Permian Basin plays in Texas identified greater than 78,000 individual flare units in 2018 (see Table 1). These flare units range in size from less than 100 thousand cubic feet per day (Mcf/d) to up to 0.1 Bcf/d, as reported on a monthly basis per lease to State-level government agencies. As delineated in Figure 1, flare units less than 100 Mcf/d represent 89 percent of the total number of flare units and more than 26 percent of the total flare gas volume in these selected producing plays. Achieving a 55 percent reduction in annual flare gas volumes would require operational modifications to greater than 75,000 individual flare units (96 percent of total number of flare units). If larger flare units were targeted to decrease flare volumes, for example, a 45 percent flare gas reduction could be achieved through operational modifications to approximately 3,000 flare units (4 percent of total number of flare units) with flare sizes greater than 300 Mcf/d.

Table 1. 2018 Associated Natural Gas Flaring Statistics by Selected Plays

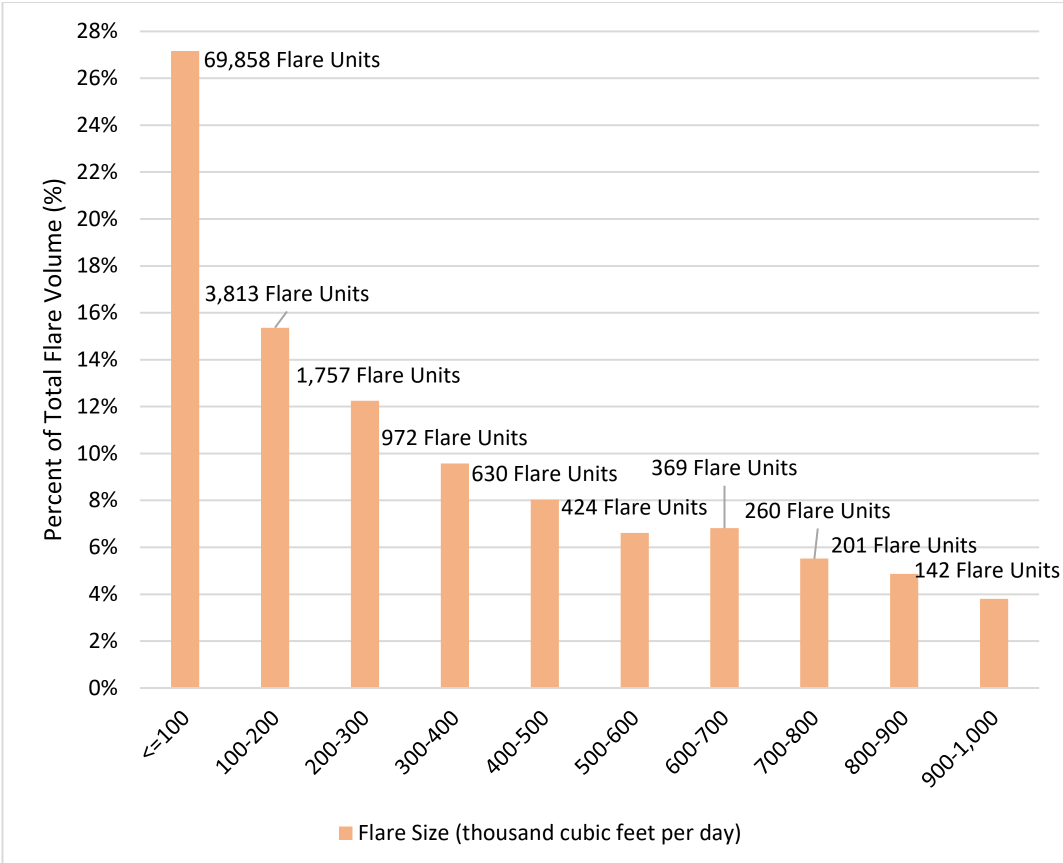
| Permian | | | Eagle Ford | | | Bakken | | |
|---|---|---|---|---|---|---|---|---|
| **Flare Size (Mcf/d)** | **Flare Units** | **Total Volume (Mcf/d)** | **Flare Size (Mcf/d)** | **Flare Units** | **Total Volume (Mcf/d)** | **Flare Size (Mcf/d)** | **Flare Units** | **Total Volume (Mcf/d)** |
| **<=100** | 44,252 | 601,057 | **<=100** | 21,825 | 253,474 | **<=100** | 3,781 | 99,761 |
| **100-200** | 2,401 | 339,660 | **100-200** | 659 | 91,092 | **100-200** | 753 | 109,036 |
| **200-300** | 1,105 | 269,029 | **200-300** | 210 | 51,644 | **200-300** | 442 | 109,508 |
| **300-400** | 596 | 205,937 | **300-400** | 96 | 33,560 | **300-400** | 280 | 96,755 |
| **400-500** | 366 | 163,629 | **400-500** | 58 | 26,053 | **400-500** | 206 | 92,716 |
| **500-600** | 240 | 131,329 | **500-600** | 35 | 19,108 | **500-600** | 149 | 81,686 |
| **600-700** | 203 | 131,534 | **600-700** | 26 | 16,528 | **600-700** | 140 | 91,261 |
| **700-800** | 146 | 108,801 | **700-800** | 16 | 11,903 | **700-800** | 98 | 73,091 |
| **800-900** | 99 | 84,003 | **800-900** | 19 | 16,139 | **800-900** | 83 | 70,739 |
| **900-1,000** | 73 | 68,990 | **900-1,000** | 11 | 10,125 | **900-1,000** | 58 | 54,669 |

