WORLDWIDE INFERENCE OF NATIONAL METHANE EMISSIONS BY INVERSION OF SATELLITE OBSERVATIONS WITH UNFCCC PRIOR ESTIMATES

This brief is based on a research paper by James D. East, et al.: "Worldwide inference of national methane emissions by inversion of satellite observations with UNFCCC prior estimates." The paper is published in Nature Communications and available here: http://doi.org/10.1038/s41467-025-67122-8. See full reference and acknowledgements at the end of this brief.

Results from the analysis, including methane emissions estimates for individual sectors and 161 countries, are available in an interactive online portal developed by John Thomas, one of the co-authors, at https://worldwidemethaneemissions.com

Summary

Methane is the second-most important greenhouse gas (GHG) after carbon dioxide. Efforts to reduce methane emissions under the Paris Agreement and Global Methane Pledge require nations to set mitigation targets and quantify reductions. However, the methods widely used to report emissions to the United Nations Framework Convention on Climate Change (UNFCCC) are subject to large uncertainties. This study uses inverse analysis of satellite observations of atmospheric methane concentrations from the Tropospheric Monitoring Instrument (TROPOMI), together with emissions information from UNFCCC reports and other data sources, to develop optimized estimates of 2023 emissions, at up to 25 km grid resolution, for 161 countries. Results suggest that global anthropogenic emissions are 15% higher than previously reported to the UNFCCC and 32% higher for the oil and gas sector in particular. For 44 countries, the new estimates exceed prior national totals reported to the UNFCCC by more than 50%. Emission intensities in the oil and gas sector vary by two orders of magnitude between countries. Sub-Saharan Africa has the highest livestock emissions intensity of any region. Hydroelectric reservoirs, which are generally not included in UNFCCC reporting, are estimated to contribute 6% of anthropogenic methane globally. Importantly, the analytical framework developed for this study can be used to update country and sector estimates in future years, enabling improved monitoring and reporting of methane trends and more effective implementation of multilateral efforts to reduce global emissions.

Background and context

Methane (CH_4), a short-lived but potent GHG, has drawn increased attention from policy makers in recent years as a major driver of near-term warming. Methane concentrations in the atmosphere have been rising at an average rate of 0.6% per year for the past decade,[1] largely due to increasing emissions from anthropogenic sources, including livestock, coal mines, oil and natural gas extraction, landfills and wastewater, and rice cultivation. Methane is also emitted from natural sources, primarily wetlands.[2]

Under the Global Methane Pledge, 159 nations plus the European Commission have committed to collectively reduce methane emissions 30% below 2020 levels by the year 2030. (https://www.globalmethanepledge.org). Countries that are party to the UNFCCC are also required to include estimated methane emissions in their national GHG inventories and in their Nationally Determined Contributions (NDCs) for GHG mitigation. There are large uncertainties around these estimates, however, because they are often calculated by applying generic emission factors (e.g., methane emitted per unit of oil production) to measures of activity (e.g., oil production) that are difficult to quantify. Uncertainty around actual emissions, in turn, risks undermining confidence in country NDCs and in the efficacy of collective mitigation actions. Thus, a better system for developing and evaluating methane inventories using common, consistent, and closer-to-real-time data is needed.

Recent advances in modeling tools and methods that allow researchers to infer emissions from satellite observations of atmospheric methane concentrations can provide the basis for such a system. A number of studies have used satellite observations to analyze individual methane point sources and regions, but computational limitations have, until recently, compromised the ability to separate emissions by country and even more by sector. This study makes use of improved software — specifically, the open-source, user-friendly, cloud-based Integrated Methane Inversion (IMI) version 2.0 modeling tool — to develop a transparent, globally consistent, and updateable framework for quantifying country- and sector-level emissions worldwide. It also compares results obtained by applying this framework to methane estimates from the latest UNFCCC reports and other sources.

Data and methods

The inversion analysis uses 2023 TROPOMI observations at 25-km grid resolution together with the GEOS-Chem chemical transport model and point source information from GHGSat to estimate methane emissions for 161 countries. The world's land masses are tiled with eight regional inversions, which relaxes computing requirements, gives better control of boundary conditions, and avoids effects of errors on the chemical loss. The inversion framework and parameters are consistent across the regional inversions, leading to a globally consistent system. The IMI software tool solves the Bayesian cost function analytically to obtain best posterior estimates of gridded emissions with closed-form error characterization and the ability to readily generate inversion ensembles by varying inversion parameters.

