Non-Peer Reviewed EarthArXiv Preprint

Methane Emissions from the Fossil Fuel Industries of the Russian Federation

Version 3.0 — 29 October 2022
https://eartharxiv.org/repository/view/3342/

Robert L. Kleinberg
Center on Global Energy Policy, Columbia University
Institute for Sustainable Energy, Boston University
robert@robertkleinberg.com

Table of Contents

Key Words: Russia, Methane, Oil and gas, Coal, Greenhouse gas inventories, Remote sensing

Abstract

Methane is second only to carbon dioxide as a driver of human-induced climate change. Moreover, reducing 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 among the main sources of anthropogenic methane. As one of the world's largest producers of fossil fuels, and one of the largest emitters of fossil fuel methane, the Russian Federation is central to methane-mitigation efforts. However, Russia's own estimates of methane emissions 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, the self-reported methane emission intensity estimate of the Russian Federation oil and gas industry is now less than that of the United States oil and gas industry. If taken at face value, this estimate would make Russia a preferred provider of oil, gas, and petroleum products to importers sensitive to the upstream greenhouse gas emissions of their suppliers. Satellite-based, national-level estimates of Russian methane emissions are available, but the error bars are large and attributions to specific economic sectors 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. If Russia seeks to play a constructive role in climate change mitigation, it will need to collect accurate, quantitative information about the state of its emissions, introduce monitoring systems, and implement prudent mitigation measures.

This report starts with an introduction to the sources of natural and anthropogenic methane, and an explanation of why the fossil fuel industries in general and the Russian industries in particular have received a disproportionate share of interest. It then describes the difference between bottom-up and top-down measurements. It reviews the reports of methane emissions in Russia and the United States, pointing out similarities and differences in methodology and consistency, and explores the capabilities and limitations of satellite-based measurements. The report then discusses how methane emissions from the fossil fuel industries can be mitigated with a two-part program, and finally discusses policy issues with respect to styles of regulation.

Although the focus of this report is the Russian Federation, many practices described here are common internationally, including in the United States. Therefore, this report's descriptions of the current practices, capabilities, and limitations of various methods of estimating and mitigating methane emissions have general applicability. Similarly, recommendations for improvement and discussions of policy have global applications.

1. Introduction

The emission of greenhouse gases into the atmosphere is probably the most important environmental challenge currently facing the fossil fuel industry. There are two greenhouse gases with substantial influence on global climate change: carbon dioxide and methane. 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 will be largely controlled by methane.

Fossil fuel industries are responsible for only a fraction of anthropogenic methane emissions, but they are the sectors most exposed to public scrutiny [see, e.g., Washington Post, 2021], in part because they are best prepared, both technically and financially, to address their contributions to environmental problems. Furthermore, unlike carbon dioxide solutions, solutions to the methane problem involve no profound economic or social disruptions. They are entirely in the technical domain.

This report has four principal parts:

- Section 1 is an introduction to the sources of natural and anthropogenic methane, and an explanation of why the fossil fuel industries have received a disproportionate share of interest in scientific circles, among policymakers, and in the popular media. It also discusses why the fossil fuel industries of the Russian Federation are of particular interest.

- Section 2 describes the difference between bottom-up and top-down measurements, as those terms are used here. It also reviews the reports of methane emissions in Russia and the United States, pointing out similarities and contrasts in methodology and consistency. Finally section 2 explores the capabilities and limitations of satellite-based measurements.

- Section 3 discusses how methane emissions from the fossil fuel industries can be mitigated with a two-part program. The first part is to acquire more reliable data so that important sources of methane can be identified and addressed. The second part provides some examples of how emissions can be reduced in three sectors that have been found to be particularly troublesome.

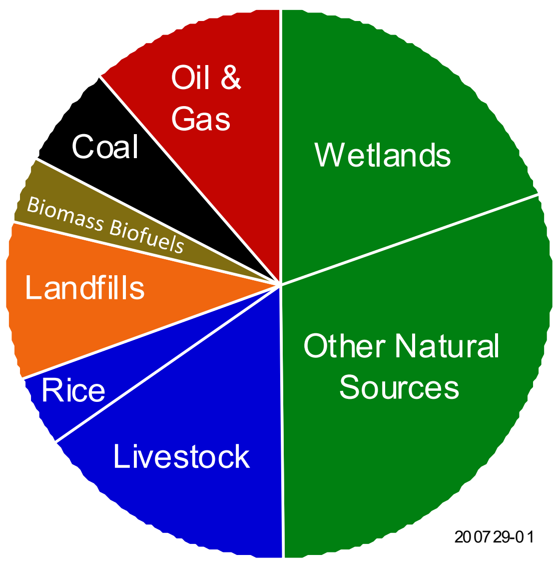
- Section 4 explores policy issues with respect to styles of regulation. Although prescriptive regulation is easy to formulate and to comply with, it has been found to be ineffective in the realm of natural gas emissions. It is argued that performance-based regulation, with verification of compliance and an adaptive element, is likely to be considerably more effective.

1.1 Methane as a Greenhouse Gas

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 fossil 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 efficiency (i.e., the change in net radiative flux due to a change in the atmospheric concentration of a greenhouse gas) of a mass of methane is more than one hundred times greater than that of the same mass of carbon dioxide [IPCC, 2021; Roy, 2015, Supplementary Information]. Therefore, the prompt effect of these two gases on global average surface temperature is comparable [Kleinberg, 2020]. While reducing the rate of carbon dioxide emissions is essential to a long-term solution to the climate problem, the only route to temperature change moderation over the next thirty years is reducing the rate of anthropogenic methane emission [Shindell, 2012].

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, and biomass burning [Jackson, 2020; Saunois, 2020a], see Figure 1.

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 damage suffered as a result of adding one ton of greenhouse gas to the atmosphere. For the purposes of developing United States government policy, the Interagency Working Group on Social Cost of Greenhouse Gases [IWG, 2021] computes the social costs of greenhouse gases. Assuming a discount rate of 3 percent, the 2020 social cost of carbon dioxide is $51 per metric ton and the 2020 social cost of methane is $1,500 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 only account for an estimated 11 percent of total methane emissions, they have been identified as the first target of reduction efforts. There are several reasons for this:

- Methane is the primary constituent of natural gas, a valuable and widely marketed fuel.
- Under certain assumptions, some methane mitigation measures pay for themselves [IEA, 2022a].
- Oil and gas supply chains are mostly managed by large industrial organizations that are technically sophisticated and well capitalized. Thus they are well equipped to deal with their methane emissions.
- Emissions from the oil and gas industry are easier to control than those from natural sources, agriculture, and biomass burning.

Russia is second only to the United States in the production of petroleum and natural gas [EIA, 2021], which alone would make it a locus of concern in terms of methane emissions. Beyond the sheer size of

Russian fossil fuel industries, satellite-based methane sensing has revealed unexpectedly large methane emissions [Washington Post, 2021; New York Times, 2022a; New York Times, 2022b].

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), self-reported methane emissions of the oil and gas industry of the Russian Federation was four million metric tons [UNFCCC, 2021b, Figures 3.44, 3.47, and 3.49]. The environmental damage calculated from this estimate and the U.S. social cost of methane of $1,500 per metric ton [IWG, 2021] is about $6 billion per year.

Coal mine methane is a secondary target of methane reduction efforts, accounting for 6 percent of total global methane emissions according to 2020 estimates [Jackson, 2020, Table 1, 2017 Bottom-Up Estimates]. The recent discovery of unexpected, gigantic methane emissions from a Russian open-pit coal mine suggests this may be an even bigger problem that had been thought [BBC, 2022]. For safety reasons, methane is prevented from concentrating during coal mining, particularly in underground mines. This makes methane sourced from coal mining hard to convert 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.

The essence of the *bottom-up* estimate 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, fixed or mobile point sensors located at or near the fence line, or aircraft or satellites capable of imaging emission plumes and connecting them to specific assets. However, bottom-up estimates are usually not based on measurements at all. Almost universally, they 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.

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 countries, 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 (NIR) (in Russian) to the secretariat of the United Nations Framework Convention on Climate Change [UNFCCC, 2021a, UNFCCC, 2022c]. The Russian NIR is the basis for computing national-level methane emissions using the inventory method. This method divides the oil and gas industry 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 methane emissions from the oil and gas industry equals the sum of all values of E.

In Russian practice, activity factors are gross quantities of oil and gas produced, transported, distributed, or flared at the national level. This method leads to anomalies. For example, transportation losses are deemed independent of distance. The NIR lists activity factors in tables.

Emission factors are estimates of gas-loss rates in each segment. The Intergovernmental Panel on Climate Change (IPCC) has issued guidelines for selecting emission factors [IPCC, 2006; IPCC, 2019], which are either universal default values provided by the IPCC (“Tier 1”) or 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 NIR.

The Russian government reconsiders its slate of oil and gas emission factors almost every year. Generally (but not always), changes are applied retroactively to the history of methane emissions since 1990. Every other year since 2014, the Russian Federation has submitted a biennial report to the secretariat of the United Nations Framework Convention on Climate Change (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 NIR changed; the activity factors remain essentially unchanged in successive NIRs. Pre-COVID-19 emission data compiled in 2021 for 2019 [UNFCCC, 2021b] are in Table 1.