## *5. Oversupply and Impact on Flaring and Venting*

The COVID-19 pandemic has resulted in a temporary, albeit significant, reduction in the demand for oil and gas. With reduced oil demand and production during the first half of 2020, natural gas flaring levels in the Permian Basin were down and are expected to continue to remain below 0.4 Bcf/d through 2021.[33] [34] Wellhead flaring is driven by well completion activity followed by gas production added from recent well vintages. Projects where gas is flared are typically more recent producing field developments, demonstrating lagging gathering lines and other inadequate midstream infrastructure.

[33] World Oil, Permian Gas Flaring Declines as Production Slows, April 7, 2020, available at: https://www.worldoil.com/news/2020/4/7/permian-gas-flaring-declines-as-production-slows#:~:text=As%20a%20slowdown%20in%20crude,said%20in%20a%20report%20Monday
[34] Permian Basin Flaring Outlook, Rystad Energy, January 2021, available at: http://blogs.edf.org/energyexchange/files/2021/01/20210120-Permian-flaring-report.pdf

Figure 1. Distribution of Flare Sizes as a Percent of Total Flare Volume




During the industry downturn between 2015 and 2016, Permian drilling activity remained robust. Even so, wellhead flaring declined by more than one-third (35 percent) between early 2015 and early 2017, due to increased efforts to capture and sell the natural gas. Reduced economic activity related to the COVID-19 pandemic has caused changes in energy demand and supply patterns in 2020-2021 and will continue to affect these patterns in the future. On an annual daily average, the EIA reported that United States produced approximately 11.31 million b/d. U.S. crude oil production averaged 11.17 million b/d in April 2021 (the most recent month for which historical data are available), down from the 12.29 million b/d average observed in 2019. In February 2021, U.S. crude oil production reached a multi-year low of 9.77 million b/d, resulting from curtailed production amid low oil prices.[35] Since then, U.S. production has increased mainly because tight oil operators have brought wells back online in response to rising prices. It is estimated that all flaring and flaring-driven emission intensity metrics will materially increase for the Permian Basin production in 2021 as curtailed production is brought back online. Despite the decline in flaring due to the temporary drop in overall oil and natural gas production and weak demand, some degree of flaring is continuous and increases can be expected with increased crude oil production in the future.

[35] U.S. Energy Information Administration, 2021. Petroleum & Other Liquids, available at: https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_m.htm

## *6. Flaring Reduction Technologies*

There are a number of reasons why gathering and transportation systems may not be in place when oil production commences. For example, the low price of natural gas may not financially justify installation of a gathering system, the pipeline capacity of existing natural gas midstream systems (storage and transportation) may not accommodate new production, and installation of gathering systems may be delayed due to regulatory or legal issues.

To create new and improved flare gas reduction alternatives that are cost-effective, FECM is expanding the research portfolio to include innovative technologies that can convert flare gas or low-value associated natural gas to higher-value chemical products and thus reduce flaring. These value-added chemical upcycling technologies complement DOE's existing R&D on mitigating emissions from midstream natural gas infrastructure. In conducting this R&D, DOE will leverage existing expertise to deliver field validated, technical solutions that reduce wellhead emissions and create a variety of value-added products from the mitigated emissions. DOE's specific focus will be on wellhead-deployable technologies that convert natural gas, via thermo-catalytic, microwave-assisted, electrochemical, or other novel processes, to higher-value energy commodities that can be easily sold in energy and chemical markets. Promising technologies will be integrated into small-scale modular systems that, in the future, can be transported from one flare site to the next for use during periods when natural gas gathering and transportation systems are not yet functional.

