

METHANE EMISSIONS FROM THE FOSSIL FUEL INDUSTRIES OF THE RUSSIAN FEDERATION

BY DR. ROBERT L. KLEINBERG
JANUARY 2023

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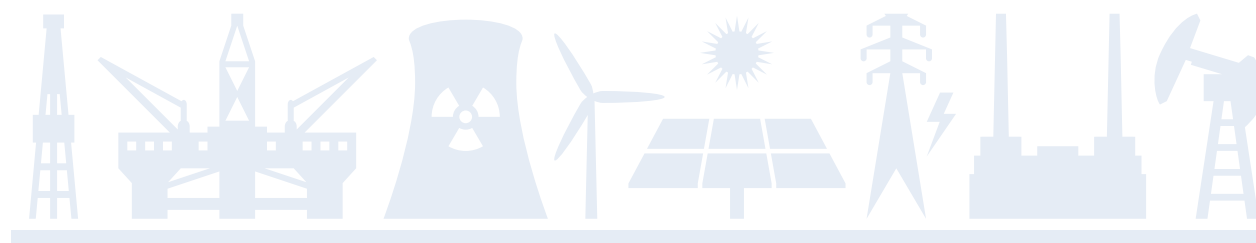
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Columbia University CGEP
1255 Amsterdam Ave.
New York, NY 10027
energypolicy.columbia.edu

   @ColumbiaUEnergy

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ABOUT THE AUTHOR

Robert L. Kleinberg is Adjunct Senior Research Scholar at the Columbia University Center on Global Energy Policy, and Senior Fellow at the Boston University Institute for Global Sustainability. His current interests include energy technology and economics, and environmental and regulatory issues associated with the oil and gas industry. From 1980 to 2018 Dr. Kleinberg was employed by Schlumberger, attaining the rank of Schlumberger Fellow, one of about a dozen to have held this rank in a workforce of 100,000. From 1978 to 1980 he was a post-doctoral fellow at the Exxon Corporate Research Laboratory. Dr. Kleinberg was educated at the University of California, Berkeley (B.S. Chemistry, 1971) and the University of California, San Diego (Ph.D. Physics, 1978). He has authored more than 120 academic and professional papers, holds 41 U.S. patents, and has invented several geophysical instruments that have been commercialized on a worldwide basis. Dr. Kleinberg is a member of the National Academy of Engineering.



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EXECUTIVE SUMMARY

Methane emissions are second only to carbon dioxide emissions 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 of the Russian Federation oil and gas industry is now less than that of the U.S. 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 account for only 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 and introduce monitoring systems. It will also need to 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 fossil fuel industries in particular have received a disproportionate share of interest. It then describes the difference between bottom-up and top-down measurements; reviews the reports of methane emissions in Russia and the United States, pointing out similarities and contrasts 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 before finally addressing 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 1 percent of fossil carbon dioxide emissions by mass and methane has a much shorter lifetime in the atmosphere than carbon dioxide, 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., Mufson et al. 2021), in part because they are best prepared, both technically and financially, to address their contribution 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 introduces the sources of natural and anthropogenic methane and explains why the fossil fuel industries have received a disproportionate share of interest in scientific circles, among policy makers, 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, it 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 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

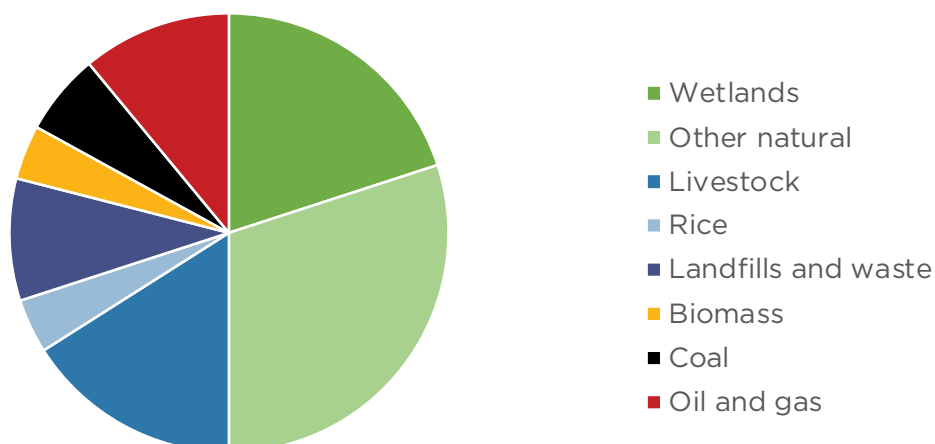


vast quantities and remains in the atmosphere for centuries. The second most important greenhouse gas is methane. The mass of anthropogenic methane emitted into the atmosphere is only 1/100 the mass of fossil carbon dioxide (Crippa et al. 2021; Saunio et al. 2020a), and methane in the atmosphere is removed relatively rapidly, with a time constant of about 12 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 100 times greater than that of the same mass of carbon dioxide (IPCC 2021; Roy et al. 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 30 years is reducing the rate of anthropogenic methane emissions (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; Saunio et al. 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 U.S. government policy, the Interagency Working Group on the 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.

Figure 1: Global natural and anthropogenic sources of methane emissions to the atmosphere



Note: Natural sources are in green; anthropogenic sources are in other colors.

Source: Jackson et al. 2020, Table 1, 2017 Bottom-Up Estimates.



1.2 Methane Emissions from Fossil Fuel Industries

Although oil and gas supply chains account for only 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 2022d, 2022f).
- 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 (Fountain 2022a, 2022b; Mufson et al. 2021).

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 (before COVID-19), self-reported methane emissions from the oil and gas industry of the Russian Federation were four million metric tons per year (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, accounting for 6 percent of total global methane emissions according to 2020 estimates (Jackson et al. 2020, Table 1, 2017 Bottom-Up Estimates), is a secondary target of methane reduction efforts. The recent discovery of unexpected gigantic methane emissions from a Russian open-pit coal mine suggests that this may be an even bigger problem than had been thought (Amos 2022). For safety reasons, methane is prevented from becoming concentrated 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 versus 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 handheld 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 et al. 2011), by aircraft (Vaughn et al. 2018), or by satellites (Saunio et al. 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) together with tables in Common Reporting Format to the secretariat of the United Nations Framework Convention on Climate Change (UNFCCC; UNFCCC 2022a, 2022b). 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 as follows:

Production and primary processing of natural gas	Oil well service
Gas transport through main pipelines	Oil and condensate production leaks and vents
Flaring during gas production and primary processing	Oil transport
Gas storage injection and extraction	Gas condensate transport
Gas distribution	Primary refining
Oil well drilling	Gas disposal during oil production
Oil well testing	Flaring of associated gas



Methane emissions from each of these segments are found from the following:

$$E = AF \times EF$$

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

AF (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.