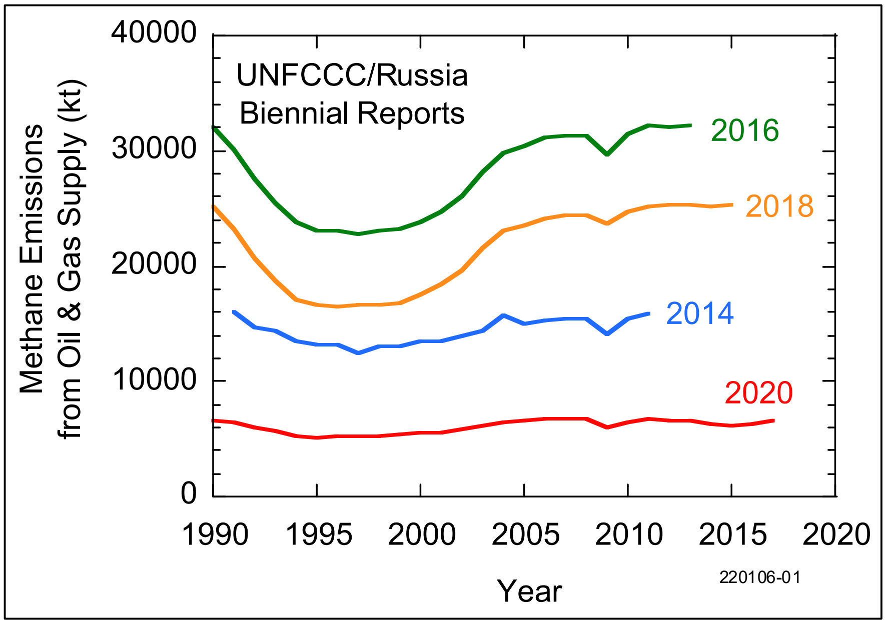


Figure 2. Methane emissions for the Russian oil and gas industry, recomputed using updated slates of emission factors reported in 2014, 2016, 2018, and 2020. Data: [UNFCCC, 2014a; UNFCCC, 2016a; UNFCCC, 2018a; UNFCCC, 2020a].

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 (pre-COVID) methane emissions from the oil and natural gas industry, computed with 2021 NIR emission factors [UNFCCC, 2021b, Figures 3.44, 3.47, and 3.49].

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 NIRs from 2014 to 2021 [UNFCCC, 2021a]. Blue and red arrows mark values that were changed from the previous year. The rightmost column lists IPCC Tier 1 default values [IPCC, 2006].

		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 NIRs, 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) equals 1000 metric tons (kt). F = fugitive; V = vent.

- In the 2014 NIR, emission factors were generally higher, and often considerably higher, than IPCC defaults.
- In the 2015 NIR, some emission factors increased while 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 to or to the same level as IPCC default values. Consequently, the 2020 biennial report emissions were very low.
- There were no emission factor changes in the 2020 NIR. The 2021 NIR reduced estimated 2019 oil and gas methane emissions to 4,050 kt, as shown in Table 1.

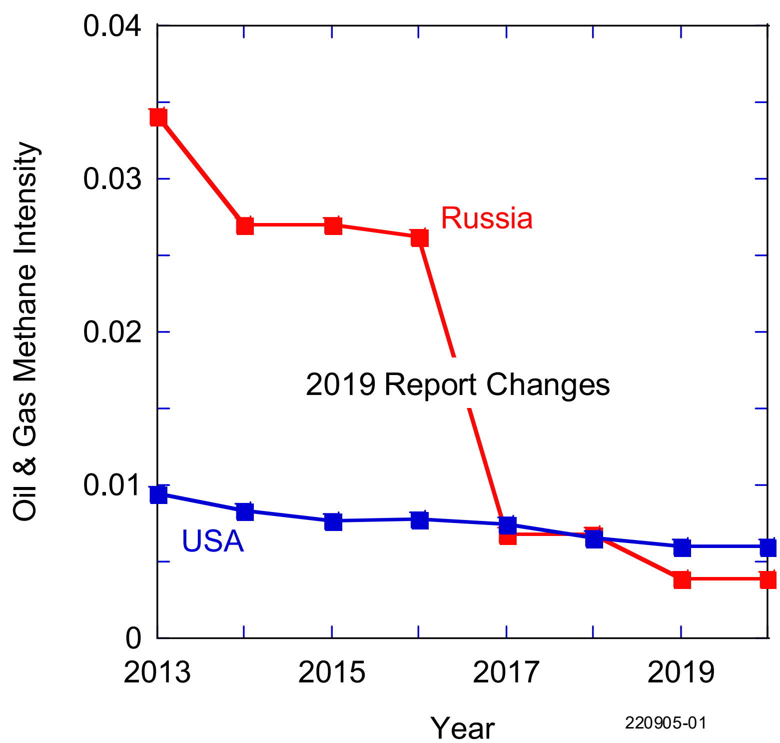


Figure 3. Methane intensities of emissions from the oil and gas industries. Numerators are self-reported methane emissions of the USA and Russia , 2013-2020, from Common Reporting Format (CRF) data reported to the UNFCCC between 2015 and 2022, expressed in barrels of oil equivalent. [UNFCCC, 2022a, Table 10s3; UNFCCC, 2022b, Table 10s3]. Denominators are totals of oil and gas production in barrels of oil equivalent [BP, 2021].

The change of emission factors in the 2019 report is explained in the 2019 NIR [UNFCCC, 2019a; UNFCCC, 2019b]. Generally, 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 [the] 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]. As a result of repeated reductions of emission factors, the self-reported methane emission intensity from the Russian oil and gas industry declined by 89 percent between 2013 and 2019, thereby surpassing the United States in this measure of environmental performance, see Figure 3.

2.2.2 National Inventory Reports – Solid Fuels

The only solid fuel methane emissions reported in the Russian Federation NIRs are from the supply of coal. Russia ranks sixth in the world in coal and lignite production [Enerdata, 2022]. Currently, there are about equal emissions from underground and open pit mines, with a minor contribution from subsequent handling [UNFCCC, 2021b, Figure 3.36]. Methane emission factors for coal production are not reported in the NIRs but can be found in the Russian Federation Common Reporting Format (CRF) Tables [UNFCCC, 2022a, Table 10s3]. These factors have remained constant since the inception of the biennial reports, see Figure 4. Methane emissions from coal mining operations depend less on equipment and processes than 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 or methane emerging from deeper sources through underground or surface mines. These are now recognized as significant problems [see, e.g., BBC, 2022].

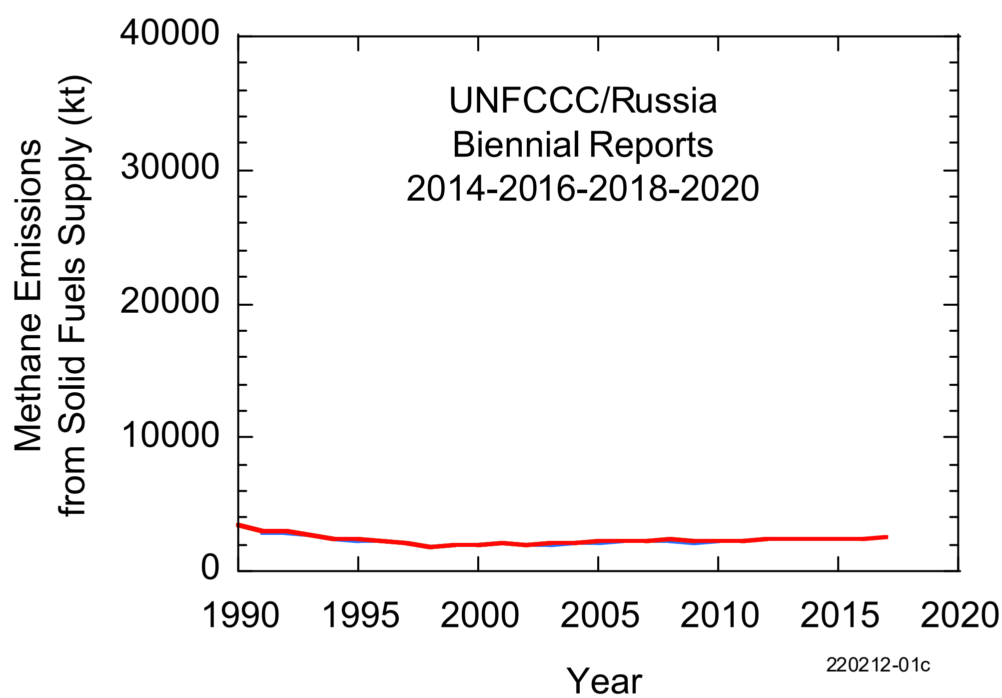


Figure 4. Methane emissions from the Russian coal industry, recomputed using minor updates of emission factors reported in 2014, 2016, 2018, and 2020. The scales are the same as in Figure 2. Data: [UNFCCC, 2014a; UNFCCC, 2016a; UNFCCC, 2018a; UNFCCC, 2020a].

2.2.3 Other Inventories

Other estimates of methane losses from the Russian fossil fuel industries are provided by the International Energy Agency (IEA), the European Union Emissions Database for Global Atmospheric Research (EDGAR), the U.S. Environmental Protection Agency (EPA), the International Institute for Applied Systems Analysis (IIASA), and the Community Emissions Data System (CEDS), see Figure 5. These estimates all fall within the range of the four Russian biennial reports to the UNFCCC shown in Figure 2.

The IEA's Methane Tracker annually reports national, sector-level methane emissions [IEA, 2022b]. The tracker's methods are documented in the Global Methane Tracker Documentation [IEA, 2022d]. The IEA estimated nineteen oil and gas, sector-level emission intensities for each of the twenty-five countries responsible for 95 percent of global oil and gas production. 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.) using inventory reports for 2019 [EPA, 2021a] modified by satellite-based estimates. The EPA's pre-COVID-19 estimate of methane emissions from U.S. petroleum and natural gas systems was 7,868 kt. The corresponding IEA estimate is 13,820 kt, a factor of 1.76 larger, in agreement with current academic literature [Shen, 2022, Figure 3]. For the other twenty-four countries, the sector intensities were multiplied by country-specific factors. Countries such as Russia, from which satellites detected very large single emitters greater than five tons of methane per hour, were given a separate line item titled "Satellite-detected large leaks."

