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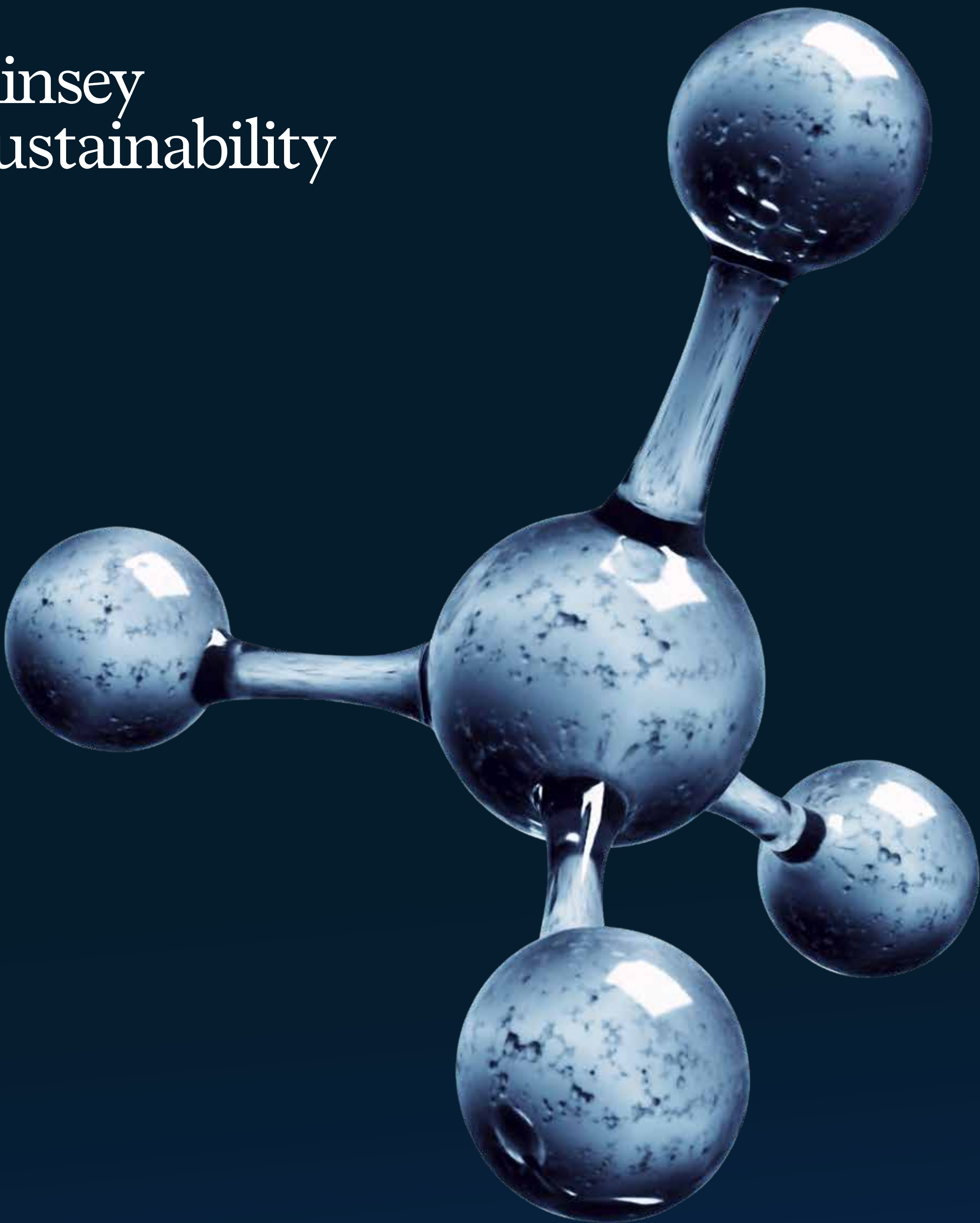

Curbing methane emissions

How five industries can counter a major climate threat

September 2021

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How five industries can counter a major climate threat

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Executive summary

Attaining a 1.5°C pathway would require cutting anthropogenic emissions of methane, a powerful greenhouse gas—and companies around the world can play a decisive role in this agenda. Methane emissions from human activities, which represent the second-largest contributor to global warming after carbon dioxide, have reached approximately 380 million metric tons per year.[1] They have risen by around 25 percent in the past 20 years, in sharp contrast to the 2 percent annual decline required to meet the objectives of the Paris Agreement on climate change.[2] According to our analysis, five industries could take actions that would have a significant impact on methane emissions, reducing annual methane emissions by 20 percent by 2030 and by 46 percent by 2050. This impact could be achieved largely with established technologies and at a reasonable cost: 90 percent of these reductions could come at a cost of less than $25 per metric ton of carbon dioxide equivalent (tCO_2e).[3]

This report maps sources of methane emissions, analyzes future scenarios, and details potential abatement measures in five industries that now account for 98 percent of human emissions: agriculture, oil and gas, coal mining, solid waste management, and wastewater management. The report provides a perspective on the mitigation potential, cost, and impacts of current methane abatement technologies. It also highlights where innovation may create opportunities in the future. Decision makers in these five key industries can use these insights to build and carry out their companies' approaches to methane abatement, as some leading organizations have already begun to do.

