

Methane Emissions from the Fossil Fuel Industries of the Russian Federation

Version 2.0 — 22 July 2022

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

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Abstract

Methane emissions are second only to carbon dioxide emissions as a major driver of human-induced climate change. Moreover, reduction of the rate of methane emissions is the fastest and least disruptive way to moderate global temperature rise over the next several decades. The production of fossil fuels - principally coal, oil, and natural gas - is an important source of anthropogenic methane. As one of the world's most important producers of fossil fuels, and one of the most important emitters of fossil fuel methane, the Russian Federation should play an important role in methane mitigation efforts. However, the Federation's own estimates of methane emission intensity vary greatly from year to year and are at variance with estimates of international data collection and research institutes. As a result of a recent series of large reductions in methane emission estimates, the self-reported methane emission intensity of the Russian Federation oil and gas industry is now less than comparable self-reports of the United States. If taken at face value, this 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 very large, and attributions to specific economic sectors are unreliable. Satellites are more reliable in characterizing plume events, but the measurements are insensitive and only account for a small fraction of total emissions. Coal mine methane emissions are easier to characterize but harder to remediate than emissions from oil and gas sources. In order for Russia to play a constructive role in climate change mitigation, quantitative information about the state of emissions is required. Monitoring systems should be introduced, and prudent mitigation measures should be widely implemented. While many mitigation measures are simple and inexpensive, regulations should recognize that some solutions need to be adapted to local conditions. Because Russian practices of methane emission reporting and remediation are broadly representative of those of most other oil-, gas-, and coal-producing nations, the recommendations presented here have global application.

1. Introduction

1.1 Methane as a Greenhouse Gas

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

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

Natural sources of methane (wetlands, bodies of water, natural seeps, etc.) constitute half or less of global methane emissions. The remainder - anthropogenic emissions - is sourced from fossil fuel supply chains,

agricultural activities, landfill and wastewater emissions, and biomass burning [Jackson, 2020; Saunois, 2020a], see Figure 1.

In economic contexts, the environmental impact of methane emissions is estimated by the social cost of methane. The social cost of a greenhouse gas is the estimate of the economic damages suffered as a result of adding one ton of greenhouse gas to the atmosphere. For the purposes of developing United States government policy, the social costs of greenhouse gases are computed by the Interagency Working Group on Social Cost of Greenhouse Gases [IWG, 2021]. Assuming a discount rate of 3%, the 2020 social cost of carbon dioxide is \$51 per metric ton and the 2020 social cost of methane is \$1500 per metric ton.

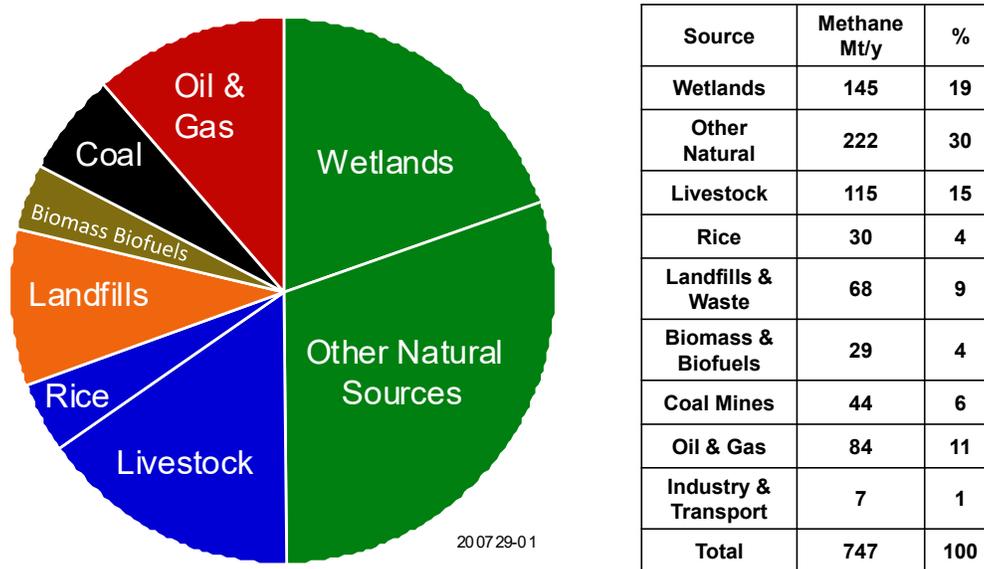


Figure 1. Global natural (green) and anthropogenic (other colors) sources of methane emissions to the atmosphere. Sums are not exact due to rounding. Data: [Jackson, 2020, Table 1, 2017 Bottom-Up Estimates]

1.2 Methane Emissions from Oil and Gas Supply

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

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

For these reasons, the oil and gas industry has been the focus of attention among policymakers and the press. Russia is second only to the United States in the production of petroleum and natural gas [EIA, 2021], and this alone would make it a locus of concern. Beyond the sheer size of its industry the Russian Federation has been singled out as a particularly important part of the methane problem [Washington Post, 2021; New York Times, 2022].

As will be shown below (Table 1), the 2021 estimate of methane intensity in the Russian Federation – methane emissions from the oil and gas sector divided by the quantity of natural gas produced – is 0.92%. Historically, a natural gas loss rate of a few percent has generally been considered acceptable. Upstream, when produced in association with oil, gas has often been considered a waste product, to be disposed of by flaring or venting. Downstream, where safety is a primary concern, care is taken to avoid emissions that could endanger life or property. However, a multitude of small vents and leaks that are inconsequential to economics or safety can, in aggregate, negatively impact climate.

In 2019 (pre-COVID) the annual dry gas production in the Russian Federation was 644 billion cubic meters [UNFCCC, 2021b, Table 3.33; see also BP, 2021]. The densities of Russian produced and marketed natural gas are both 0.68 kg/m³ [Uvarova, 2014], so 2019 Russian gas production was 438 million tons per year. A methane loss rate of 0.92% of gas production implies a loss of 4 million tons per year. Russian marketed gas is 98.2% methane, therefore to a good approximation this loss represents 6 billion cubic meters (bcm) of natural gas.

The 2016-2017 average price of Russian gas at the German border was \$4.82/MMBtu [IMF, 2017; Y-Charts, 2022]. 1 MMBtu = 29.3 m³ [BP, 2021, Approximate Conversion Factors], so an annual loss of 6 bcm equates to an economic loss of \$1 billion per year. The environmental damage calculated from the U.S. social cost of methane [IWG, 2021], \$1500/ton = \$1.00/m³ = \$32/MMBtu, was about \$6 billion per year.

1.3 Methane Emissions from Coal Mines

Russia ranks sixth in the world in coal and lignite production [Enerdata, 2022]. Coal mine methane is a secondary target of methane reduction efforts, accounting for 6% of total global methane emissions according to 2020 estimates [Jackson, 2020, Table 1, 2017 Bottom-Up Estimates]. A recent discovery of unexpected, gigantic methane emissions from a Russian open-pit coal mine suggests this may be an underestimate [BBC, 2022]. Coal mine methane is easier to find but harder to remediate than methane from the oil and gas industry. For safety reasons, methane is prevented from concentrating during coal mining, particularly in underground mines. This makes methane sourced from coal mining hard to burn off (converting it to relatively benign carbon dioxide) and even harder to monetize.

Although the focus of this report is the Russian Federation, many practices described here are common internationally. Even the United States, whose methane emission reporting system is extraordinarily granular and conscientious, is not above reproach [Kleinberg, 2021; Kleinberg, 2022]. Therefore, the current practices and recommendations for improvement described in this paper have global implications. These include a review of the capabilities and limitations of the various methods by which methane emissions are estimated in the oil and gas and coal industries. The variety of environments in which the Russian fossil fuel industries operate is a large subset of those found around the world. Similarly, the discussion of policy in Section 4 has applications beyond Russia and the United States.