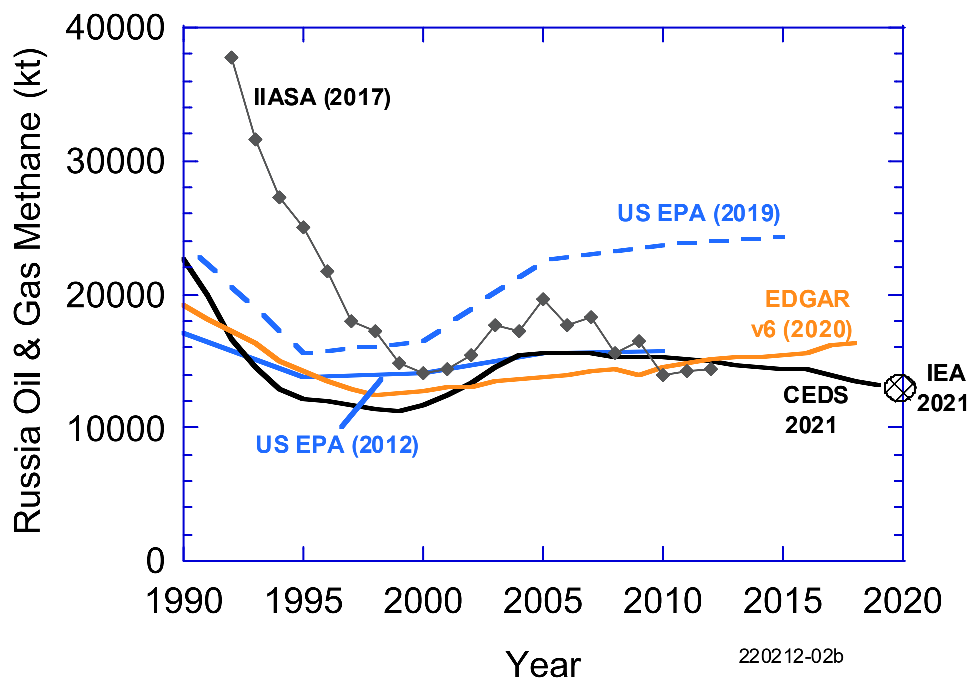


Figure 5. Diverse estimates of methane emissions from the Russian oil and gas industry. EDGAR v6 also includes coal.

The International Institute for Applied Systems Analysis (IIASA) conducted a careful study of methane emissions connected with country-specific associated gas production. It combined its findings with the

2006 IPCC default emission factors to estimate methane emissions from oil and gas production [Hoglund-Isaksson, 2017]. Whereas the associated gas calculation is country-specific and detailed, the IPCC estimates are not. The spreadsheets furnished in the Supplementary Material allow others, including the IEA, 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] that estimates emissions from fossil fuel supply, including oil, gas, and coal. Its methodology details are published elsewhere [Crippa, 2018]. In version 4.3.2, EDGAR included forty-two years of data, twenty-six aggregated emission sectors, 226 countries, and nine substances [EDGAR, 2021b]. The Community Emissions Data System for Historical Emissions (CEDS) [CEDS, 2022] methodology is also published elsewhere [Hoesly, 2018]. 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. As shown in Figure 2 and Table 1, the Russian Federation 2018 and 2019 methane emissions, reported in 2020 and 2021 respectively, were much lower than reported in previous years while U.S. emissions scarcely changed. Data from the U.S. biennial reports are shown in Figure 6. The horizontal and vertical scales in Figures 2 and 6 are the same. U.S. bottom-up inventories are much more stable than their Russian equivalents.

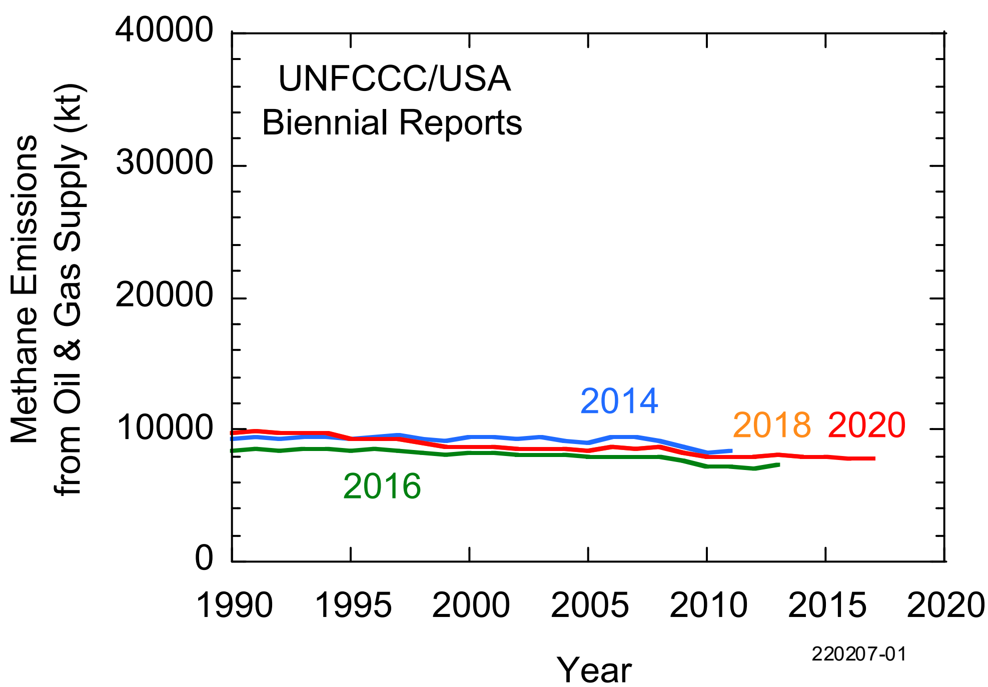


Figure 6. Methane emissions for the U.S. oil and gas industry, recomputed using updated slates of emission factors reported in 2014, 2016, 2018, and 2020. Data: [UNFCCC, 2014b; UNFCCC, 2016b; UNFCCC, 2018b; UNFCCC, 2020b].

The U.S. computations of methane emissions are also much more granular than those of the Russian Federation [EPA, 2021a, Additional Information, Methodology Annexes]. Various equipment types have been studied and assigned individual emission factors. For example, the EPA tracks the number of oil tanks with vapor recovery units, with flares, and without vapor controls, and estimates methane emissions separately for each of these classes. Approximately 250 classes of equipment are tracked, which corresponds to IPCC Tier 3. Emission factors continue to be refined and are the product of considerable, serious, ongoing effort [EPA, 2022]. The relationship between methane emissions and gas production in the United States from 1990 to 2019 has been discussed elsewhere [Kleinberg, 2021, section 2].

The emission factor-based inventory is an accounting exercise that does not require measurements of equipment operating in the field. Bottom-up inventories informed by field measurements and top-down satellite-based national estimates are systematically higher than EPA emission factor inventories [Rutherford, 2021; Shen, 2022, Figure 3 and Supplementary Information Table S1]. It is widely understood that emission factor methods systematically underestimate methane emissions due to intermittent but very large emission events associated with so-called “super emitters” [see, e.g., Zavala-Araiza, 2017; Duren, 2019; Lauvaux, 2022]. In fact, the larger and more thorough the measurement program, the larger the discrepancy between inventories and measurements [Chen, 2022]. However, in preparing their NIRs, neither the Russian Federation nor the United States incorporates field measurements of methane emissions from operating equipment, which are not required in the regulations of either country nor by the UNFCCC in connection with the submission of NIRs from Annex 1 nations. 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 from academia and non-governmental organizations. This problem is recognized in the Inflation Reduction Act of 2022, which mandates the reporting of methane emissions is based on “empirical data”. However, that term is not defined in the law [Public Law 117-169].

The United States and Russia are the two largest producers of natural gas in the world [BP, 2021], two of the largest exporters of gas [BP, 2021] and, according to International Energy Agency estimates, the two largest sources of oil- and gas-related methane emissions [IEA, 2022e]. However, their self-reported emission intensities over time have been very different. If, in the future, Russia and the United States compete to supply natural gas to importing nations that discriminate on the basis of upstream greenhouse gas emissions, the current self-reported intensity of methane emissions could give Russia a commercial advantage over the United States [Kleinberg, 2022].

2.3 Top-Down Estimates

Methane emissions can be estimated indirectly using earth-orbiting satellites capable of measuring atmospheric methane concentrations. Launched by national space agencies [see, e.g., NIES, 2022; ESA, 2022a], private companies [e.g., GHGSat, 2022], and non-governmental organizations [MethaneSAT, 2022], these satellites produce data that are in many cases made freely available for analysis 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 inherent shortcomings of data-processing algorithms.

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	2024	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 Country-Level Top-Down Surveys

The two principal satellite systems used for global and country-level top-down surveys are GOSAT (Greenhouse Gases Observing Satellite) and TROPOMI (Tropospheric Monitoring Instrument). The fundamental measurement made by satellites is the line integral of methane concentration along a path extending from a pixel on the earth to the orbiting detector. *Global* average determinations can be performed accurately. Figure 7 shows the result of eleven inversions of GOSAT data for 2017. Estimated total methane emission rates (black) are highly 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 from 0.14 to 0.20, with a mean of 0.18 and a standard deviation of 0.017.

