Methane Emissions from the Fossil Fuel Industries of the Russian Federation

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Abstract

Methane emissions are a major driver of human-induced climate change. Moreover, reduction of the rate of methane emissions is the fastest and least disruptive way to moderate global temperature rise over the next several decades. The production of fossil fuels - principally coal, oil, and natural gas – is an important source of anthropogenic methane. As one of the world's most important producers of fossil fuels, the Russian Federation should play an important role in methane mitigation efforts. However, the Federation's own estimates of methane emission intensity vary greatly from year to year, and are at variance with estimates of international data collection and research institutes. As a result of a recent series of large reductions in methane emission estimates, the self-reported methane emission intensity of the Russian Federation oil and gas industry is now less than comparable self reports of the United States. Satellite-based national-level estimates of Russian methane emissions are available, but the error bars are very large, and attributions to specific economic sectors are unreliable. Satellites are more reliable in characterizing plume events, but the measurements are insensitive and only account for a small fraction of total emissions. Coal mine methane emissions are easier to characterize but harder to remediate than emissions from oil and gas sources. In order for Russia to play a constructive role in climate change mitigation, better information about the state of emissions is required. Monitoring systems should be introduced, and common sense mitigation measures should be widely implemented.

1. Introduction

1.1 Methane as a Greenhouse Gas

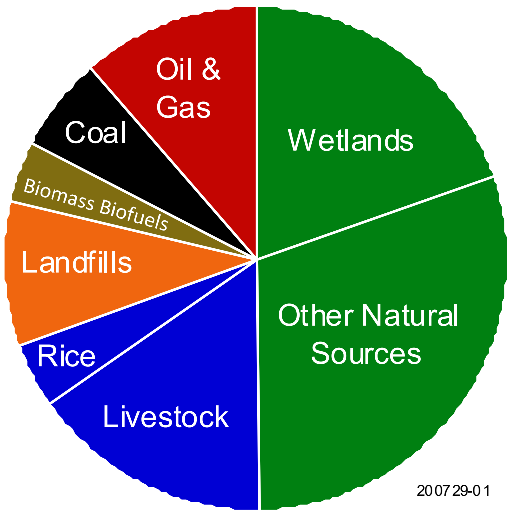
Climate change is widely recognized as one of the most important environmental challenges of our time. Climate change is largely driven by anthropogenic emissions of greenhouse gases into the atmosphere. The principal greenhouse gas is carbon dioxide, which is emitted in vast quantities and remains in the atmosphere for centuries. The second most important greenhouse gas is methane. The mass of anthropogenic methane emitted into the atmosphere is only 1/100 the mass of anthropogenic carbon dioxide [EDGAR, 2021a; Saunois, 2020a], and methane in the atmosphere is removed relatively rapidly with a time constant of about twelve years [IPCC, 2013, Appendix 8.A, Table 8.A.1]. However, the radiative forcing per ton of methane emissions is more than a hundred times greater than that of carbon dioxide [Roy, 2015]. Therefore the prompt effect of these two gases on global-average surface temperature is comparable [Kleinberg, 2020].

Reduction of the rate of anthropogenic methane emission is the only route to temperature change moderation over the next thirty years [Shindell, 2012]. Although reducing the rate of carbon dioxide emissions is essential to a long term solution to the climate problem, only methane reduction will produce noticeable changes in temperature trends by 2050.

Natural sources of methane (wetlands, bodies of water, natural seeps, etc.) constitute half or less of global methane emissions. The remainder – anthropogenic emissions – is sourced from fossil fuel supply chains, agricultural activities, landfill and wastewater emissions, and biomass burning [Jackson, 2020; Saunois, 2020a], see Figure 1.

In economic contexts, the environmental impact of methane emissions is estimated by the social cost of methane. The social cost of a greenhouse gas is the estimate of the economic damages suffered as a result of adding one ton of greenhouse gas to the atmosphere. For the purposes of developing United States government policy, the social costs of greenhouse gases are computed by the Interagency

Working Group on Social Cost of Greenhouse Gases [IWG, 2021]. Assuming a discount rate of 3%, the 2020 social cost of carbon dioxide is $51 per metric ton and the 2020 social cost of methane is $1500 per metric ton.



Source	Methane Mt/y	%
Wetlands	145	19
Other Natural	222	30
Livestock	115	15
Rice	30	4
Landfills & Waste	68	9
Biomass & Biofuels	29	4
Coal Mines	44	6
Oil & Gas	84	11
Industry & Transport	7	1
Total	747	100

Figure 1. Global natural (green) and anthropogenic (other colors) sources of methane emissions to the atmosphere. Sums are not exact due to rounding. Data: [Jackson, 2020, Table 1, 2017 Bottom-Up Estimates]

1.2 Methane Emissions from Fossil Fuel Industries

Although oil and gas supply chains are estimated to constitute only 11% of total methane emissions, they have been identified as the first target for reduction efforts. There are several reasons why the oil and gas sector has been singled out for attention:

- Methane is the primary constituent of natural gas, a valuable and widely marketed fuel.
- Under certain assumptions, some methane mitigation measures pay for themselves, in addition to their environmental benefits [IEA, 2022a].
- Oil and gas supply chains are mostly managed by large industrial organizations that are technically sophisticated and well-capitalized.
- Emissions from natural sources, agriculture, and biomass burning are deemed harder to control.

For these reasons, the oil and gas industry has been the focus of attention among policymakers and the press. The oil and gas industry of the Russian Federation has been singled out as a particularly important part of the picture [Washington Post, 2021; New York Times, 2022].

As will be shown below (Table 1), the most recent estimate of methane intensity in the Russian Federation – methane emissions from the oil and gas sector divided by the quantity of natural gas produced – is 0.92%. Historically, a natural gas loss rate of a few percent has generally been considered acceptable. Upstream, when produced in association with oil, gas has often been considered a waste product, to be disposed of by flaring or venting. Downstream, where safety is a primary concern, care is taken to avoid emissions that could endanger life or property. However, a multitude of small vents and leaks that are inconsequential to economics or safety can, in aggregate, negatively impact climate.

In 2019 (pre-COVID) the annual dry gas production in the Russian Federation was 644 billion cubic meters [UNFCCC, 2021b, Table 3.33; see also BP, 2021]. The densities of Russian crude and marketed natural gas are both 0.68 kg/m^3 [Uvarova, 2014], so 2019 Russian gas production was 438 million tons per year. A methane loss rate of 0.92% of gas production implies a loss of 4 million tons per year. Russian marketed gas is 98.2% methane, so to a good approximation this loss represents 6 billion cubic meters (bcm) of natural gas.

The 2016-2017 average price of Russian gas at the German border was $4.82/MMBtu [IMF, 2017; Y-Charts, 2022]. 1 MMBtu = 29.3 m^3 [BP, 2021, Approximate Conversion Factors], so an annual loss of 6 bcm equates to an economic loss of $1 billion per year. The environmental damage calculated from the U.S. social cost of methane [IWG, 2021], $1500/ton = $1.00/m^3 = $32/MMBtu, was about $6 billion per year.

Coal mine methane is emerging as a secondary target of methane reduction efforts, accounting for 6% of total global methane emissions. Coal mine methane is easier to find but harder to remediate than methane from the oil and gas industry. For safety reasons, methane is prevented from concentrating during coal mining, particularly in underground mines. This makes methane sourced from coal mining hard to burn off (converting it to relatively benign carbon dioxide) and even harder to monetize.

2. Survey of Methane Emission Estimates

2.1 Bottom-Up vs. Top-Down Estimates

Fundamentally there are two kinds of emission estimates: bottom-up and top-down [Allen, 2014]. These terms are sometimes misinterpreted as synonyms for ground-based versus aircraft or satellite measurements.

Bottom-up estimates may not be based on measurements at all. Almost universally, bottom-up estimates are inventories based on engineering calculations. Inventories are activity factors, which are counts of equipment or throughput, multiplied by emission factors, which are estimates of gas-loss rates per unit of activity. This is explained more fully in the next section.

An important but less common type of bottom-up estimate is based on field measurements of emissions. These measurements may be made on individual components (e.g. valves, meters, connections), assemblies (e.g. separators, dehydrators, compressors), or sites (individual locations with groups of equipment). The essence of the bottom-up measurement is that it identifies an emission with a specific asset or asset type. Within this definition, bottom-up measurements can be performed by hand-held cameras, by fixed or mobile point sensors located at or near the fence line, or by aircraft or satellites capable of imaging emission plumes and connecting them to specific assets.

Top-down estimates are based on measurements of the concentration of methane in the atmosphere. The focus is not generally on individual sites but on nations, oil and gas producing provinces, or large grid cells on the order of 100 km in extent. These measurements may be made on the ground, with towers [Wunch, 2011], by aircraft [Vaughn, 2018], or by satellites [Saunois, 2016 and references therein].

Some measurements from aircraft and satellites may be thought of as bottom-up if they detect and measure methane plumes from individual facilities. These measurements utilize the same data used for top-down atmospheric measurements, but the data are processed differently.

2.2 Bottom-Up Estimates

2.2.1 National Inventory Reports – Oil and Gas

Every year the Russian Federation submits its greenhouse gas National Inventory Report (in Russian) to the secretariat of the United Nations Framework Convention on Climate Change [UNFCCC, 2021a]. The Russian Federation National Inventory Report is the basis for computing national-level methane emissions using the inventory method. In this method, the oil and gas industry is divided into segments, which change from time to time. In the 2021 report, the oil and natural gas segments were:

Production and primary processing of natural gas
Gas transport through main pipelines
Flaring during gas production and primary processing
Gas storage injection and extraction
Gas distribution

Oil well drilling
Oil well testing
Oil well service
Oil and condensate production leaks and vents
Oil transport
Gas condensate transport
Primary refining
Gas disposal during oil production
Flaring of associated gas

Methane emissions from each of these segments are found from:

$$E = A \times EF$$

E is the amount of methane emitted annually from an industry segment
A (activity factor) is the annual volume of gas or oil involved in that segment
EF (emission factor) is the methane emitted per unit volume of gas or oil involved in the segment

The total of methane emissions from the oil and gas industry is found by summing all values of E.

Activity factors are gross quantities of oil and gas produced, transported, distributed, or flared at national level. This method leads to anomalies. For example, transportation losses are deemed independent of distance. The activity factors are provided in tables in the National Inventory Report.

Emission factors are estimates of gas-loss rates in each segment. The Intergovernmental Panel on Climate Change (IPCC) has issued guidelines for the selection of emission factors [IPCC, 2006; IPCC, 2019]. The emission factors are either universal default values provided by the IPCC ("Tier 1") or are country-specific ("Tier 2") [NASEM, 2018, Box 2.1]. The Russian Federation uses a mixture of IPCC default and country-specific emission factors, as tabulated in the National Inventory Report.

The Russian government reconsiders its slate of oil and gas emission factors almost every year. Generally (but not always) these changes are applied retroactively and the history of methane emissions since 1990 is recomputed. Every other year since 2014 the Russian Federation has submitted a Biennial Report to UNFCCC recapitulating total methane emissions from the oil and gas industry since 1990 [UNFCCC, 2014a; UNFCCC, 2016a; UNFCCC, 2018a; UNFCCC, 2020a]. These data are shown in Figure 2. The curves shift in successive Biennial Reports because the emission factors reported in the respective National Inventory Reports have changed; the activity factors remain essentially unchanged in successive National Inventory Reports. The latest emission data, compiled in 2021 for 2019 [UNFCCC, 2021b], are in Table 1.

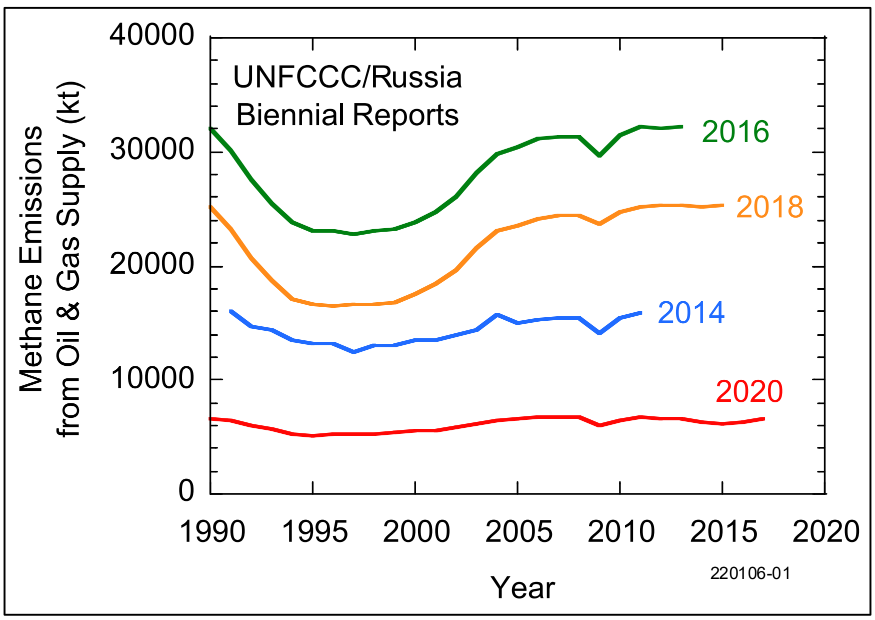


Figure 2. Methane emissions for the Russian oil and gas industry, recomputed using updated slates of emission factors in 2014, 2016, 2018, and 2020. Data: [UNFCCC, 2014a; UNFCCC, 2016a; UNFCCC, 2018a; UNFCCC, 2020a].