2. Survey of Methane Emission Estimates

2.1 Bottom-Up vs. Top-Down Estimates

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

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

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

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

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

2.2 Bottom-Up Estimates

2.2.1 National Inventory Reports – Oil and Gas

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

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

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

Methane emissions from each of these segments are found from:

$$E = A \times EF$$

E is the amount of methane emitted annually from an industry segment

A (activity factor) is the annual volume of gas or oil involved in that segment

EF (emission factor) is the methane emitted per unit volume of gas or oil involved in the segment

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

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

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

The Russian government reconsiders its slate of oil and gas emission factors almost every year. Generally (but not always) these changes are applied retroactively and the history of methane emissions since 1990 is recomputed. Every other year since 2014 the Russian Federation has submitted a Biennial Report to 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 National Inventory Reports have changed; the activity factors remain essentially unchanged in successive National Inventory Reports. Pre-COVID emission data compiled in 2021 for 2019 [UNFCCC, 2021b], are in Table 1.

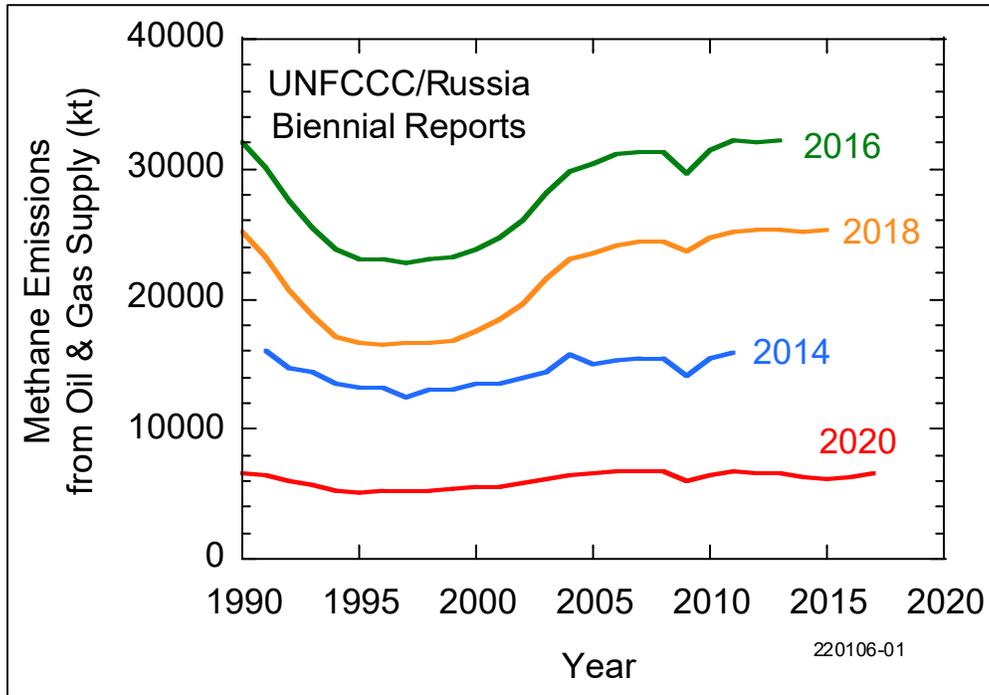


Figure 2. Methane emissions for the Russian oil and gas industry, recomputed using updated slates of emission factors in 2014, 2016, 2018, and 2020. Data: [UNFCCC, 2014a; UNFCCC, 2016a; UNFCCC, 2018a; UNFCCC, 2020a].

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

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

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

		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	6.00x10 ⁻³	F: 6.6x10 ⁻⁵ to 4.8x10 ⁻⁴
Gas Transport Through Main Pipelines since 2017										↓ 1.84x10 ⁻³	V: 4.4x10 ⁻⁵ to 3.2x10 ⁻⁴
Flaring During Production		1.1x10 ⁻⁵	↓ 8.8x10 ⁻⁷	↓ 7.6x10 ⁻⁷	7.6x10 ⁻⁷	7.6x10 ⁻⁷					7.6x10 ⁻⁷
Flaring During Primary Gas Processing		1.3x10 ⁻⁵	↓ 1.4x10 ⁻⁶	1.4x10 ⁻⁶	1.4x10 ⁻⁶	1.4x10 ⁻⁶	↓ 1.12x10 ⁻⁷	1.12x10 ⁻⁷	1.12x10 ⁻⁷	↓ 1.01x10 ⁻⁷	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	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	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									2.2x10 ⁻³
Oil & Condensate production vents		1.381x10 ⁻³	↑ 1.96x10 ⁻²	1.96x10 ⁻²	1.96x10 ⁻²	1.96x10 ⁻²	↓ 1.80x10 ⁻³	1.80x10 ⁻³	1.80x10 ⁻³	1.80x10 ⁻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	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	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	2.18x10 ⁻⁵	2.6x10 ⁻⁶ to 4.10x10 ⁻⁵
Gas Disposal											
Gas Disposal During Oil Production	Gg / 10 ³ m ³	1.38x10 ⁻³	↑ 1.04x10 ⁻²	1.04x10 ⁻²	1.04x10 ⁻²	1.04x10 ⁻²	↓ 7.2x10 ⁻⁴	7.2x10 ⁻⁴	7.2x10 ⁻⁴	2.1x10 ⁻⁵	
Flaring Associated Gas	Gg / 10 ⁶ m ³	1.2x10 ⁻²	1.2x10 ⁻²	1.2x10 ⁻⁶	1.2x10 ⁻⁶	1.2x10 ⁻⁶	1.2x10 ⁻²	1.2x10 ⁻²	1.2x10 ⁻²		

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

- In the 2014 National Inventory Report, emission factors were generally higher than IPCC defaults, in many cases considerably higher.
- In the 2015 NIR, some emission factors increased, others decreased, leading to a large overall increase in estimated emissions, which were reflected in the 2016 Biennial Report.
- In the 2016 NIR, the emission factors of the natural gas segments (except pipeline transport) were lowered to IPCC default values. There were no further changes in the 2017 and 2018 emission factors. The 2018 Biennial Report showed a large reduction in methane emissions compared to the 2016 Biennial Report.

- In 2019, emission factors for the natural gas segments were reduced to below IPCC defaults while emission factors for the oil segments were reduced closer or to IPCC default values. Consequently, 2020 Biennial Report emissions were very low.
- There were no emission factor changes in the 2020 NIR. Reductions in the 2021 NIR reduced estimated 2019 oil and gas methane emissions to 4050 kt, as shown in Table 1.

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

As the result of repeated reductions of emission factors, self-reported methane emissions from the Russian oil and gas industry declined by a *factor of eight* in the six years from 2013 to 2019, see Figure 3. This is a period during which Russian oil production increased by eight percent and gas production increased by ten percent [BP, 2021], and self-reported American oil and gas methane emissions increased by one percent [UNFCCC, 2021a].

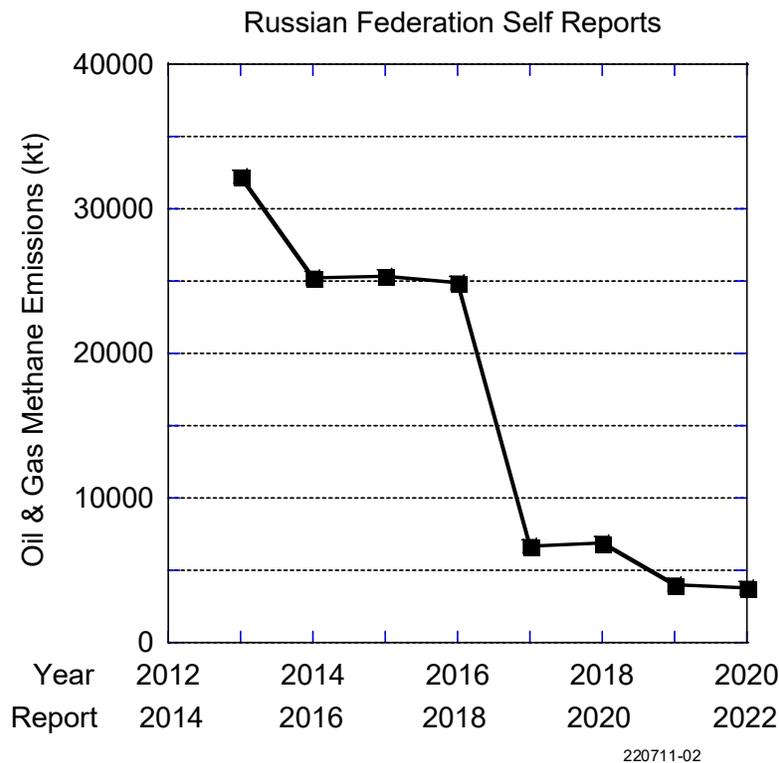


Figure 3. Self-reported methane emissions from the Russian oil and gas industry, 2013-2020 from Common Reporting Format (CRF) data submitted to the UNFCCC between 2015 and 2022. Data: [UNFCCC, 2022].