Country-level emissions estimates are far more uncertain than global estimates, and particular economic segments, such as the fossil fuel industry, can be poorly determined, even for a large country such as Russia. This point is illustrated by Figure 8, which is sourced from the same data sets, analysts, and algorithms as Figure 7. Here, the fraction of methane attributed to fossil fuel emissions ranges from 0.21 to 0.51, with a mean of 0.39 and a standard deviation of 0.11.

At least some of the scatter of satellite-based determinations is due to the inescapable limitations of the data and processing. Satellite data do not distinguish between natural and anthropogenic sources, nor between fossil fuel and 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 outcomes, or posteriors [Saunois, 2016, sec. 4.2.1]. As Saunois et al. observe, “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.”

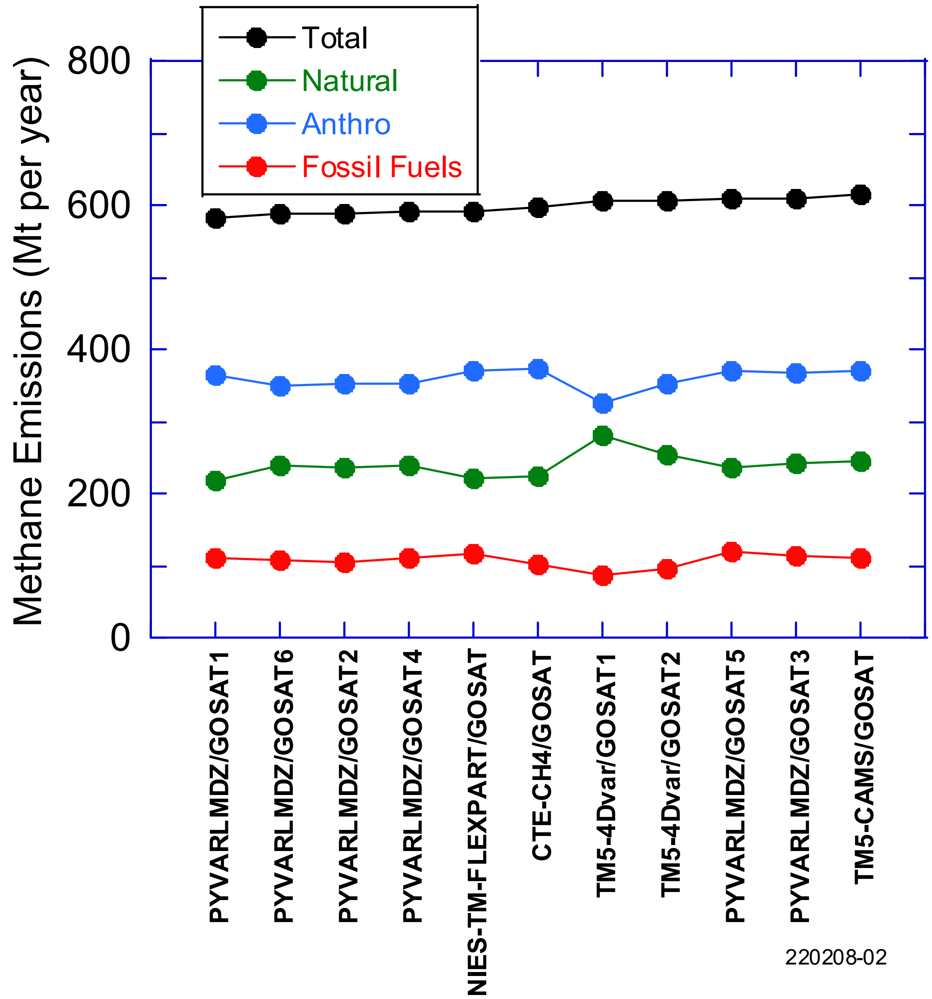


Figure 7. Global methane emissions in 2017 determined by inversions of GOSAT satellite data performed by various analysts. The inversions are named on the horizontal axis. The inversions are ordered according to the estimated total emission rate (black). Estimates of natural emissions are shown in green, anthropogenic emissions in blue, and fossil fuel emissions (a subset of anthropogenic emissions) in red. Data: [Saunois, 2020b].

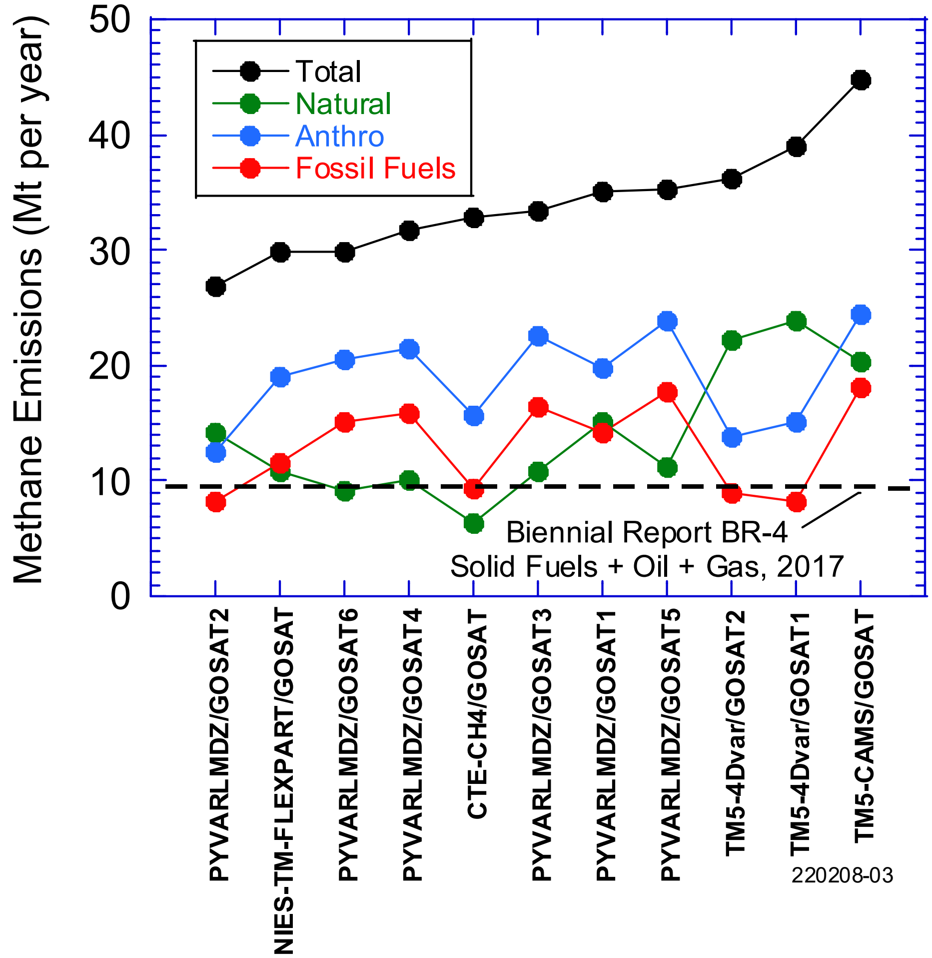


Figure 8. Russian methane emissions in 2017 determined by inversions of GOSAT satellite data performed by various analysts. The inversions are named on the horizontal axis. The inversions are ordered according to the estimated total emission rate (black). Estimates of natural emissions are shown in green, 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].

The dependence of top-down-estimated emission rates (posteriors) on initializing bottom-up inventories (priors) is illustrated in Figure 9 for the 2017 GOSAT data set. In this example, the total 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, total emissions 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 strong: the ratio of posteriors to their respective priors is 1.01 ± 0.12. At least some of the scatter in the natural, anthropogenic, and fossil fuel estimates in Figure 8 is likely due to scatter in the priors chosen to initialize the inversions.

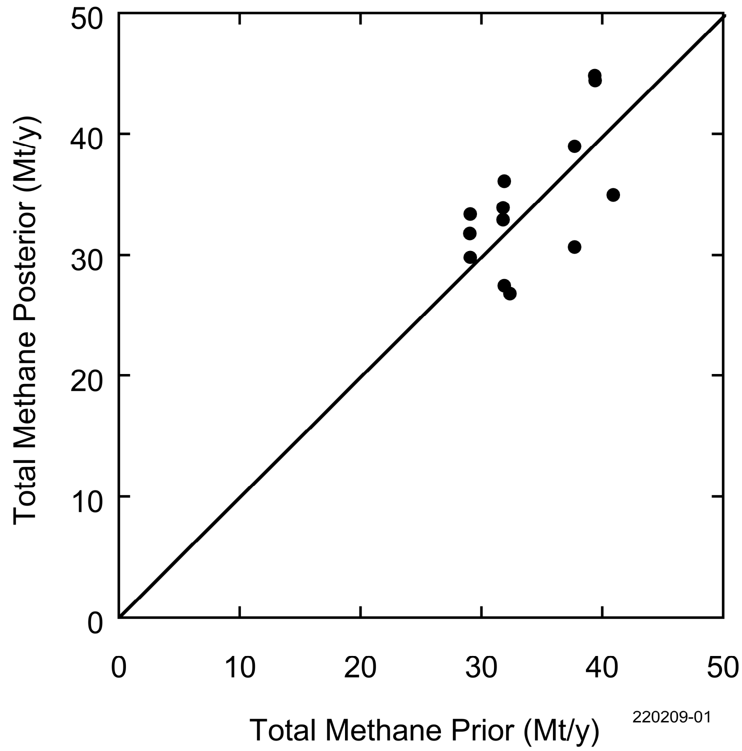


Figure 9. Relationship between prior initializations and posterior results of thirteen Bayesian inversions of GOSAT top-down data for total methane emissions in Russia during 2017. The correlation suggests that variations in top-down emission estimates are driven in part by the inventory data used as priors. Data: [Saunois, 2020b].