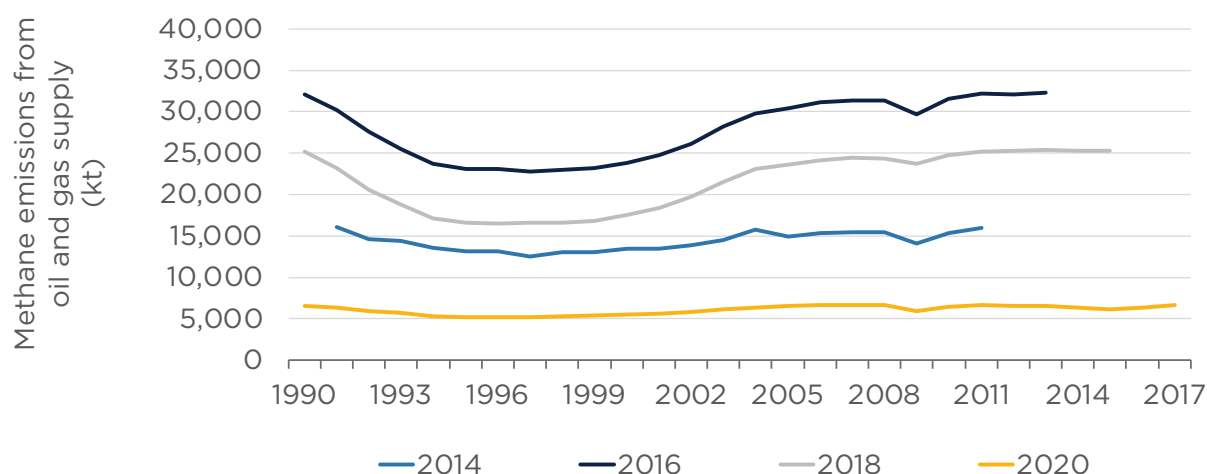
The total methane emissions from the oil and gas industry equals the sum of all values of E.

In practice in Russia, activity factors are the 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 determined independently 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, 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 UNFCCC recapitulating its total methane emissions from the oil and gas industry since 1990 (UNFCCC 2014a, 2016a, 2018a, 2020a). These data are shown in Figure 2. The curves shift in successive biennial reports because the emission factors reported in the respective NIRs changed; the activity factors remain essentially unchanged in successive NIRs. Pre-COVID-19 emissions data compiled in 2021 for 2019 (UNFCCC 2021b) are in Table 1.



Figure 2: Methane emissions for the Russian oil and gas industry

Note: Figures are recomputed using updated slates of emission factors reported in 2014, 2016, 2018, and 2020.

Source: UNFCCC 2014a, 2016a, 2018a, 2020a.

Table 1: Russian Federation 2019 (pre-COVID-19) methane emissions from the oil and natural gas industry, computed with 2021 NIR emission factors

Source	Methane emissions (kt)
Oil well drilling, testing, service	140
Oil and gas condensate production	1,190
Gas production and processing	138
Gas transport and storage	1,290
Gas distribution	572
Gas disposal during oil and condensate production	480
Associated gas flaring	240
Total oil and gas emissions	4,050

Source: 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).



Table 2: Methane emission factors reported in Russian NIRs, 2014–2021, with comparison IPCC Tier 1 default values

Natural gas		2014	2015	2016	2017	2018	2019	2020	2021	IPCC 2006
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	↓ 6.0x10 ⁻³	6.0x10 ⁻³	6.0x10 ⁻³	Fugitive: 6.6x10 ⁻⁵ to 4.8x10 ⁻⁴
Gas transport through main pipelines since 2017									↓ 1.84x10 ⁻³	Vent: 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	↓ 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	↓ 1.8x10 ⁻³	↓ 1.0x10 ⁻³	1.0x10 ⁻³	1.0x10 ⁻³	1.0x10 ⁻³	1.0x10 ⁻³	1.0x10 ⁻³	1.0x10 ⁻³

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Oil		2014	2015	2016	2017	2018	2019	2020	2021	IPCC 2006
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 and 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 and 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		2014	2015	2016	2017	2018	2019	2020	2021	IPCC 2006
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	

Note: Blue upward-pointing arrows mark values that increased from the prior year. Red downward-pointing arrows mark values that decreased from the prior year. One gigagram (Gg) equals 1,000 metric tons (kt).

Source: UNFCCC 2021a; IPCC 2006.

- 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 was 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

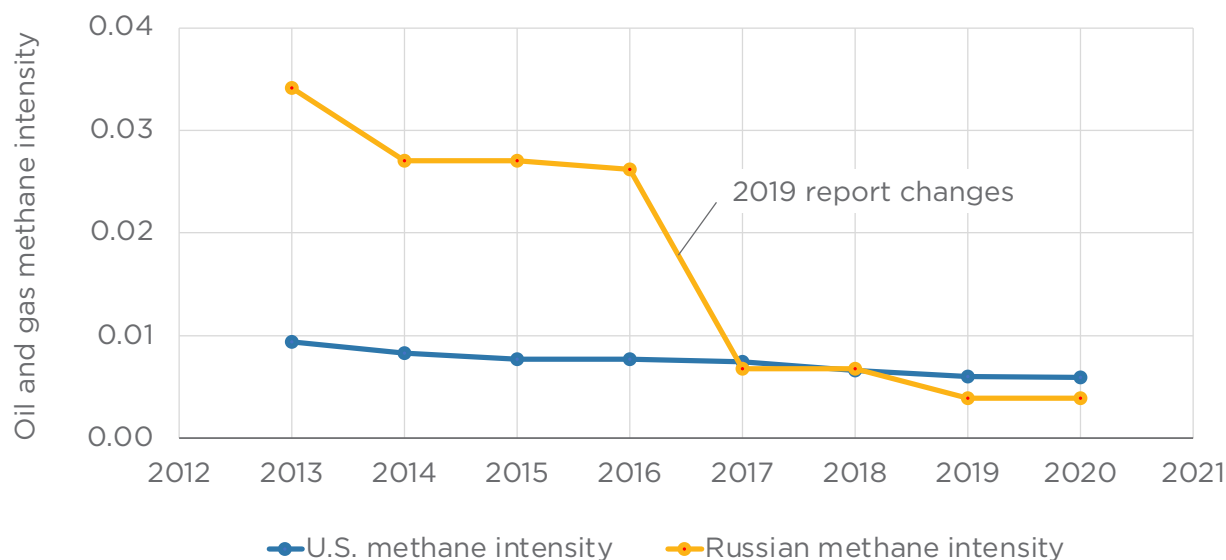


2017 and 2018 emission factors. The 2018 biennial report showed a large reduction in methane emissions compared with the 2016 biennial report.