This section summarizes current commercial and semi-commercial options for reducing flaring of natural gas and describes DOE R&D plans for a parallel technology focus on upcycling technologies. As part of DOE's research efforts, there will be continuous evaluations of economic and market information that provide critical insight into future R&D opportunities, areas for accelerating potential market adoption, and ultimate technology commercialization. Current options fall under the six main categories listed below.

***1. Compressing natural gas and trucking it short distances for use as a fuel***

Natural gas can be captured and compressed (CNG) at the well pad and trucked to a gas processing plant or to a location where it is used as a fuel. This approach may be economically feasible at wells relatively close to a processing plant or other location where gas can enter the pipeline system (20 to 25 miles, or fewer). It may also be economically feasible if the compressed gas can be used to power equipment within the producing field.

***2. Extracting natural gas liquids from the pre-flare gas stream***

Natural gas liquids can be removed from associated gas using mobile equipment located at the well pad and trucked away for sale. Such systems work best with associated or wet natural gas streams, which are rich in gas liquids . Once separated, the remaining light hydrocarbons—methane (C1), ethane (C2), and other volatile organics—or gas is otherwise flared. Commercial systems that can capture pentane (C5) and heavier hydrocarbons (C5+) are simple and inexpensive, and only reduce flaring volumes a limited amount. Technologies that also capture propane (C3) and butane (C4) recover a larger portion of the input gas and result in less flaring and do require a larger initial investment. Higher rates of flare reduction can be achieved by coupling NGL recovery with other technologies where the residual dry gas remaining can be captured and trucked offsite as CNG or used for onsite power generation. This approach only makes economic sense in niche situations where gas composition and nearby NGL market conditions align.

***3. Small-scale, gas-to-methanol or gas-to-liquids conversion plants***

Systems are available to convert natural gas to chemicals or fuels and some of them have been marketed toward flaring reduction. Some aspects of these systems have not been adapted, sized, or optimized for application to U.S. flaring situations as evidenced by their lack of widespread application. Novel combinations of existing technology elements must be conceived and tested to prove technical and economic capabilities. Researchers will develop technologies to upgrade the flare gas into industrially-relevant chemicals. There may also be an opportunity to leverage solid oxide fuel cell technology research in combination with chemical upgrading.

***4. Converting natural gas to electric power using small-scale generators***

A variety of technologies are available for local power generation, including the use of reciprocating engines and gas turbines to electricity generators. Local load systems work best when using lean associated gas (e.g., the residual gas after NGL recovery). To make economic sense, all of these approaches require a constant nearby demand for electric power or the option of selling power to the local grid.

***5. Utilizing gas that would otherwise be flared for beneficial use within the field***

Captured natural gas can be used for onsite power generation, space heating, or for other purposes through small-scale combined heat and power systems. The disparity between the volumes of gas being flared and the volumes required for such end uses makes this solution unlikely to be economic. While onsite technology solutions have been tested and found to work, many have not been widely deployed, generally due to unfavorable economics when compared to the alternative of flaring. The capital cost of installation (or the rental cost), plus the costs of operation, currently do not appear to justify widespread application of these solutions.

***6. Converting captured gas to liquefied natural gas and trucking it short distances for use as a fuel***

Natural gas can also be liquefied and trucked to a location where it can be used as a fuel. This may be appropriate when the gas does not require extensive conditioning (cleaning and treating of gas). A recent proposed option is to use micro-LNG plants that produce small-scale LNG in the Permian basin.[36] Small LNG plants can produce up to 100,000 gallons of LNG daily, which can then be transported to power plants and other markets. Gas-to-liquids conversion systems are operating in some parts of the United States, however, these applications are not widely used within producing shale plays where the gas flaring occurs.

## *7. R&D Pathways for Flared Associated Gas Conversion*

DOE's objective is to accelerate the development of modular conversion technologies that, when coupled with the currently available commercial alternatives outlined in the previous section, will provide a portfolio of options for producers seeking to monetize flared gas volumes of practically any magnitude and at any location. Programmatic R&D will assess research targets (e.g., cost, performance) for the successful development and commercialization of transformational technologies for upcycling associated natural gas. Continued investment in R&D focused on these modular conversion technologies is the best pathway for expanding the economic options available for utilization of stranded or flared gas resources.