2.2.2 National Inventory Reports – Solid Fuels

The only solid fuel methane emissions reported in the Russian Federation National Inventory Reports are from the supply of coal. Currently, there are about equal emissions from underground and open pit mines, with subsequent handling making a minor contribution, see Figure 4.

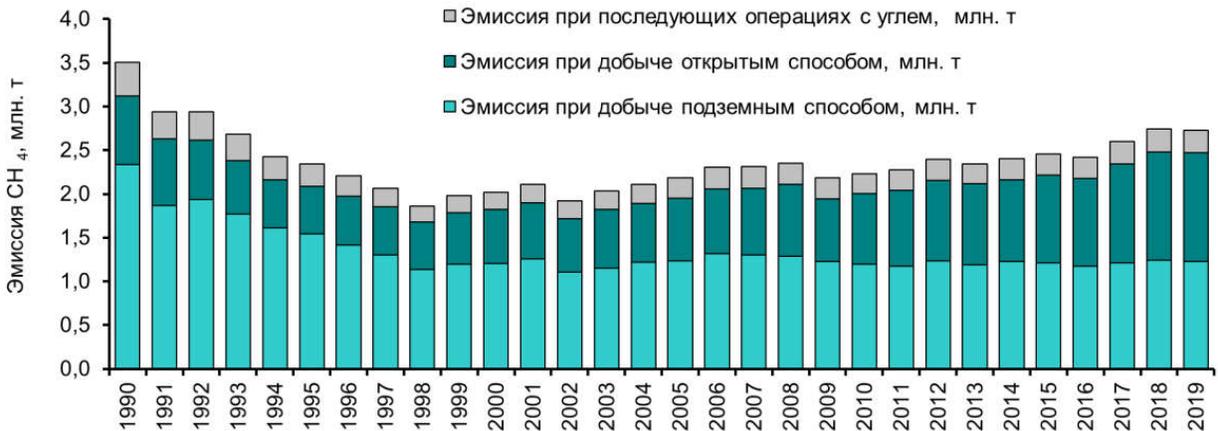


Figure 4. Russian Federation methane emissions in millions of tons per year, from underground coal mining (light blue), open pit coal mining (dark blue) and subsequent operations (gray) [UNFCCC, 2021b, Figure 3.36].

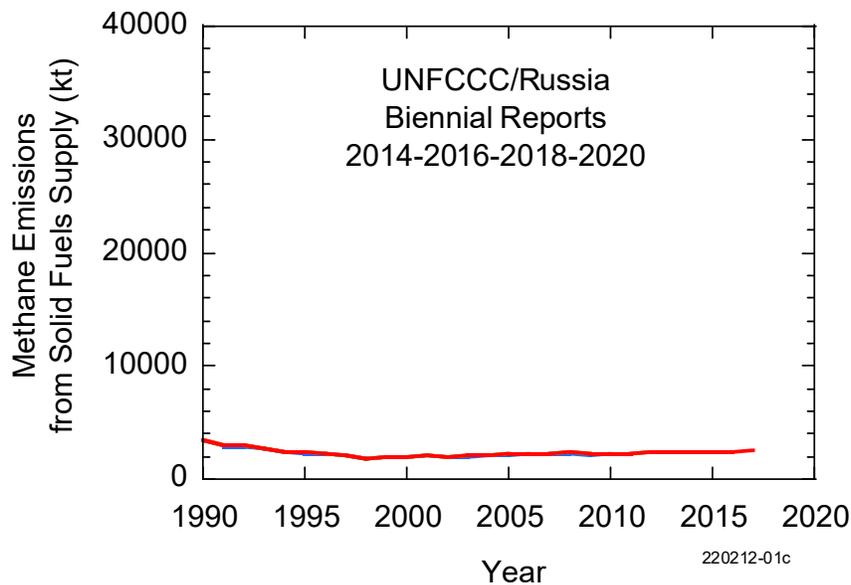


Figure 5. Methane emissions from the Russian coal industry, recomputed using updated slates of emission factors in 2014, 2016, 2018, and 2020. The scales are the same as in Figure 2. Data: [UNFCCC, 2014a; UNFCCC, 2016a; UNFCCC, 2018a; UNFCCC, 2020a].

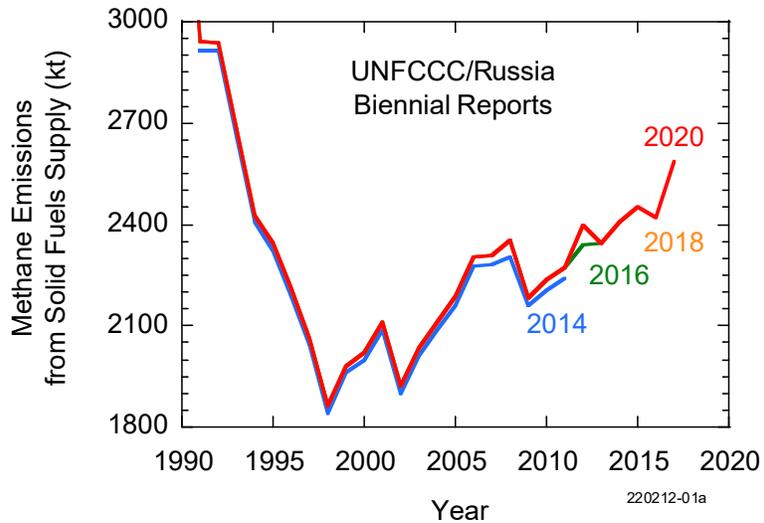


Figure 6. The same data as in Figure 5, on an expanded vertical scale.

Methane emission factors for coal production are not reported in the National Inventory Reports but have remained constant since the inception of the Biennial Reports, see Figures 5 and 6. This is unlike oil and gas emission factors, but it is not unexpected. Methane emissions from coal mining operations do not depend very much on equipment and processes, but primarily on the amount of methane in produced coal – a quantity that depends not on engineering practice but on the organic geochemistry of coal and the depth of the mine [Kholod, 2020] or source of gas. However, inventories based only on the kinds and amounts of coal being mined can overlook methane emissions from inactive mines, or methane emerging through mines from deeper sources. This is now recognized as a growing problem.

2.2.3 Other Inventories

There are numerous other estimates of methane losses from the Russian fossil fuel industries. These include estimates from the International Energy Agency (IEA), the European Union Emissions Database for Global Atmospheric Research (EDGAR), the U.S. Environmental Protection Agency (U.S. EPA), the International Institute for Applied Systems Analysis (IIASA), and the Community Emissions Data System (CEDS), see Figure 7. The estimates all fall within the range of the four Russian Federation Biennial Reports to UNFCCC shown in Figure 2.

The International Energy Agency (IEA) publishes a Methane Tracker, which annually reports national sector-level methane emissions [IEA, 2022b]. Methods are documented in the Global Methane Tracker Documentation [IEA, 2022d]. IEA estimated nineteen oil and gas sector-level emission intensities for each of the twenty-five nations responsible for 95% 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 most recent (2019) U.S. EPA reported methane emissions from petroleum and natural gas systems is 7868 kt. The corresponding (2021) 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 nations, the sector intensities were multiplied by country-specific factors. Countries such as Russia, from which satellites could detect very large single emitters greater than five tons of methane per hour, were given a separate line item, “Satellite detected large leaks”.