- 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.

The change of emission factors in the 2019 report is explained in the 2019 NIR (UNFCCC 2019a, 2019b). Generally, 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 [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 et al. 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).

Figure 3: Methane intensities of emissions from the oil and gas industries



Note: Methane intensity: Numerators are self-reported methane emissions of the United States and Russia, 2013–2020, from common reporting format (CRF) data expressed in barrels of oil equivalent and reported to the UNFCCC between 2015 and 2022. Denominators are totals of oil and gas production in barrels of oil equivalent.

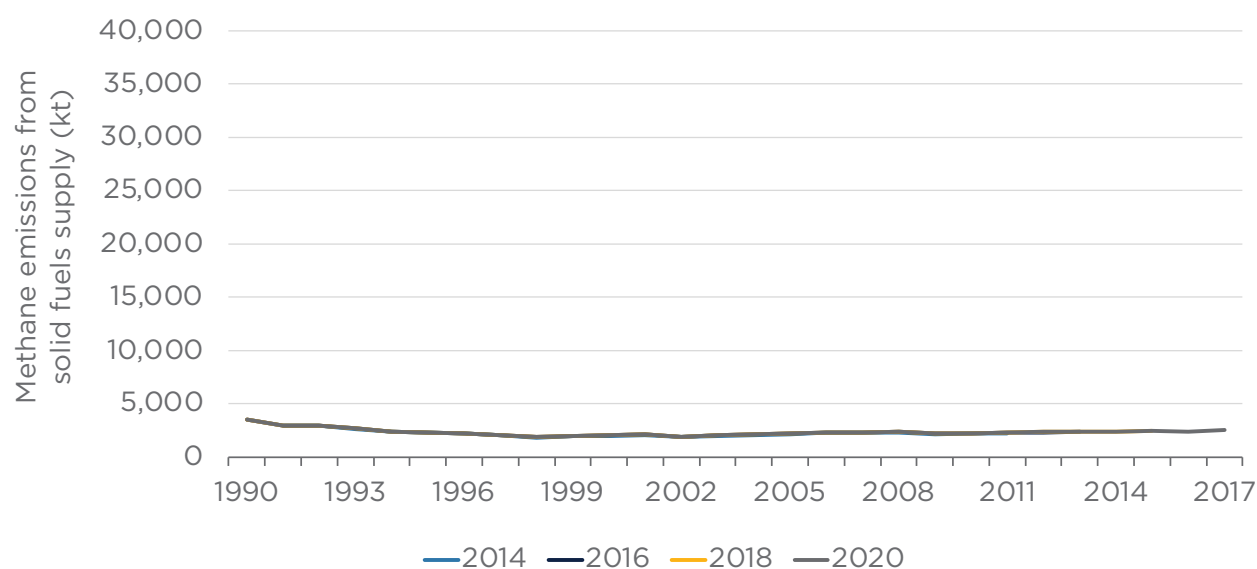
Source: UNFCCC 2022b, Table 10s3; UNFCCC 2022c, Table 10s3; BP 2021.



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 CRF tables (UNFCCC 2022b, 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 et al. 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., Amos 2022).

Figure 4: Methane emissions from the Russian coal industry



Note: Figures are recomputed using minor updates of emission factors reported in 2014, 2016, 2018, and 2020. The scales are the same as in Figure 2.

Source: UNFCCC 2014a, 2016a, 2018a, 2020a.

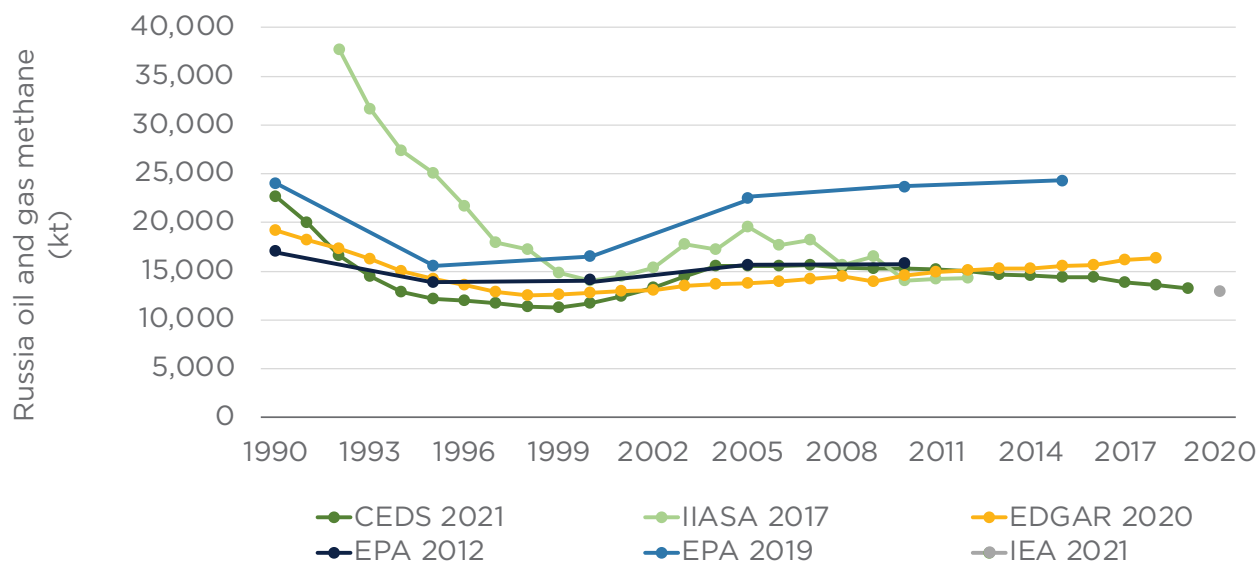


2.2.3 Other Inventories

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 2022e). The tracker's methods are documented in the Global Methane Tracker Documentation (IEA 2022c). The IEA estimated 19 oil and gas sector-level emission intensities for each of the 25 countries responsible for 95 percent of global oil and gas production. First, it estimated emission intensities for each of 19 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 2021b) 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 et al. 2022, Figure 3). For the other 24 countries, the sector intensities were multiplied by country-specific factors. Countries such as Russia, from which satellites detected very large single emitters emitting more than five tons of methane per hour, were given a separate line item titled "satellite-detected large leaks."