Operating within these modular systems, FECM is specifically targeting two areas where early-stage research opportunities have been identified: (1) multifunctional catalysts and (2) modular conversion equipment designs. The first area involves the early-stage development and evaluation of multifunctional catalysts for the direct conversion of methane to liquid petrochemicals (e.g., methanol, ethanol, ethylene glycol, acetic acid, and other hydrocarbons) that can be easily transported for subsequent conversion into commercial products. The second area of interest is the development of novel equipment and process design concepts for high-selectivity pyrolysis, which is integral to the manufacture of high-value carbon products from methane (or the mixtures of methane, ethane, propane, and butanes represented). Research in this area focuses on the application of process intensification at modular-equipment scales suitable for deployment, and transport between, remote locations where gas is being flared. Across these competing technologies, engineering assessments will be performed to define the thermodynamic minimum energy required to convert associated natural gas to high-value liquid and solid products. Results from these analyses will be used to set the lower bound "energy penalty" allowable for any conversion technology. Further evaluations will include an identification of the priority conversion products from flared and stranded gas resources. Ongoing market assessments will also determine if there is a viable market for the products by defining the liquid market potential, as there exists an infinite number of chemical intermediates that can be produced from associated natural gas. It is therefore critical to identify and analyze, for example, the top liquid chemical intermediates that make the most economic sense to produce. DOE continues its ongoing efforts to explore technologies that curtail methane gas emissions from flaring and venting in shale formations.

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[36] Houston Chronicle. Companies offer super-cool solution to flaring gas in the Permian, August 13, 2020, available at: https://www.houstonchronicle.com/business/energy/article/Companies-offer-super-cool-solution-to-flaring-15479547.php

In response to the Administration's Fiscal Year (FY) 2019 Budget Request and House/Senate FY 2019 Appropriations, DOE issued a funding opportunity announcement (FOA) in 2019 to strategically execute research proposals focused on mitigating emissions from upstream and midstream natural gas infrastructure. One of the areas of interest focused on accelerating the development of technologies capable of converting gas that would otherwise be flared into transportable, value-added products. It is envisioned that successful technologies developed in this R&D effort will be integrated into small-scale modular systems that, in the future, can be transported to flare sites for use during periods when natural gas gathering and distribution systems are not yet functional.

The FOA targeted two areas, where basic research opportunities have been identified: (1) multifunctional catalysts and (2) modular conversion equipment designs.

1. *Multi-Functional Catalysts*: One research area that could provide significant benefit is the early-stage development and evaluation of multifunctional catalysts for the direct conversion of methane to liquid petrochemicals (e.g., methanol, ethanol, ethylene glycol, acetic acid, C3 and C4 analogs, C4+ olefins, and Benzene, Toluene, Xylene) that can be easily transported and are suitable for subsequent conversion into commercial products. Research in this area will focus on methods for process intensification at the nano- to micro-scale and on facilitating high catalyst activity, product yield, selectivity, and mass/heat transfer rates.

2. *Modular Equipment Design Concepts for Conversion to High-Value Carbon Products*: Another area of interest is the development of novel equipment and process design concepts for achieving high-selectivity pyrolysis, which is integral to the manufacture of high-value carbon products (e.g., carbon nano- or micro-fibers, carbon nano-tubes, and graphene sheets) from methane or the mixtures of methane, ethane, propane, and butanes representative of natural gas streams being flared. Research in this area will focus on the application of process intensification at modular equipment scales suitable for deployment and transport between remote locations where gas is being flared.

Of particular interest are approaches that:

- Result in modular, compact, integrated, and transportable technologies;
- Have a large turndown ratio and can operate continuously under varying feed rates and compositions;
- Have the potential to convert a higher fraction of an associated gas stream, lessening the requirements for NGL recovery;
- Can make use of oxygen in the air directly without the need for a separate air fractionation unit, or can make direct use of a weak oxidant, such as $CO_2$, which may be more readily available—in the case of direct conversion technologies that require oxygen (e.g., partial oxidation of methane to methanol, oxidative coupling of methane);

- Can make use of excess hydrogen in methane to offset energy requirements of the conversion process;
- Initially target high-value, small-volume product markets and can pivot toward commodity markets as the technology develops and matures; and
- Result in technology platforms capable of producing a variety of products using the same or similar materials, equipment, or processes.