Source	Methane Emissions (kt)
Oil Well Drilling, Testing, Service	140
Oil & Gas Condensate Production	1190
Gas Production & Processing	138
Gas Transport & Storage	1290
Gas Distribution	572
Gas Disposal During Oil & Condensate Production	480
Associated Gas Flaring	240
Total Oil & Gas Emissions	4050

Table 1. Russian Federation 2019 methane emissions from the oil and natural gas industry, computed with 2021 National Inventory Report emission factors [UNFCCC, 2021b, Figures 3.44, 3.47, and 3.49]. For 2019, gas production was 644.0 bcm = 438,000 kt [UNFCCC, 2021b, Table 3.33; see also BP, 2021], so methane intensity was 0.92%.

The large changes in successive Russian Biennial Reports can be traced to specific emission factor changes. Table 2 is a record of emission factors used in National Inventory Reports from 2014 to 2021 [UNFCCC, 2021a]. Green and red arrows mark values that were changed from the previous year. The rightmost column lists IPCC Tier 1 default values [IPCC, 2006].

- In the 2014 National Inventory Report, emission factors were generally higher than IPCC defaults, in many cases considerably higher.
- In the 2015 NIR, some emission factors increased, others decreased, leading to a large overall increase in estimated emissions, which were reflected in the 2016 Biennial Report.
- In the 2016 NIR, the emission factors of the natural gas segments (except pipeline transport) were lowered to IPCC default values. There were no further changes in the 2017 and 2018 emission factors. The 2018 Biennial Report showed a large reduction in methane emissions compared to the 2016 Biennial Report.
- In 2019, emission factors for the natural gas segments were reduced to below IPCC defaults while emission factors for the oil segments were reduced closer or to IPCC default values. Consequently, 2020 Biennial Report emissions were very low.
- There were no emission factor changes in the 2020 NIR. Reductions in the 2021 NIR reduced estimated 2019 oil and gas methane emissions to 4050 kt, as shown in Table 1.

The change of emission factors in 2019 is explained in the 2019 National Inventory Report [UNFCCC, 2019, section 3.3.3.2]. Generally speaking, the Russian Federation uses the IPCCC Tier 2 (country specific) method to compile emission factors. "The use of IPCC defaults [Tier 1] leads to overestimation of current emissions in oil and gas sector of the Russian Federation. This is due to the fact that oil and gas industry of the Russian Federation has implemented more stringent quality standards for process operation control. The country-specific emission factors adequately reflect specific features of national oil and gas industry operations." [Uvarova, 2017].

		2014	2015	2016	2017	2018	2019	2020	2021	IPCC 2006
Natural Gas										
Gas Production Leaks	Gg / 10^{6} m^{3}	2.75x10^{-3}	↑ 1.22x10^{-2}	↓ 1.34x10^{-3}	1.34x10^{-3}	1.34x10^{-3}	↓ 2.13x10^{-4}	2.13x10^{-4}	2.13x10^{-4}	3.8x10^{-4} to 2.3x10^{-3}
Primary Processing of Natural Gas		8.8x10^{-4}	↓ 7.9x10^{-4}	↓ 7.55x10^{-4}	7.55x10^{-4}	7.55x10^{-4}				1.5x10^{-4} to 1.03x10^{-3}
Gas Transport Through Main Pipelines to 2000		9x10^{-3}	9x10^{-3}	9x10^{-3}	9x10^{-3}	9x10^{-3}	↓ 6.00x10^{-3}	6.00x10^{-3}	6.00x10^{-3}	F: 6.6x10^{-5} to 4.8x10^{-4} V: 4.4x10^{-5} to 3.2x10^{-4}
Gas Transport Through Main Pipelines since 2017									↓ 1.84x10^{-3}	
Flaring During Production		1.1x10^{-5}	↓ 8.8x10^{-7}	↓ 7.6x10^{-7}	7.6x10^{-7}	7.6x10^{-7}	↓ 1.12x10^{-7}	1.12x10^{-7}	↓ 1.01x10^{-7}	7.6x10^{-7}
Flaring During Primary Gas Processing		1.3x10^{-5}	↓ 1.4x10^{-6}	1.4x10^{-6}	1.4x10^{-6}	1.4x10^{-6}				2.0x10^{-6}
Gas Storage Injection		3.2x10^{-4}	↓ 4.15x10^{-5}	↓ 2.50x10^{-5}	2.50x10^{-5}	2.50x10^{-5}	2.50x10^{-5}	2.50x10^{-5}	2.50x10^{-5}	2.50x10^{-5}
Gas Storage Extraction		2.75x10^{-3}								
Gas Distribution		3.2x10^{-2}	↓ 1.80x10^{-3}	↓ 1.10x10^{-3}	1.10x10^{-3}	1.10x10^{-3}	1.10x10^{-3}	1.10x10^{-3}	1.10x10^{-3}	1.10x10^{-3}
Oil										
Well Drilling	Gg / 10^{3} m^{3}		2.97x10^{-4}	2.97x10^{-4}	2.97x10^{-4}	2.97x10^{-4}	↓ 3.30x10^{-5}	3.30x10^{-5}	3.30x10^{-5}	3.30x10^{-5}
Well Testing			4.51x10^{-4}	4.51x10^{-4}	4.51x10^{-4}	4.51x10^{-4}	↓ 5.10x10^{-5}	5.10x10^{-5}	5.10x10^{-5}	5.10x10^{-5}
Well Service			9.55x10^{-4}	9.55x10^{-4}	9.55x10^{-4}	9.55x10^{-4}	↓ 1.10x10^{-4}	1.10x10^{-4}	1.10x10^{-4}	1.10x10^{-4}
Oil & Condensate production leaks		1.45x10^{-3}	↑ 1.96x10^{-2}	1.96x10^{-2}	1.96x10^{-2}	1.96x10^{-2}	↓ 1.80x10^{-3}	1.80x10^{-3}	1.80x10^{-3}	2.2x10^{-3}
Oil & Condensate production vents		1.381x10^{-3}								8.7x10^{-3}
Oil Transport		5.4x10^{-6}	5.4x10^{-6}	5.4x10^{-6}	5.4x10^{-6}	5.4x10^{-6}	5.4x10^{-6}	5.4x10^{-6}	5.4x10^{-6}	5.4x10^{-6}
Gas Condensate Transport			1.1x10^{-4}	1.1x10^{-4}	1.1x10^{-4}	1.1x10^{-4}	1.1x10^{-4}	1.1x10^{-4}	1.1x10^{-4}	1.1x10^{-4}
Primary Refining			2.18x10^{-5}	2.18x10^{-5}	2.18x10^{-5}	2.18x10^{-5}	2.18x10^{-5}	2.18x10^{-5}	2.18x10^{-5}	2.6x10^{-6} to 4.10x10^{-5}
Gas Disposal										
Gas Disposal During Oil Production	Gg / 10^{3} m^{3}	1.38x10^{-3}	↑ 1.04x10^{-2}	1.04x10^{-2}	1.04x10^{-2}	1.04x10^{-2}	↓ 7.2x10^{-4}	7.2x10^{-4}	7.2x10^{-4}	2.1x10^{-5}
Flaring Associated Gas	Gg / 10^{6} m^{3}	1.2x10^{-2}	1.2x10^{-2}	1.2x10^{-6}	1.2x10^{-6}	1.2x10^{-6}	1.2x10^{-2}	1.2x10^{-2}	1.2x10^{-2}	

Table 2. Methane emission factors reported in Russian Federation National Inventory Reports, 2014-2021 [UNFCCC, 2021a], with comparison to IPCC Tier 1 default values (last column) [IPCC, 2006]. Blue up-pointing arrows mark values that increased from the prior year. Red down-pointing arrows mark values that decreased from the prior year. 1 gigagram (Gg) = 1000 metric tons (kt). F = fugitive, V = vent.

2.2.2 National Inventory Reports – Solid Fuels

The only solid fuel methane emissions reported in the Russian Federation National Inventory Reports are from the supply of coal. Currently, there are about equal emissions from underground and open pit mines, with subsequent handling making a minor contribution, see Figure 3.

Methane emission factors for coal production are not reported in the National Inventory Reports but have remained constant since the inception of the Biennial Reports, see Figures 4 and 5. This is unlike oil and gas emission factors, but it is not unexpected. Methane emissions from coal mining operations do not depend very much on equipment and processes, but primarily on the amount of methane in produced coal – a quantity that depends not on engineering practice but on the organic geochemistry of coal and the depth of the mine [Kholod, 2020]. However, inventories based only on the kinds and amounts of coal being mined can overlook methane emissions from inactive mines. This is now recognized as a growing problem.

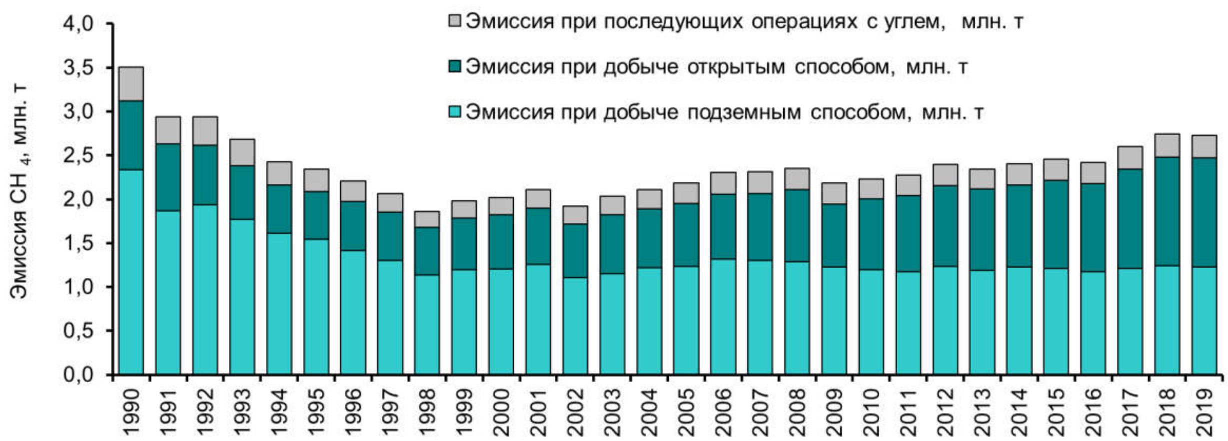


Figure 3. Russian Federation methane emissions in millions of tons per year, from underground coal mining (light blue), open pit coal mining (dark blue) and subsequent operations (gray) [UNFCCC, 2021b, Figure 3.36].

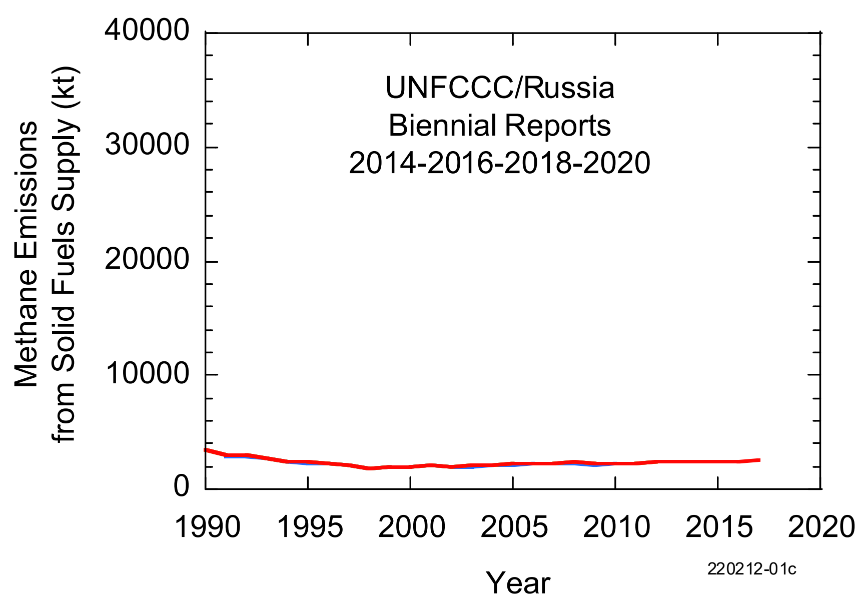


Figure 4. Methane emissions from the Russian coal industry, recomputed using updated slates of emission factors in 2014, 2016, 2018, and 2020. The scales are the same as in Figure 2. Data: [UNFCCC, 2014a; UNFCCC, 2016a; UNFCCC, 2018a; UNFCCC, 2020a].