Figure 5: Estimates of methane emissions from the Russian oil and gas industry



Note: EDGAR 2020 also includes coal.



The 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 (Höglund-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.

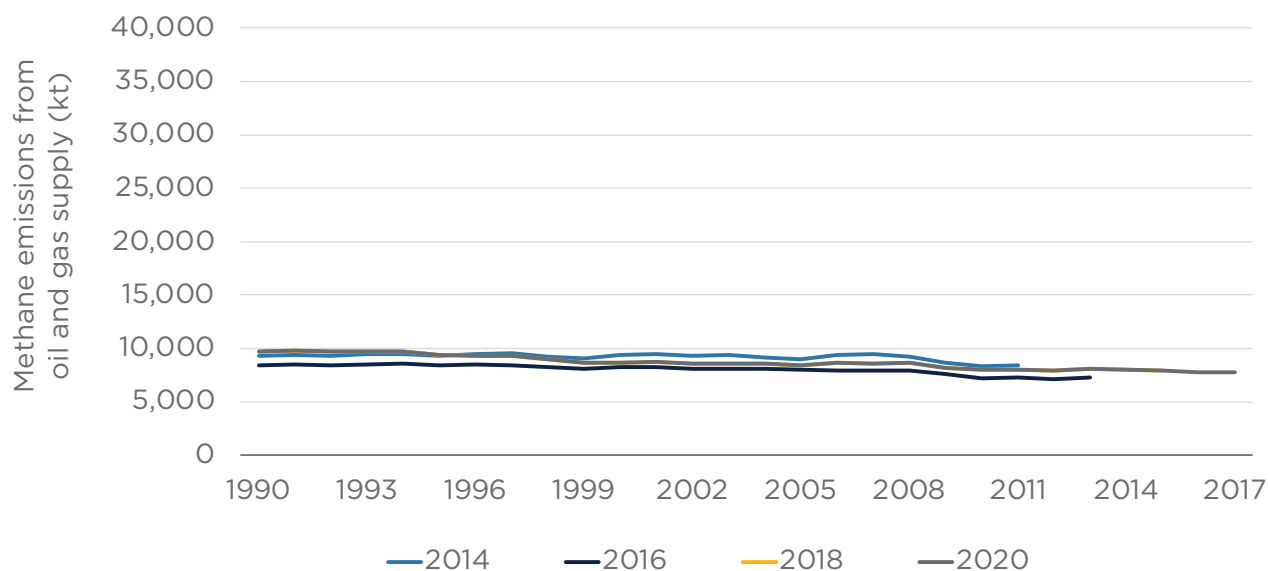
EDGAR is a joint project of the European Commission Joint Research Centre and the Netherlands Environmental Assessment Agency (Crippa et al. 2021) that estimates emissions from fossil fuel supply, including oil, gas, and coal. Its methodology details are published elsewhere (Crippa et al. 2018). In version 4.3.2, EDGAR included 42 years of data, 26 aggregated emission sectors, 226 countries, and 9 substances (EDGAR 2021). The CEDS historical emissions methodology is also published elsewhere (Hoesly et al. 2018). EPA assessments of other countries track the UNFCCC submissions of those countries (EPA 2012, 2019a).

2.2.4 National Inventory Reports—Russia versus the 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 those 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.

The U.S. computations of methane emissions are also much more granular than those of the Russian Federation (EPA 2021b, 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 it 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 2021b, section 2).



Figure 6: Methane emissions for the U.S. oil and gas industry

Note: Figures are recomputed using updated slates of emission factors reported in 2014, 2016, 2018, and 2020.

Source: UNFCCC 2014b, 2016b, 2018b, 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 et al. 2022, Figure 3 and Supplementary Information Table S1). It is widely understood that emission factor methods systematically underestimate methane emissions because of intermittent but very large emission events associated with so-called superemitters (see, e.g., Duren et al. 2019; Lauvaux et al. 2022; Zavala-Araiza et al. 2017). In fact, the larger and more thorough the measurement program, the larger the discrepancy between inventories and measurements (Chen et al. 2022). However, in preparing their NIRs, neither the Russian Federation nor the United States incorporates field measurements of methane emissions from operating equipment, which is not required in the regulations of either country or 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 nongovernmental organizations. This problem is recognized in the Inflation Reduction Act of 2022, which mandates that the reporting of methane emissions be 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 IEA estimates, the two largest sources of oil- and gas-related methane emissions (IEA 2022b). 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., ESA 2022b; NIES 2022), private companies (e.g., GHGSat 2022), and nongovernmental 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 2022a) in theory permit inspection of the entire Earth. These features might lead 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