Global temperatures in 2021 are 1.1°C higher than preindustrial levels,[4] with anthropogenic methane emissions being the second-largest driver of that warming.[5] Methane stays in the atmosphere for about a decade—a relatively brief period compared with carbon dioxide. However, it is a potent greenhouse gas, and it accounts for around 30 percent of today's observed warming.[6] Moreover, as temperatures continue to rise, climate feedbacks could accelerate the warming impact of methane from sources in the Arctic, wetlands, and landfills. In the Arctic, for example, permafrost releases methane as it thaws. On the current emissions trajectory, permafrost release alone could add an incremental 5 to 20 percent to long-term methane emissions.[7]

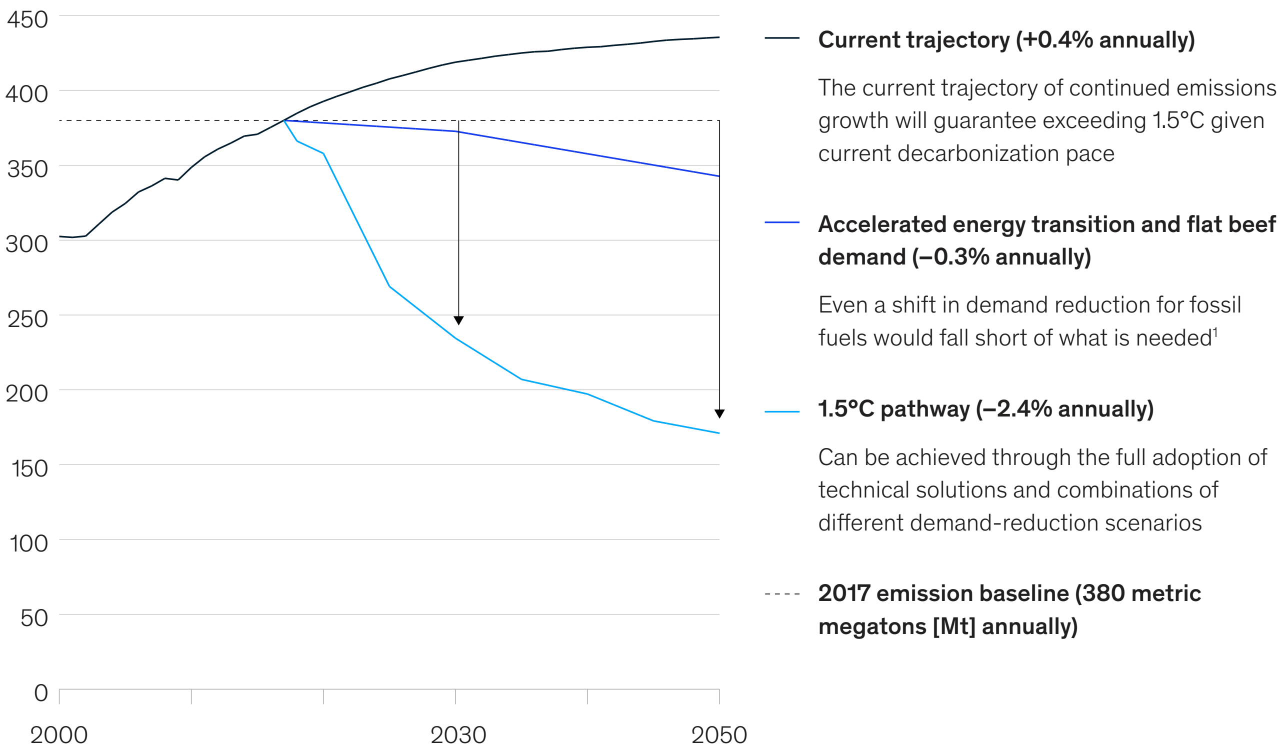
1 Marielle Saunois et al., "The global methane budget 2000–2017," *Earth System Science Data*, 2020, Volume 12, Number 3, pp. 1561–1623, essd.copernicus.org.
2 Under the 2015 Paris Agreement, 195 governments agreed on an objective to limit warming to well below 2.0°C, and preferably to 1.5°C.
3 Global warming potential on a 20-year time frame (GWP20) is used to convert methane into carbon dioxide equivalents (1 metric ton of methane equals 84 metric tons of carbon dioxide) for the sole purpose of calculating abatement costs. Use of global warming potential (GWP) is covered in more detail within the report.
4 The increase in global average temperatures is defined over a multi-decade period, rather than an individual year. Although warming in 2021 has reached 1.2°C, the current decadal average (2011–20) is reported as 1.1°C, of which 30 percent is contributed by methane. *Sixth assessment report* (AR6), Intergovernmental Panel on Climate Change (IPCC), August 2021, ipcc.ch.
5 There are significant regional variations in warming. Parts of the Arctic in the Northern Hemisphere have already warmed more than 5.0°C above preindustrial levels. *The state of the global climate 2020: Unpacking the indicators*, World Meteorological Organization (WMO), April 2021, public.wmo.int.
6 Defined as the net warming contribution from methane as a share of the 1.1°C of observed global warming, provided in Figure SPM.2. This net warming can be derived by taking the gross positive contribution of methane (0.5°C) and subtracting its proportional share of gross negative contributions (–0.2°C) from cooling agents, such as aerosols. *Sixth assessment report* (AR6), Intergovernmental Panel on Climate Change (IPCC), August 2021, ipcc.ch.
7 T. Gasser et al., "Path-dependent reductions in CO_2 emission budgets caused by permafrost carbon release," *Nature Geoscience*, September 2018, Volume 11, pp. 830–5, nature.com.