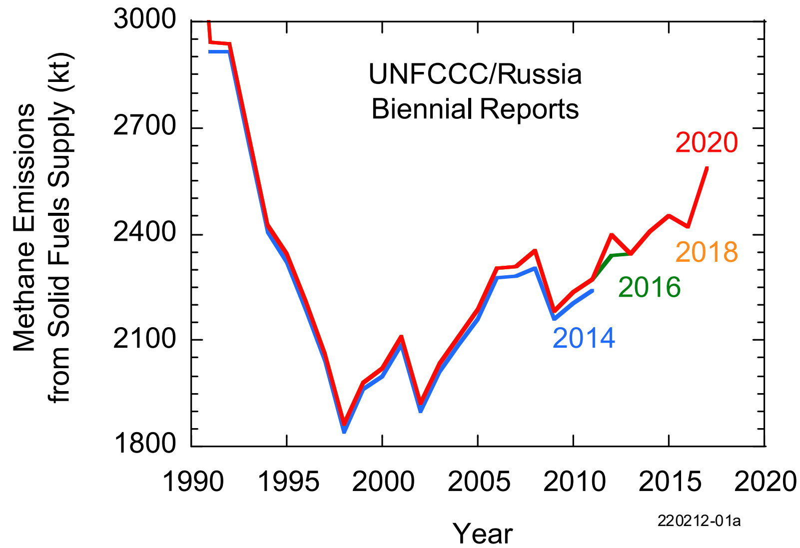


Figure 5. The same data as in Figure 4, on an expanded vertical scale.

2.2.3 Other Inventories

There are numerous other estimates of methane losses from the Russian fossil fuel industries. These include estimates from the International Energy Agency (IEA), the European Union Emissions Database for Global Atmospheric Research (EDGAR), the U.S. Environmental Protection Agency (US EPA), the International Institute for Applied Systems Analysis (IIASA), and the Community Emissions Data System (CEDS), see Figure 6. The estimates all fall within the range of the four Russian Federation Biennial Reports to UNFCCC shown in Figure 2.

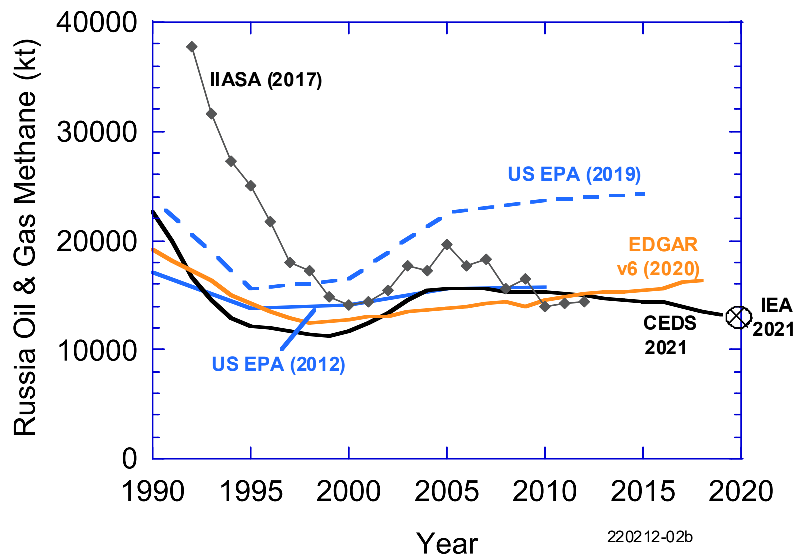


Figure 6. Diverse estimates of methane emissions from the Russian oil and gas industry. EDGAR v6 also includes coal.

The International Energy Agency (IEA) publishes a Methane Tracker, which annually reports national sector-level methane emissions [IEA, 2022b]. The data are derived from the Oil and Gas Methane Emissions Model of the World Energy Model [IEA, 2021a], which is the analytical engine used to generate quantitative data for the annual World Energy Outlook. Given the objective of estimating nineteen oil and gas sector-level emission intensities for each of the twenty-five nations responsible for 95% of global oil and gas production, IEA adopted a simple method. First, it estimated emission intensities for each of nineteen sectors of the U.S. oil and gas industry (upstream onshore conventional oil, upstream onshore conventional gas, upstream offshore oil, upstream offshore gas, etc.). For the other twenty-four nations, the sector intensities were multiplied by country-specific factors, which are mostly based on secondary characteristics of a nation's oil industry, such as whether producers are international or national oil companies. Countries such as Russia, from which satellites could detect very large single emitters greater than five tons of methane per hour, were given a separate line item, "Satellite detected large leaks".

The International Institute for Applied Systems Analysis (IIASA) did a careful study of methane emissions connected with associated gas production. It combined this with the 2006 IPCC default emission factors to estimate methane emissions from oil and gas production [Hoglund-Isaksson, 2017]. While the associated gas calculation is country-specific and detailed, the IPCC estimates are not. Spreadsheets in the Supplementary Material allow others to benefit from this work's original research.

The Emissions Database for Global Atmospheric Research (EDGAR) is a joint project of the European Commission Joint Research Centre and the Netherlands Environmental Assessment Agency [EDGAR, 2021a]. In its version 4.3.2, EDGAR included forty-two years of data, twenty-six aggregated emission sectors, 226 countries, and nine substances [EDGAR, 2021b]. EDGAR publishes fossil fuel supply emission estimates, including oil, gas, and coal. Methodology details are published elsewhere [Crippa, 2018]. The Community Emissions Data System for Historical Emissions (CEDS) [CEDS, 2022] methodology is also published elsewhere [Hoesly, 2018]. U.S. EPA assessments of other countries track the UNFCCC submissions of those countries [EPA 2012; EPA, 2019a].

2.2.4 National Inventory Reports – Russia vs United States

Like Russia, the United States uses the inventory method to compute methane emissions from its oil and gas industry. The 2019 (pre-COVID) emissions of methane from the petroleum and natural gas systems were reported to be 8016 kt [EPA, 2021a]. Dry gas production that year was 33.90 trillion cubic feet, or 934 billion cubic meters [EIA, 2022a; see also BP, 2021]. Assuming the average density is the same as Russian dry gas, this amounts to 635 million tons of gas per year, so the reported methane intensity is approximately 1.26%. This is higher than the comparable Russian methane intensity, 0.92%, see Table 1.

The U.S. computations of methane emissions are much more granular than that of the Russian Federation [EPA, 2021a]. Various equipment types have been studied and assigned individual emission factors. For example, EPA tracks the numbers of oil tanks with vapor recovery units, oil tanks with flares, and oil tanks without vapor controls, and estimates methane emissions separately for each of these classes. Approximately 250 classes of equipment are tracked. This corresponds to IPCC Tier 3. Emission factors continue to be refined and are the product of considerable, serious, ongoing effort [EPA, 2022].

Data from the Biennial Reports submitted by the United States are shown in Figure 7. The horizontal and vertical scales in Figures 2 and 7 are the same. U.S. bottom-up inventories are much more stable than Russian inventories.

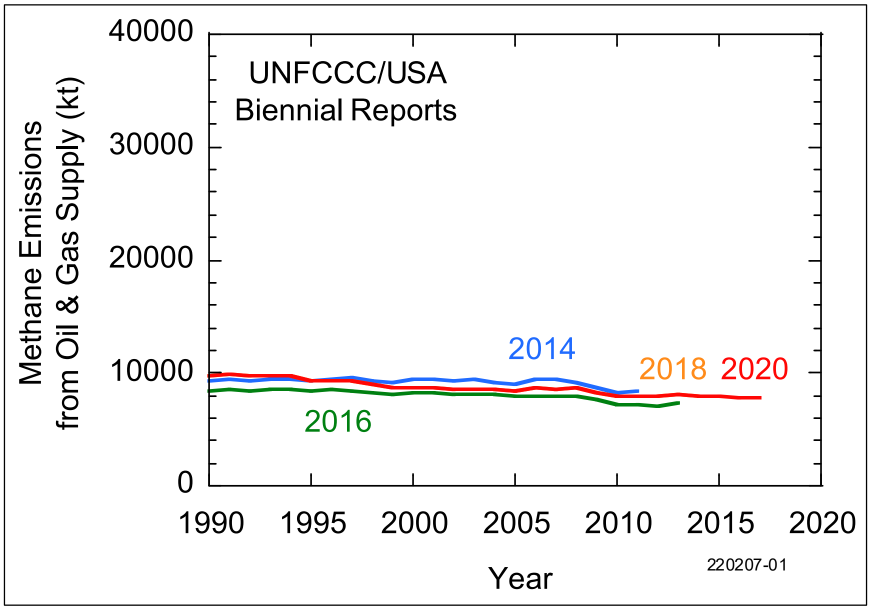


Figure 7. Methane emissions for the United States oil and gas industry, recomputed using updated slates of emission factors in 2014, 2016, 2018, and 2020. Data: [UNFCCC, 2014b; UNFCCC, 2016b; UNFCCC, 2018b; UNFCCC, 2020b].

The inventory method is an accounting exercise that does not require measurements of equipment operating in the field. Field measurements have repeatedly demonstrated the inaccuracies of inventories [Alvarez, 2018, Supplementary Materials Table S1], and it is widely agreed that inventory methods systematically underestimate methane emissions, which are heavily affected by intermittent but very large emission events associated with so-called "super-emitters" [see e.g. Zavala-Araiza, 2017; Duren, 2019; Lauvaux, 2022]. However, in preparing their National Inventory Reports, neither the Russian Federation nor the United States incorporate field measurements of methane emissions from operating equipment. U.S. national-level inventories informed by measurements consistently exceed EPA estimates by large margins [see e.g. Alvarez, 2018; Rutherford, 2021]. In fact, the larger and more thorough the measurement program, the larger the discrepancy between inventories and measurements [Chen, 2021]. Therefore, despite the enormous data collection and analytical effort devoted to the U.S. greenhouse gas inventory, and the obvious care and conscientiousness with which those tasks are undertaken, the American estimates are not held in high regard by specialists in academic and non-governmental organizations.

2.3 Top-Down Estimates

Measurements of atmospheric methane concentrations by earth orbiting satellites constitute another method of estimating methane emissions. Launched by national space agencies [see e.g. NIES, 2022; ESA, 2022a], private companies [e.g. GHGSat, 2022], and non-governmental organizations [MethaneSAT, 2022], the data are in many cases made freely available to be analyzed by competing multinational teams of scientists. The orbits of polar sun-synchronous satellites [ESA, 2022b] in theory permit inspection of the entire earth. These features have led some to believe that satellite-based measurements avoid the shortcomings of inventories. However the actual performance of remote sensing instrumentation is limited by measurement physics and the shortcomings of data processing algorithms, as explained below. In reality, satellites have grave deficiencies when applied to the estimation of methane emissions from individual countries and their economic sectors.

2.3.1 Satellite Systems Discussed in this Report

System	Launch	Point-Source Detection Threshold (kg/h)	Coverage Pixel Size (km x km)	Source
GOSAT	2009		Global 10 x 10	Jacob, 2022; IEA, 2021b
TROPOMI	2017	4000	Global 5.5 x 7	
MethaneSat	2023	500	Targeted 0.13 x 0.40	Jacob, 2022
GHGSat - D	2016	1000-3000	Targeted 0.05 x 0.05	
GHGSat - C	2021 - 2023	100	Targeted 0.025 x 0.025	McKeever, 2021

Table 3. Properties of methane-detecting satellites discussed in this report.

2.3.2 Nation-Level Top-Down Surveys

The principal satellite system used for global and national-level top-down surveys is GOSAT (Greenhouse Gases Observing Satellite), launched in 2009 by the government of Japan [Jacob, 2022]. GOSAT-2, with similar or improved capabilities, was launched in 2018 [eoPortal, 2022a].

The fundamental measurement made by satellites is the line integral of methane concentration along a path extending from the earth to the orbiting detector. Global-average determinations can be performed very accurately. Figure 8 shows the result of eleven inversions of GOSAT data for 2017. Estimated total methane emission rates (black line) are very consistent for all data inversions. This total is partitioned into natural (green) and anthropogenic (blue) methane fractions. Anthropogenic methane is further partitioned; here only the fossil fuel fraction (red) is shown. The fraction of methane emissions attributed to fossil fuel supply ranges between 0.14 and 0.20, with a mean of 0.18 and a standard deviation of 0.017.