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

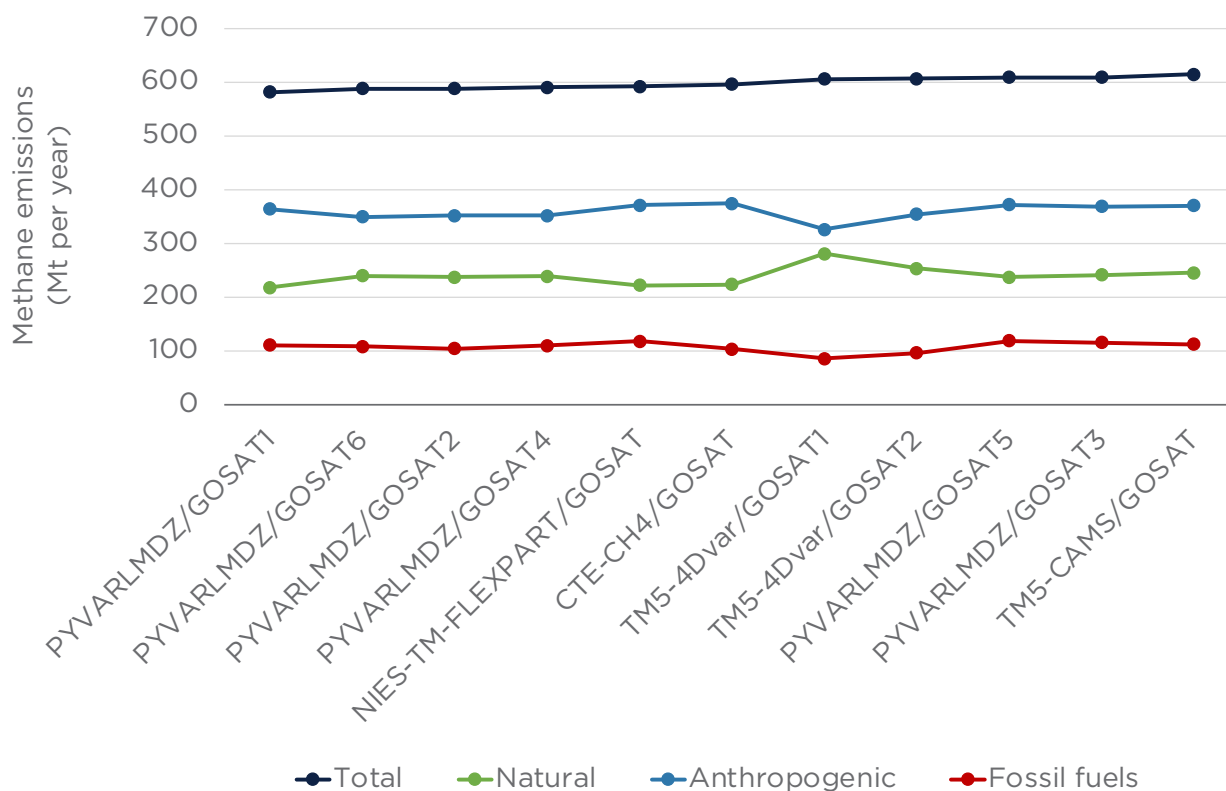
System	Launch	Point-source detection threshold (kg/h)	Coverage pixel size (km × km)	Source
GOSAT	2009		Global (10 × 10)	IEA 2021a; Jacob et al. 2022
TROPOMI	2017	4,000	Global (5.5 × 7)	
MethaneSAT	2024	500	Targeted (0.13 × 0.40)	Jacob et al. 2022
GHGSat—D	2016	1,000–3,000	Targeted (0.05 × 0.05)	
GHGSat—C	2021–2023	100	Targeted (0.025 × 0.025)	McKeever et al. 2021

2.3.2 Nation-Level Top-Down Surveys

The two principal satellite systems used for global and country-level top-down surveys are the Greenhouse Gases Observing Satellite (GOSAT) and Tropospheric Monitoring Instrument (TROPOMI). 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 accurately. Figure 7 shows the result of 11 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.



Figure 7: Global methane emissions in 2017 determined by inversions of GOSAT satellite data performed by various analysts



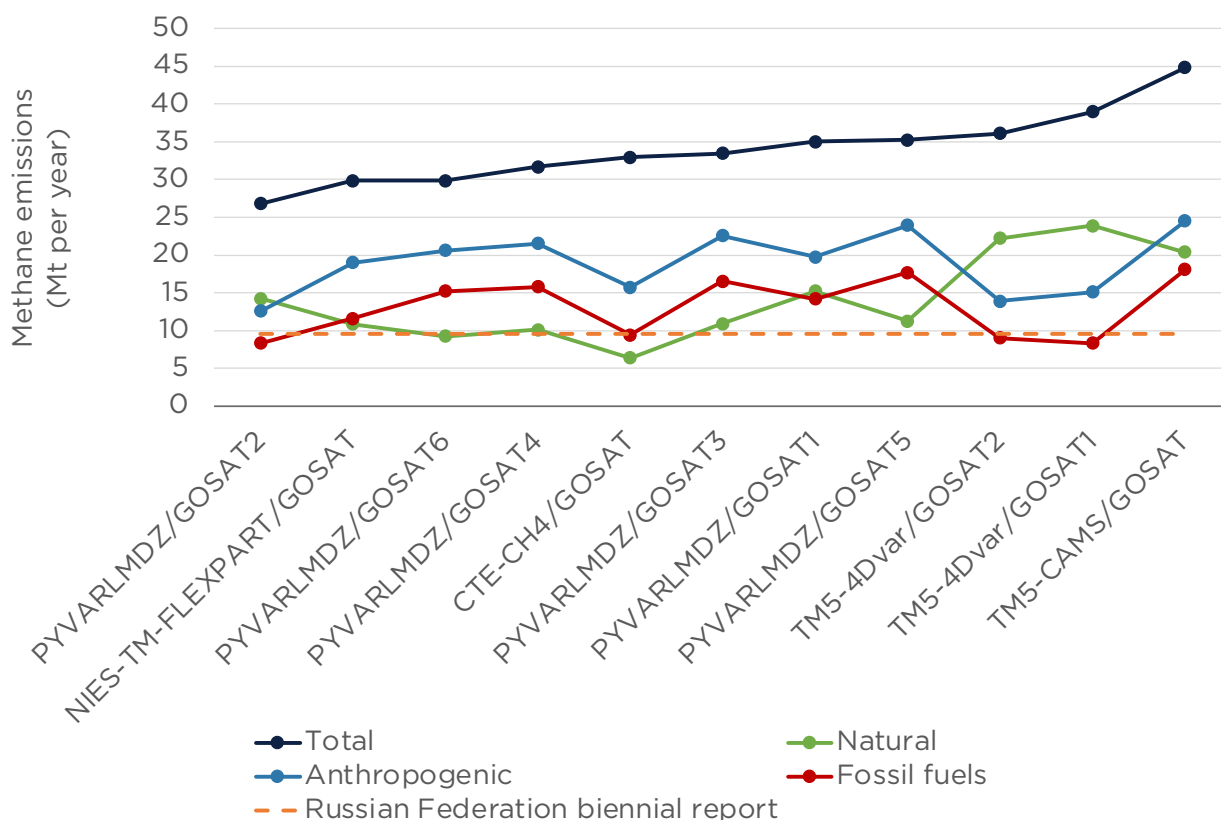
Note: The inversions are named on the horizontal axis. The inversions are ordered according to the total emission rate (black).

Source: Saunio et al. 2020b.

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 in the case of 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.



Figure 8: Russian methane emissions in 2017 determined by inversions of GOSAT satellite data performed by various analysts



Note: The inversions are named on the horizontal axis. The inversions are ordered according to the total emission rate (black). Russian Federation biennial report of methane emissions includes emissions from solid fuels, oil, and gas for 2017.

Source: Saunio et al. 2020b; UNFCCC 2020a.