TROPOMI observations are from the blended TROPOMI+GOSAT product of Balasus *et al*.,[3] which corrects TROPOMI artifacts using the more precise but much sparser observations from the Greenhouse Gases Observing Satellite (GOSAT) satellite. The inversions use country reports to the UNFCCC, spatially allocated following bottom-up inventories, as prior emission estimates so that results can be directly interpreted as corrections to these estimates. Prior emissions for the few countries that are not reporting to the UNFCCC are estimated using Tier 1 methods from the Intergovernmental Panel on Climate Change (IPCC). The full study provides further details concerning the inversion methodology, the attribution of emissions to countries and sources, data sources and availability, and uncertainty analysis.

Inversion results for global and national emissions and comparison to UNFCCC reports

The authors' best posterior estimate for global methane emissions in 2023 is 598 (475–625) Tg a^{-1}, where parentheses indicate the range from the inversion ensemble. This is higher than the prior estimate of 536 Tg a^{-1} from UNFCCC reports and consistent with the Global Carbon Project top-down estimate of 608 Tg a^{-1} for 2023.[4] Global anthropogenic emissions are estimated at 375 (299–392) Tg

a^{-1}, which is 15% larger than the global total from UNFCCC reports (326 Tg a^{-1}). The anthropogenic total includes 313 Tg a^{-1} from UNFCCC-reporting countries for livestock, waste, oil-gas, coal, and rice; 13 Tg a^{-1} from countries not reporting to the UNFCCC (with Pakistan as the largest emitter in this group); 24 Tg a^{-1} from hydroelectric reservoirs, and 26 Tg a^{-1} from minor anthropogenic methane sources that are not consistently included in UNFCCC reports, including emissions from combustion and some industrial processes. The global total from this analysis also includes 188 Tg a^{-1} from wetlands.

Figure 1 shows the geographic distribution of global emissions from this study and compares results for major anthropogenic source sectors to prior estimates in UNFCCC reports. It shows that the inversion analysis yields a higher estimate of global emissions for most sectors, including livestock (17% higher than the UNFCCC total), waste (16% higher), oil and gas (32% higher), and rice (26% higher). Coal is the only sector for which the inversion analysis yields a *lower* global emissions total (24% below UNFCCC reports).