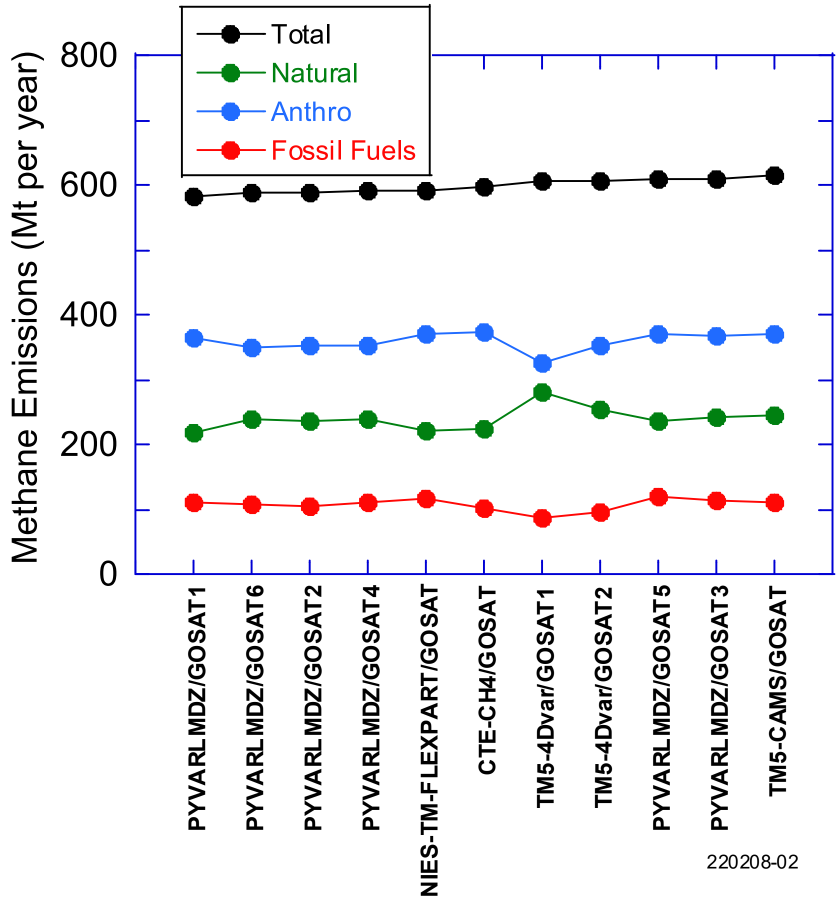


Figure 8. Global methane emissions in 2017 determined by inversions of satellite data performed by various analysts. The inversions are named on the horizontal axis. The inversions are ordered according to the total emission rate (black). Estimates of natural emissions are shown in green, anthropogenic emissions in blue, and fossil fuel emissions (a subset of anthropogenic emissions) in red. Data: [Saunois, 2020b].

National-level emissions estimates are far more uncertain than global estimates, and any particular economic segment, such as the fossil fuel industry, is quite poorly determined, even for a large nation like the Russian Federation. This is illustrated by Figure 9, which is sourced from the same data sets, analysts, and algorithms as Figure 8. Here, the fraction of methane attributed to fossil fuel emissions ranges between 0.21 and 0.51, with a mean of 0.39 and a standard deviation of 0.11.

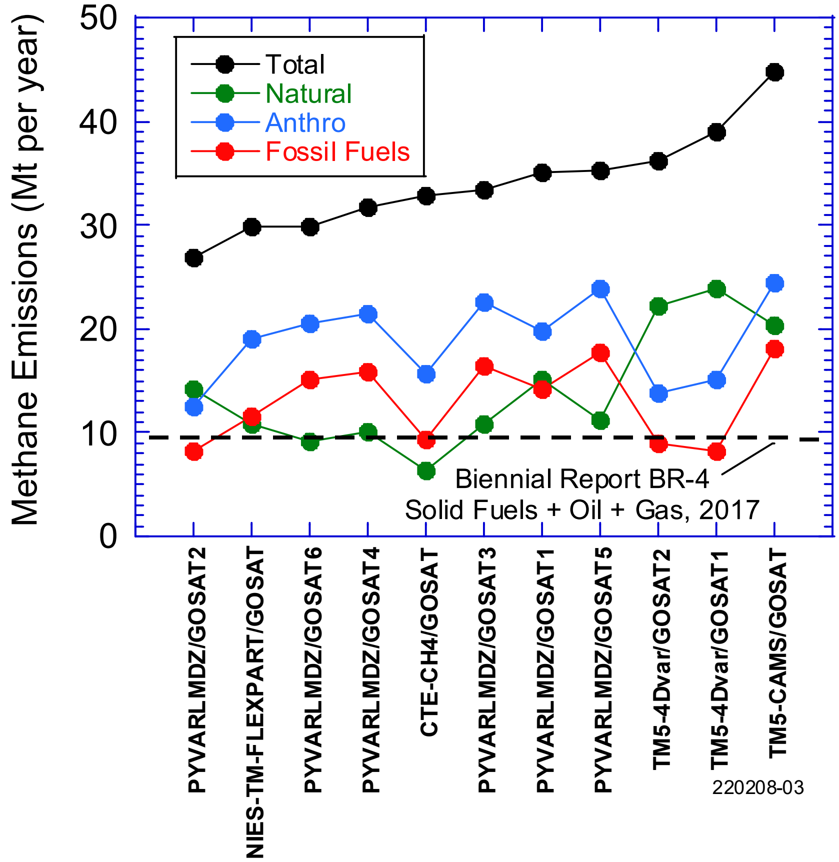


Figure 9. Russian methane emissions in 2017 determined by inversions of satellite data performed by various analysts. The inversions are named on the horizontal axis. The inversions are ordered according to the estimate of total emission rate (black). Estimates of natural emissions are shown in green, anthropogenic emissions in blue, and fossil fuel emissions (a subset of anthropogenic emissions) in red. Data: [Saunois, 2020b]. Russian Federation Biennial Report of methane emissions from solid fuels, oil, and gas for 2017 (dashed horizontal line) [UNFCCC, 2020a].

At least some of the scatter of satellite-based determinations is due to inescapable limitations in the data and processing. There is nothing inherent in the satellite data that distinguish natural from anthropogenic sources, nor fossil fuel sources from other anthropogenic sources. Modern inversions use the Bayesian method, an error-minimizing algorithm that is initialized with a set of priors. The priors are the best guesses of the outcomes, the so-called posteriors [Saunois, 2016, sec. 4.2.1]. Quoting Saunois, et al., “Atmospheric inversions use bottom-up models and inventories as prior estimates of the emissions and sinks in their setup, which make bottom-up and top-down approaches generally not independent.”

The dependence of top-down-estimated emission rates (posteriors) on initializing bottom-up inventories (priors) is illustrated in Figure 10. In this example, the methane emissions from all sources in Russia were estimated from observations using the Bayesian method. Because the total of all methane emissions is closely related to what a satellite actually measures, it is a better-determined product than any of the subsets, such as emissions only from the fossil fuel sector. The correlation between posteriors and priors for the thirteen inversions is good: the ratio of posteriors to their respective priors is 1.01 ± 0.12. We conclude that at least some of the scatter in the natural, anthropogenic, and fossil fuel estimations in Figure 9 is likely due to scatter in the priors chosen to initialize the inversions.

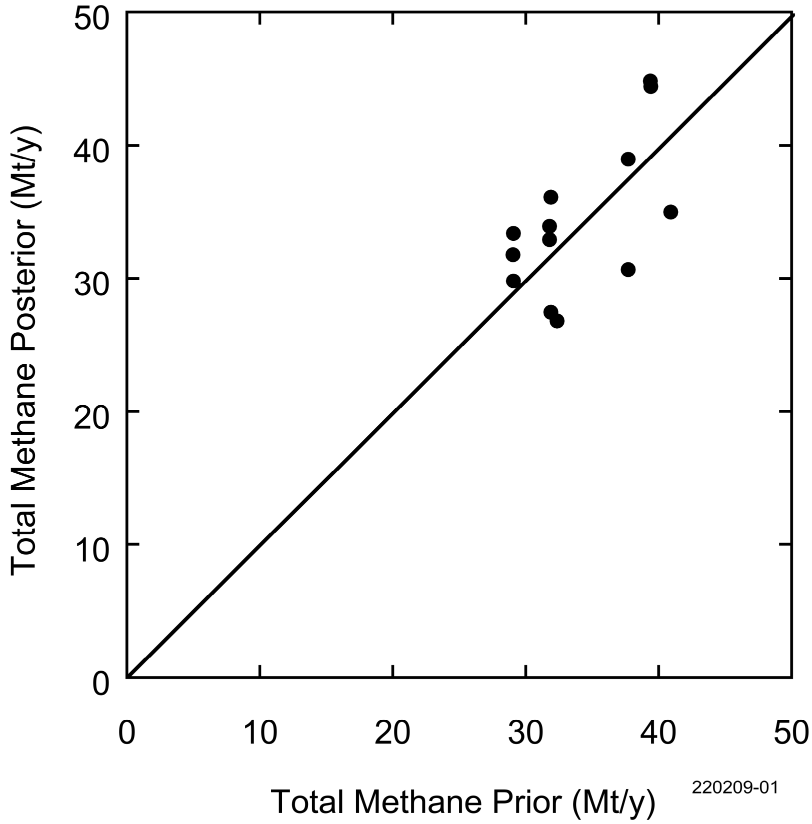


Figure 10. Relationship between prior initializations and posterior results of thirteen Bayesian inversions of top-down data for total methane emissions in Russia during 2017. The correlation suggests that variations in top-down emission estimates are driven in part by the inventory data used as priors.

The variability of satellite-based estimates of Russian methane emissions is further partly explained by the inefficiency of data collection. Over most of Russia, averaged over a year, the GOSAT satellite collects an average of only a few data points per month in each 2.5° x 2.5° (37-103 km x 278 km) grid cell [Stavert, 2022]. TROPOMI collects a hundred times more data, but at its present state of development TROPOMI is more susceptible to error in the presence of wetlands [Qu, 2021], which are common in some Russian oil and gas provinces. Data collection from both satellites is hindered by the presence of clouds, open water, and wet snow. Limited and low angle daylight are important limitations at high latitudes. These circumstances further confound the Bayesian method: “In poorly observed regions, top-down inversions rely on the prior estimates and bring little or no additional information.” [Saunois, 2016, sec. 5.1.1]. However, although satellite-based top-down estimates are imperfect at present, there are many opportunities for improvement [Saunois, 2020a, section 6].

2.4 Satellite Measurements of Methane Plumes

GOSAT and earlier methane-measuring satellites are not suitable for point source measurements. While GOSAT is a superior platform for top-down measurements [Qu, 2021], TROPOMI has a superior ability to image plumes of methane emanating from point sources [see e.g. Varon, 2019; Pandey, 2019]. The sensitivity of this satellite-based measurement is modest. Only methane plumes emitting more than about five tons per hour can be quantified [IEA, 2021b]. Unlike top-down atmospheric concentration measurements, inventory-based priors are not required to determine point-source emission rates.

Using TROPOMI data from 2019 to 2020, it is estimated that release events of more than 25 tons per hour (37,000 cubic meters per hour) accounted for global annual emissions of eight million tons of methane [Lauvaux, 2022]. Lauvaux et al. estimated that Russia was responsible for one-eighth of this total. Much of this activity appears to be coincident with major pipeline routes extending southwest from the arctic.

The satellite-based estimate can be compared to the Russian Federation's estimate of methane losses from gas pipelines in 2019 [UNFCCC, 2021b, Figure 3.47, Table 3.33, Table 3.35]. The amount of gas transported in main lines that year was 551 million tons = 810 billion cubic meters. This is greater than total Russian gas production of 680 billion cubic meters. The pipeline activity factor could be greater than production because the pipeline emission factor does not take distance into account. Perhaps gas is counted multiple times if it travels through two or more pipelines. The emission factor for mainline pipe transport is 1.84×10^{-3} Mt/bcm. Therefore, the National Inventory Report estimate of methane loss is 1.5 million tons. This is the largest single category of reported methane loss from the Russian gas supply chain, and is not inconsistent with the TROPOMI analysis.

A third kind of satellite-based methane survey is carried out by sensors with much better sensitivity and spatial resolution than GOSAT and TROPOMI. The current leader in this technology is the Canadian company GHGSat, which has detected a controlled release of methane at a rate of 100 kg/h with a pixel size of 25 x 25 meters in a 10 kilometer by 15 kilometer field of view [McKeever, 2021].

Unlike GOSAT and TROPOMI, the GHGSat platforms do not scan the entire earth and must be tasked to specific, pre-determined targets. Some interesting GHGSat acquisitions have involved cooperation with TROPOMI. For example, after TROPOMI discovered large methane emissions from a Madrid landfill at 7 km pixel resolution, GHGSat was tasked to acquire high resolution images useful for remediation [ESA, 2021].

MethaneSAT, which will be launched by the Environmental Defense Fund in 2023, has capabilities intermediate between TROPOMI and GHGSat [Hamburg, 2020]. Among other things, it will be able to collect methane data over Russia more frequently than GOSAT or TROPOMI [Benmergui, 2020].

3. Methane Emission Reduction in the Russian Federation

Greenhouse gas emissions associated with the supply and consumption of fossil fuels has emerged as one of the most important environmental issues of our time. These concerns cannot be ignored by the Russian Federation, which is by far the world's largest exporter of natural gas and the second largest exporter of oil [BP, 2021]. It is also a leading producer of coal.

Carbon dioxide emissions are the most important driver of climate change. Unfortunately, the mitigation of these emissions is a genuinely difficult economic and technical problem. However, there is a growing realization in both scientific and popular spheres that methane is the second most important influence on climate. Moreover, reducing anthropogenic methane emissions is the only way to slow the rate of global warming between now and 2050 [Shindell, 2012]. In widely quoted newspaper stories Russia has been specifically implicated in emissions of methane from fossil fuel infrastructure [Washington Post, 2021; New York Times, 2022].

Fortunately, reducing methane emissions from the oil and gas industry is not a particularly hard problem. Engineering solutions exist that often can be implemented at low cost. While abatement cost curves such as those published by the International Energy Agency [IEA, 2022a] cannot be taken too literally, the overarching message is valid. The main barrier to methane reduction is finding the sources of emission, which are varied and sometimes unexpected [NASEM, 2018, Figure 4.1 and accompanying discussions]. Once found, the sources are often easy to fix – sometimes it is just a matter of lighting a flare, closing a vent that is stuck open, or tightening bolts on a flange.