In 2018, the Intergovernmental Panel on Climate Change (IPCC) estimated[8] that the world's remaining carbon budget to keep warming below 1.5°C was 570 metric gigatons of carbon dioxide ($GtCO_2$).[9] Humans emit 41 $GtCO_2$ a year, meaning that, on the current emissions trajectory, the budget would be exhausted by 2031. Critically, the IPCC's remaining carbon budget assumes the world would reduce methane emissions by more than 2 percent a year, reaching 37 percent below 2017 levels by 2030 and 55 percent by 2050 (Exhibit E1).[10] These targets were reaffirmed in the IPCC's *Sixth Assessment Report* (AR6) in 2021, which called for "strong, rapid and sustained reductions in methane emissions." Failure to hit these targets would effectively put the 1.5°C objective beyond reach. Exceeding the IPCC's targets for methane emissions, on the other hand, would increase the remaining CO_2 budget before the 1.5°C threshold is crossed and thereby support a more gradual and less disruptive transition to net-zero greenhouse gas emissions.

Exhibit E1

Methane emissions are expected to rise in the absence of intentional mitigation.

Projected global anthropogenic methane emissions by scenario, metric ton of methane per year



1. Assumes no change to beef demand or deployment of technical solutions for methane reduction.

Source: Historical data based on Marielle Saunois et al., "The global methane budget 2000–2017," *Earth System Science Data*, 2020, Volume 12, Number 3, pp. 1561–1623, essd.copernicus.org and the Emissions Database for Global Atmospheric Research (EDGAR). Projected data based on McKinsey analysis

[8] According to the range of scenarios in the IPCC's *Special report on global warming of 1.5°C* (SR1.5), published in 2018. The IPCC is a 195-member organization of governments that provides regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation.

[9] One metric gigaton is equal to one billion metric tons.

[10] Given in chapter 2 of the IPCC's SR1.5, figures 2.6 and 2.7. The 37 percent and 55 percent reduction in methane emissions by 2030 and 2050, respectively, are based on ten underlying 1.5°C scenarios (no overshoot) which yield a simple average methane reduction required on this pathway. The scenarios for 2030 have a reduction range of 20 percent to 60 percent in magnitude, the average being 37 percent. As with the requirements for CO_2 budgets, these estimates are averages of several possible scenarios within the parameters of a 1.5°C pathway.

Barriers to addressing methane emissions

Compared with CO_2, methane's role in causing global warming has been less discussed by policy makers, corporate decision makers, and wider society. This is partly due to the irregularity of emissions sources. Many sources of methane emit sporadically; are dispersed across remote geographies; and account for only a tiny portion of the whole, such as small, privately owned farms. There are several complications that follow from this emissions profile.