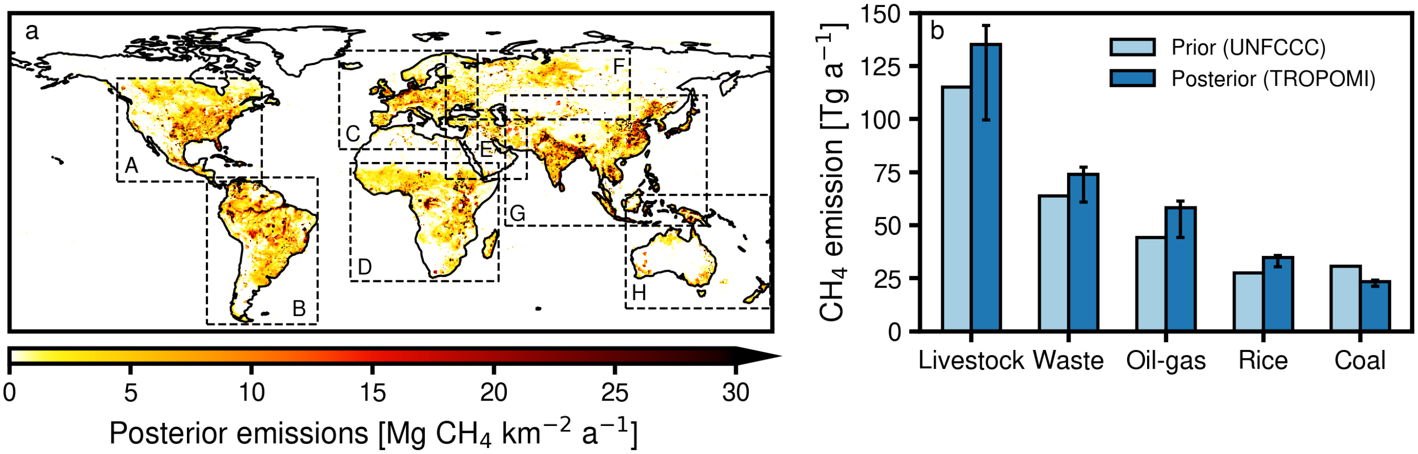

Fig. 1 | Global methane emissions in 2023 estimated by inverse analysis using TROPOMI observations and UNFCCC prior estimates: (a) *posterior emissions from eight regional inversions (boxes A-H show the regional inversion domains);* ***(b)*** *global emissions for major anthropogenic sectors, with error bars from the inversion ensemble.*

Figure 2 shows results of the inversion analysis for the top 15 methane emitting countries. Collectively these countries account for 61% of the global anthropogenic emissions total. The four largest emitters — China, the United States, India, and Brazil — account for nearly 40% of the global total.