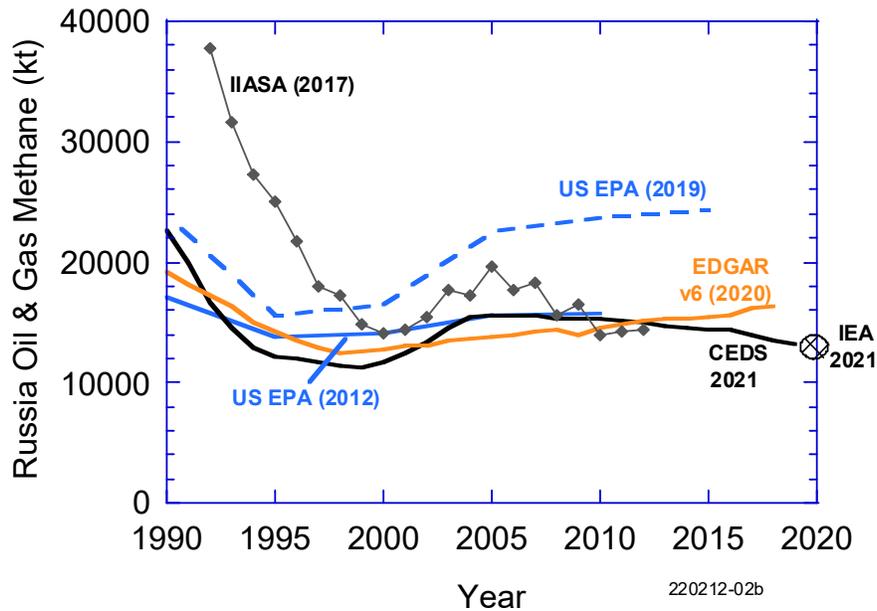


Figure 7. Diverse estimates of methane emissions from the Russian oil and gas industry. EDGAR v6 also includes coal.

The International Institute for Applied Systems Analysis (IIASA) did a careful study of methane emissions connected with associated gas production. It combined this with the 2006 IPCC default emission factors to estimate methane emissions from oil and gas production [Hoglund-Isaksson, 2017]. While the associated gas calculation is country-specific and detailed, the IPCC estimates are not. Spreadsheets in the Supplementary Material allow others, including 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]. In its version 4.3.2, EDGAR included forty-two years of data, twenty-six aggregated emission sectors, 226 countries, and nine substances [EDGAR, 2021b]. EDGAR publishes fossil fuel supply emission estimates, including oil, gas, and coal. Methodology details are published elsewhere [Crippa, 2018]. The Community Emissions Data System for Historical Emissions (CEDS) [CEDS, 2022] methodology is also published elsewhere [Hoesly, 2018]. U.S. EPA assessments of other countries track the UNFCCC submissions of those countries [EPA 2012; EPA, 2019a].

2.2.4 National Inventory Reports – Russia vs United States

Like Russia, the United States uses the inventory method to compute methane emissions from its oil and gas industry. The Russian Federation activity-weighted emission factors in 2021 were one-eighth their 2015 values [UNFCCC, 2021a]. Over the same period U.S. activity-weighted emission factors scarcely changed. Data from the Biennial Reports submitted by the United States are shown in Figure 8. The horizontal and vertical scales in Figures 2 and 8 are the same. U.S. bottom-up inventories are much more stable than Russian inventories.

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

The 2019 (pre-COVID) emissions of methane from the petroleum and natural gas systems were reported to be 7868 kt [EPA, 2021a]. Dry gas production that year was 33.90 trillion cubic feet, or 934 billion cubic meters [EIA, 2022a; see also BP, 2021]. Assuming the average density is the same as Russian dry gas, this amounts to 635 million tons of gas per year, so the reported methane intensity is approximately 1.24%. This is higher than the comparable Russian methane intensity, 0.92%, see Table 1. If taken at face value, this would make Russia a preferred provider of oil, gas, and petroleum products to importers sensitive to the upstream greenhouse gas emissions of their suppliers.

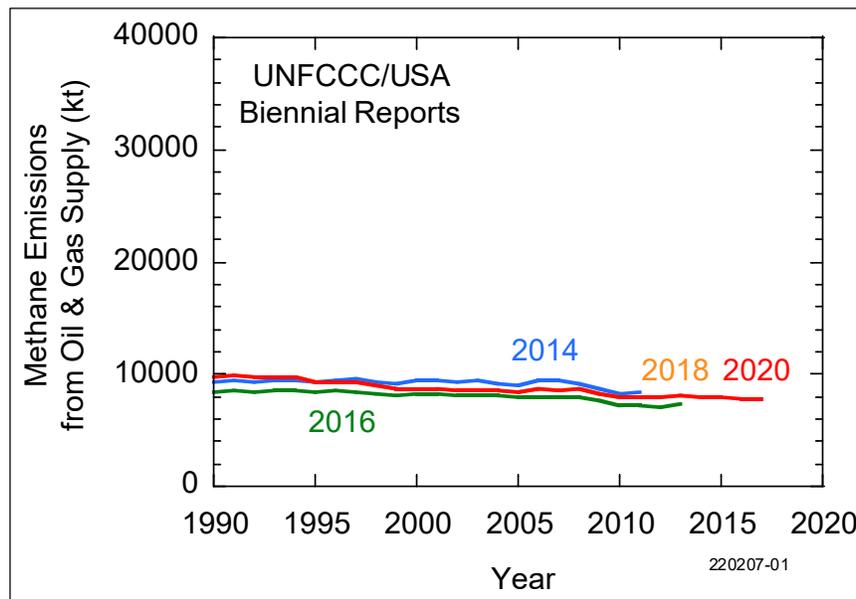


Figure 8. Methane emissions for the United States oil and gas industry, recomputed using updated slates of emission factors in 2014, 2016, 2018, and 2020. Data: [UNFCCC, 2014b; UNFCCC, 2016b; UNFCCC, 2018b; UNFCCC, 2020b].

The 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, Supplementary Information Table S1]. It is widely agreed 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 National

Inventory Reports, neither the Russian Federation nor the United States incorporate field measurements of methane emissions from operating equipment. These measurements are not made because they are not required in the regulations of either country, nor are they required by the UNFCCC in connection with the submission of National Inventory Reports 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 in academic and non-governmental organizations.

2.3 Top-Down Estimates

Measurements of atmospheric methane concentrations by earth orbiting satellites constitute another method of estimating methane emissions. Launched by national space agencies [see e.g. NIES, 2022; ESA, 2022a], private companies [e.g. GHGSat, 2022], and non-governmental organizations [MethaneSAT, 2022], the data are in many cases made freely available to be analyzed by competing multinational teams of scientists. The orbits of polar sun-synchronous satellites [ESA, 2022b] in theory permit inspection of the entire earth. These features have led some to believe that satellite-based measurements avoid the shortcomings of inventories. However the actual performance of remote sensing instrumentation is limited by measurement physics and 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	2023	500	Targeted 0.13 x 0.40	Jacob, 2022
GHGSat - D	2016	1000-3000	Targeted 0.05 x 0.05	
GHGSat - C	2021 - 2023	100	Targeted 0.025 x 0.025	McKeever, 2021

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

2.3.2 Nation-Level Top-Down Surveys

The two principal satellite systems used for global and national-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 the earth to the orbiting detector. Global-average determinations can be performed very accurately. Figure 9 shows the result of eleven inversions of GOSAT data for 2017. Estimated total methane emission rates (black) are very consistent for all data inversions. This total is partitioned into

natural (green) and anthropogenic (blue) methane fractions. Anthropogenic methane is further partitioned; here only the fossil fuel fraction (red) is shown. The fraction of methane emissions attributed to fossil fuel supply ranges between 0.14 and 0.20, with a mean of 0.18 and a standard deviation of 0.017.