The complete elimination of event-based and routine flaring and venting may require disruptive changes to the overall energy economy in addressing greenhouse gases. To reduce the carbon intensity of flaring and venting emissions, modular technologies could work in support of a carbon-free, hydrogen economy in which natural gas is decarbonized and transported away from the site of production as hydrogen (a carbon-free fuel). Advanced and mature commercial technologies exist for producing hydrogen from natural gas. Similarly, advanced and mature $CO_2$ capture technologies are also commercially available. Next generation versions of these capture technologies developed with funding from DOE and others are in various stages of testing for initial deployment. The coupling of hydrogen production and $CO_2$ capture technologies will become the mainstay for the deployment of hydrogen derived from natural gas combined with carbon capture, utilization and storage (CCUS), or blue hydrogen, over the remainder of this decade. Due to inherent costs and efficiency limitations, currently existing technologies alone are not sufficient to address the projected demand for decarbonized natural gas applications.

In response to the House/Senate FY 2021 Appropriations, DOE issued a FOA in 2021 to execute research proposals focused on Fossil Energy Based Production, Storage, Transport and Utilization of Hydrogen Approaching Net-Zero or Net-Negative Carbon Emissions. The funding opportunity addresses many R&D areas of interest that are necessary to enable a hydrogen economy, including Hydrogen Production and Infrastructure for Natural Gas Decarbonization. This area of interest focuses on the advancing transformational and disruptive technologies needed to produce hydrogen from natural gas with CCUS and net-zero life-cycle greenhouse gas emissions, while radically reducing the cost and decarbonizing the equipment and processes used in fossil-based energy production.

This research effort supports FECM’s Oil and Natural Gas R&D Program long-term objective to facilitate a rapid, efficient, and cost-effective transformation by mid-century of the U.S. natural gas industry from being a direct supplier of natural gas to also being a strategic supplier of carbon-free hydrogen gas derived from the Nation’s plentiful oil and natural gas resources. To achieve this objective, R&D proposals are being sought to identify and develop new natural gas-to-hydrogen process concepts employing novel conversion, separation, and heat and mass integrated technologies. Some examples of the concepts and technologies of interest include, but are not limited to, chemical-looping reforming, electrochemical reforming, non-equilibrium plasma/microwave-based conversion methods, mechano-chemical conversion methods, and in situ thermochemical or biological conversion methods suitable for hydrogen production within the natural gas reservoir.  These technologies must include a clear mechanism or pathway for separation and capture of the carbon stream.

FECM efforts will continue to focus on developing conversion processes, especially those utilizing natural gas for conversion to hydrogen and solid carbon product technologies, in support of a low-carbon energy future.  This work will necessitate advanced R&D on new sensor capabilities related to being able to safely produce and transport hydrogen, as well as artificial intelligence (AI)/machine learning (ML) applications in order for the conversion technologies to fully and efficiently use the ever-changing make-up of the produced gas stream.

Further, an expansion of the necessary infrastructure options to address venting and flaring challenges could benefit from the collection and analysis of vast amounts of data metrics. Successful integration of well-to-basin-level oil and natural gas information presents an opportunity to make sense of the significant store of data and knowledge available to the industry and government.  DOE's experience in applying advanced computational science tools to solve complex problems can be leveraged to address these and other challenges across the natural gas supply chain.  Ongoing R&D regarding AI and ML will be used to analyze massive datasets quickly for answers needed to develop technology solutions to America's energy challenges.

DOE is applying these tools in its mission to discover, integrate, and mature technology solutions to enhance the Nation's energy foundation and protect the environment for future generations.  AI and ML will further facilitate innovations across a range of oil and natural gas applications, including: methane leak detection and sensor applications across the supply chain; identifying data as input for models to accelerate innovation and technology development; using AI/ML to predict novel materials for fossil energy applications—from hypothesis to validation; enabling dramatic improvements in subsurface visualization, dynamic forecasting, and autonomous control; and enabling real-time early warnings for incident prevention and minimizing environmental impacts.  Overall, the flaring and venting R&D portfolio will be fully integrated into opportunities to enhance research through computational analysis to improve the efficiency, productivity, and environmental safety in the oil and natural gas industries.