First, methane emissions are notoriously difficult to measure. This can make it challenging to build a business case for methane abatement and track the impact of mitigation measures on a source-by-source basis. Reported emissions footprints,[11] meanwhile, tend to be unreliable.[12]

Second, shortfalls in measuring and reporting mean that companies are unable to accurately account for emissions or to publish accurate product-level data on methane intensity. This limits public awareness, supply chain transparency, and the ability of business leaders and policy makers to act.

Third, abatement costs and feasibility vary significantly from one asset to another. The cost of methane recovery in coal mining, for example, is four to five times higher than that of leak detection and repair (LDAR) in oil and gas.

Finally, most solutions require trade-offs, either between costs and benefits or in terms of environmental impact. Dry seeding in rice farming, for instance, would cut emissions associated with flooding but might boost emissions of nitrous oxide, another greenhouse gas.

Methane abatement solutions and costs

Given the need to abate methane emissions within a short timeframe, what actions can policy makers and corporate decision makers take to address this part of the net-zero equation? Despite the abatement challenges, some solutions can be implemented now. Our analysis illustrates the mitigation potential of current technical solutions by 2030 and 2050 across five industries.

Agriculture

Accounting for an estimated 40 to 50 percent of anthropogenic methane, agriculture could achieve a 12 percent reduction in sectoral emissions by 2030 and a 30 percent reduction by 2050. Agricultural emissions are primarily the result of ruminant animals (principally cows and sheep), farming practices, and rice production. Ruminants create methane during digestion, along with CO_2 and other gases. The impact is significant: ruminants account for almost 70 percent of agricultural emissions and are responsible globally for more carbon dioxide equivalent (CO_2e) emissions than every country except China.[13] Elsewhere in agriculture, biomass burning is a moderate source of emissions, driven by the expansion of land for pasture and crops, while rice farming produces methane via mechanical flooding used to manage pests in many countries. A large proportion of the emissions from agriculture could be addressed with existing technologies. Several companies are already commercializing feed additives for cattle, for example, while alternative approaches to water, soil carbon, nitrogen, and land management provide proven options to rice and crop farmers.

Oil and gas

Accounting for an estimated 20 to 25 percent of anthropogenic methane, oil and gas could achieve a 40 percent reduction in sectoral emissions by 2030 and a 73 percent reduction by 2050. The oil and gas industry emits "fugitive methane" through venting, leaks, and incomplete combustion in flaring. Since methane is the primary constituent of natural gas,

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11 Ramón Alvarez et al., "Assessment of methane emissions from the U.S. oil and gas supply chain," *Science*, July 2018, Volume 361, Number 6398, pp. 186–8, science.sciencemag.org.

12 Nazar Khholod et al., "Global methane emissions from coal mining to continue growing even with declining coal production," *Journal of Cleaner Production*, May 2020, Volume 256, sciencedirect.com.

13 Calculated using GWP20. Using GWP100, cow emissions would still be on par with the third largest emitting country.

these emissions are an untapped source of value, contingent on the necessary infrastructure being put in place. Moreover, there are numerous options to prevent losses in upstream production, including LDAR, equipment electrification or replacement, instrument air systems, and vapor recovery units.[14]

Coal mining

Accounting for an estimated 10 to 15 percent of anthropogenic methane, coal mining could achieve a 2 percent reduction in sectoral emissions by 2030 and a 13 percent reduction by 2050. The vast majority of coal mine methane (CMM) emissions emanate from either working or abandoned deep mines. There is a significant challenge in measuring and recovering these emissions. However, established technologies can capture CMM and use it to generate power. The investment case is probably strongest for companies in China, which account for around 70 percent of CMM emissions and which have invested in coal gasification for the industrial sector.

Solid waste

Accounting for an estimated 7 to 10 percent of anthropogenic methane, solid waste could achieve a 39 percent reduction in sectoral emissions by 2030 and a 91 percent reduction by 2050. The majority of methane emissions from waste originate in landfills and open dumps, where anaerobic organic material generates methane over time. Through biogas markets and other incentives, authorities could capture these emissions and either sell the methane as renewable natural gas or use it in the production of fertilizer. However, revenues may not be sufficient to offset the costs.

Wastewater

Accounting for an estimated 7 to 10 percent of anthropogenic methane, wastewater could achieve a 27 percent reduction in sectoral emissions by 2030 and a 77 percent reduction by 2050. Wastewater emits methane from the breakdown of organic material in wastewater streams. The primary method of reducing emissions would be to build out modern sanitation infrastructure and technology. However, capital costs and policy requirements would be a significant burden in many countries. Where there is funding and access to technology, alternative abatement approaches could include the use of covered lagoons or the application of microalgae to prevent gas formation. Biosolids responsible for producing methane could be collected and sold as fertilizer or bioenergy.