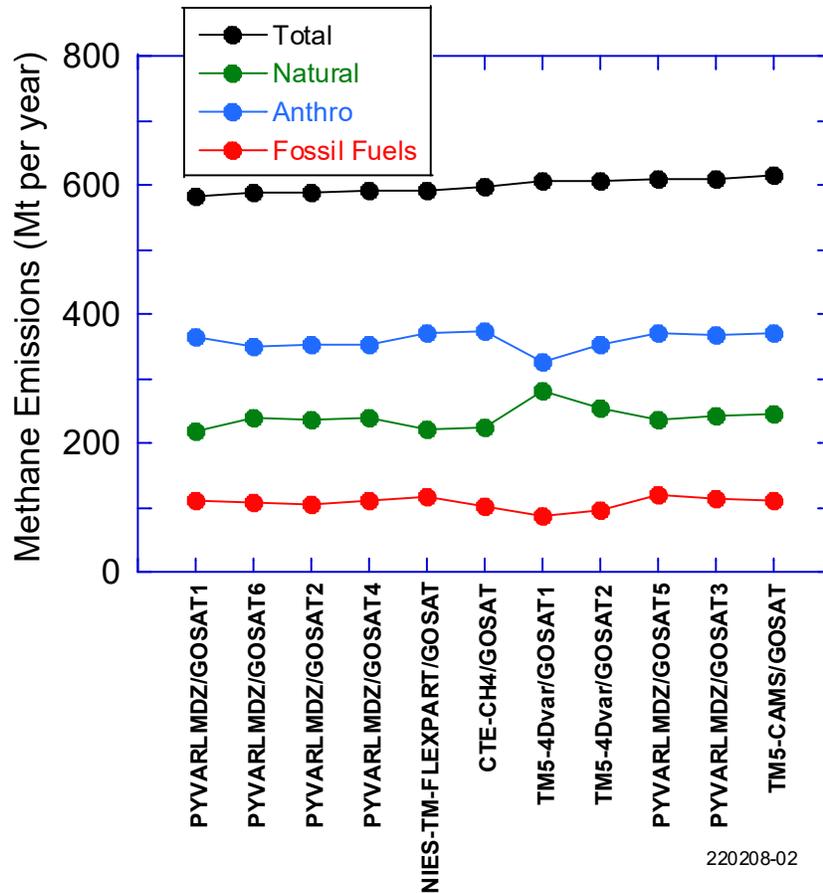


Figure 9. Global methane emissions in 2017 determined by inversions of GOSAT satellite data performed by various analysts. The inversions are named on the horizontal axis. The inversions are ordered according to the total emission rate (black). Estimates of natural emissions are shown in green, anthropogenic emissions in blue, and fossil fuel emissions (a subset of anthropogenic emissions) in red. Data: [Saunio, 2020b].

National-level emissions estimates are far more uncertain than global estimates, and any particular economic segment, such as the fossil fuel industry, can be quite poorly determined, even for a large nation like the Russian Federation. This is illustrated by Figure 10, which is sourced from the same data sets, analysts, and algorithms as Figure 9. Here, the fraction of methane attributed to fossil fuel emissions ranges between 0.21 and 0.51, with a mean of 0.39 and a standard deviation of 0.11.

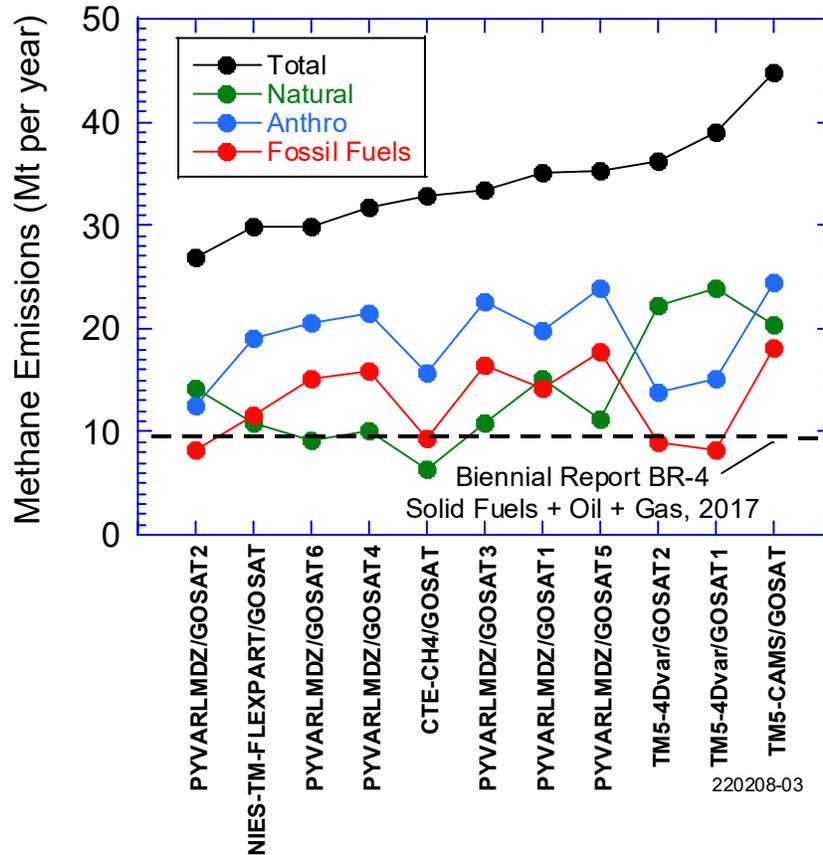


Figure 10. Russian methane emissions in 2017 determined by inversions of GOSAT satellite data performed by various analysts. The inversions are named on the horizontal axis. The inversions are ordered according to the estimate of total emission rate (black). Estimates of natural emissions are shown in green, anthropogenic emissions in blue, and fossil fuel emissions (a subset of anthropogenic emissions) in red. Data: [Saunois, 2020b]. Russian Federation Biennial Report of methane emissions from solid fuels, oil, and gas for 2017 (dashed horizontal line) [UNFCCC, 2020a].

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

The dependence of top-down-estimated emission rates (posteriors) on initializing bottom-up inventories (priors) is illustrated in Figure 11 for the 2017 GOSAT data set. In this example, the methane emissions from all sources in Russia were estimated from observations using the Bayesian method. Because the total of all methane emissions is closely related to what a satellite actually measures, it is a better-determined product than any of the subsets, such as emissions only from the fossil fuel sector. The correlation

between posteriors and priors for the thirteen inversions is good: the ratio of posteriors to their respective priors is 1.01 ± 0.12 . We conclude that at least some of the scatter in the natural, anthropogenic, and fossil fuel estimations in Figure 10 is likely due to scatter in the priors chosen to initialize the inversions.

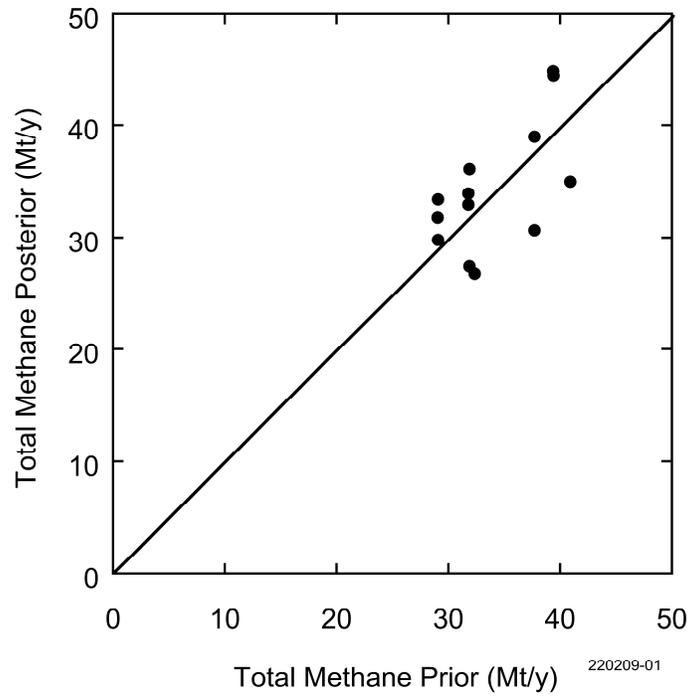


Figure 11. Relationship between prior initializations and posterior results of thirteen Bayesian inversions of GOSAT top-down data for total methane emissions in Russia during 2017. The correlation suggests that variations in top-down emission estimates are driven in part by the inventory data used as priors.

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 OPEC 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 poor areas 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-Pecora, 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].

As a consequence of these factors, over much of Russia, the GOSAT satellite collects an average of only a few data points per month in each $2.5^\circ \times 2.5^\circ$ (37-103 km x 278 km) grid cell [Stavert, 2022]. TROPOMI collects much more data than GOSAT, but at its present state of development TROPOMI is more susceptible to error in the presence of wetlands [Qu, 2021], which are common in some Russian oil and gas provinces. 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." [Sauniois, 2016, sec. 5.1.1]. However, although satellite-based top-down estimates are imperfect at present, there are many opportunities for improvement [Sauniois, 2020a, section 6].

2.4 Satellite Measurements of Methane Plumes

GOSAT and earlier methane-measuring satellites are not suitable for point source measurements. While GOSAT is a good platform 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% 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 [Lauvaux, 2022]. Lauvaux et al. estimated that Russia was responsible for one-eighth of this total. Much of this activity appears to be coincident with major pipeline routes extending southwest from the arctic.