Methane-detecting satellites perform well in arid regions where skies are clear and ground surfaces are homogenous and not mountainous [Shen, 2022]. These conditions are found in many of the countries of North Africa and the Middle East, Australia, and the southwest United States. However, data collection is hindered by the presence of clouds, wetlands, and open water. This makes Amazonia, Equatorial Africa, and Southeast Asia difficult regions for data collection. Wet snow and limited and low angle daylight are important limitations at high latitudes, affecting satellite performance in Alaska, Canada, and large portions of the Volga-Ural, Timan-Pechora, and Western Siberia Sedimentary Basins, which are Russia's prime oil- and gas-producing regions [Jacob, 2022; Shen, 2022, Supplementary Information, Figure S15.; EIA, 2014].

In consequence, over much of Russia, the GOSAT satellite collects an average of only a few data points per month in each 2.5° by 2.5° (37-103 km by 278 km) grid cell [Stavert, 2022]. TROPOMI collects much more data than GOSAT, but at its present state of development it is more susceptible to error in the presence of wetlands [Qu, 2021], which are common in some Russian oil and gas provinces. These circumstances 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

While GOSAT is useful for top-down measurements in some environments [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]. These plumes account for 6 percent of oil and gas emissions in the countries where they were detected [IEA, 2022c]. Unlike top-down regional emission estimates, 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, approximately one-eighth of which is attributable to Russia [Lauvaux, 2022]. Much of this activity appears to be coincident with major pipeline routes extending southwest from the arctic.

The sum of satellite-estimated plumes can be compared to the Russian Federation's declaration 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, equaling 810 billion cubic meters. This is greater than total Russian gas production (680 billion cubic meters). The pipeline activity factor could be greater than production because the pipeline emission factor does not account for distance. It is possible that gas is being counted multiple times if it travels through two or more pipelines. The emission factor for mainline pipe transport is 1.84×10^{-3} million tons per billion cubic meters. Therefore, the NIR estimate of methane loss is 1.5 million tons. Mainline pipe transport 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 by 25 meters in a 10 by 15 kilometer field of view [McKeever, 2021].

Unlike GOSAT and TROPOMI, the GHGSat platforms do not scan the entire earth. Rather, they 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 with acquiring high resolution images useful for remediation [ESA, 2021].

As shown in Table 3, MethaneSAT, which will be launched by the Environmental Defense Fund in 2024, has capabilities intermediate between TROPOMI and GHGSat [Hamburg, 2020]. One advantage of this platform is that it will be able to collect methane data over Russia more frequently than GOSAT or TROPOMI [Benmergui, 2020].

3. Methane Emission Reduction

Reducing methane emissions from the oil and gas industry is not necessarily a difficult problem to solve, though solutions may need to be customized to address location-specific conditions. Engineering solutions exist that often can be implemented at a low cost relative to other operating company expenses and revenues. While abatement cost curves such as those published by the IEA [IEA, 2022a] cannot be taken too literally, their overarching message is valid. The main barrier to methane reduction is finding the sources of emission, which are varied, often intermittent, and sometimes unexpected [NASEM, 2018, Figure 4.1 and accompanying discussions]. Once found, sources can be addressed through measures as simple as 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, coal mine mitigation can be difficult because gas in active mines is deliberately diluted and dispersed for safety reasons. Recovering the methane is therefore technically and economically challenging. An additional challenge is emissions from abandoned mines, which have received little attention until recently [Kholod, 2020].

In discussing methods for reducing methane emissions, we use U.S. experience as a benchmark for several reasons. First, the official self-reports of the United States to the UNFCCC are extraordinarily detailed and transparent. Second, the modern art and science of methane emission characterization is dominated by U.S. technology and service providers {Kleinberg, 2022]. Third, U.S. technology has been used to supplement official data compiled by U.S. government agencies with extraordinary measurement campaigns conducted by academic groups, nongovernmental organizations, and the private sector. There have been few or no similar campaigns conducted in the Russian Federation. Third, there is abundant English-language literature, including numerous compendia of guides to engineering practice as examples of methane emission-control practices. Fourth, both countries have continent-spanning petroleum industries operating in desert, arctic, and marine environments. Similarities of upstream and midstream practices are discussed below in reference to Figure 10.

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, whose official methane emissions data are held in low regard due to reliance on inventories untethered from field measurements [Alvarez, 2018; Rutherford 2021] and whose environmental regulations based on them have been largely ineffective [Kleinberg, 2021]. Data from the United States at least have the virtue of being meticulously curated, however, displaying a high degree of consistency from year to year within an extraordinarily transparent reporting system [EPA, 2021a; EPA, 2022]. This has not been true of data from the Russian Federation, the reporting systems of which have been criticized in the Russian language literature [Gritsevich, 2009; Sorokin, 2019].

The main problem with emission inventories as commonly implemented is their inaccuracy. Using emission factors based on the average behavior of components and equipment types (as in U.S. practice) or based on throughput (as in IPCC and Russian practices) ignores the “heavily skewed distribution of site-based CH_4 emissions” [Zavala-Araiza, 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. Properly characterizing these skewed distributions has proved challenging. A study involving 98,000 well site visits found that measured distributions depended on the number of visits: the mean emission rate increased as the number of visits increased [Chen, 2022]. 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, 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 emissions, but under favorable conditions average site emission rates decrease with repeated inspections [Ravikumar, 2020].

Conventional ground-based leak detection and repair (LDAR) (discussed at greater length in section 3.2.1) is not the solution to this problem. Measurements at oil and gas production sites show that LDAR, as commonly implemented with handheld instruments, successfully finds small emission sources but systematically misses the largest ones, which are detected by aircraft [Tyner, 2021].

Devising a complete solution to the problem of locating methane emissions from the oil and gas industry will be difficult at the very least, and may not be technically or economically feasible. However, partial solutions that can be implemented quickly may prove more effective in mitigating climate change than comprehensive solutions that are 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 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 between 2019 and 2021. Site-level emissions were measured by various means, principally aircraft, in west Texas and southeast New Mexico, and emission sources were matched with operating companies. The fall 2019 campaign detected 3,067 plumes originating from 1,756 unique sources [Cusworth, 2021; EDF, 2022].

It is likely that many of the emissions seen in these surveys, even the largest ones, are unregulated under present EPA rules. With this newly available information in hand, regulators can decide whether regulations should be changed to limit the largest discharges.

Large-scale surveys of oil- and gas-producing regions make economic sense. It is estimated that 2.7 million tons (4 billion cubic meters equals 140 billion cubic feet) of methane were lost in one year from the Permian Basin [Zhang, 2020], worth about $420 million at Henry Hub. Aerial surveys cost about $100 per well site [Kemp, 2021, Table 1] so tens of thousands of well sites can be surveyed for a few million dollars – the cost of drilling and hydraulically fracturing a single well. 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 EPA deems only two methods legally acceptable for volatile organic compound and methane leak detection, both of which involve ground-based hand-held devices: optical gas imaging and a sniffer device ("Method 21") [40 CFR 60.5397a(c)(2)]. Neither is capable of quantitative measurements. However, the 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 [Alden, 2020; Alden, 2022]. There are several promising approaches to implementing continuous surveillance of oil and gas infrastructure, including the use of networks of stationary point gas sensors, scanning infrared cameras ("continuous optical gas imaging"), and laser-based scanning open-path atmospheric concentration measurements. These approaches share common advantages that make them attractive prospects for methane emission control [LongPath, 2022]. Though currently at various stages of maturity, they appear to be developing rapidly with the encouragement of private and government investment.

3.2 Methods to Reduce Oil and Gas Methane Emissions

There is no one solution to the problem of methane emissions. For numerous reasons, a wide variety of equipment types can emit methane. Some of these emissions are simple to address: a malfunctioning part can be repaired or replaced. Others are more difficult. The earth is not a factory with a well-controlled environment, on-site human supervision, and predictable inputs and processes. Oilfield equipment must operate faultlessly in arctic, desert, tropical, and marine environments, in remote, unmanned locations. Devices must be fully reliable in the presence of high-pressure explosive, corrosive, and toxic liquids and vapors. Changes in source pressure or ambient temperature can result in tank overpressures, and it is vitally important that separators and storage vessels never exceed their pressure ratings. Therefore, gas must occasionally be vented. This gas can sometimes be collected by a vapor-recovery unit and routed to a sales line or a flare for combustion. While the latter process produces carbon dioxide, this is less damaging than allowing methane into the atmosphere, as shown below. These solutions do not always work. But problems must be solved in the context of an industry that operates at almost unimaginable scale, producing 1,000 barrels of oil per second, 30 million seconds per year.

The far-flung oil and gas industry of the Russian Federation faces all these challenges. Given the diversity of problems faced by petroleum engineers, and the diversity of environments in which these problems must be solved, it is beyond the scope of this report to catalogue all the methods of remedying them. Only a high-level overview is presented. Fugitive and vented sources are distinguished, and within those broad categories some pointers to remedies are provided, see, e.g., Table 6, which references multiple compendia of engineering solutions. A principal message of this report is that it is impossible for regulators to anticipate every problem that can develop and every solution that might be implemented. Oilfield problems are best solved in the oilfield. Therefore, this report strongly recommends performance-based regulations, under which regulated entities are responsible for reducing the amount of methane entering the atmosphere, not simply satisfying prescriptions that may prove inefficient or ineffective in the real world.