Many of the measures discussed here could be achieved via existing technologies. Furthermore, on a 30-year timeline, more than 90 percent of the emissions reduction potential discussed above could be achieved at a cost of less than $25 per tCO_2e (Exhibit E2).

Key enablers

Significant methane abatement is possible, practical, and economically achievable. However, to meet the targets established by the Paris Agreement, urgent action would be required. We see three no-regret initiatives for the five key industries. First, they should take bold action to expand monitoring, reporting, and verification, with data based on observed measurements that are validated and accessible. Methane emissions should be reported separately from CO_2 emissions, enabling transparent target setting and benchmarking. Second, stakeholders could develop mechanisms to track, confirm, and score products based on their methane footprints. With this, retailers and consumers could make more informed purchasing decisions, producers could define new foundations for competitive advantage, and investors could better understand portfolio risk. Finally, none of this will be possible without a collective effort from both the public and private sectors to unlock innovation throughout the value chains of methane-emitting industries. Innovative solutions supported by at-scale investment will be needed for tools, processes, and market mechanisms that reduce methane emissions.

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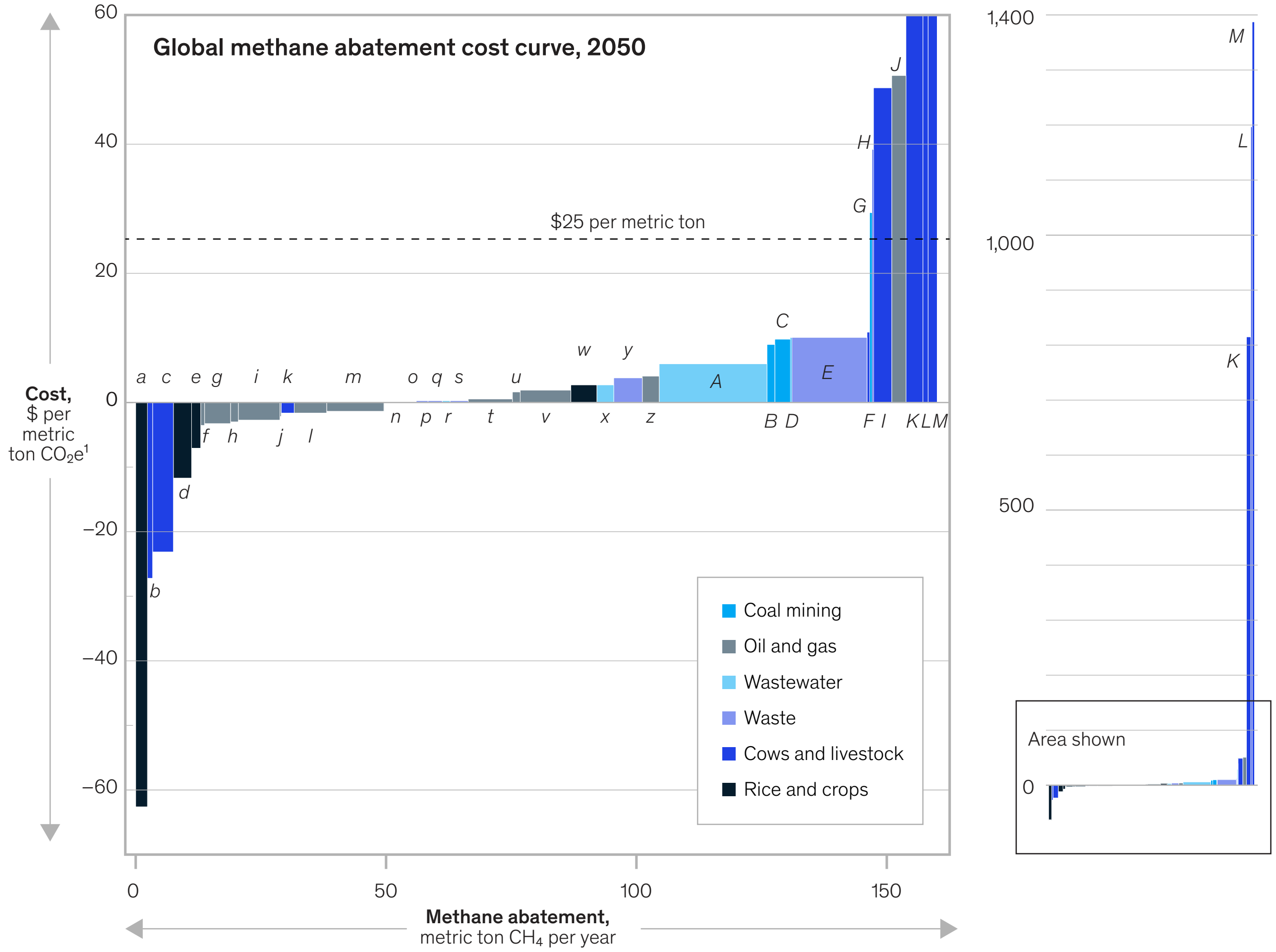
[14] For more, see Chantal Beck, Sahar Rashidbeigi, Occo Roelofsen, and Eveline Speelman, "The future is now: How oil and gas companies can decarbonize," January 7, 2020, McKinsey.com.