The 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 equalling 810 billion cubic meters. This is greater than total Russian gas production of 680 billion cubic meters. The pipeline activity factor could be greater than production because the pipeline emission factor does not take distance into account. Perhaps gas is counted multiple times if it travels through two or more pipelines. The emission factor for mainline pipe transport is 1.84×10^{-3} Mt/bcm. Therefore, the National Inventory Report estimate of methane loss is 1.5 million tons. This is the largest single category of reported methane loss from the Russian gas supply chain, and is not inconsistent with the TROPOMI analysis.

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

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

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

3. Methane Emission Reduction in the Russian Federation

Greenhouse gas emissions associated with the supply and consumption of fossil fuels has emerged as one of the most important environmental issues of our time. These concerns cannot be ignored by the Russian

Federation, which is by far the world's largest exporter of natural gas and the second largest exporter of oil [BP, 2021]. It is also a leading producer of coal.

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

Fortunately, reducing methane emissions from the oil and gas industry is often not a particularly hard problem, though solutions may need to be customized to deal with location-specific conditions. Engineering solutions exist that often can be implemented at low cost relative to other expenses and revenue. While abatement cost curves such as those published by the International Energy Agency [IEA, 2022a] cannot be taken too literally, the overarching message is valid. The main barrier to methane reduction is finding the sources of emission, which are varied, often intermittent, and sometimes unexpected [NASEM, 2018, Figure 4.1 and accompanying discussions]. Once found, fixing sources can be 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, some coal mine mitigation problems are difficult because gas in active mines is deliberately diluted and dispersed for safety reasons. Recovering this methane can be technically and economically challenging. A further challenge is emissions from abandoned mines, to which little attention has been paid until recently [Kholod, 2020].

3.1 Improving the Accuracy of Reported Emissions

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

The main problem with emission inventories is that, as commonly implemented, they are inherently inaccurate. Using emission factors based on the average behavior of components and equipment types (as in United States practice) or based on throughput (as in IPCC and Russian practices) ignores the "heavily skewed distribution of site-based CH₄ 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. It has been found very difficult to properly characterize these skewed distributions. A study involving 117,000 well visits found that measured distributions depended on the number of visits: 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 emission, but under favorable conditions average site emission rates will decrease with repeated inspections [Ravikumar, 2020].

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

3.1.1 Aircraft-Based Measurements

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

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

Large scale surveys of oilfields make economic sense. It is estimated that 2.7 million tons (4.0 billion cubic meters = 140 billion cubic feet) of methane are lost per year 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 wells sites can be surveyed for a few million dollars. A small operator claimed the cost of a survey of 27,000 acres encompassing 170 surface assets and 31 miles of natural gas pipeline paid for itself in five days of additional gas sales [Johnson, 2021].

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

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

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

Remarkably, this industry has grown in the absence of regulatory mandates. The U.S. Environmental Protection Agency accepts only two methods as legally acceptable for volatile organic compound and methane leak detection, both of which are ground-based hand-held devices: optical gas imaging and a sniffer device (“Method 21”) [40 CFR 60.5397a(c)(2)]. Neither is capable of quantitative measurements. However, U.S. EPA has recently signaled interest in finding a role for airborne devices (“Advanced Methane Detection Technology”) in leak detection and repair [EPA, 2021b].

3.1.2 Continuous Monitoring

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

3.2 Methods to Reduce Oil and Gas Methane Emissions

There is no one solution to the problem of methane emissions. A wide variety of equipment types can emit methane for a wide variety of reasons. Some problems are simple to remedy: a malfunctioning part can be repaired or replaced. Other problems are genuinely difficult to deal with. 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 100% 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. Sometimes this gas can be collected by a vapor recovery unit and routed to a sales line, or routed to a flare for combustion. While the latter process produces carbon dioxide, this is less damaging than allowing methane into the atmosphere, as shown below. However, these solutions do not always work. Nonetheless, problems must be solved in the context of an industry that operates at almost unimaginable scale, producing 1000 barrels of oil per second, 30 million seconds per year.

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 the myriad methods used to remedy oilfield problems. 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 for example Table 6 below, which references multiple compendia of engineering solutions. However, 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 International Energy Agency 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 (e.g.

flares, vapor recovery units, etc), which are in turn divided into subcategories (e.g. onshore gas, offshore oil, etc). To compare 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 12. In both countries, 40% 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 leak detection and repair (LDAR). Downstream LDAR is relatively less important in Russia because Russia consumes less of its gas locally than the United States does. These results suggest that abatement measures that have been considered for the United States may be relevant for Russia, at least in part.

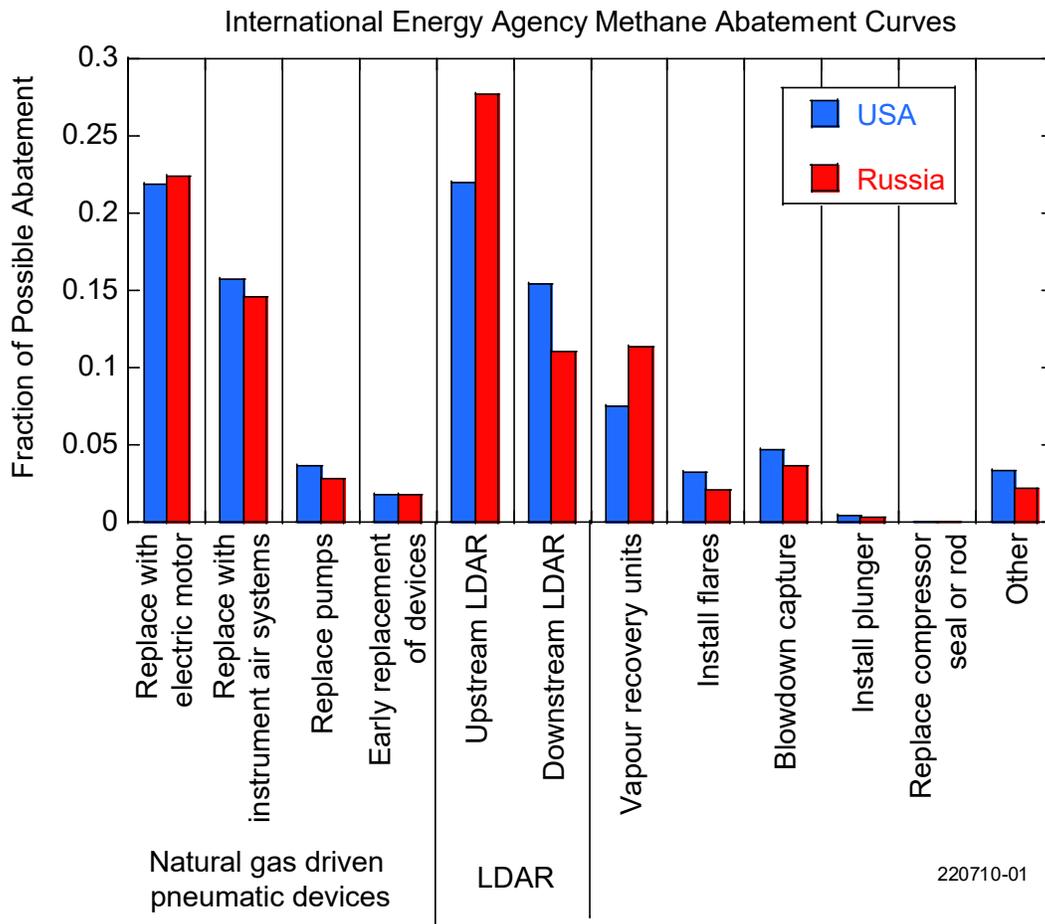


Figure 12. Comparison of IEA methane abatement potentials for the United States (blue) and the Russian Federation (red). Data: [IEA 2022a].

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. Remote sensing from aircraft or satellites cannot distinguish between leaks and vents, which might call into question the utility of these advanced techniques in current regulatory schemes.

3.2.1 Fugitive Emissions

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

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

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

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

the resulting emission reduction amounts to 2% of total oil and gas methane emissions shown on the bottom line of Table 5.