The IEA publishes methane-abatement data for every oil- and gas-producing nation in the world [IEA, 2022a; IEA, 2022d]. Possible abatements are divided into twelve categories (flares, vapor recovery units, etc.), which are in turn divided into subcategories (onshore gas, offshore oil, etc.). Comparing potential Russian and U.S. abatements, the fractional contribution of each subcategory was computed and summed to find the fractional contribution of each category. The results are shown in Figure 10. In both countries, 40 percent of possible abatements are due to replacement of natural gas-driven pneumatic devices, which emit natural gas as a normal aspect of their operation. The second-largest category is LDAR. Downstream LDAR is relatively less important in Russia because Russia consumes less of its gas locally than does the United States. These results suggest that abatement measures that have been considered for the United States may be relevant for Russia, at least in part.

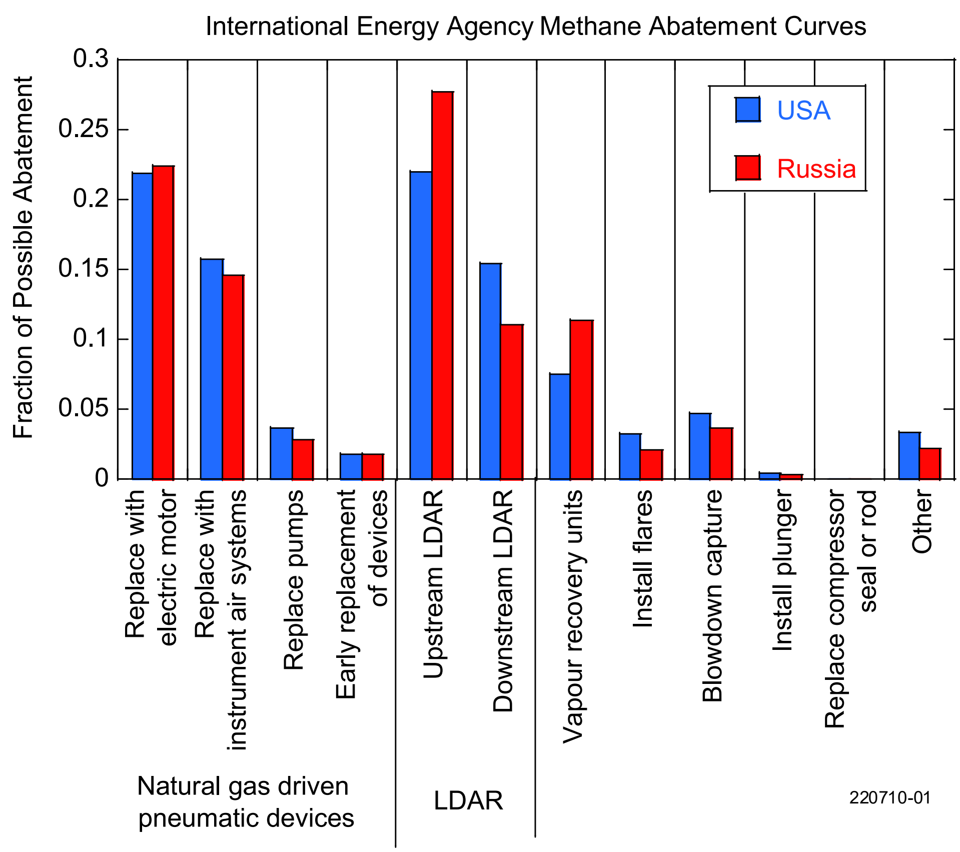


Figure 10. Comparison of IEA methane abatement potentials for the United States (blue) and the Russian Federation (red). Data: [IEA 2022a].

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 and gas transport, are routine and expected (though not necessarily scheduled) aspects of normal operation, and are either subject to engineering controls or simply allowed.

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. By contrast, remote sensing from aircraft or satellites cannot distinguish between leaks and vents. Methane is a powerful climate pollutant, whether it originates from leaks or vents. Therefore regulations should be changed to limit both types of sources.

3.2.1 Fugitive Emissions

LDAR looms large in both regulated and technology communities. For the oil and gas industry, it is an ongoing and potentially costly commitment. For technology developers, it is a technically interesting challenge. In reality, though, LDAR represents a small fraction of the methane emission problem.

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
For comparison: 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: For comparison, reported vented, fugitive, and flared methane emissions from petroleum and natural gas systems, 2019 [EPA, 2021a].

The costs and benefits of leak detection and repair were studied by the EPA 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 2020 by 169,646 tons at an approximate nationwide cost of $227 million. The cost per metric ton of methane avoided is $1,340. The social cost of methane cited in the 2016 Regulatory Impact Analysis for 2020 at a discount rate of 3 percent is $1,300 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 percent 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.

3.2.2 Vents

In the oil and gas industry, methane emissions from 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 emissions from 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. All web sites accessed May 2022.

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 it 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 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, both high-bleed and low-bleed (< 6 scf/h) valves are replaced by unregulated, intermittently discharging pneumatic valves [Kleinberg, 2021]. 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 the EPA [EPA, 2021a]. A study of several such regulatory failures concluded that to be effective, engineering controls and performance-based regulations must include measurement requirements [Kleinberg, 2021].

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]. One 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 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. It may not be obvious, therefore, why gas should be burned off – and thereby wasted – routinely. The fundamental problem is that 20 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 also 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]. When gas is not needed for reinjection or local fuel use, it is sometimes regarded as a nuisance to oil producers and is 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, pp. 7-9].

The World Bank Zero Routine Flaring by 2030 initiative has attracted the endorsement of 34 governments, 51 oil companies, 15 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 Russia had established a goal of limiting associated gas flaring to 5 percent 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 [Rystad, 2021].

If flares burn with 100 percent efficiency, the primary products of combustion are water vapor and carbon dioxide. The latter is an undesirable greenhouse gas. However, measured combustion efficiencies are less than 100 percent, leading to even more undesirable outcomes. In 1996, the EPA estimated a typical flaring efficiency in the production segment of the natural gas industry to be 98 percent [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 percent 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 11. Unlit flares lead to even worse outcomes, as shown in Figure 12.

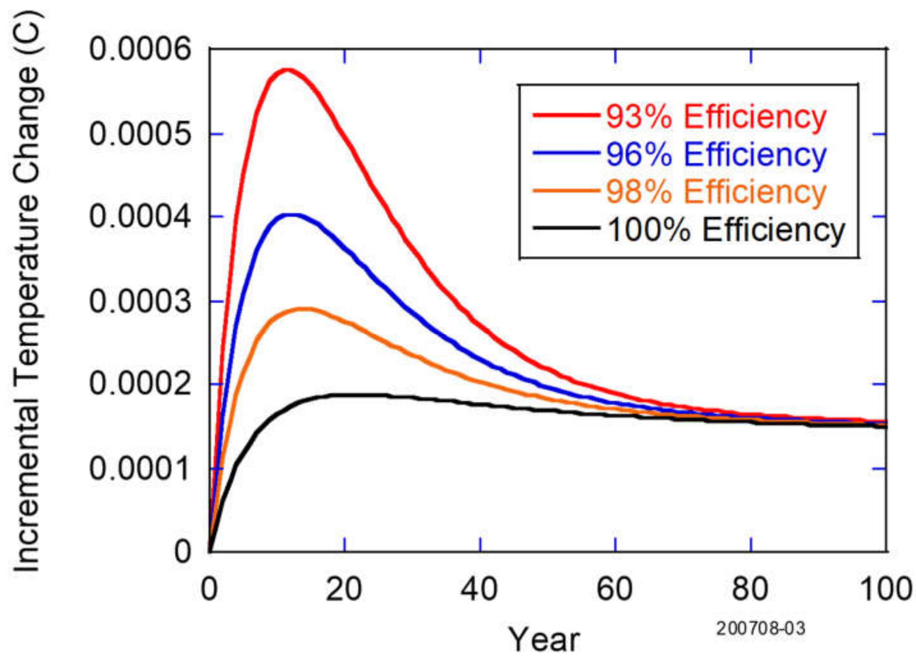


Figure 11. Effect of flare inefficiency. Temperature change is a result of one year of flaring 100 percent methane at the global rate of natural gas flaring, 146 billion cubic meters per year, with various levels of efficiency [Kleinberg, 2020].

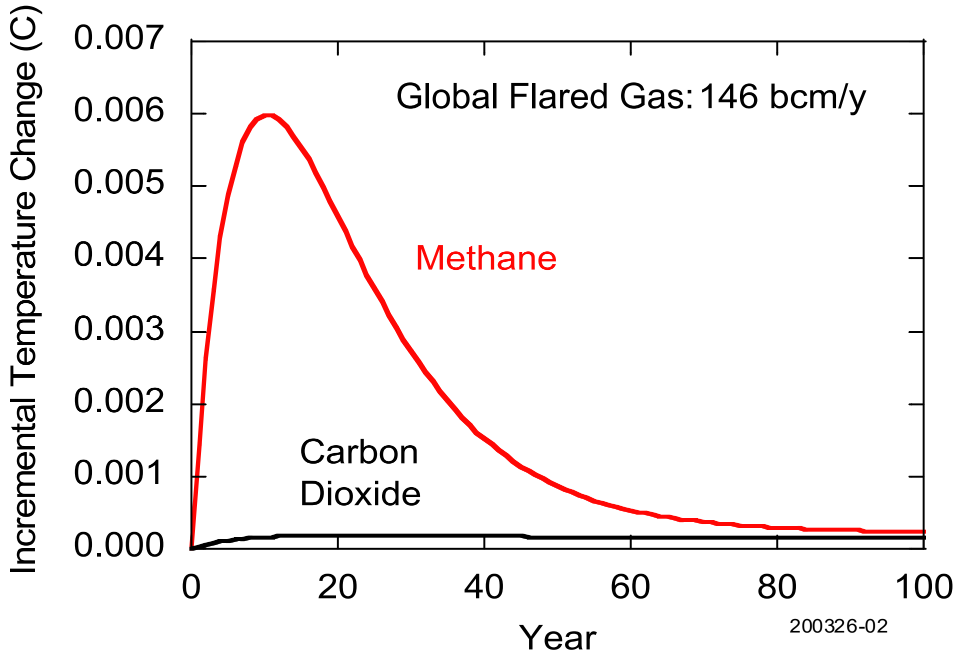


Figure 12. Effect of venting 146 billion cubic meters of 100 percent methane at year zero (red), versus flaring it at 100 percent efficiency to carbon dioxide (black). [Kleinberg, 2020]. Note the vertical axis differs from Figure 11.