Methane emissions from coal mining operations present the opposite problem. The locations of large coal mines are well known, and emissions from those mines are easier to estimate than oil and gas emissions {NASEM, 2018, Figure 4.1]. However, some coal mine mitigation problems are difficult because gas in active mines is deliberately diluted and dispersed for safety reasons. Recovering this methane can be technically and economically challenging. A further challenge is emissions from abandoned mines, to which little attention has been paid until recently [Kholod, 2020].

3.1 Improving the Accuracy of Reported Emissions

Methane emission reduction requires the collection of accurate and comprehensive data. The consequences of using inaccurate and incomplete data are illustrated by experience in the United States. Due to reliance on inventories untethered to field measurements, official methane emission data are held in low regard [Alvarez, 2018; Rutherford 2021] and environmental regulations based on them have been largely ineffective [Kleinberg, 2021].

The main problem with emission inventories is that, as commonly implemented, they are inherently inaccurate. Using emission factors based on the average behavior of components and equipment types (as in United States practice) or based on throughput (as in IPCC and Russian practices) ignores the "heavily skewed distribution of site-based CH_4 emissions" [Zavala, 2017]. These heavily skewed distributions have been found for all component and equipment types [Brandt, 2016] and all facility types [Cusworth, 2021] that have been investigated. It has been found very difficult to properly characterize these skewed distributions. A study involving 117,000 well visits found that measured distributions depended on the number of sites visited: mean emission rate increased as the number of visits increased [Chen, 2021]. This finding has profound implications for the partitioning of methane emissions between natural and anthropogenic sources, and among anthropogenic source types. It also suggests that estimating methane emissions by extrapolating from a limited number of site visits, termed the "gold standard" in at least one popular system [OGMP, 2020] while perhaps helpful, is unlikely to be a comprehensive solution.

The problem is further compounded by the intermittency of gas leaks [Alden, 2020; Cusworth, 2021]. A single site visit will not find all sources of emission, but under favorable conditions average site emission rates will decrease with repeated inspections [Ravikumar, 2020].

A complete solution to the problem of locating methane emissions from the oil and gas industry will be at least difficult, and may not be technically or economically feasible. However, partial solutions that can be implemented quickly may well be more effective in mitigating climate change than those that are comprehensive but slower to implement.

3.1.1 Aircraft-Based Measurements

A solution that confronts some of these problems has already been implemented by the Environmental Defense Fund: the Permian Methane Analysis Project [EDF, 2022]. The Permian Basin is the most prolific hydrocarbon province in the United States, with a daily production of five million barrels of oil and almost 20 billion cubic feet (more than 500 million cubic meters) of natural gas [EIA, 2022b]. It is also notorious for its vast methane emissions [Zhang, 2020]. Four major surveys were conducted during 2019-2021. Site-level emissions were measured by various means, principally by aircraft, in west Texas and southeast New Mexico. Operating companies were matched with emission sources. The Fall 2019 campaign detected 3067 plumes originating from 1756 unique sources [Cusworth, 2021; EDF, 2022].

It is likely that many of the emissions seen here, even the largest ones, are legal under present Environmental Protection Agency regulations. With this newly available information in hand, regulators can decide whether regulations need to be changed to limit the largest discharges.

Surveys of the Permian Basin make economic sense. It is estimated that 2.7 million tons (4.0 billion cubic meters = 140 billion cubic feet) of methane are lost per year [Zhang, 2020], worth about $420 million at Henry Hub. Aerial surveys of the basin cost about $100 per well site; a survey of the PermianMAP study area reportedly cost several million dollars [EDF, 2021]. (Prices may be higher elsewhere.) Following a different survey by another contractor, a small operator claimed the cost of a survey of 27,000 acres encompassing 170 surface assets and 31 miles of natural gas pipeline paid for itself in five days of additional gas sales [Johnson, 2021].

Aerial detection of methane emissions, by fixed-wing aircraft, helicopters, and drones, has quickly become a technically and commercially mature field, with numerous private entities offering services with various combinations of sensitivity, spatial resolution, domains of application, and economic efficiency. Listed in Table 4, in alphabetical order, is a representative list of contractors that have successfully performed large-scale aerial surveys for oil and gas operating companies in the United States and Canada.

Aerial Production Services	https://www.flyaps.io/oil-gas
Baker Hughes	https://www.bakerhughes.com/emissions-management
Bridger Photonics	https://www.bridgerphotonics.com/
Carbon Mapper	https://carbonmapper.org/
Kairos Aerospace	https://kairosaerospace.com/
LaSen	https://www.lasen.com/
Scientific Aviation	https://www.scientificaviation.com/
SeekOps	https://seekops.com/

Table 4. Representative aerial methane detection contractors in North America.

Remarkably, this industry has grown in the absence of regulatory mandates. The U.S. Environmental Protection Agency accepts only two methods as legally acceptable for volatile organic compound and methane leak detection, both of which are ground-based hand-held devices: optical gas imaging and a sniffer device (“Method 21”) [CFR, 2021]. Neither is capable of quantitative measurements. However, U.S. EPA has recently signaled interest in finding a role for airborne devices (“Advanced Methane Detection Technology”) in leak detection and repair [EPA, 2021b].

3.1.2 Continuous Monitoring

Intermittency is a problem for both inventory methods and periodic measurement methods of emission characterization. Continuous surveillance is required to understand the problem, and there have been few comprehensive studies of this nature [Alden, 2020]. There are several promising approaches to implementing continuous surveillance of oil and gas infrastructure. These include networks of stationary point gas sensors, scanning infrared cameras (“continuous optical gas imaging”), and laser-based scanning open-path atmospheric concentration measurements. All techniques share common advantages that make them attractive prospects for methane emission control [LongPath, 2022]. These technologies are at various stages of maturity but appear to be developing rapidly with the encouragement of private and government investments.

3.2 Methods to Reduce Oil and Gas Methane Emissions

Regulations that seek to limit methane emissions, such as 40 CFR 60 Subpart OOOOa in the United States Code of Federal Regulations, distinguish between fugitive emissions (“leaks”) and vents. Fugitive emissions are unexpected, result from equipment or process failures, and call for repair or replacement of parts or equipment. Vents, which are predominantly but not exclusively connected with oil production, are routine and expected (though not necessarily scheduled) aspects of normal operation, and are either subject to engineering controls or simply allowed. The author speculates that a significant fraction of emissions detected in PermianMAP surveys are allowed vents.

Hand-held leak detection devices such as the Method 21 sniffer or the optical gas imager can distinguish between leaks and vents. In fact, fugitive emission detection protocols direct inspections to components that might leak; known sources of vents are not included in the surveys. Remote sensing from aircraft or satellites cannot distinguish between leaks and vents, which might call into question the utility of these advanced techniques in current regulatory schemes.

3.2.1 Fugitive Emissions

Leak detection and repair (LDAR) loom large in both regulated and technology communities. For the oil and gas industry, LDAR is an ongoing and potentially costly commitment. For technology developers, it is a technically interesting challenge. However, in reality LDAR represents a small fraction of the methane emission problem.

The costs and benefits of leak detection and repair were studied by the U.S. Environmental Protection Agency in connection with the LDAR regime mandated by its 2016 methane rule [40 CFR 60.5397a(g)], as restored by Public Law 117-23. The rule stipulates that oil and gas well sites be inspected semiannually (Regulatory Option 2) and compressor stations be inspected quarterly (Regulatory Option 3), using the optical gas imager. The results are shown in Table 5, which shows that the LDAR rules were estimated to reduce methane emissions from the U.S. oil and natural gas sector, in the year 2020, by 169,646 tons per year at an approximate nationwide cost of $227 million per year. The cost per metric ton of methane avoided is $1340. The social cost of methane cited in the 2016 Regulatory Impact Analysis for the year 2020 at a discount rate of 3% is $1300 per metric ton [EPA, 2016a, Table 4-3]. While LDAR comes close to passing the cost-benefit test, it is not the solution to methane emissions from oil and gas infrastructure: the resulting emission reduction amounts to 2% of total oil and gas methane emissions shown on the bottom line of Table 5.

Because efficient and cost effective remote sensing techniques are unable to distinguish leaks from vents, it seems inevitable that most of the resulting detections will be "false positives", if only leaks and not vents are subject to detection and repair.

Source Type		Facilities Subject to NSPS	Cost per Facility (USD/year)	Nationwide Costs (USD/year)	Emission Reduction (tons/year)
Well Sites (Option 2)		93,578	2,285	213,800,000	152,656
Compressor Stations (Option 3)	Gathering and Boosting	480	25,049	12,000,000	13,495
	Transmission	20	27,369	550,000	646
	Storage	25	42,093	1,100,000	2,849
LDAR Totals		94,103		227,450,000	169,646
Oil and Gas Totals (GHGI, 2019)					7,868,000

Table 5. Nationwide U.S. emission and cost analysis for optical gas imaging leak detection and repair of oil and gas well sites (regulatory option 2 – semiannual inspections) and compressor stations (regulatory option 3 – quarterly inspections). Data from the 2016 OOOOa Background Technical Support Document projected costs and benefits for 2020 [EPA, 2016b, Tables 9.3 and 9.4]. Bottom line: Reported vented, fugitive, and flared methane emissions from petroleum and natural gas systems, 2019 [EPA, 2021a].

3.2.2 Vents

In the oil and gas industry methane vents are often ignored, on the grounds that they are a normal part of operations. The Russian gas pipeline system furnishes an example. Using TROPOMI data, analysts discovered a series of massive gas releases along the tracks of major gas pipeline systems [Lauvaux, 2022]. Gazprom confirmed most of these events were deliberate operations connected with the maintenance of compressor stations [Stern, 2022, page 23].

Numerous authoritative guides to engineering controls that reduce methane vents have been published in recent years. Some of these are listed in Table 6.

Methane Guiding Principles, Best Practice Guides https://methaneguidingprinciples.org/best-practice-toolkit/
Oil and Gas Methane Partnership, Technical Guidance Documents https://www.ogmpartnership.com/templates-guidance
U.S. Environmental Protection Agency, Standards of Performance EPA-453/R-11-002, July 2011 https://nepis.epa.gov/Exe/ZyPDF.cgi/P100CHTC.PDF?Dockey=P100CHTC.PDF
U.S. Environmental Protection Agency, Control Techniques Guidelines EPA-453/B-16-001, October 2016 https://www.epa.gov/sites/production/files/2016-10/documents/2016-ctg-oil-and-gas.pdf
U.S. Environmental Protection Agency, Recommended Technologies to Reduce Methane Emissions https://www.epa.gov/natural-gas-star-program/recommended-technologies-reduce-methane-emissions

Table 6. Guidance for engineering controls to reduce methane emissions from the oil and gas industry.

In some cases, engineering controls have been incorporated into environmental regulations but, in the United States at least, these controls appear to have had little effect [Kleinberg, 2021]. Pneumatic controllers provide a particularly egregious example. The oil and gas industry relies on automated controls to ensure the safety and efficiency of its operations. In remote locations electric power may not be available, so valves and similar devices are actuated by a readily available source of energy: the pressure of produced gas, comprising primarily methane and volatile organic compounds. A pneumatic controller either vents ("bleeds") gas continuously, or discharges gas intermittently, upon actuation [EPA, 2006].

In the 2012 EPA OOOO rule, renewed in the 2016 OOOOa rule, high-bleed pneumatic valves were restricted: "Each pneumatic controller . . . must have a bleed rate less than or equal to 6 standard cubic feet per hour" [40 CFR 60.5390(c)(1)]. The term "bleed rate" has a specific legal definition: "Bleed rate means the rate in standard cubic feet per hour at which natural gas is *continuously* [emphasis added] vented (bleeds) from a pneumatic controller" [40 CFR 60.5430a].

Therefore, while high-bleed controllers were regulated, there was no regulation at all on intermittently discharging controllers. Along with voluntary retirements, this rule resulted in a substantial decrease in the number of high-bleed (> 6 scf/h = 0.11 kg/h)) pneumatic valves deployed at U.S. oil and gas facilities. Generally speaking, both high-bleed and low-bleed (< 6 scf/h) valves have been replaced by unregulated intermittently discharging pneumatic valves, see Figures 11 and 12. However, the performance of intermittent valves varies widely [Allen, 2015; Methane Guiding Principles, 2019]. As a result, this costly regulation had absolutely no environmental benefit, and each year two million tons of methane are lost to the atmosphere from pneumatic controllers, amounting to a quarter of all emissions from petroleum and natural gas systems as estimated by EPA. A study of several such regulatory failures concluded that to be effective, engineering controls and performance-based regulations must include measurement requirements [Kleinberg, 2021].