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

3.2.2 Vents

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

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

<p>Methane Guiding Principles, Best Practice Guides https://methaneguidingprinciples.org/best-practice-toolkit/</p>
<p>Oil and Gas Methane Partnership, Technical Guidance Documents https://www.ogmpartnership.com/templates-guidance</p>
<p>U.S. Environmental Protection Agency, Standards of Performance EPA-453/R-11-002, July 2011 https://nepis.epa.gov/Exe/ZyPDF.cgi/P100CHTC.PDF?Dockkey=P100CHTC.PDF</p>
<p>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</p>
<p>U.S. Environmental Protection Agency, Recommended Technologies to Reduce Methane Emissions https://www.epa.gov/natural-gas-star-program/recommended-technologies-reduce-methane-emissions</p>

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

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

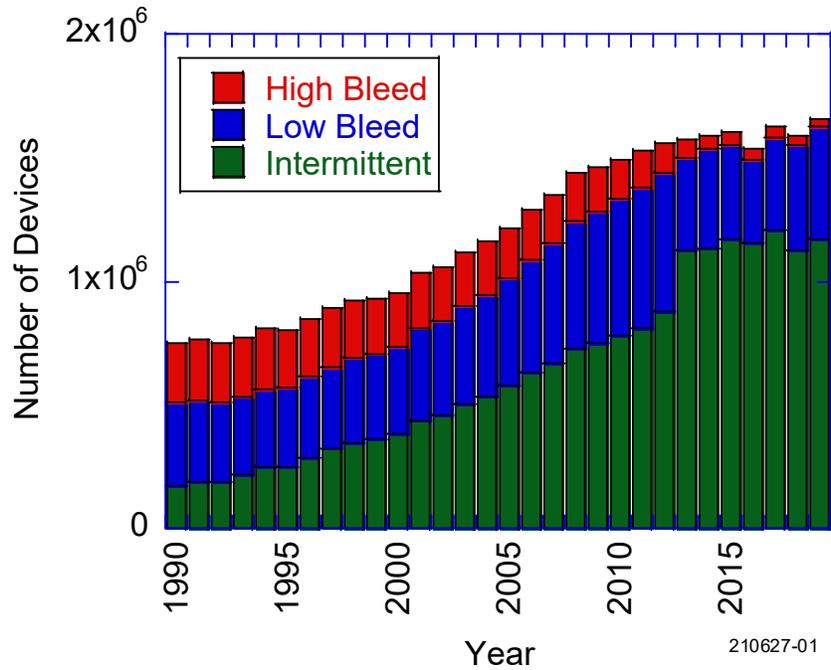


Figure 13. Population of pneumatic controllers in the oil and natural gas sector. U.S. Inventory of Greenhouse Gas Emissions and Sinks [EPA, 2021a, Additional Information, Methodology Annexes].

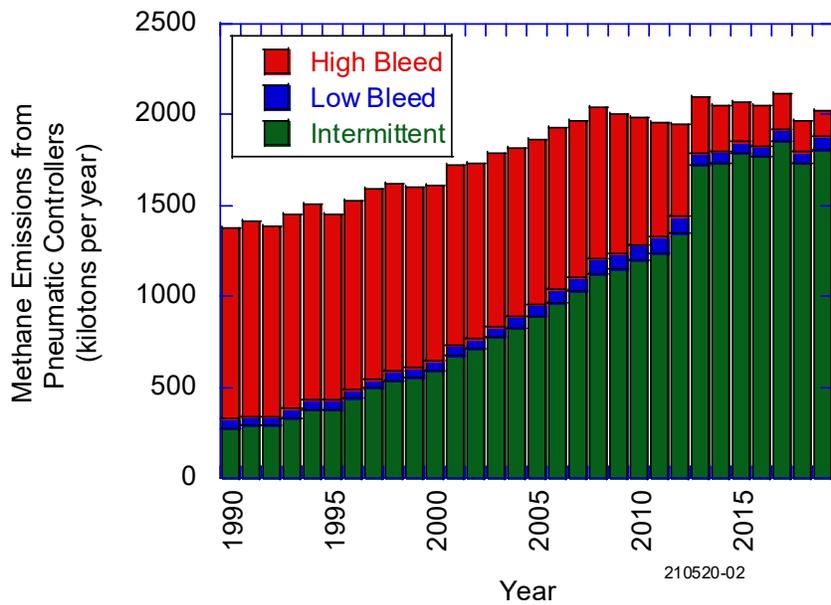


Figure 14. Methane emissions from pneumatic controllers in the oil and natural gas sector. U.S. Inventory of Greenhouse Gas Emissions and Sinks [EPA, 2021a, Additional Information, Methodology Annexes].

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

Therefore, while high-bleed controllers were regulated, there was no regulation at all on intermittently discharging controllers. Along with voluntary retirements, this rule resulted in a substantial decrease in the number of high-bleed (> 6 scf/h = 0.11 kg/h) pneumatic valves deployed at U.S. oil and gas facilities.

Generally speaking, both high-bleed and low-bleed (< 6 scf/h) valves have been replaced by unregulated intermittently discharging pneumatic valves, see Figures 13 and 14. However, the performance of intermittent valves varies widely [Allen, 2015; Methane Guiding Principles, 2019]. As a result, this costly regulation had absolutely no environmental benefit, and each year two million tons of methane are lost to the atmosphere from pneumatic controllers, amounting to a quarter of all emissions from petroleum and natural gas systems as estimated by EPA. A study of several such regulatory failures concluded that to be effective, engineering controls and performance-based regulations must include measurement requirements [Kleinberg, 2021].

3.2.3 Routine and Event-Driven Flaring

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

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

The World Bank Zero Routine Flaring by 2030 initiative has attracted the endorsement of thirty-four governments, fifty-one oil companies, fifteen development organizations, and six supporting organizations [World Bank, 2022b]. When it endorsed this initiative in 2016, the Russian Federation pledged to “provide a legal, regulatory, investment, and operating environment that is conducive to upstream investments and to the development of viable markets for utilization of the gas and the infrastructure necessary to deliver the gas to these markets.” In fact, years earlier the Government of

Russia had established a goal limiting associated gas flaring to 5% of its production. However, “the level of useful use of associated gas in the country in 2019 amounted to 80.9%” [UNFCCC, 2021b, page 92].

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

If flares burned with 100% efficiency, the primary products of combustion would be water vapor and carbon dioxide. The latter is an undesirable greenhouse gas. However, measured combustion efficiencies are less than 100%, leading to even more undesirable outcomes. In 1996, the U.S. Environmental Protection Agency estimated a typical flaring efficiency in the production segment of the natural gas industry to be 98% [EPA, 1996, section 5.2.1]. Aircraft-based measurements of associated gas flares in the Bakken field of North Dakota indicate that on average 4.2% of gas is uncombusted, and that the presence of heavier hydrocarbons in the gas, typical of associated gas plays, significantly enhances the greenhouse gas effect of the unburned gases [Kleinberg, 2019]. Efficiency reductions of just a few percent lead to substantial climate effects, as shown in Figure 15. Unlit flares lead to even worse outcomes, as shown in Figure 16.

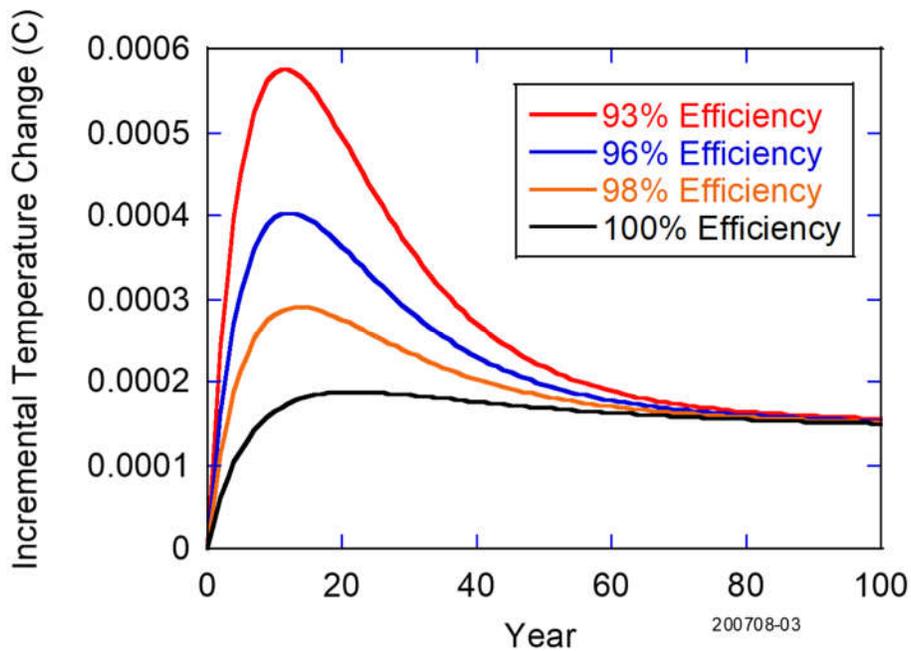


Figure 15. Effect of flare inefficiency. Temperature change is a result of one year of flaring 100% methane at the global rate of natural gas flaring, 146 billion cubic meters per year, with various levels of efficiency [Kleinberg, 2020].