Unfortunately, low efficiency and unlit flares are common. Aerial surveys of the Permian Basin have found that more than five percent of active flares are malfunctioning and an additional five percent are unlit. This demonstrates that EPA estimates of methane emissions from flares in the basin are seriously in error [EDF, 2022].

Flares may be highly visible nuisances, but poorly constructed regulations 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. Prior to 2020, coal mine methane could be considered a small part of Russian 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. Moreover, a recent discovery of unexpected, gigantic methane emissions from a Russian open-pit coal mine [BBC, 2022] suggests that emissions from surface mines may be a far greater problem than estimated.

According to official estimates, the origin of coal mine methane emissions has shifted over the last three decades. 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 [UNECE, 2019, Figure 3.3; 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 percent 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 percent) during the mining process, or extraction of concentrated methane prior to mining [UNECE, 2021].

Globally, dilute methane, or ventilation air methane (VAM), accounts for 60-80 percent of methane emissions from active underground mines [UNECE, 2021, page 11]. 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]. There is also increasing interest in methane emissions from abandoned mines [UNECE, 2019].

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 oilfield standard conditions (15°C, 101.325 kPa) is 678.37 grams per standard cubic meter [Kleinberg, 2019], which is equivalent to 70,000-140,000 tons of methane per year. Methane concentrations are as high as 80 percent. 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 percent [Tailakov, 2017].

On the other hand, less than 4 percent of liberated methane is recovered or flared during and after underground coal mining operations, and none is recovered or flared during and after surface mining [UNFCCC, 2022a, Table 10s3].

4. Methane Control Policy

Because methane is a valuable commodity in commerce, claims are sometimes made that the methane emission problem can largely be solved by market forces. This appears not always to be the case. IEA data show that 18% of current total U.S. oil and gas-related methane emissions are profitable to repair [IEA, 2022a], suggesting that U.S. owners and operators have been reasonably diligent in reducing methane emissions where there has been a clear profit motive to do so. By contrast, 44% of current total Russian emissions are profitable to repair [IEA, 2022a], about equal to the global average, suggesting a lack of awareness of or concern for this problem.

Devising a methane-control policy for the Russian Federation is beyond the scope of this report. However, the successes and failures of regulating the oil and gas industry in the United States may provide some insights for this industry in Russia. The focus here is on two regulatory styles, prescriptive and performance based. Each has advantages and disadvantages in the context of the industry as described in the first paragraph of section 3.2. The characteristics of prescriptive and performance-based regulations for methane emission control are outlined in Table 7.

4.1 Prescriptive Regulation

Prescriptive regulations direct regulated entities to take specific actions. For example, in the United States the Standards of Performance for Crude Oil and Natural Gas Facilities [40 CFR 60 Subpart OOOOa] is pointlessly prescriptive in its leak detection and repair mandates, even to the extent of specifying the meter resolution and probe diameter of Method 21 instruments [40 CFR 60 Appendix A-7]. If prescriptive regulations could be perfectly designed, mandated actions would produce the desired environmental benefit, but in the real world, regulated entities can comply with all mandates without delivering the desired environmental outcome.

Prescriptive Regulation	Performance-Based Regulation
Focus on Components	Focus on Facilities or Companies
Separate Rules for Leaks, Vents, Flares	Unified Target for all Emissions
Regulators Write Rules	Facility Engineers Figure Out How to Hit Target
Measurements Not Required	Accurate Measurements Essential
Compliance Unverified (Honor System)	Compliance Verified by Validated Third-Party Measurements
Suppliers Rated Pass/Fail	Suppliers Rated Quantitatively

Table 7. Characteristics of prescriptive and performance-based regulations.

Prescriptive regulations are generally well tolerated by risk-averse regulated entities because they lay out clear, unvarying mandates that can often be reduced to checklists. The owner or operator and its employees need to show no initiative to avoid sanctions. The oil and gas industry places a premium on compliance with rules of all kinds, many of which are essential for safe operations in what can be hazardous conditions. Thus, prescriptive regulations blend well with the corporate cultures of oil and gas companies.

Another common aspect of oilfield corporate culture is the drive to reduce costs. Universally, asset managers are evaluated on their ability to deliver profits to their organizations. A dutiful facility engineer or technician will comply with the letter of relevant regulations at the lowest possible cost.

An example of how prescriptive regulations can lead to unintended outcomes was discussed in connection with pneumatic controllers, see Section 3.2.2. Pneumatic controllers alone account for about a quarter of methane emissions from all natural gas and petroleum systems in the United States, according to EPA estimates. High-bleed pneumatic controllers, which vent natural gas continuously in normal operation, were banned from all facilities constructed or modified after October 15, 2013. Well before that, industry had already been swapping them out. High-bleed controllers were replaced mainly by intermittently discharging controllers, which emit gas only when actuated. According to recent EPA estimates, the average intermittently discharging controller emits less gas than the average high bleed controller, but a factor of ten more than the average low-bleed controller [EPA, 2021a Additional Information, Methodology Annexes]. However, since intermittent-bleed controllers are unregulated, this has been largely ignored by industry.

If EPA regulations command retirement of high-bleed pneumatic controllers, those controllers will be replaced with the most economical alternative that complies with the regulation, without regard to its impact on total methane emissions – an example of the common observation that asset managers and facility engineers will comply with the letter of the law in ways that minimize capital and operational expenses.

4.2 Performance-Based Regulation

Performance-based regulations mandate the outcome, encouraging regulated entities to innovate to find efficient solutions that regulators may not have anticipated. To be effective, a performance-based regulation should include a measurement requirement. An example of an incomplete implementation of a performance-based regulation is the basic requirement for controlling volatile organic compound (VOC) emissions from storage vessel affected facilities. The EPA directs owners or operators to determine the potential for VOC emissions and reduce VOC emissions from that level by 95 percent [40 CFR 60.5395a(a)(1)-(2)]. Performance-based regulations can fail, as they have in the case of oilfield storage vessels, when they lack a mechanism to verify compliance quantitatively [Kleinberg, 2021].

The broader society has no interest in the kinds of valves used in the oilfield but is very concerned with how much methane is being emitted by the oil and gas industry. Effective regulation aligns the interests of asset managers and facility engineers with broad societal interests.

It makes no sense that current EPA regulations command finding methane leaks as small as thirty grams per hour but ignore unlit flares that can emit three tons per hour. Petroleum engineers are adept at solving technical problems, given incentives to do so. Oilfield problems are diverse and highly technical. Local engineers are far more capable of finding and fixing the most important problems at their sites than are rule makers working in national capitals. Performance-based regulation, when implemented correctly, engages the ingenuity of engineers working on what they know best. If penalties or rewards are meted out to owners and operators based on environmental performance, their environmental performance will improve.

When the 2012 OOOO and 2016 OOOOa rules were being written, emissions estimates were based on emission factor methodology and were limited to infrastructure and emission mechanisms commonly thought to be the main sources of vented and fugitive gas. The EPA had approved only two methods for detecting natural gas leaks in the field, neither of which was capable of quantitative emission rate measurements. Absent the ability to verify emissions quantitatively it was logical to adopt prescriptive regulations or performance-based regulations lacking a verification component. With the advent of numerous competing remote sensing methods for the quantitative determination of methane emissions, at facility scale and with sensitivities of around 10 kilograms of methane per hour, measurement-verified performance-based regulation is now a realistic option.

Performance-based regulation relies on quantitative measurements to verify compliance. Judging operator performance based on current emission factor methods would render performance-based regulation essentially worthless. In the oilfield, emission data is most efficiently and comprehensively obtained by remote sensing, using means such as aircraft, drones, ground-based mobile sensors, permanent monitors, and satellites.

Some of these platforms are incapable of providing component-level information or distinguishing vented from fugitive methane. However, fugitive methane and vented methane have identical effects on the environment. Measurement-reporting-verification protocols are most appropriately directed not at components and assemblies but at sites and facilities as well as their owners and operators. Such measurements are already being performed at tens of thousands of sites [Chen, 2022], and company-specific performance data are already being compiled [Berman, 2020].

4.3 Adaptive Regulation

The absence of field measurements in the NIRs of both the Russian Federation and the United States exemplifies a common problem: the mismatch between the slow evolution of regulations and the rapid evolution of technologies that could make those regulations more efficient and effective. In fact, remote sensing measurements of methane emissions are improving rapidly. As improved methods are certified by environmental regulators, standards for suppression of methane emissions could be strengthened. A theory of adaptive regulation has been designed to address this situation [Bennear, 2019]. However, such tools are not commonly used in developing international agreements such as those of the UNFCCC.

5. Conclusions

It is a time-worn adage that "you cannot manage what you cannot measure," and methane emission measurements in Russia and other countries have been essentially nonexistent. Comprehensive, accurate measurements are a necessary first step in mitigating methane emissions. Inventory methods provide an incomplete and inaccurate view of the extent of the problem and provide misleading indications as to how to solve it.