Exhibit E2

About 90 percent of methane emissions tracking to these levers could be abated at a cost of less than \$25 per metric ton of CO_2e, according to our analysis.



Global methane abatement cost, 2050, \$ per metric ton CO_2e[1]

a. Dry direct seeding	−\$62	*n. Genetic selection and breeding*	\$0	*A. New treatment connection*	\$6
b. Anaerobic manure digestion	−\$27	*o. Varietal rice selection*	\$0	*B. Coal methane to flare*	\$9
c. Animal health monitoring	−\$23	*p. Landfill gas to feedstock*	<\$1	*C. Coal methane to heat*	\$10
d. Rice paddy water management	−\$12	*q. Landfill gas to power*	<\$1	*D. Coal methane to power*	\$10
e. Straw management in rice	−\$7	*r. Operational improvement*	<\$1	*E. Mechanical biological treatment*	\$10
f. Blowdown capture	−\$3	*s. Landfill gas to flare*	<\$1	*F. Plug flow digestors*	\$11
g. Replace pumps	−\$3	*t. Downstream leak detection and repair*	<\$1	*G. Coal methane to feedstock*	\$29
h. Replace compressor seal or rod	−\$3	*u. Early replacement of devices*	\$2	*H. Small scale dome digestors*	\$39
i. Replace with instrument air systems	−\$3	*v. Replace with electric motor*	\$2	*I. Animal feed-mix optimization*	\$49
j. Install plunger	−\$2	*w. Sulfate fertilizers*	\$3	*J. Other*	\$50
k. Feed grain processing	−\$2	*x. Advanced technologies*	\$3	*K. Animal feed additives*	\$88
l. Vapour recovery units	−\$2	*y. Composting*	\$4	*L. Covered lagoon and anaerobic digesters*	\$205
m. Upstream leak detection and repair	−\$1	*z. Install flares*	\$4	*M. Animal growth promoters*	\$1378

Note: Some levers are not depicted on cost curve due to the lack of cost data and the skew of the chart due to high cost.
1. Carbon dioxide equivalent. Cost is based on 20-year global warming potential where 1 metric ton of methane is equivalent to 84 metric ton of carbon dioxide.
Source: McKinsey analysis

Key questions for business leaders

Companies have an opportunity to drive significant methane reduction quickly. Experience suggests that leading CEOs are pursuing this opportunity by asking a number of direct questions:

1. How do we baseline, measure, track, and disclose our methane emissions?
2. What are the operational solutions available to reduce our methane footprint quickly?
3. What are the economics of each solution, and where is there potential to capture advantage?
4. What capabilities and processes are required?
5. What is our overall target and ambition on methane as part of our environmental, social, and governance strategy?
6. How would a shift in demand to products of a lower methane intensity impact our supply chain?
7. What set of actions would we need to take to meet customer requirements?
8. Where can we lead with innovation?

A clear and aggressive methane management plan could provide a significant opportunity to keep costs down and accelerate growth.

What this report is and is not

Since this report is focused on five industries and their potential role in abating methane emissions, it does not address some issues.

What this report is:

- an overview of global methane emissions in five key sectors: agriculture (40 to 50 percent of emissions), oil and gas (20 to 25 percent), coal mining (10 to 15 percent), waste management (7 to 10 percent), and wastewater (7 to 10 percent)
- an assessment of methane's impact on the remaining carbon budget, based on different scenarios
- an analysis of the feasibility and impact of levers for potentially reducing methane in the five sectors
- a summary of the potential solutions available to reduce methane emissions and trade-offs for stakeholders to consider

What this report is not:

- a perspective on the future of methane-emitting products, including natural gas, oil, beef, and dairy
- a fully detailed climate model that forecasts feedback loops and weather patterns
- a comprehensive, regional, or individual stakeholder cost-benefit analysis of methane abatement measures
- a recommendation for any specific methane abatement approach
- an attempt to draft a comprehensive methane map
- an analysis of natural sources of methane, such as wetlands
- an individualized or asset-specific implementation road map to reduce methane emissions
- a guide for updating carbon dioxide equivalency frameworks for methane, which the scientific community (IPCC) advises to account for as a separate gas
- an assessment of the uncertainty in current measurement and reporting of methane emissions