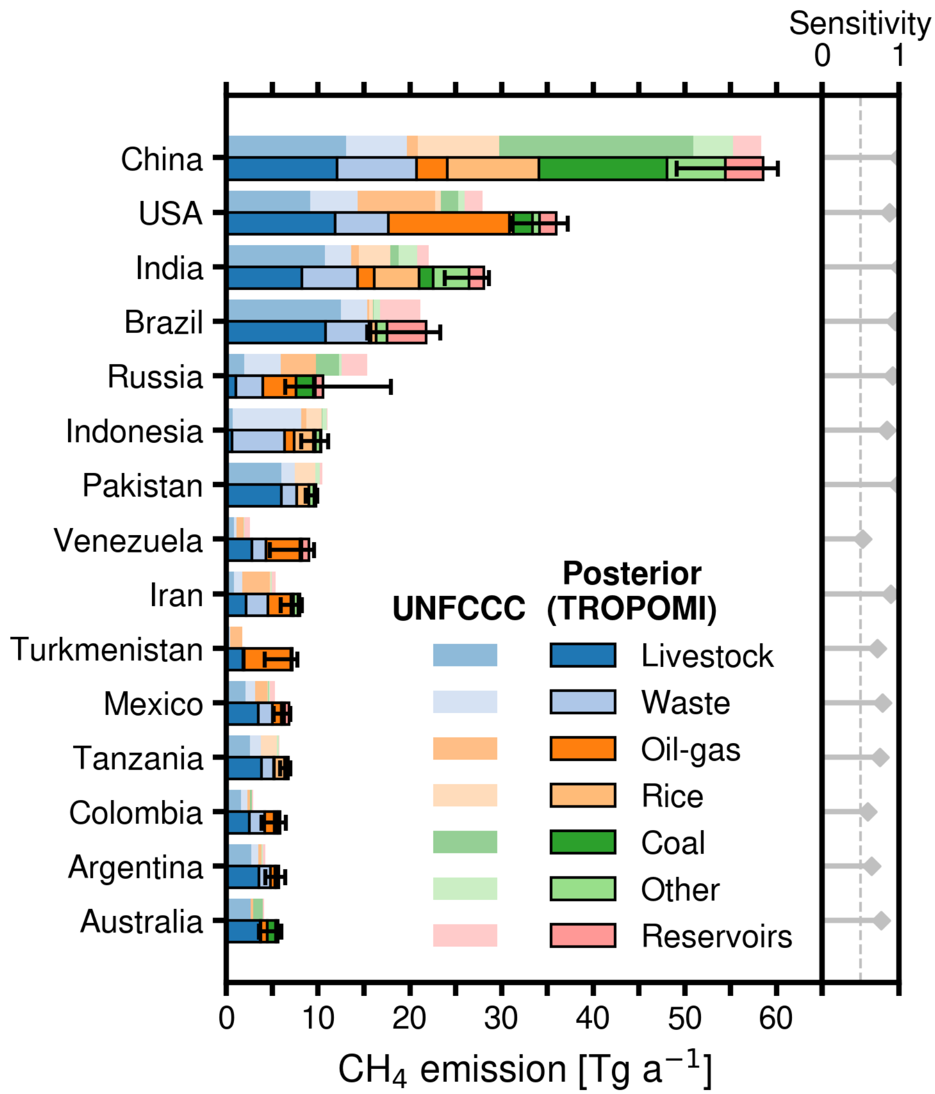

Fig. 2 | National anthropogenic methane emissions from the 15 highest-emitting countries in 2023. *Best posterior estimates from the TROPOMI inversion, with error ranges from the inversion ensemble, are compared to UNFCCC reports, including for individual sectors. Grey markers show the sensitivity of the inverse estimate to TROPOMI satellite observations as obtained from the trace of the averaging kernel matrix (labeled Sensitivity, see Methods discussion in the full study). Dashed grey line shows averaging kernel sensitivity value 0.5.*

For more than a quarter (44) of the 161 countries included in the analysis, emissions calculated using the 2023 TROPOMI data exceed national totals reported to the UNFCCC by more than 50%. In another quarter of countries, the inversion analysis yields national totals that are at least 23% lower than the latest UNFCCC reports. The largest discrepancies are seen in estimates for the U.S., Venezuela, India, and Turkmenistan, which all have significantly higher emissions in this analysis; the largest downward corrections are seen for Russia and the Democratic Republic of the Congo.

Sectoral emissions and intensities for individual countries

Figure 3 shows posterior emissions and emission intensities by sector for the ten highest emitting countries in each sector, along corresponding values from the UNFCCC reports. Emission intensities are computed by dividing posterior emissions by activity levels for each sector.