The UNFCCC annual and biennial reports of the Russian Federation dramatically illustrate the instability of inventories. The self-reported methane emissions from the Russian oil and gas industry declined by a remarkable 89 percent from 2013 to 2019, with the result that the declared methane intensity of the Russian Federation is now less than that of the United States. If left unchallenged, this could affect the behavior of importing countries sensitive to the upstream greenhouse gas emissions of their supplier countries. However, due to improvements in technology, the industry can now 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. Although they work in very challenging conditions, petroleum engineers can help reduce the cost of keeping gas in the pipe, given appropriate incentives in the context of performance-based regulations.

A quantitative comparison of IEA methane abatement cost curves, Figure 10, suggests that the United States and the Russian Federation face similar challenges in reducing their methane emissions. Therefore, numerous compendia of guides to engineering practice, Table 6, are likely to be relevant methane emission-control practices. However, as pointed out in the introduction to section 3.2, the conditions in which the fossil fuel industries operate are extraordinarily diverse, making it impossible to rely on rigidly prescriptive solutions to solve methane problems. If the United States, Russia, and other countries are to cut their methane emissions, facility engineers will need to adapt solutions to local conditions, guided and incentivized by performance-based regulation with verified compliance.

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. Sometimes, when an emitter is found, it is cheap and easy to fix, whether by replacing a part, freeing a stuck vent, or tightening the bolts on a flange. In other cases, engineering solutions are required, and these depend on circumstantial details. The coal industry is more concentrated, and it is usually obvious where the methane is coming from. However, remediation is inherently challenging.

The Russian Federation is second only to the United States in its production of petroleum liquids and natural gas, and is also a major producer of coal. While the Russian oil and gas industry does not lack technical expertise, the claim of “more stringent quality standards for process operation control” requires validation. Along with the United States and other major producers, the Russian Federation must be a leader in methane emission measurement and control if the goal of methane emission reduction is to be achieved.

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

C.B. Alden, 2022. Testimony to the U.S. House of Representatives Select Committee on the Climate Crisis, 24 June 2022.
https://climatecrisis.house.gov/committee-activity/hearings/cutting-methane-pollution-safeguarding-health-creating-jobs-and-0
https://docs.house.gov/meetings/CN/CN00/20220624/114942/HHRG-117-CN00-Wstate-AldenC-20220624.pdf

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., 2012. Greater focus needed on methane leakage from natural gas infrastructure, Proceedings of the National Academy of Sciences, 109, 6435-6440
https://doi.org/10.1073/pnas.1202407109

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

BBC, 2022. Huge methane emission from Russian coal mine, British Broadcasting Corporation, 16 June 2022.
https://www.bbc.com/news/science-environment-61811481

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

L.S. Bennear, J.B. Wiener, 2019. Adaptive Regulation: Instrument Choice for Policy Learning over Time, preprint, 12 February 2019.
https://www.hks.harvard.edu/sites/default/files/centers/mrcbg/files/Regulation%20-%20adaptive%20reg%20-%20Bennear%20Wiener%20on%20Adaptive%20Reg%20Instrum%20Choice%202019%2002%2012%20clean.pdf

E. Berman, S. Deiker, 2020. Source-attributable, quantitative results from a basin-wide survey of New Mexico Permian methane emissions, Presentation #280, MIT A+B Applied Energy Symposium, 13-14 August 2020
https://www.youtube.com/watch?v=ySDjZdHMYBA

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

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

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, accessed 14 February 2022.
http://www.globalchange.umd.edu/ceds/

Y. Chen, et al., 2022. Quantifying Regional Methane Emissions in the New Mexico Permian Basin with a Comprehensive Aerial Survey, Environmental Science and Technology, 56, 4317–4323
https://doi.org/10.1021/acs.est.1c06458

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., 2022. Comparing national greenhouse gas budgets reported in UNFCCC inventories against atmospheric inversions, Earth Systems Science Data, 14, 1639–1675
https://doi.org/10.5194/essd-14-1639-2022

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, 2022. Permian Methane Analysis Project, Environmental Defense Fund, accessed 13 February 2022
https://permianmap.org/
Methodology for EDF's Permian Methane Analysis Project (PermianMAP), Data Collection and Analysis, 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, accessed 11 February 2022
https://edgar.jrc.ec.europa.eu/dataset_ghg60

EIA, 2014. Russia looks beyond West Siberia for future oil and natural gas growth. U.S. Energy Information Administration, Today in Energy, 19 September 2014
https://www.eia.gov/todayinenergy/detail.php?id=18051

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

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

Enerdata, 2022. Coal and lignite production, World Energy & Climate Statistics Yearbook 2022.
https://yearbook.enerdata.net/coal-lignite/coal-production-data.html

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

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

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.
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, 2022. Stakeholder Process for Natural Gas and Petroleum Systems in the 1990-2020 Inventory, U.S. Environmental Protection Agency. 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, accessed 7 February 2022.
http://www.tropomi.eu/

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

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

I.G. Gritsevich, E.A. Kutepova, 2009. Methane Accounting and Reporting Regulation for Oil and Gas Companies in Russia and New Greenhouse Gas Accounting Rules in the USA. Moscow: WWF Russia, October 2009 (in Russian)
https://wwf.ru/resources/publications/booklets/regulirovanie-ucheta-i-otchetnosti-po-vybrosam-metana-dlya-neftegazovykh-kompaniy-v-rossii-i-novye-p/

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

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

IEA, 2022c. Global Methane Tracker 2022: Estimating methane emissions, International Energy Agency, accessed 10 July 2022
https://www.iea.org/reports/global-methane-tracker-2022/estimating-methane-emissions

IEA, 2022d. Global Methane Tracker: Documentation, 2022 Version, International Energy Agency, 23 February 2022
https://iea.blob.core.windows.net/assets/b5f6bb13-76ce-48ea-8fdb-3d4f8b58c838/GlobalMethaneTracker_documentation.pdf

IEA, 2022e. Global Methane Tracker 2022: Overview, accessed 23 October 2022
https://www.iea.org/reports/global-methane-tracker-2022/overview

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

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/

IPCC, 2021. Climate Change 2021, The Physical Science Basis, Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Annex VII – Glossary
https://www.ipcc.ch/report/ar6/wg1/

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, 22, 9617-9646.
https://doi.org/10.5194/acp-22-9617-2022

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/

C.E. Kemp, A.P. Ravikumar, 2021. New Technologies Can Cost Effectively Reduce Oil and Gas Methane Emissions, but Policies Will Require Careful Design to Establish Mitigation Equivalence, Environmental Science and Technology, 55, 9140–9149
https://doi.org/10.1021/acs.est.1c03071

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

R.L. Kleinberg, 2022. Testimony to the U.S. House of Representatives Select Committee on the Climate Crisis, 24 June 2022.
https://climatecrisis.house.gov/committee-activity/hearings/cutting-methane-pollution-safeguarding-health-creating-jobs-and-0
https://docs.house.gov/meetings/CN/CN00/20220624/114942/HHRG-117-CN00-Wstate-KleinbergR-20220624.pdf

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

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, 2022a. 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

New York Times, 2022b. One Site, 95 Tons of Methane an Hour, 14 June 2022.
https://www.nytimes.com/2022/06/14/climate/methane-emissions-russia-coal-mine.html

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

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/article/10.1088/1748-9326/10/11/114024
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

L. Shen, et al., 2022. Satellite quantification of oil and natural gas methane emissions in the U.S. and Canada including contributions from individual basins, Atmospheric Chemistry and Physics, 22, 11203–11215.
https://doi.org/10.5194/acp-22-11203-2022

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

N.D. Sorokin, 2019. Correctness of information on the mass of emissions of pollutants, Ecology in Production, September 2019, 52-57 (in Russian)

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

D.R. Tyner, M.R. Johnson, 2021. Where the Methane Is — Insights from Novel Airborne LiDAR Measurements Combined with Ground Survey Data. Environmental Science and Technology, 55, 9773–9783.
https://pubs.acs.org/doi/10.1021/acs.est.1c01572

UNECE, 2019. Best Practice Guidance for Effective Methane Recovery and Use from Abandoned Coal Mines, Nations Economic Commission for Europe
https://unece.org/sustainable-energy/publications/best-practice-guidance-effective-methane-recovery-and-use-0

UNECE, 2021. Best Practice Guidance for Effective Management of Coal Mine Methane at National Level, United Nations Economic Commission for Europe
https://unece.org/sustainable-energy/publications/best-practice-guidance-effective-management-coal-mine-methane

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, 2019a. Russian Federation, 2019 National Inventory Report (NIR), Volume 1, Section 3.3.3.2 (in Russian)
https://unfccc.int/documents/194838

UNFCCC, 2019b. 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; 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

UNFCCC, 2022a. Russian Federation. 2022 Common Reporting Format (CRF) Table https://unfccc.int/documents/461969

UNFCCC, 2022b. United States of America. 2022 Common Reporting Format (CRF) Table https://unfccc.int/documents/461947

UNFCCC, 2022c. National Inventory Submissions 2003-2022; 2022 Annex I Party GHG Inventory Submissions, United Nations Framework Convention on Climate Change https://unfccc.int/ghg-inventories-annex-i-parties/2022

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, accessed 18 February 2022 https://www.worldbank.org/en/programs/zero-routine-flaring-by-2030/qna#2

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

D. Wunch, et al., 2011. The Total Carbon Column Observing Network, Philosophical Transactions of the Royal Society A, 369, 2087–2112, accessed 6 February 2022
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

Zavala-Araiza, D., et al, 2017. Super-emitters in natural gas infrastructure are caused by abnormal process conditions, Nature Communications, 8:14012.
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