Introduction

Leaders in business and government increasingly recognize that there are limited pathways to solve the net-zero equation—that is, to balance sources and sinks of greenhouse gases (GHGs)—and limit global warming to 1.5°C unless humankind can reduce its emissions of methane. Without substantial reductions, the remaining carbon budget would shrink to levels that put the 1.5°C warming objective beyond realistic reach. The remaining carbon budget from the Intergovernmental Panel on Climate Change (IPCC) indicates that the world would need a 37 percent reduction in methane emissions by 2030 and a 55 percent reduction by 2050 to align with a 1.5°C warming pathway.[15]

McKinsey's recent report, "Climate math: What a 1.5-degree pathway would take," shows that achieving a 1.5°C pathway is technically feasible if companies and other stakeholders, including governments, take rapid action to solve the net-zero equation. This report adds an important element to that equation, focusing on the criticality of methane reductions in slowing climate change and illustrating the measures that leaders can take to bring about these reductions.

The five industries discussed in this report, if supported by governments and consumers, could make a difference in softening methane's impact on global warming. However, because emissions tend to be sporadic and geographically dispersed, abatement can be challenging, both operationally and financially. Among the hurdles faced by specific sectors, oil and gas companies would need to continuously address natural gas leaks on millions of kilometers of pipelines. Thousands of cities and municipalities, meanwhile, would need to modernize their waste infrastructure.

The challenges associated with action on the required scale are daunting. But they are not insurmountable. The acceleration of climate change and rising public awareness create a powerful impetus for change. This report, therefore, proposes technical solutions that may lower aggregate levels of emissions and ensure the world gives itself the best chance of aligning with a 1.5°C pathway.

15 According to the Intergovernmental Panel on Climate Change's Special report on global warming of 1.5°C (IPCC SR1.5) and Sixth assessment report (AR6), as well as McKinsey's 1.5°C Scenario analysis.

1. The climate impact of methane

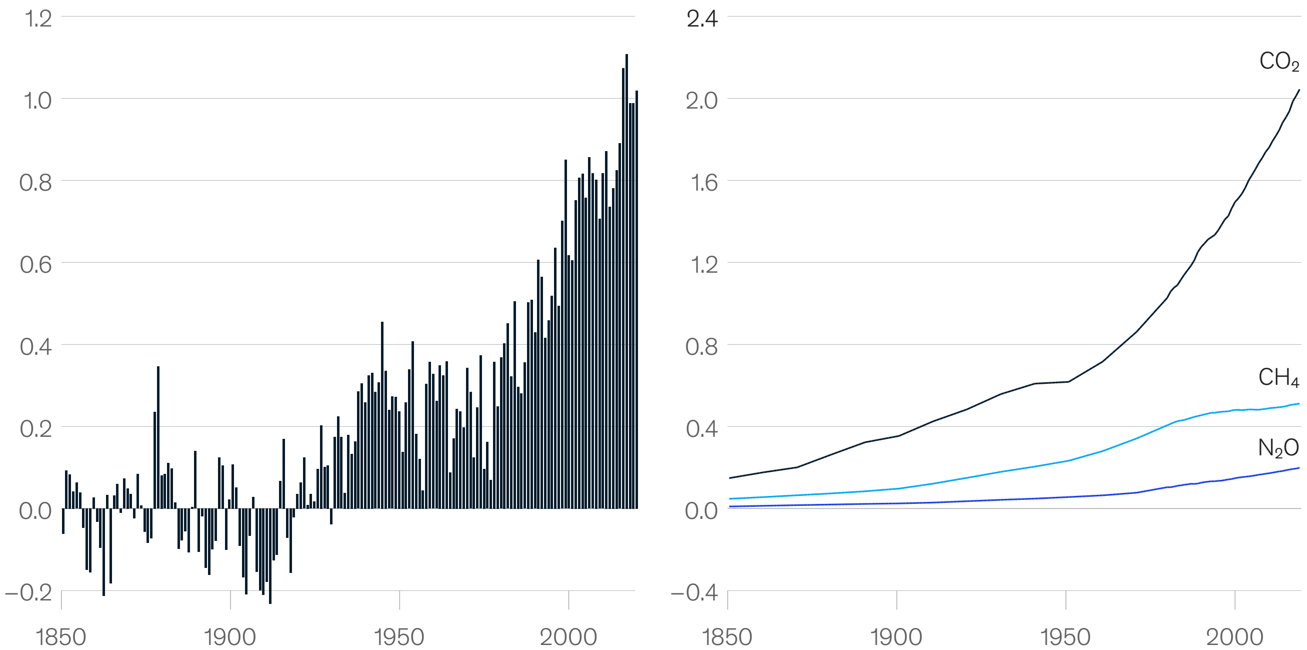
As of early 2021, the earth's temperature has risen by 1.1°C above preindustrial levels, driven by the emission of greenhouse gases from human activities (Exhibit 1). Keeping temperatures below 1.5°C would avoid the worst effects of climate change.