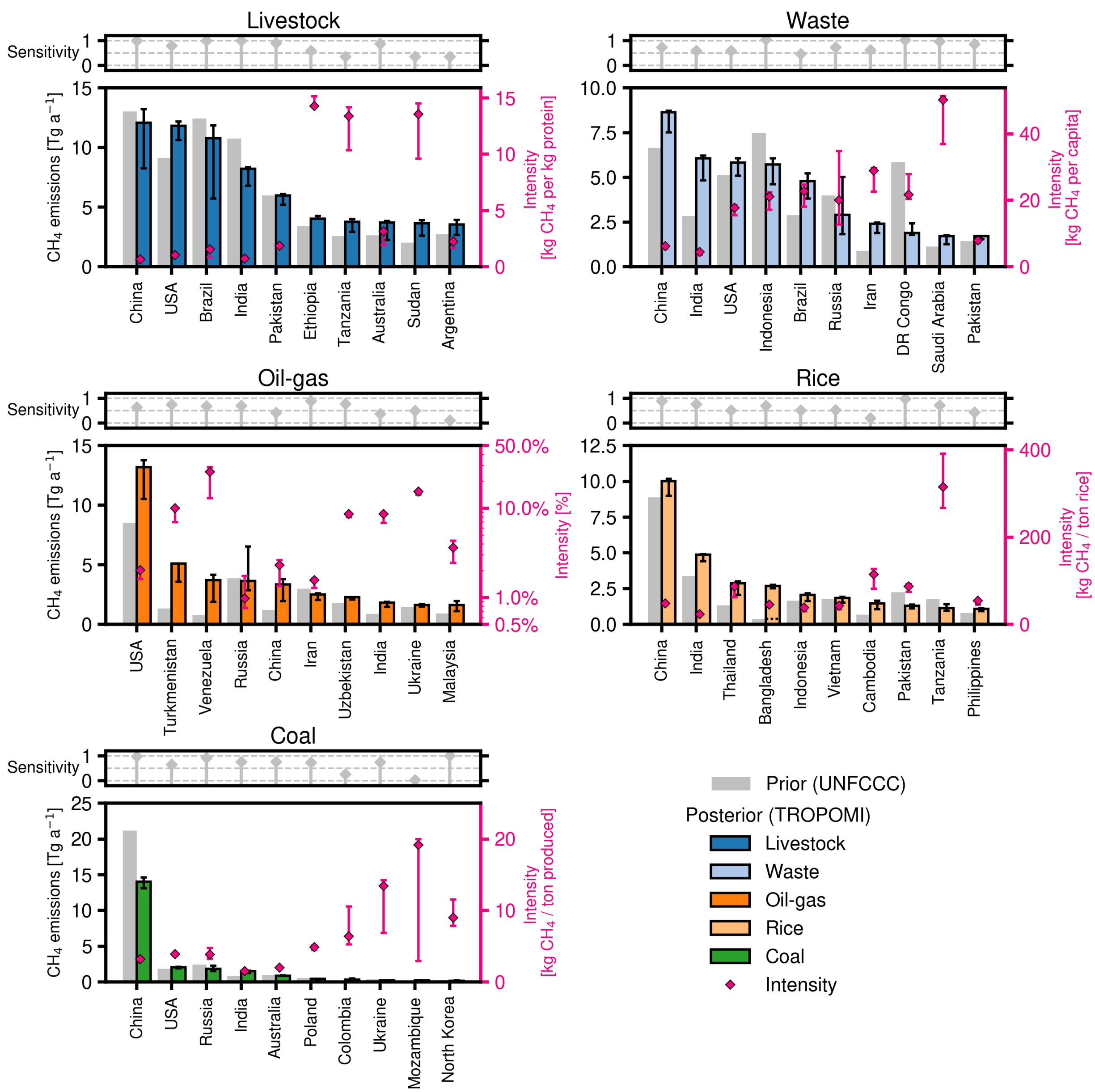

***Fig. 3 | National methane emissions and intensities from different sectors.** Best posterior estimates from the TROPOMI inversion for 2023 (with ranges from the inversion ensemble) are compared to UNFCCC reports. Intensities are computed from the posterior emissions and activity levels. Gray markers show averaging kernel sensitivities, with grey dashed lines at 0.0, 0.5, and 1.0 for visualization. Additional details concerning sources of data on activity or production levels are provided in the full study.*

Livestock: China, the United States, Brazil, and India are the top emitters from the livestock sector. Worldwide, most of the change to UNFCCC reports comes from lower emitting countries, with a +2.9 Tg a^{-1} net change for the top 10 countries and a +17.0 Tg a^{-1} net change for remaining countries. The largest increases are in East Africa (notably Kenya, Sudan, and Tanzania) and the Middle East (particularly Turkmenistan and Iran). In Brazil, the authors find a decrease from the UNFCCC report (-1.6 Tg a^{-1}). Across Sub-Saharan Africa, the methane intensity of protein production is notably higher than in North America and South and East Asia, possibly because of lower livestock productivity.

Waste: China and India have the highest combined emissions from wastewater and landfills, which the authors report together as waste, but the lowest per-capita intensity. The largest changes from UNFCCC reports for this sector are seen for the Democratic Republic of the Congo (-68%; -4.0 Tg a^{-1}) and

India (+117%; +3.3 Tg a^{-1}). In China, rapidly increasing waste incineration rates may contribute to lower intensity,[5] while low per-capita waste production in India leads to lower intensity. Treating wastewater could reduce methane emissions in countries with high emissions intensity and low rates of wastewater treatment, such as Indonesia, the Democratic Republic of the Congo, and Iran.[6,7]

Oil–gas: The U.S. has the largest oil–gas sector emissions at 13.2 Tg a^{-1}. This represents a large upward correction (+4.7 Tg a^{-1}) to the prior UNFCCC estimate (previous undercounting of U.S. oil and gas emissions has already been widely reported). The inversion analysis also indicates upward corrections for this sector in Turkmenistan (+3.8 Tg a^{-1}), Venezuela (+2.9 Tg a^{-1}), and China (+2.2 Tg a^{-1}). Results for the Russian oil and gas sector are in line with that country's UNFCCC report, but there are large uncertainties (other inversion analyses have produced higher estimates).

The study also examines the methane emissions intensity of natural gas production for the 40 top natural gas producing countries. It finds that five countries are meeting the 0.2% methane intensity target put forward by the Oil and Gas Climate Initiative (OGCI) (among these countries, Norway and Qatar are the largest producers). If all countries met the OGCI target, global emissions from the oil and gas sector would drop 81% to 11.0 Tg a^{-1} and become minimal relative to other sectors. The highest oil-and-gas emission intensities are seen in Venezuela, Ukraine, Colombia, and Turkmenistan, whereas some of the largest producers, including China, the U.S., Iran, Canada, and Rusia, have much lower intensities.