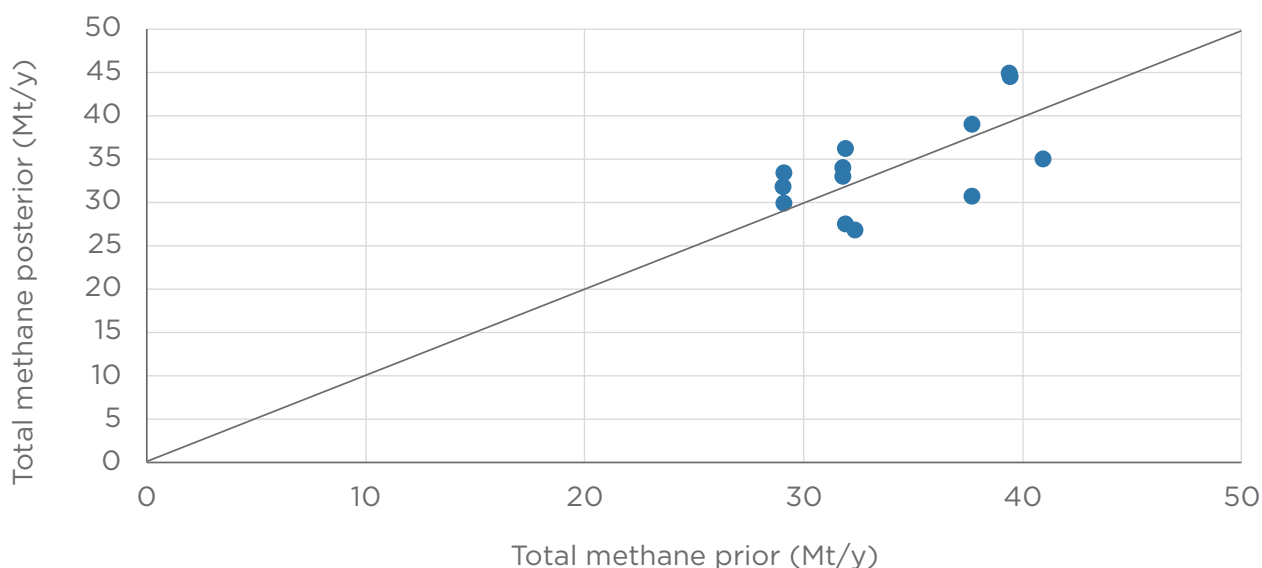
At least some of the scatter of satellite-based determinations is due to the inescapable limitations of the data and processing. Satellite data do not distinguish between natural and anthropogenic sources or between fossil fuel and other anthropogenic sources. Modern inversions use the Bayesian method, an error-minimizing algorithm that is initialized with a set of priors. The priors are the best guesses of outcomes, or posteriors (Saunio et al. 2016, section 4.2.1). As Saunio 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” (725).

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 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 are 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 13 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 13 Bayesian inversions of GOSAT top-down data for total methane emissions in Russia in 2017



Note: The correlation suggests that variations in top-down emission estimates are driven in part by the inventory data used as priors.

Source: Saunio et al. 2020b.

Methane-detecting satellites perform well in arid regions where skies are clear and ground surfaces are homogeneous and not mountainous (Shen et al. 2022). These conditions are found in many of the countries of North Africa and in 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 (EIA 2014; Jacob et al. 2022; Shen et al. 2022, Supplementary Information, Figure S15).

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 et al. 2022). TROPOMI collects much more data than GOSAT, but in its present state of development, it is more susceptible to error in the presence of wetlands (Qu et al. 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” (Saunio et al. 2016, section 5.1.1). However, although satellite-based top-down estimates are imperfect at present, there are many opportunities for improvement (Saunio et al. 2020a, section 6).

2.4 Satellite Measurements of Methane Plumes

While GOSAT is useful for top-down measurements in some environments (Qu et al. 2021), TROPOMI is better able to image plumes of methane emanating from point sources (see, e.g., Pandey et al. 2019; Varon et al. 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 2021a). These plumes account for 6 percent of oil and gas emissions in the countries where they were detected (IEA 2022a). Unlike for 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 (37,000 cubic meters [m^3]) per hour accounted for global annual emissions of eight million tons of methane, approximately one-eighth of which is attributable to Russia (Lauvaux et al. 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 with the Russian Federation's declaration of methane losses from gas pipelines in 2019 (UNFCCC 2021b, Figure 3.47, Tables 3.33 and 3.35). The amount of gas transported in main lines that year was 551 million tons (810 billion m^3). This is greater than total Russian gas production (680 billion m^3). 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} thousand tons per million cubic meters (see Table 2). 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 m in a 10-by-15-km field of view (McKeever et al. 2021).

Unlike GOSAT and TROPOMI, the GHGSat platforms do not scan the entire Earth. Rather, they must be tasked to specific, predetermined 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 those of 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 et al. 2020).



3. METHANE EMISSION REDUCTION

Reducing methane emissions from the oil and gas industry is not necessarily a difficult problem to solve, although 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 (2022d, 2022f) 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 et al. 2020).

In discussing methods for reducing methane emissions, this report uses the 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, 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. Fourth, there is abundant English-language literature, including numerous compendia of guides for engineering practice as examples of methane emission-control practices. Fifth, 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 because of a reliance on inventories untethered from field measurements (Alvarez et al. 2018; Rutherford et al. 2021) and whose environmental regulations based on them have been largely ineffective (Kleinberg 2021b). 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 2021b, 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 and Kutepova 2009; Sorokin 2019).



The main problem with emission inventories as they are 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 CH₄ emissions” (Zavala-Araiza et al. 2017). These heavily skewed distributions have been found for all component and equipment types (Brandt et al. 2016) and all facility types (Cusworth et al. 2021) that have been investigated. Properly characterizing them 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 et al. 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 et al. 2020; Cusworth et al. 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 et al. 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 and Johnson 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 2022a, 2022b). 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 m³) of natural gas (EIA 2022). It is also notorious for its vast methane emissions (Zhang et al. 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 et al. 2021; EDF 2022a, 2022b).

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 (four billion m³ equals 140 billion cubic feet) of methane were lost from



the Permian Basin in one year (Zhang et al. 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 that 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 et al. 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. Contractors that have successfully performed large-scale aerial surveys in the United States and Canada include Aerial Production Services, Baker Hughes, Bridger Photonics, Carbon Mapper, Kairos Aerospace, LaSen, Scientific Aviation, and SeekOps.

Remarkably, this industry has grown in the absence of regulatory mandates. The EPA deems only two methods legally acceptable for volatile organic compound (VOC) and methane leak detection, both of which involve ground-based handheld 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 LDAR (EPA 2021a).