Flaring and venting in the field continue to represent an environmental concern, a loss of valuable natural resources, and a technology gap where DOE and its partners can accelerate technologies, tools, and best practices to reduce the need to flare or vent during oil and natural gas production.  This R&D portfolio continues to support energy security so that domestic and international markets can be effectively operated with minimal environmental footprints.  The U.S. Department of Energy continues to be a world leader in advancing technologies to reduce flaring and venting and add value to the energy economy.  Active R&D projects relevant to flaring and venting are further described in Appendix A.

The Office of Fossil Energy and Carbon Management's Office of Oil and Natural Gas annually undertakes an effort to compile state-level natural gas flaring and venting regulations currently implemented by States in the United States. A total of 32 information fact sheets were developed for each oil- and gas-producing State (and the Federal Offshore Gulf of Mexico), along with the accompanying report, *Natural Gas Flaring and Venting: State and Federal Regulatory Overview, Trends, and Impacts*, that summarizes the findings and analysis of the information collected. In addition, a compendium regulatory database was developed to include an aggregated list of State regulations with hyperlinks to full policy text and reference to specific sections relevant to flaring and venting. Each fact sheet includes information on: (1) FECM's role and research portfolio for capture and utilization of flared or vented gas; (2) producing oil and gas plays and basins in the State; (3) Key State regulations associated with natural gas flaring and venting; (4) relevant State oil and gas statistics for the last six years, including flared and vented natural gas volumes, as data is available; and (5) State regulatory points of contact.[37] [38] The analysis report further describes technology options available to capture and use natural gas and offers additional insights on R&D efforts of the Office of Fossil Energy and Carbon Management, Office of Oil and Natural Gas, and its partners to accelerate technology solutions to reduce flaring and venting.

[37] U.S. Department of Energy, Office of Fossil Energy, Natural Gas Flaring and Venting: State and Federal Regulatory Overview, Trends, and Impact, June 2019, available at: https://www.energy.gov/sites/prod/files/2019/08/f65/Natural%20Gas%20Flaring%20and%20Venting%20Report.pdf

[38] U.S. Department of Energy, Office of Fossil Energy, Natural Gas Flaring and Venting Regulations Fact Sheets by State, available at: https://www.energy.gov/fe/findyourstate-natural-gas-flaring-and-venting-regulations-fact-sheets-state

# III. References

Adams-Heard, Rachel. World Oil. 2020. Permian gas flaring declines as production slows. April 7, 2020.
https://www.worldoil.com/news/2020/4/7/permian-gas-flaring-declines-as-production-slows#:~:text=As%20a%20slowdown%20in%20crude,said%20in%20a%20report%20Monday.Fwq

Bradley, David. Natural Gas Intelligence. Texas, North Dakota Lead U.S. to Record 1.28 Bcf/d Venting/Flaring in 2018. December 9, 2019.
https://www.naturalgasintel.com/texas-north-dakota-lead-u-s-to-record-1-28-bcf-d-venting-flaring-in-2018/

U.S. Energy Information Administration. Annual Energy Outlook 2021 (with projections to 2050). February 2021. https://www.eia.gov/outlooks/aeo/

U.S. Energy Information Administration. United States Energy Profile. 2021.
https://www.eia.gov/international/rankings/country/USA

U.S. Energy Information Administration. After 2020 decline, EIA expects energy-related $CO_2$ emissions to increase in 2021 and 2022. Posted January 26, 2021.
https://www.eia.gov/todayinenergy/detail.php?id=46537#

U.S. Energy Information Administration. In 2020, the United States produced the least CO2 emissions from energy in nearly 40 years. Posted July 26, 2021.
https://www.eia.gov/todayinenergy/detail.php?id=48856

U.S. Energy Information Administration. United States continued to lead global petroleum and natural gas production in 2020. Posted July 19, 2021.
https://www.eia.gov/todayinenergy/detail.php?id=48756

U.S. Energy Information Administration. U.S. Economic Assumptions and Energy-Related Carbon Dioxide Emissions. Released February 9, 2021.
https://www.eia.gov/outlooks/steo/report/renew_co2.php?src=Environment-b1

U.S. Energy Information Administration. Annual Energy Outlook 2020. January 2020.
https://www.eia.gov/outlooks/aeo/pdf/AEO2020%20Full%20Report.pdf

U.S. Energy Information Administration. Petroleum & Other Liquids. Released June 30, 2021
https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_m.htm