Rice: Six countries — China (10.0 Tg a^{-1}), India (4.9 Tg a^{-1}), Thailand (2.9 Tg a^{-1}), Bangladesh (2.7 Tg a^{-1}), Indonesia (2.1 Tg a^{-1}), and Vietnam (1.9 Tg a^{-1}) — dominate global methane emissions from rice cultivation. At a global level, the discrepancy between posterior results from this analysis and previous estimates is not large but there are significant changes from individual countries' reports, most notably in the case of Bangladesh, where this study's estimate is seven times higher than previously reported to the UNFCC. Consistent with other studies, the authors also find higher emissions from rice cultivation in China compared to that country's UNFCCC report.[8]

Coal: China accounts for the dominant share (60%) of global methane emissions from coal mining. This study's estimate of 14.0 Tg a^{-1} from coal in China is lower than the UNFCCC estimate of 21.2 Tg a^{-1}, with most of the difference coming from the Shanxi region. This result aligns with an ongoing shift in Chinese coal production to surface mines that have lower emissions, with some of the reduction seen in the inversion analysis offset by accounting for emissions from abandoned mines in southern China that continue to emit.[9]

Compared to UNFCCC reports, the authors find a 0.6 Tg a^{-1} decrease in coal emissions from Russia, a 0.6 Tg a^{-1} increase from India, and negligible changes to U.S. coal emissions. Though Indonesia is the world's second largest coal producer, the inversion analysis cannot provide a correction to the low coal methane estimates reported to the UNFCCC due to a low density of satellite observations over this region.[10]

Discussion

Inversions of TROPOMI satellite observations can be used to improve bottom-up emission estimates, help governments identify sectors where previous estimates are too low or too high, and track progress toward NDCs. In turn, more accurate bottom-up inventories can improve the results obtained through inversion analyses. Future satellite observations can benefit from higher spatial resolution or intelligent pointing, which shows promise for providing increased observation density.[11,12] Information on the spatial and temporal variability of emissions, which is generally lacking in UNFCCC reports, is also critical for the inversion analysis. Incorporating spatial and temporal information in future inventories would be helpful and improve the sectoral attribution of inversion results.[13]

Improved characterization of the spatial and seasonal distribution of wetland emissions, along with their interannual variability, is also important, particularly to enable improved attribution of anthropogenic emissions in inversions. Current wetland emission inventories have large uncertainties[14,15] and there is extensive spatial overlap of wetland and anthropogenic emissions, for example for the oil and gas sectors in Canada and Nigeria, for livestock in South America and Africa, and for rice in Bangladesh and Southeast Asia. New satellite-based observation products could be useful for this purpose.[16]

Reference to full paper and acknowledgements

A more detailed account of the research on which this brief is based may be found in: James D. East, Daniel J. Jacob, Dylan Jervis, Nicholas Balasus, Lucas A. Estrada, Sarah E. Hancock, Melissa P. Sulprizio, John Thomas, Xiaolin Wang, Zichong Chen, Daniel J. Varon, and John R. Worden. "Worldwide inference of national methane emissions by inversion of satellite observations with UNFCCC prior estimates." *Nature Communications*. December 2025. http://doi.org/10.1038/s41467-025-67122-8.

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About the Program

The Harvard Methane Initiative seeks meaningful and sustained progress in reducing global emissions of this very important greenhouse gas — through research and effective engagement with policymakers and key stakeholders. This Initiative is supported by the Salata Institute for Climate and Sustainability at Harvard University. The Harvard Methane Initiative and other Research Clusters supported by the Salata Institute comprise interdisciplinary teams of researchers from across Harvard's schools, whose varied expertise is required to address the complexity of the climate-related problems that they seek to solve. Robert N. Stavins, A.J. Meyer Professor of Energy and Economic Development at Harvard Kennedy School, directs the Harvard Methane Initiative. The findings, views, and conclusions in this publication are those of the authors alone.