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 2022; Alden et al. 2020). 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 et al. 2022). Although currently at different 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. Oil field equipment must operate faultlessly in arctic, desert, tropical, and marine environments and 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 overpressure, 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



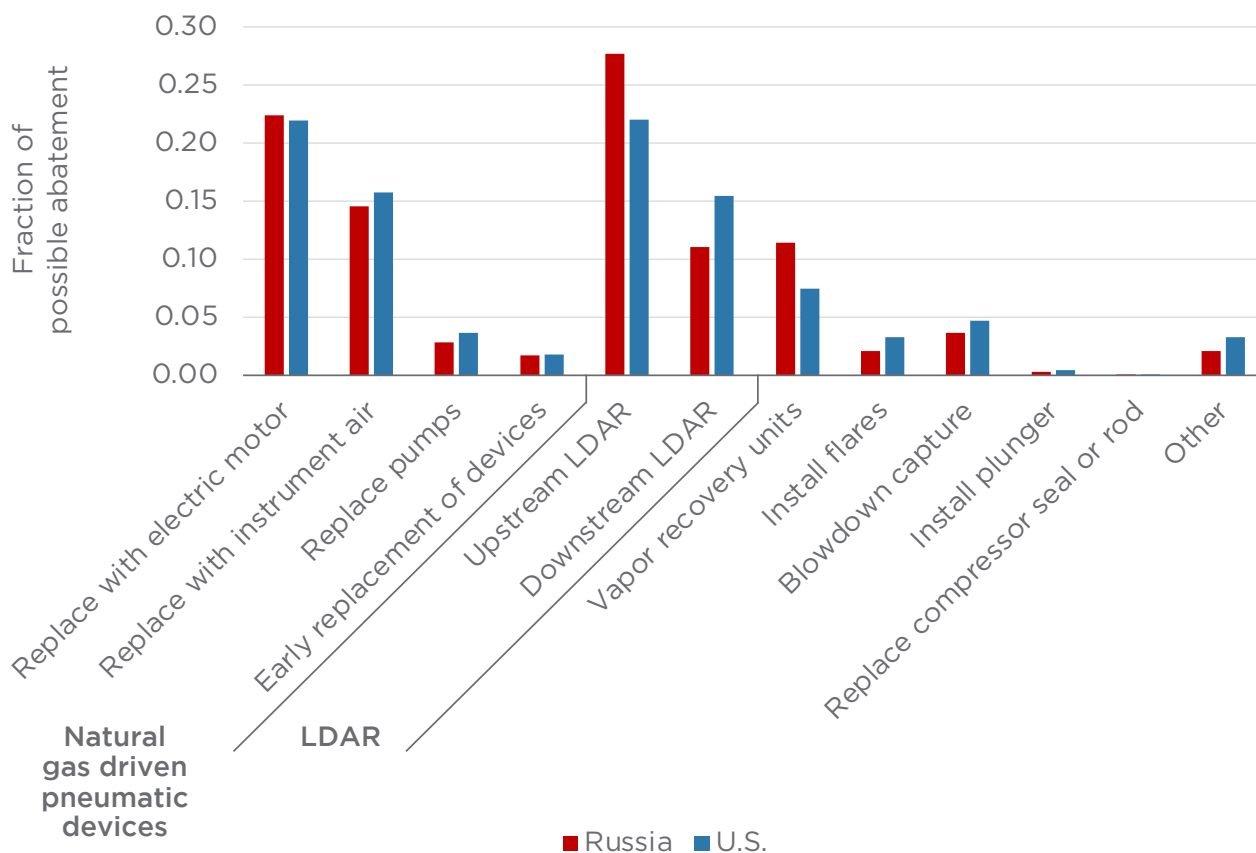
carbon dioxide, this is less damaging than allowing methane into the atmosphere, as shown below. These solutions do not always work. But problems must be solved in the context of an industry that operates at almost unimaginable scale, producing 1,000 barrels of oil per second, 30 million seconds per 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 catalog 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 5, 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. Oil field problems are best solved in the oil field. 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 (see, e.g., IEA 2022c, 2022d, 2022f). Possible abatements are divided into 12 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 and the Russian Federation



Source: IEA 2022d, 2022f.

Regulations that seek to limit methane emissions, such as 40 CFR 60 Subpart OOOOa in the U.S. 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.

Handheld 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. If the goal is to limit both types of sources, regulations should be changed.



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.

Table 4: Nationwide U.S. emission and cost analysis for optical gas imaging LDAR of oil and gas well sites (New Source Performance Standards Regulatory Option 2: semiannual inspections) and compressor stations (Regulatory Option 3: quarterly inspections)

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					7,868,000

Note: For comparison, the bottom row includes reported vented, fugitive, and flared methane emissions from petroleum and natural gas systems, 2019.

Source: EPA 2016a, Tables 9.3 and 9.4; EPA 2021b.

The costs and benefits of LDAR 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 appear in Table 4, which shows that the LDAR rules were estimated to reduce methane emissions from the U.S. oil and natural gas sector by 169,646 tons at an approximate nationwide cost of \$227 million in 2020. 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 2016b, 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 4.

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 et al. 2022). Gazprom confirmed that 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 5.

Table 5: Guidance for engineering controls to reduce methane emissions from the oil and gas industry

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

Note: All websites 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 2021b). 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, primarily comprising methane and VOCs. 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 of 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 2021b). 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 (2021b). A study of several such regulatory failures concluded that to be effective, engineering controls and performance-based regulations must include measurement requirements (Kleinberg 2021b).

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 also readily detectable by Earth-orbiting satellites (Elvidge et al. 2016). One recently published study quantified the veracity of company-reported flaring in Russia (Zhizhin et al. 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 2022b). Oil is not only more valuable than gas but also much easier to transport. The only two practical methods for transporting gas in bulk are in high-pressure pipelines (1.4–10 MPa = 200–1,500 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, pages 7–9).

The World Bank Zero Routine Flaring by 2030 initiative has attracted the endorsement of 34 governments, 54 oil companies, 15 development organizations, and 6 supporting organizations. 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” (World Bank 2022a). 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).