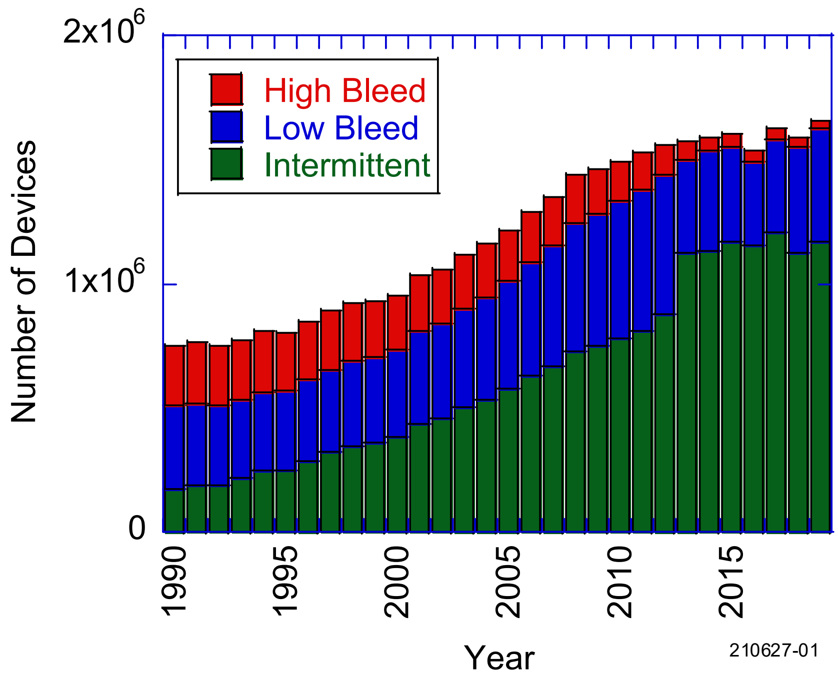


Figure 11. Population of pneumatic controllers in the oil and natural gas sector. U.S. Inventory of Greenhouse Gas Emissions and Sinks [EPA, 2021a, Additional Information, Methodology Annexes].

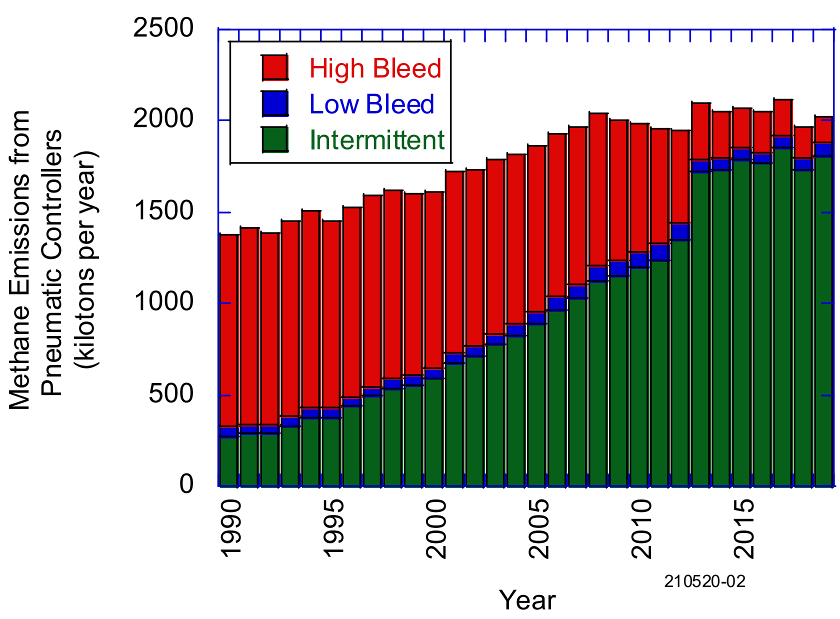


Figure 12. Methane emissions from pneumatic controllers in the oil and natural gas sector. U.S. Inventory of Greenhouse Gas Emissions and Sinks [EPA, 2021a, Additional Information, Methodology Annexes].

3.2.3 Routine and Event-Driven Flaring

Flaring is a highly visible operation. Not only is it evident to observers on the ground, but it is readily detectable by earth-orbiting satellites [Elvidge, 2016]. A recently published study quantified the veracity of company-reported flaring in Russia [Zhizhin, 2021]. For the most part, satellite-measured flaring is greater than company reports.

Routine flaring is the process by which unwanted natural gas is disposed of in a controlled manner. Natural gas is a valuable natural resource that is increasingly prized as a high-quality fuel that emits less carbon dioxide per unit energy than coal or oil. In some places it can also be usefully reinjected into oil reservoirs to maintain reservoir pressure. Therefore it may not be obvious why gas should be burned off – and thereby wasted – routinely. The fundamental problem is that twenty percent of all gas produced globally comes from wells drilled to produce oil; this is called associated gas [World Bank, 2022a]. Oil is not only more valuable than gas, but it is much easier to transport. The only two practical methods for transporting gas in bulk are in high pressure pipelines (1.4–10 MPa = 200–1500 psi), or as a refrigerated liquid (–162°C). Both approaches require large-scale, expensive infrastructure. For example, "a few high flaring oil fields in East Siberia in Russia are extremely remote, lacking the infrastructure to capture and transport the associated gas" [World Bank, 2021, page 5]. Therefore, when gas is not needed for reinjection or local fuel use, it is sometimes regarded as a nuisance to oil producers, and is therefore at risk of being flared. However, when gas pipelines become available, flaring reduction can be dramatic, as in the Khanty–Mansi Autonomous Okrug [World Bank, 2021, pages 7-9].

The World Bank Zero Routine Flaring by 2030 initiative has attracted the endorsement of thirty-four governments, fifty-one oil companies, fifteen development organizations, and six supporting organizations [World Bank, 2022b]. When it endorsed this initiative in 2016, the Russian Federation pledged to "provide a legal, regulatory, investment, and operating environment that is conducive to upstream investments and to the development of viable markets for utilization of the gas and the infrastructure necessary to deliver the gas to these markets." In fact, years earlier the Government of Russia had established a goal limiting associated gas flaring to 5% of its production. However, "the level of useful use of associated gas in the country in 2019 amounted to 80.9%" [UNFCCC, 2021b, page 92].

While routine flaring has been in the spotlight, less attention has been paid to event-driven flaring, during which gas must be released for safety and other operational reasons. Data from the Permian Basin show that event-driven flaring can be consequential, and therefore deserving of attention from petroleum engineers [Rystad, 2021].

If flares burned with 100% efficiency, the primary products of combustion would be water vapor and carbon dioxide. The latter is an undesirable greenhouse gas. However, measured combustion efficiencies are less than 100%, leading to even more undesirable outcomes. In 1996, the U.S. Environmental Protection Agency estimated a typical flaring efficiency in the production segment of the natural gas industry to be 98% [EPA, 1996, section 5.2.1]. Aircraft-based measurements of associated gas flares in the Bakken field of North Dakota indicate that on average 4.2% of gas is uncombusted, and that the presence of heavier hydrocarbons in the gas, typical of associated gas plays, significantly enhances the greenhouse gas effect of the unburned gases [Kleinberg, 2019]. Efficiency reductions of just a few percent lead to substantial climate effects, as shown in Figure 13. Unlit flares lead to even worse outcomes, as shown in Figure 14.

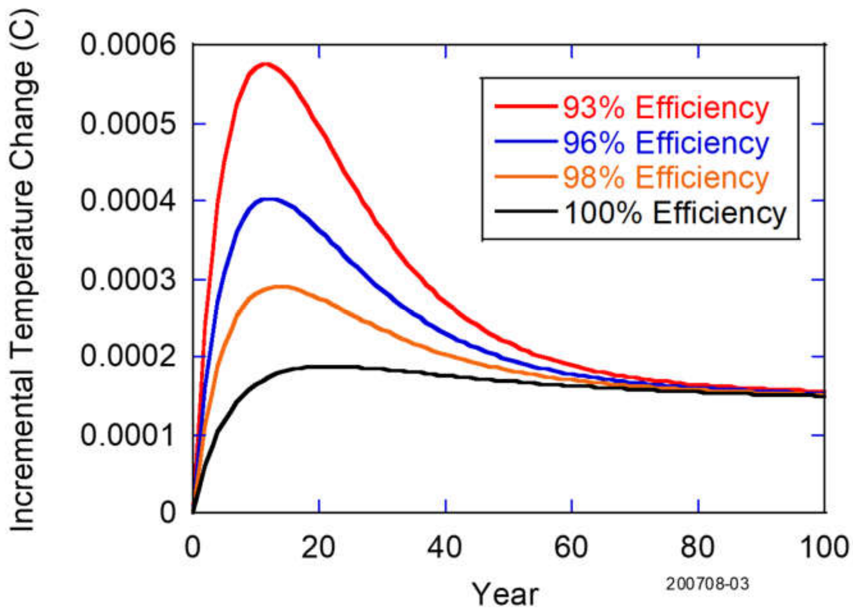


Figure 13. Effect of flare inefficiency. Temperature change is a result of one year of flaring 100% methane at the global rate of natural gas flaring, 146 billion cubic meters per year, with various levels of efficiency [Kleinberg, 2020].

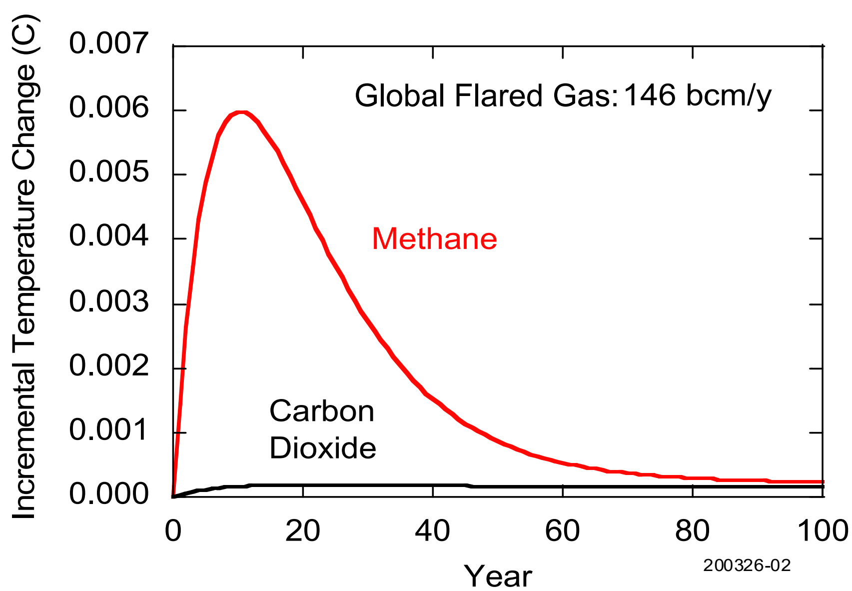


Figure 14. Effect of venting 146 billion cubic meters of 100% methane at year zero (red), versus flaring it at 100% efficiency to carbon dioxide (black). [Kleinberg, 2020]. Note the vertical axis differs from Figure 13.

Unfortunately, low efficiency and unlit flares are not uncommon. Aerial surveys of the Permian Basin have found that about five percent of active flares are malfunctioning and another five percent are unlit. This demonstrates U.S. EPA estimates of methane emissions from flares in the basin are seriously underestimated [EDF, 2022].

Flares may be highly visible nuisances, but foolish regulation can be much more harmful. In at least one case in Turkmenistan, enormous amounts of gas were vented instead of flared, apparently to comply with a government ban on routine flaring [Calel, 2020].

3.3 Methods to Reduce Coal Mine Methane Emissions

Coal mine methane emissions in the Russian Federation are described in section 2.2.2. Unlike the methane emissions from oil and gas infrastructure, coal mine methane is relatively easy to locate and estimate, but hard to remediate. Prior to 2020, coal mine methane could be considered a small part of fossil fuel methane emissions, compare Figures 2 and 4. However, since estimates of methane emissions from the oil and gas industry were reduced in 2020 and again in 2021, emissions from coal are now considered comparable to those from oil and gas sources.

The origin of coal mine methane emissions has shifted over the last three decades, see Figure 3. In the early 1990s, emissions were primarily from underground mines; recently underground and open pit mines have contributed equally. Abandoned underground mines are flooded with water, and considered to have no methane emissions [UNFCCC, 2021b, page 81]. Throughout the period, methane emissions during transport and handling have been minimal.

Methane is explosive at volumetric concentrations of 5-15% in air [EPA, 2019b]. Mine safety dictates that methane concentrations must be well below or well above these explosion limits. Therefore, the two primary classes of coal mine methane disposal are dilution (typically to less than 1%) during the mining process, or extraction of concentrated methane prior to mining.

Dilute methane, termed ventilation air methane (VAM), can be disposed of in an environmentally responsible manner by either of two techniques, regenerative thermal oxidation (RTO), which generates heat as a byproduct, and regenerative catalytic oxidation (RCO), which simply neutralizes methane. VAM can also be used as combustion air in internal combustion engines or gas turbines. These techniques have been used at a few locations, mostly in Australia, with the biggest such project in China [EPA, 2019c].

More than half of Russian coal is produced from underground mines of the Kuznetsk Basin (Kuzbass) [Mochalnikov, 2015], making the region a focus of coal mine methane mitigation research and development [Tailakov, 2017]. The emphasis there is on gas produced from coal beds that are not yet mined ("drained gas"). Large-scale drained gas systems are in place, producing 100-200 million cubic meters of methane per year. The density of methane at international standard conditions is 678.37 grams per standard cubic meter [Kleinberg, 2019], so this is equivalent to 70,000-140,000 tons of methane per year. Methane concentrations are as high as 80%. Four options have been screened for technological and economic viability: electric power generation; thermal energy production in boilers; fueling of vehicles with compressed coal mine methane; and fueling of vehicles with liquefied coal mine methane. Thermal energy production in boilers is the most desirable option on technological grounds. Fueling vehicles with compressed coal mine methane scores highest economically when methane concentrations are greater than 80% [Tailakov, 2017].