U.S. Energy Information Administration. Natural Gas Gross Withdrawals and Production. Dated January 29, 2021.
https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_FPD_mmcf_a.htm

U.S. Energy Information Administration. Henry Hub Natural Gas Spot Price. Released February 10, 2021. https://www.eia.gov/dnav/ng/hist/rngwhhdm.htm

U.S. Energy Information Administration. How much of U.S. carbon dioxide emissions are associated with electricity generation? Dated January 21, 2020. https://www.eia.gov/tools/faqs/faq.php?id=77&t=11

U.S. Energy Information Administration. Natural Gas Gross Withdrawals and Production. Released January 29, 2021. https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_FGW_mmcf_a.htm

U.S. Energy Information Administration. U.S. Natural Gas Vented and Flared. Released January 21, 2021. https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_VGV_mmcf_a.htm

U.S. Energy Information Administration. Natural Gas Consumption by End Use. Released January 29, 2021. www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm

U.S. Department of Energy, Office of Fossil Energy. Natural Gas Flaring and Venting Regulations Fact Sheets by State. 2020. https://www.energy.gov/fe/findyourstate-natural-gas-flaring-and-venting-regulations-fact-sheets-state

U.S. Department of Energy, Office of Fossil Energy. Natural Gas Flaring and Venting: State and Federal Regulatory Overview, Trends, and Impacts. June 2019. https://www.energy.gov/sites/prod/files/2019/08/f65/Natural%20Gas%20Flaring%20and%20Venting%20Report.pdf

Magill, Jim. Houston Chronicle. Companies offer super cool solution to flaring gas. August 13, 2020. https://www.houstonchronicle.com/business/energy/article/Companies-offer-super-cool-solution-to-flaring-15479547.php

Nemec, Richard. Natural Gas Intelligence. North Dakota Sees Oil, Natural Gas Production Climb in August. October 19, 2020. https://www.naturalgasintel.com/north-dakota-sees-oil-natural-gas-production-climb-in-august/

Railroad Commission of Texas. Dubois, Paul. RRC Regulation of Flaring and Venting. November 2020. https://www.tceq.texas.gov/assets/public/assistance/sblga/oil-gas/RRC-Flare-Vent-Program-Presentation.pdf

Railroad Commission of Texas. Research and Statistics. Accessed February 13, 2021. https://www.rrc.state.tx.us/oil-and-gas/research-and-statistics/

Rystad Energy. Permian Basin Flaring Outlook, Condensed Report, January 2021. Available at: http://blogs.edf.org/energyexchange/files/2021/01/20210120-Permian-flaring-report.pdf

Woodruff, Nicholas. Oilfield Technology. Rystad Energy: Permian gas flaring declining. April 7, 2020. www.oilfieldtechnology.com/special-reports/07042020/rystad-energy-permian-gas-flaring-declining

# Appendix

Table A-1 summarizes new projects FECM initiated to advance Flaring and Venting reduction technologies in 2020.

Table A.1 — FOA No. 2006 Projects Related to Flaring and Venting

| PROJECT | PERFORMER | COMPLETION DATE | FOCUS |
|---|---|---|---|
| Modular System for Direct Conversion of Methane into Methanol via Photocatalysis | Stanford University, Susteon, Casale SA | 2021 | Develop process for photocatalytic activation of methane at a gas-water interface such that methanol can be formed at room temperature. Use photons to excite hydroxyl radicals in aqueous media, which then excite methane to form methanol on a catalyst surface. Identify the best photocatalyst to achieve the highest selectivity and methane conversion efficiency. Design and build a new photoreactor system that is modular and scalable for direct methane to methanol conversion. |
| Electrocatalytically Upgrading Methane to Benzene in a Highly Compacted Microchannel Protonic Ceramic Membrane Reactor | Clemson, Oak Ridge National Laboratory | 2022 | Develop process-intensified technology for methane dehydroaromatization (MDA) in highly compacted microchannel protonic ceramic membrane reactors (HCM-PCMRs) by integrating multiple functions of single-atom catalysis, electrocatalysis, membrane catalysis, membrane separation, and advanced manufacturing. |
| Core-Shell Oxidative Aromatization Catalysts for Single Step Liquefaction of Distributed Shale Gas | NC State U., Lehigh U., WVU, Susteon, Kenan Institute, Shell | 2022 | Design and demonstrate a multifunctional, core shell catalyst for conversion of methane, ethane and propane to liquid aromatics. This catalyst combines breakthroughs in the understanding of alkane dehydroaromatization (DHA) and redox-based selective hydrogen combustion catalysts to overcome limitations of conventional DHA. |
| Isolated Single Metal Atoms Supported on Silica for One-step Non-Oxidative Methane Upgrading to Hydrogen and Value-Added Hydrocarbons | University of Maryland, University of Delaware | 2022 | Support efficient, non-oxidative methane conversion (NMC) via catalyst innovation to convert methane in one step to olefins and aromatics and hydrogen co-product. The catalysts are made of supported single metal atoms and operated at medium-high temperatures. The single metal atoms achieve methane activation by heterogeneous surface dehydrogenation to generate a hydrocarbon pool and limit coke formation. |