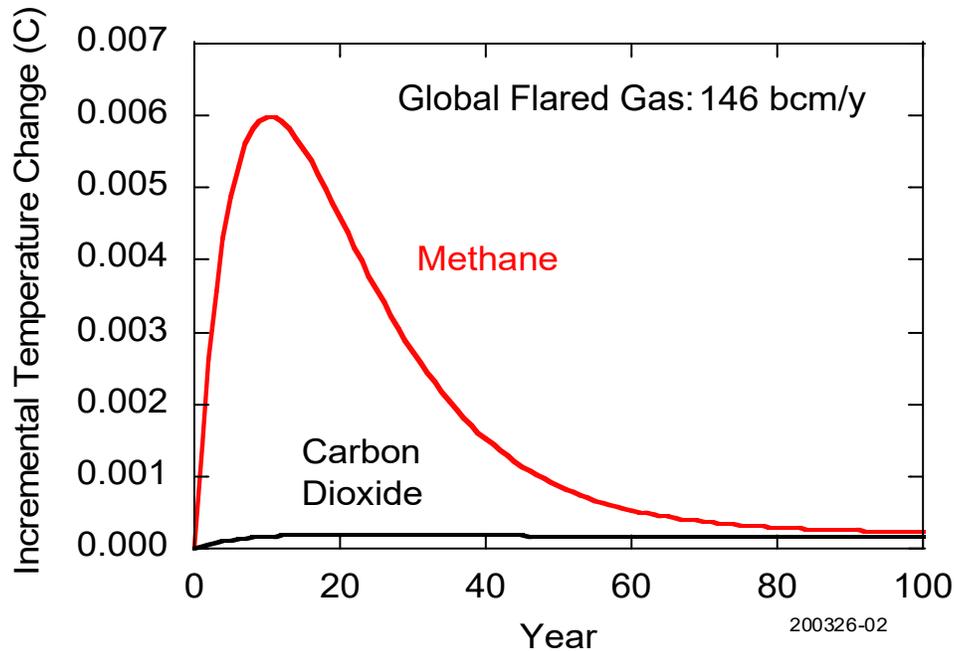


Figure 16. Effect of venting 146 billion cubic meters of 100% methane at year zero (red), versus flaring it at 100% efficiency to carbon dioxide (black). [Kleinberg, 2020]. Note the vertical axis differs from Figure 15.

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

Flares may be highly visible nuisances, but 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. Relative to methane emissions from oil and gas infrastructure, coal mine methane is fairly easy to locate and estimate, but hard to remediate. Prior to 2020, coal mine methane could be considered a small part of fossil fuel methane emissions, compare Figures 2 and 5. 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 heretofore estimated.

According to official estimates, the origin of coal mine methane emissions has shifted over the last three decades, see Figure 4. In the early 1990s, emissions were primarily from underground mines; recently underground and open pit mines have contributed equally. Abandoned underground mines are flooded

with water, and considered to have no methane emissions [UNFCCC, 2021b, page 81]. Throughout the period, methane emissions during transport and handling have been minimal.

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

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

More than half of Russian coal is produced from underground mines of the Kuznetsk Basin (Kuzbass) [Mochalnikov, 2015], making the region a focus of coal mine methane mitigation research and development [Tailakov, 2017]. The emphasis there is on gas produced from coal beds that are not yet mined (“drained gas”). Large-scale drained gas systems are in place, producing 100-200 million cubic meters of methane per year. The density of methane at international oilfield standard conditions (15°C, 101.325 kPa) is 678.37 grams per standard cubic meter [Kleinberg, 2019], so this is equivalent to 70,000-140,000 tons of methane per year. Methane concentrations are as high as 80%. Four options have been screened for technological and economic viability: electric power generation; thermal energy production in boilers; fueling of vehicles with compressed coal mine methane; and fueling of vehicles with liquefied coal mine methane. Thermal energy production in boilers is the most desirable option on technological grounds. Fueling vehicles with compressed coal mine methane scores highest economically when methane concentrations are greater than 80% [Tailakov, 2017].

4. 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 to be the case. The oil and gas industry is not known for “leaving money on the table”. If it were profitable to reduce methane emissions, it would already have been done. Although voluntary efforts to reduce methane emissions are increasing in number, they are in almost all cases technology pilot projects, as opposed to revenue generating business ventures. Regulation will be essential to solving this problem.

Devising a methane control policy for the Russian Federation is beyond the scope of this report. However, some broad principles, based on the successes and failures of regulating the oil and gas industry in the United States, may provide some insights into dealing with this industry in Russia. We focus 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. 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 regulation is 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 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 regulation blends well with the corporate cultures of oil and gas companies and with the ingrained mindsets of their employees.

Another widespread aspect of oilfield corporate culture is the drive to reduce costs. Universally, asset managers are evaluated on their ability to deliver profits to the organization. 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 15 October 2013. Well before that, industry had already been swapping them out. High-bleed controllers were replaced mainly by intermittent-bleed controllers, which emit gas only when actuated. According to recent EPA estimates, the average intermittent-bleed 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 intermediate-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 whether total methane emissions are reduced – 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 regulation mandates 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. EPA directs owners or operators to determine the potential for VOC emissions and reduce VOC emissions from that level by 95.0 percent [40 CFR 60.5395a(a)(1)-(2)]. Performance-based regulation can fail, as it has for oilfield storage vessels, when the regulation lacks 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 thousands 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. EPA had approved only two methods for detecting natural gas leaks in the field, neither of which was capable of quantitative emission rate measurements. Without a path to verified performance-based regulation, 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 by using 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, those distinctions are not particularly interesting. Fugitive methane and vented methane have identical effects on the environment. Measurement-reporting-verification protocols are most appropriately directed not to components and assemblies but to sites and facilities, and their owners and operators. Such measurements are already being performed at hundreds 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 National Inventory Reports of both the Russian Federation and the United States is an example of 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. Ideally, as improved methods are certified by environmental regulators, standards for suppression of methane emissions could be strengthened. There is a theory of adaptive regulation designed to address this problem [Bennear, 2019]. However, such tools are not commonly used in the development of international agreements such as those of the UNFCCC..

5. Conclusions

The emission of greenhouse gases into the atmosphere is probably the most important environmental issue currently facing the fossil fuel industry. There are two greenhouse gases with substantial influence on global climate change: carbon dioxide and methane. Although global anthropogenic methane emissions are only one percent by mass of fossil carbon dioxide emissions, and methane has a much shorter lifetime in the atmosphere, it is a much more powerful warming agent. Not only are the prompt warming effects of methane and carbon dioxide about equal at current emission rates, but global average temperature trajectories over the next several decades are largely controlled by methane.

Fossil fuel industries are responsible for only a fraction of anthropogenic methane emissions, but they are the sectors most exposed to public scrutiny. They are regarded as the economic sectors best prepared, both technically and financially, to address their environmental problems. Unlike carbon dioxide solutions, solving the methane problem will not entail profound economic or social disruptions.

Comprehensive, accurate measurements are a necessary first step in mitigating methane emissions. It is a time-worn adage that “you can’t manage what you can’t measure”, and measurements in Russia and other countries have been essentially non-existent.

Inventory methods provide an incomplete and inaccurate view of the extent of the problem and provide misleading indications of 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 *factor of eight* 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, inaccurate inventory data could affect the behavior of importing nations sensitive to the upstream greenhouse gas emissions of their supplier nations. If a trade rule such as the European Union Carbon Border Adjustment Mechanism, which applies to methane, were to be enacted, inaccurate methane inventories would have the effect of distorting international trade. However, due to improvements in technology, measurement tools are now available that can achieve the spatial and temporal granularity needed to have a meaningful impact on the emission problem.

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