4. Conclusions

The emission of greenhouse gases into the atmosphere is probably the most important environmental issue currently facing the fossil fuel industry. There are two greenhouse gases with substantial influence on global climate change: carbon dioxide and methane. The carbon dioxide problem is both bigger and more intractable: it is an inevitable product of fossil fuels “when used as directed”.

Although global anthropogenic methane emissions are only one percent by mass of fossil carbon dioxide emissions, and methane has a much shorter lifetime in the atmosphere, it is a much more powerful warming agent. Not only are the prompt warming effects of methane and carbon dioxide about equal at current emission rates, but global average temperature trajectories over the next several decades are largely controlled by methane.

Although fossil fuel industries are responsible for only a fraction of anthropogenic methane emissions, they are the sectors most exposed to public scrutiny. They are also regarded as the economic sectors best prepared, both technically and financially, to address their environmental problems. Moreover, unlike carbon dioxide solutions, solutions to the methane problem involve no profound economic or social disruptions. They are entirely in the technical domain.

It is in the solutions to the methane problem that fossil fuels bifurcate cleanly, into oil and gas on one hand, and coal on the other. In the oil and gas industry, emission events can be both large and intermittent. The industry is widely dispersed and can be difficult or expensive to monitor. On the other hand, when an emitter is found, it is often cheap and easy to fix – sometimes as easy as replacing a part, freeing a stuck vent, or tightening the bolts on a flange. The coal industry is more concentrated, and it is usually obvious where the methane is coming from. However, remediation can be challenging.

A principal challenge is understanding the scale of the methane problem. Inventory methods, which are used universally, are known to be inaccurate. The biennial reports of the Russian Federation dramatically illustrate the instability of inventories. It is a time-worn adage that “you can’t manage what you can’t measure”, and measurements in Russia and other countries have been essentially non-existent. However, technology has been improving, and the industry is on the verge of being able to acquire measurement tools that will, for the first time, achieve the spatial and temporal granularity needed to have a meaningful impact on the emission problem.

Another challenge is to abandon the increasingly artificial distinction between “accidental” leaks and “operational” vents. Petroleum engineers are resourceful, and given appropriate incentives can and will reduce the cost of keeping gas in the pipe.

References

C.B. Alden, et al., 2020. Temporal Variability of Emissions Revealed by Continuous, Long Term Monitoring of an Underground Natural Gas Storage Facility, Environmental Science & Technology, 54, 14589−14597.
https://pubs.acs.org/doi/10.1021/acs.est.0c03175

D.T. Allen, et al., 2014. Methane emissions from natural gas production and use: reconciling bottom-up and top-down measurements, Current Opinion in Chemical Engineering, 5, 78–83.
http://dx.doi.org/10.1016/j.coche.2014.05.004

D.T. Allen, et al., 2015. Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers, Environmental Science & Technology, 49, 633−640.
https://pubs.acs.org/doi/10.1021/es5040156

R.A. Alvarez, et al., 2018. Assessment of methane emissions from the U.S. oil and gas supply chain, Science 10.1126/science.aar7204
https://science.sciencemag.org/content/361/6398/186

J. Benmergui, et al., 2020. Science Planning for the MethaneSAT Mission, Poster A015-11, American Geophysical Union Fall Meeting, 1-17 December 2020.

A.R. Brandt, et al., 2016. Methane Leaks from Natural Gas Systems Follow Extreme Distributions, Environmental Science & Technology, 50, 12512−12520.
https://pubs.acs.org/doi/10.1021/acs.est.6b04303

BP, 2021. BP Statistical Review of World Energy, July 2021 http://www.bp.com/statisticalreview

R. Calel, et al., 2020. The unintended consequences of antiflaring policies—and measures for mitigation, Proceedings of the National Academy of Sciences, 117, 12503–12507.
https://www.pnas.org/content/117/23/12503

CEDS, 2022. A Community Emissions Data System (CEDS) for Historical Emissions, Joint Global Change Research Institute. http://www.globalchange.umd.edu/ceds/ accessed 14 February 2022

CFR, 2021. What fugitive emissions VOC standards apply to the affected facility which is the collection of fugitive emissions components at a well site and the affected facility which is the collection of fugitive emissions components at a compressor station?, Code of Federal Regulations 40 CFR 60.5397a, 15 September 2020. Changes effected by Public Law 117-23 are not yet reflected here.

Y. Chen, et al., 2021. Comprehensive aerial survey quantifies high methane emissions from the New Mexico Permian Basin, Preprint, EarthArXiv, 24 September 2021.
https://eartharxiv.org/repository/view/2632/

M. Crippa, et al., 2018. Gridded emissions of air pollutants for the period 1970–2012 within EDGAR v4.3.2, Earth Systems Science Data, 10, 1987–2013 https://doi.org/10.5194/essd-10-1987-2018

D.H. Cusworth, et al., 2021. Intermittency of Large Methane Emitters in the Permian Basin, Environmental Science & Technology Letters, 567-573.
https://pubs.acs.org/doi/10.1021/acs.estlett.1c00173

Z. Deng, et al., 2021. Comparing national greenhouse gas budgets reported in UNFCCC inventories against atmospheric inversions, Earth Systems Science Data, Preprint 13 August 2021.
https://doi.org/10.5194/essd-2021-235

R.M. Duren, et al., 2019. California's methane super-emitters, Nature, 575, 180-185.
https://www.nature.com/articles/s41586-019-1720-3

EDF, 2021. private communication

EDF, 2022. Permian Methane Analysis Project, Environmental Defense Fund
https://permianmap.org/ accessed 13 February 2022
Methodology for EDF's Permian Methane Analysis Project (PermianMAP), Data Collection and Analysis, Last Updated: January 31, 2022
https://permianmap.org/our-research
https://www.edf.org/sites/default/files/documents/PermianMapMethodology_1.pdf

EDGAR, 2021a. GHG emissions of all world countries, 2021 Report, Emissions Database for Global Atmospheric Research, JRC Science for Policy Report, EUR 30831 EN
https://edgar.jrc.ec.europa.eu/report_2021

EDGAR, 2021b. Emissions Database for Global Atmospheric Research
https://edgar.jrc.ec.europa.eu/dataset_ghg60 accessed 11 February 2022

EIA, 2022a. Natural Gas Gross Withdrawals and Production: Dry Production, Energy Information Administration, 29 April 2022
https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_FPD_mmcf_a.htm

EIA, 2022b. Drilling Productivity Report, Permian, Energy Information Administration, 18 January 2022
https://www.eia.gov/petroleum/drilling/

C.D. Elvidge, et al., 2016. Methods for Global Survey of Natural Gas Flaring from Visible Infrared Imaging Radiometer Suite Data, Energies, 9, 14.
https://www.mdpi.com/1996-1073/9/1/14

eoPortal, 2022a. Missions Database
https://eoportal.org/web/eoportal/satellite-missions/a accessed 10 February 2022

eoPortal, 2022b. GHGSat Constellation
https://eoportal.org/web/eoportal/satellite-missions/g/ghgsat-con accessed 10 February 2022

EPA, 1996. Methane Emissions from the Natural Gas Industry, Volume 6: Vented and Combustion Source Summary, U.S. Environmental Protection Agency, EPA-600/R-96-080f, June 1996.
https://www.epa.gov/sites/default/files/2016-08/documents/6_vented.pdf

EPA, 2006. Options For Reducing Methane Emissions From Pneumatic Devices In The Natural Gas Industry.
https://www.epa.gov/sites/production/files/2016-06/documents/ll_pneumatics.pdf

EPA, 2012. Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990 – 2030, U.S. Environmental Protection Agency, EPA 430-R-12-006, December 2012
https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases/global-non-co2-ghg-emissions-1990-2030

EPA, 2016a. Regulatory Impact Analysis of the Final Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources, U.S. Environmental Protection Agency, EPA-452/R-16-002, May 2016.
https://www3.epa.gov/ttnecas1/docs/ria/oilgas_ria_nsps_final_2016-05.pdf

EPA, 2016b. Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources, Background Technical Support Document for the Final New Source Performance Standards 40 CFR Part 60, subpart OOOOa, U.S. Environmental Protection Agency, May 2016.
https://beta.regulations.gov/document/EPA-HQ-OAR-2015-0216-0212

EPA, 2019a. Global Non-CO2 Greenhouse Gas Emission Projections and Mitigation, 2015–2050, U.S. Environmental Protection Agency, EPA-430-R-19-010, October 2019.
https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases/global-non-co2-greenhouse-gas-emission-projections

EPA, 2019b. Coal Mine Methane Recovery: A Primer, U.S. Environmental Protection Agency, EPA-430-R-09-013, July 2019.
https://www.epa.gov/sites/default/files/2016-03/documents/cmm_primer.pdf

EPA, 2019c. Ventilation Air Methane (VAM) Utilization Technologies, U.S. Environmental Protection Agency, EPA-430-F-19-023, July 2019.
https://www.epa.gov/sites/default/files/2019-11/documents/vam_technologies.pdf

EPA, 2021a. Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2019. U.S. Environmental Protection Agency, 2021.
https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks
Additional Information, Methodology Annexes. Accessed 18 May 2021.
https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2019-ghg

EPA, 2021b. EPA's Proposal to Reduce Climate- and Health-Harming Pollution from the Oil and Natural Gas Industry, Fact Sheet: Overview of the Proposed Rule. U.S. Environmental Protection Agency, 2 November 2021.
https://www.epa.gov/controlling-air-pollution-oil-and-natural-gas-industry/epa-proposes-new-source-performance

EPA, 2021c. EPA Proposes New Source Performance Standards Updates, Emissions Guidelines to Reduce Methane and Other Harmful Pollution from the Oil and Natural Gas Industry: Overview.
https://www.epa.gov/system/files/documents/2021-11/2021-oil-and-gas-proposal.-overview-fact-sheet.pdf

EPA, 2022. Stakeholder Process for Natural Gas and Petroleum Systems in the 1990-2020 Inventory, U.S. Environmental Protection Agency. Last updated on APRIL 14, 2022
https://www.epa.gov/ghgemissions/stakeholder-process-natural-gas-and-petroleum-systems-1990-2020-inventory

ESA, 2021. Satellites detect large methane emissions from Madrid landfills, European Space Agency, 10 November 2021.
https://www.esa.int/Applications/Observing_the_Earth/Satellites_detect_large_methane_emissions_from_Madrid_landfills

ESA, 2022a. TROPOspheric Monitoring Instrument, European Space Agency.
http://www.tropomi.eu/ accessed 7 February 2022

ESA, 2022b. Missions/Sentinel-5P/Satellite Description/Orbit, European Space Agency.
https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-5p/orbit accessed 7 February 2022

GHGSat, 2020. private communication, June 2020.

GHGSat, 2022. Global Emissions Monitoring. https://www.ghgsat.com/en/ Accessed 12 February 2022

S. Hamburg, 2020. Methane emissions from Global Oil and Gas Infrastructure: What we know, MethaneSAT, Florence School of Regulation, 1 June 2020.
https://fsr.eui.eu/event/how-can-aerial-measurements-aid-methane-emissions-reduction/

R.M. Hoesly, et al., 2018. Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS), Geoscientific Model Development, 11, 369–408.
https://doi.org/10.5194/gmd-11-369-2018

L. Höglund-Isaksson, 2017. Bottom-up simulations of methane and ethane emissions from global oil and gas systems 1980 to 2012. Environmental Research Letters 12, 024007.
https://doi.org/10.1088/1748-9326/aa583e

IEA, 2021a. World Energy Model Documentation, Oil and gas methane emissions model. pg 66-74, International Energy Agency, October 2021.
https://www.iea.org/reports/world-energy-model
https://iea.blob.core.windows.net/assets/932ea201-0972-4231-8d81-356300e9fc43/WEM_Documentation_WEO2021.pdf

IEA, 2021b. Improving methane data: Focus on the role of satellites, International Energy Agency
https://www.iea.org/reports/methane-tracker-2021/improving-methane-data-focus-on-the-role-of-satellites#abstract
accessed 10 February 2022

IEA, 2022a. Methane Tracker Data Explorer, Russia: Methane abatement potential in oil and gas, International Energy Agency, 23 February 2022
https://www.iea.org/articles/methane-tracker-data-explorer
https://api.iea.org/methane/abatement/?country=Russia&csv=true

IEA, 2022b. Methane Tracker Data Explorer, Russia: Estimates of methane emissions, International Energy Agency, 23 February 2022
https://www.iea.org/articles/methane-tracker-data-explorer
https://api.iea.org/methane/comparison/?country=Russia&source=IEA&csv=true

IMF, 2017. Russian Natural Gas border price in Germany, International Monetary Fund
https://www.imf.org/external/np/res/commod/External_Data.xls accessed 6 February 2022

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy, Chapter 4: Fugitive Emissions, Intergovernmental Panel on Climate Change
https://www.ipcc-nggip.iges.or.jp/public/2006gl/
https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_4_Ch4_Fugitive_Emissions.pdf