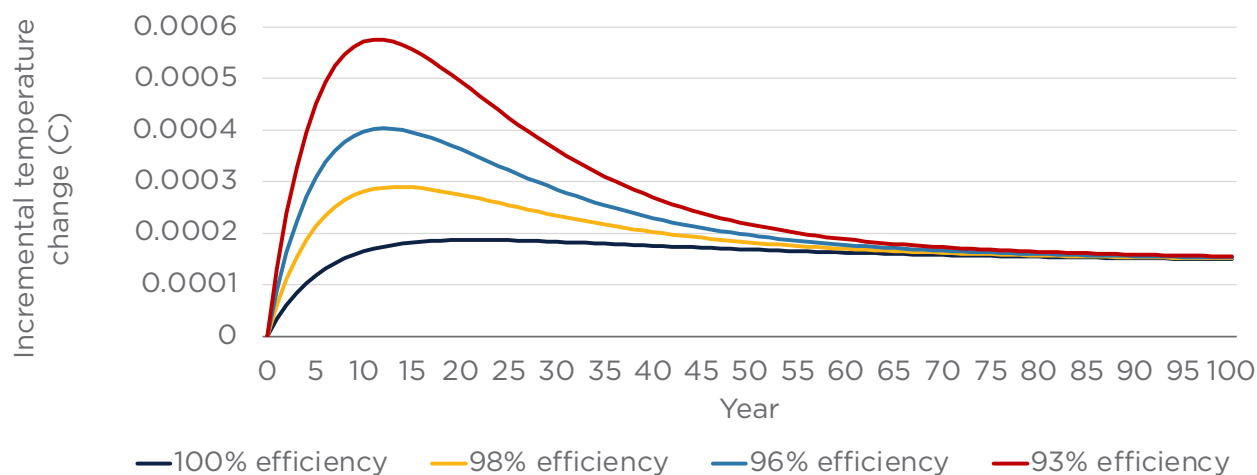
While routine flaring has been in the spotlight, less attention has been paid to event-driven flaring, during which gas must be released for safety and other operational reasons. Data from the Permian Basin show that event-driven flaring can be consequential (Rystad 2021).

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.

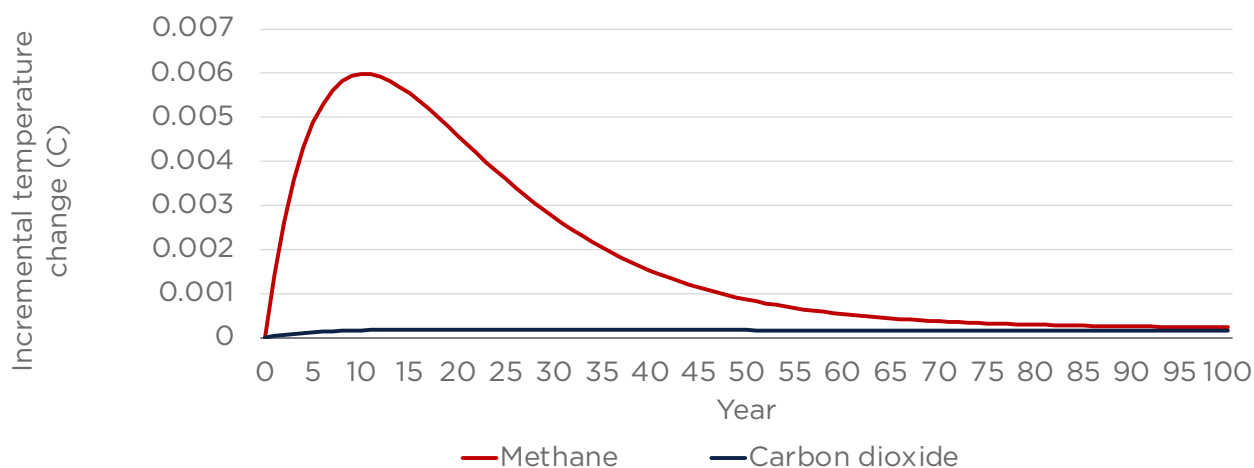
Figure 11: Effect of flare inefficiency



Note: Temperature change is a result of one year of flaring 100 percent methane at the global rate of natural gas flaring, 146 billion m³ per year, with various levels of efficiency.

Source: Kleinberg 2020.

Figure 12: Effect of venting 146 billion m³ of 100 percent methane at year zero versus flaring it at 100 percent efficiency to carbon dioxide



Note: The vertical axis of this figure differs from that of Figure 11.

Source: Kleinberg 2020.



Unfortunately, low-efficiency and unlit flares are common. Aerial surveys of the Permian Basin have found that more than 5 percent of active flares are malfunctioning and an additional 5 percent are unlit. This demonstrates that EPA estimates of methane emissions from flares in the basin are seriously in error (EDF 2022a, 2022b).

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 and Mahdavi 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 to be comparable to those from oil and gas sources. Moreover, a recent discovery of unexpected gigantic methane emissions from a Russian open-pit coal mine (Amos 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 2019a). 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, which generates heat as a by-product, and regenerative catalytic oxidation, 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 2019b). 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 et al. 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 m³ of methane per year. The density of methane



at international oil field standard conditions (15°C, 101.325 kPa) is 678.37 g per standard m³ (Kleinberg 2019), so the produced gas amounts 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 2022b, 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 percent of current total U.S. oil- and gas-related methane emissions are profitable to repair (IEA 2022f), 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 percent of current total Russian emissions are profitable to repair (IEA 2022d), 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 6.

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 LDAR 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.

Table 6: Characteristics of prescriptive and performance-based regulations

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



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 oil field 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, the 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 at a factor of 10 more than the average low-bleed controller (EPA 2021b, Additional Information, Methodology Annexes). However, since intermittent-bleed controllers are unregulated, this has been largely ignored by the industry.

If EPA regulations command the 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 VOC emissions from storage vessel-affected facilities. The EPA directs owners or operators to determine the potential for VOC emissions and reduce VOC emissions by 95 percent from that level (40 CFR 60.5395a(a)(1)–(2)). Performance-based regulations can fail when they lack a mechanism to verify compliance quantitatively, as they have in the case of oil field storage vessels (Kleinberg 2021b).

Broader society has no interest in the kinds of valves used in the oil field 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 30 g 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. Oil field 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 (Kleinberg 2021a).

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 kg 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 oil field, emissions data are 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 et al. 2022), and company-specific performance data are already being compiled (Berman and Deiker 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 reporting requirements and 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 the suppression of methane emissions could be strengthened. A theory of adaptive regulation has been designed to address this situation (Bennear and Wiener 2019). However, such tools are not commonly used in developing international agreements such as those of the UNFCCC.



5. CONCLUSIONS

It is a timeworn adage that “you cannot manage what you cannot measure,” and methane emissions 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 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 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, because of 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 5) 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 and natural gas, and it 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.



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