| PROJECT | PERFORMER | COMPLETION DATE | FOCUS |
|---|---|---|---|
| Process Intensification by One-step, Plasma-Assisted Catalytic Synthesis of Liquid Chemicals from Light Hydrocarbons | Notre Dame | 2022 | Design, develop, and test a process for direct light hydrocarbons-to-liquid conversion via a modular and flexible plasma-assisted catalytic reactor. Leads to the development of new catalytic materials designed specifically for operation under plasma stimulation. Control of plasma properties, coupled with appropriate catalyst selection, will generate non-thermal intermediates and open surface kinetic pathways at ambient temperature and pressure to facilitate high production rates of liquids from natural gas feeds at the wellhead. |
| Methane Partial Oxidation over Multifunctional 2-D Materials | U. South Carolina, Pajarito Powder, U. Colorado at Boulder | 2022 | This project creates a process for partial oxidation of methane to methanol using a set of multifunctional, graphene-based materials as selective catalysts using scalable techniques. This project will computationally design the active sites for the catalyst that will then be synthesized based on atomically dispersed metal-nitro-carbide active sites. |
| Gas to Carbon Fiber Crystals | PARC, Modular Chemical, eo, Creative Engineers, Inc., UC Riverside, ETCH, Inc. | 2022 | Develop a modular, field-transportable, methane pyrolysis unit that converts flared natural gas into hydrogen that is used to provide process heat and solid carbon powder. Also, develop a molten metal carbon fiber production process that converts the carbon powder into high-value carbon fiber by using a carbon-saturated molten metal reservoir. |
| Modular Processing of Flare Gas for Carbon Nanoproducts | Colorado U. | 2022 | Develop a natural gas conversion to carbon nanoproducts using a one-step chemical vapor deposition (CVD) process to grow carbon nanoparticles and nanofibers (CNF) during natural gas decarbonization. |
| Microwave Catalysis for Process Intensified Modular Production of Carbon Nanomaterials from Natural Gas | WVU | 2022 | Develop a new, low-cost modular process that directly converts flare or stranded gas to carbon nanomaterials and hydrogen using a microwave enhanced, multifunctional catalytic system in a single step without emitting carbon dioxide. |

| PROJECT | PERFORMER | COMPLETION DATE | FOCUS |
|---|---|---|---|
| Production of hydrogen and carbon from catalytic flare gas pyrolysis | NETL RIC | 2021 | Methane pyrolysis is a new process technology that employs the thermal decomposition to separate natural gas or methane directly into the components hydrogen and solid carbon. |
| Modular Production of Olefins from Associated Natural Gas | NETL RIC | 2021 | High activity, nanostructured, Fe on C catalyst to convert syngas to olefins will be combined with proprietary natural gas to syngas reformer and integrated into full natural gas to olefins process. |
| Benzene, Toluene, and Xylene (BTX) Synthesis via Microwave-Enhanced Catalysis | NETL RIC | 2021 | Pursue innovative catalyst technologies to maximize $CH_4$ conversion and selectivity to BTX under microwave irradiation. |
| Olefin Production via Electrocatalysis | NETL RIC | 2021 | Technical basis in electrochemical upgrading – combining electrons and heat to do chemistry through a reverse fuel cell to turn inexpensive electrons and associated gas into commodity and specialty chemicals. |
| Associated Natural Gas Utilization and Mitigation Assessment, Opportunities, and Economic Impact | NETL RIC | 2021 | Information developed in this task will be used to assess the market viability of natural gas-based carbon product technologies by establishing the current market size of products serving the market, develop an understanding of the current state of technology of carbon products, and determine an economic competitive range for emerging technologies to enter the market. |