IPCC, 2013. Anthropogenic and Natural Radiative Forcing, Chapter 8 and Supplementary Material, in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press
https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf
https://www.ipcc.ch/site/assets/uploads/2018/07/WGI_AR5.Chap_.8_SM.pdf

IPCC, 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Intergovernmental Panel on Climate Change.
https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

IWG, 2021. Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide: Interim Estimates under Executive Order 13990, Interagency Working Group on Social Cost of Greenhouse Gases, February 2021. https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf

R.B. Jackson, et al., 2020. Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources, Environmental Research Letters, 15, 071002
https://iopscience.iop.org/article/10.1088/1748-9326/ab9ed2

D.J. Jacob, et al., 2022. Quantifying methane emissions from the global scale down to point sources using satellite observations of atmospheric methane, Atmospheric Chemistry and Physics, preprint
https://acp.copernicus.org/preprints/acp-2022-246/

F. Johnson, et al., 2021. Airborne methane surveys pay for themselves: An economic case study of increased revenue from emissions control, EarthArXiv, 15 July 2021.
https://eartharxiv.org/repository/view/2532/

N. Kholod, et al., 2020. Global methane emissions from coal mining to continue growing even with declining coal production, Journal of Cleaner Production 256: 120489
https://doi.org/10.1016/j.jclepro.2020.120489

R.L. Kleinberg, 2019. Greenhouse Gas Footprint of Oilfield Flares Accounting for Realistic Flare Gas Composition and Distribution of Flare Efficiencies, Earth and Space Science Open Archive, 16 December 2019. https://www.essoar.org/doi/10.1002/essoar.10501340.1

R.L. Kleinberg, 2020. The Global Warming Potential Misrepresents the Physics of Global Warming Thereby Misleading Policy Makers, EarthArXiv Working Paper, 25 October 2020.
https://eartharxiv.org/repository/view/1686/

R.L. Kleinberg, 2021. Reducing Emissions of Methane and Other Air Pollutants from the Oil and Natural Gas Sector: Recommendations to the Environmental Protection Agency, Public submission posted by the EPA. July 6, 2021.
https://www.regulations.gov/comment/EPA-HQ-OAR-2021-0295-0035
Data File: Public submission posted by the EPA. August 2, 2021.
https://www.regulations.gov/comment/EPA-HQ-OAR-2021-0295-0071

T. Lauvaux, et al., 2022. Global assessment of oil and gas methane ultra-emitters, Science, 375, 557–561.
https://www.science.org/doi/10.1126/science.abj4351

LongPath, et al., 2022. Comment submitted by LongPath Technologies, Inc. et al., Posted by the Environmental Protection Agency on Feb 2, 2022.
https://www.regulations.gov/comment/EPA-HQ-OAR-2021-0317-0759

J. McKeever, et al., 2021. First Methane Sensing Results from GHGSAT's Commercial Constellation. 17th International Workshop on Greenhouse Gas Measurements from Space, 14-17 June 2021.
https://cce.nasa.gov/iwggms17/
https://cce-datasharing.gsfc.nasa.gov/files/conference_presentations/Talk_McKeever_117_25.pdf

Methane Guiding Principles, 2019. Reducing Methane Emissions: Best Practice Guide, Pneumatic Devices, November 2019.
https://methaneguidingprinciples.org/wp-content/uploads/2019/11/Reducing-Methane-Emissions-Pneumatic-Devices-Guide.pdf

MethaneSAT, 2022. About MethaneSAT https://www.methanesat.org/about/ accessed 12 February 2022

S.V. Mochalnikov, 2015. Current Status and Development Prospects of Coal Industry in Russia, Ministry of Energy of the Russian Federation, September 2015.
http://www.jcoal.or.jp/coaldb/shiryo/material/upload/1-12speech%203%20Russia%20Mr.%20Mochalnikov.pdf

NASEM, 2018. Improving Characterization of Anthropogenic Methane Emissions in the United States, National Academy of Sciences, Engineering, and Medicine.
https://www.nap.edu/catalog/24987/improving-characterization-of-anthropogenic-methane-emissions-in-the-united-states

New York Times, 2022. European Satellite Detects Huge Methane Leaks in the U.S., Russia and Elsewhere, 5 February 2022
https://www.nytimes.com/2022/02/04/climate/methane-leaks-satellites.html

NIES, 2022. Greenhouse gases observing satellite "IBUKI". National Institute for Environmental Studies
https://www.gosat.nies.go.jp/en/ accessed 7 February 2022

OGMP, 2020. Oil and Gas Methane Partnership (OGMP) 2.0 Framework, United Nations Environment Program, Climate and Clean Air Coalition, 19 November 2020
https://www.ccacoalition.org/en/resources/oil-and-gas-methane-partnership-ogmp-20-framework

S.Pandey, et al., 2019. Satellite observations reveal extreme methane leakage from a natural gas well blowout, Proceedings of the National Academy of Sciences 116, 26376-26381.
https://doi.org/10.1073/pnas.1908712116

Z. Qu, et al., 2021. Global distribution of methane emissions: a comparative inverse analysis of observations from the TROPOMI and GOSAT satellite instruments, Atmospheric Chemistry and Physics, 21, 14159–14175. https://acp.copernicus.org/articles/21/14159/2021/

A.P. Ravikumar et al., 2020. Repeated leak detection and repair surveys reduce methane emissions over scale of years, Environmental Research Letters, 15, 034029
https://doi.org/10.1088/1748-9326/ab6ae1

Roy, M., Edwards, M.R., Trancik, J.E., 2015. Methane mitigation timelines to inform energy technology evaluation, Environmental Research Letters, 10 (2015) 114024, Supplementary Information.
https://iopscience.iop.org/1748-9326/10/11/114024/media/erl114024_suppdata.pdf

Rutherford, J.S., et al., 2021. Closing the gap: Explaining persistent underestimation by U.S. oil and natural gas production-segment methane inventories, Nature Communications, 12: 4715.
https://www.nature.com/articles/s41467-021-25017-4

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

M. Saunois, et al., 2016. The global methane budget 2000–2012, Earth System Science Data, 8, 697–751.
https://essd.copernicus.org/articles/8/697/2016/

M. Saunois, et al., 2020a. The Global Methane Budget 2000–2017, Earth System Science Data, 12, 1561–1623
https://essd.copernicus.org/articles/12/1561/2020/essd-12-1561-2020.pdf

M. Saunois, et al., 2020b. Reference of the Full Global Methane Budget 2000-2017; Supplemental data to Global Methane Budget 2000-2017
https://www.icos-cp.eu/GCP-CH4/2019
http://pure.iiasa.ac.at/16569/3/Global_Methane_Budget_2000_2017_v2.0_full.xlsx

D. Shindell, et al., 2012. Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security, Science, 335, 183-189.
https://science.sciencemag.org/content/335/6065/183

A.R. Stavert, et al., 2022. Regional trends and drivers of the global methane budget, Global Change Biology 28, 182–200.
https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.15901

J. Stern, 2022. Measurement, Reporting, and Verification of Methane Emissions from Natural Gas and LNG Trade, Oxford Institute for Energy Studies, OIES Paper ET06, January 2022
https://www.oxfordenergy.org/wpcms/wp-content/uploads/2022/01/Measurement-Reporting-and-Verification-of-Methane-Emissions-from-Natural-Gas-and-LNG-Trade-ET06.pdf

O. Tailakov, et al., 2017. Utilization prospects for coal mine methane (CMM) in Kuzbass, 1st International Innovative Mining Symposium, E3S Web of Conferences, 15, 02002.
https://www.e3s-conferences.org/articles/e3sconf/abs/2017/03/e3sconf_iims2017_02002/e3sconf_iims2017_02002.html
https://www.e3s-conferences.org/articles/e3sconf/pdf/2017/03/e3sconf_iims2017_02002.pdf

UNFCCC, 2014a. Russian Federation. First Biennial Reporting Common Tabular Format (BR-CTF). BR-CTF 1, Tables 1(b)s1, 1(b)s2, 1(b)s3, Category 1.B.2 https://unfccc.int/documents/199056

UNFCCC, 2014b. United States of America. First Biennial Reporting Common Tabular Format (BR-CTF). BR-CTF 1, Tables 1(b)s1, 1(b)s2, 1(b)s3, Category 1.B.2 https://unfccc.int/documents/199074

UNFCCC, 2016a. Russian Federation. Second Biennial Reporting Common Tabular Format (BRCTF). BR-CTF 2, Tables 1(b)s1, 1(b)s2, 1(b)s3, Category 1.B.2 https://unfccc.int/documents/199047

UNFCCC, 2016b. United States of America. Second Biennial Reporting Common Tabular Format (BR-CTF). BR-CTF 2, Tables 1(b)s1, 1(b)s2, 1(b)s3, Category 1.B.2 https://unfccc.int/documents/199068

UNFCCC, 2018a. Russian Federation. Third Biennial Reporting Common Tabular Format (BRCTF). BR-CTF 3, Tables 1(b)s1, 1(b)s2, 1(b)s3, Category 1.B.2 https://unfccc.int/documents/198864

UNFCCC, 2018b. United States of America. Fourth [*sic*] Biennial Reporting Common Tabular Format (BR-CTF). BR-CTF 3, Tables 1(b)s1, 1(b)s2, 1(b)s3, Category 1.B.2 https://unfccc.int/documents/307994

UNFCCC, 2019. Russian Federation, 2019 National Inventory Report (NIR), Volume 2, Appendix 3.4 (in Russian) https://unfccc.int/documents/194838

UNFCCC, 2020a. Russian Federation. Fourth Biennial Reporting Common Tabular Format (BRCTF). BR-CTF 4, Tables 1(b)s1, 1(b)s2, 1(b)s3, Category 1.B.2 https://unfccc.int/documents/230954

UNFCCC, 2020b. United States of America. Fourth Biennial Reporting Common Tabular Format (BR-CTF). BR-CTF 4, Tables 1(b)s1, 1(b)s2, 1(b)s3, Category 1.B.2 https://unfccc.int/documents/307956

UNFCCC, 2021a. National Inventory Submissions 2003-2021; Annex I Party GHG Inventory Submissions, United Nations Framework Convention on Climate Change
https://unfccc.int/ghg-inventories-annex-i-parties/2021

UNFCCC, 2021b. Russian Federation. 2021 National Inventory Report (NIR), Volume 1 (in Russian)
https://unfccc.int/documents/273477

N.E. Uvarova, et al., 2014. The update of methane emission parameters for natural gas operations in Russia, Carbon Management, 5, 573-577.
https://www.tandfonline.com/doi/full/10.1080/17583004.2015.1049105

N.E. Uvarova, et al., 2017. The country-specific Emission Factors and Parameters for Greenhouse Gas Inventory in the Russian Oil and Gas Sector. 17th International Multidisciplinary Scientific GeoConference SGEM 2017 Proceedings. – Sofia, Bulgaria: STEF92 Technology LTD, 2017. p. 605-612
https://www.sgem.org/index.php/peer-review-and-metrics/jresearch?view=publication&task=show&id=3681

D.J. Varon, et al., 2019. Satellite Discovery of Anomalously Large Methane Point Sources From Oil/Gas Production, Geophysical Research Letters, 46.
https://doi.org/10.1029/2019GL083798

T.L. Vaughn, et al., 2018. Temporal variability largely explains top-down/bottom-up difference in methane emission estimates from a natural gas production region, Proceedings of the National Academy of Sciences, 115, 11712–11717
https://www.pnas.org/content/115/46/11712

Washington Post, 2021. Russia allows methane leaks at planet's peril, 19 October 2021.
https://www.washingtonpost.com/climate-environment/interactive/2021/russia-greenhouse-gas-emissions/

World Bank, 2021. Global Gas Flaring Tracker Report, April 2021. accessed 24 February 2022
https://www.worldbank.org/en/topic/extractiveindustries/publication/global-gas-flaring-tracker-report

World Bank, 2022a. Zero Routine Flaring by 2030 (ZRF) Initiative; Frequently Asked Questions and Answers; About Associated Gas.
https://www.worldbank.org/en/programs/zero-routine-flaring-by-2030/qna#2 accessed 18 February 2022

World Bank, 2022b. Zero Routine Flaring by 2030.
https://www.worldbank.org/en/programs/zero-routine-flaring-by-2030 accessed 18 February 2022

D. Wunch, et al., 2011. The Total Carbon Column Observing Network, Philosophical Transactions of the Royal Society A, 369, 2087–2112.
https://royalsocietypublishing.org/doi/10.1098/rsta.2010.0240

Y-Charts, 2022. Germany Natural Gas Border Price (Source International Monetary Fund)
https://ycharts.com/indicators/germany_natural_gas_border_price accessed 6 February 2022

Zavala-Araiza, D., et al, 2017. Super-emitters in natural gas infrastructure are caused by abnormal process conditions, Nature Communications, 8:14012, DOI: 10.1038/ncomms14012
https://www.nature.com/articles/ncomms14012

Y. Zhang, et al., 2020. Quantifying methane emissions from the largest oil-producing basin in the United States from space, Science Advances, 6: eaaz5120.
https://www.science.org/doi/10.1126/sciadv.aaz5120

M. Zhizhin, et al., 2021. Measuring Gas Flaring in Russia with Multispectral VIIRS Nightfire Profile Image, Remote Sensing, 13, 3078.
https://doi.org/10.3390/rs13163078