Exhibit 1

Methane is the second-largest contributor to global warming after carbon dioxide.

Rise in global temperature,[1] °C

Rise in greenhouse gases, radiative forcing (W/m_2)[2]



Global warming to date,[3] % share

1. Temperature values shown represent the annual global mean temperature relative to the pre-industrial temperature mean from 1850–1900.
2. Radiative forcing represents the contribution of each gas to global warming. The units of W/m_2 describe how much energy (watts) each gas "forces" onto the Earth's surface (square meters) due to its concentration and physical properties.
3. Defined as the net warming contribution from each gas. This number was calculated by taking the gross positive contribution of each gas and subtracting its proportional share of gross negative contributions from cooling agents, such as aerosols.
4. "Other" includes about 15 gases, namely, HFCs, CFCs, and aerosols, which contribute the remaining 15% of warming to date.

Source: The Goddard Institute for Space Studies (GISS) Surface Temperature Analysis v4, National Oceanic and Atmospheric Administration (NOAA); *Sixth assessment report* (AR6), Intergovernmental Panel on Climate Change (IPCC), August 2021, ipcc.ch

About 380 metric megatons (Mt) of anthropogenic methane are emitted annually, and the atmospheric concentration of methane has more than doubled since the industrial revolution—from 800 parts per billion (ppb) in the year 1850 to more than 1800 ppb today.[16] As a result of that increase, methane is responsible for about 30 percent of the observed 1.1°C of global warming, making it the second-largest contributor after carbon dioxide.[17] Although all methane emissions behave identically, the climate impact of fossil methane—emitted by coal and oil and gas industries—could be considered more significant than biogenic methane—emitted by agriculture, solid waste, and wastewater—because it introduces a new carbon atom into the atmosphere.

On a geographic basis, the biggest emitter is China—a symptom of its heavy reliance on coal. As of 2017, companies in China emit about 64 Mt of emissions every year (Exhibit 2), of which 25 Mt is from coal mining. Behind China, the leading methane emitters are India (35 Mt), Russia (34 Mt) and the United States (33 Mt). Each country has a different mix of emissions per sector, requiring its own targeted mix of mitigation solutions to reduce its methane footprint.

Exhibit 2

Methane sources are unevenly distributed across regions.

Anthropogenic methane emissions by region in 2017, metric ton methane

	China	India	Other Asia excl. Central Asia	Russia	Sub-Saharan Africa	United States	Middle East	Europe	North Africa	Brazil	South America	Oceania	Central Asia	Canada
Enteric fermentation and manure	12	16	5	8	8	9	3	12	10	14	10	6	3	1
Solid waste and wastewater	12	9	7	6	6	7	6	7	3	3	4	1	1	1
Oil and gas	3	1	4	6	6	12	19	3	7	1	2		5	3
Coal mining	25		4	2	2	3	0	2	0	0	2	1	1	0
Biomass and biofuel burning	3	3	3	9	9	1	0	1	2	3	1	1	0	1
Rice cultivation	8	4	11	2	2	0	0	0	1	0	1	1	0	0
Total	**64**	**35**	**35**	**34**	**34**	**33**	**29**	**25**	**23**	**21**	**21**	**10**	**10**	**6**

Note: Figures may not sum, because of rounding.
Source: Marielle Saunois et al., "The global methane budget 2000–2017," *Earth System Science Data*, 2020, Volume 12, Number 3, pp. 1561–1623, essd.copernicus.org.

[16] "Climate change indicators: Atmospheric concentrations of greenhouse gases," US Environmental Protection Agency (EPA), accessed July 2021, epa.gov.
[17] *Sixth assessment report* (AR6), Intergovernmental Panel on Climate Change (IPCC), August 2021, ipcc.ch.

The imperative to reduce methane emissions

To limit climate change, steep reductions of all greenhouse gases would be needed. However, the top two gases—carbon dioxide and methane—are contrasting: methane's impact on warming is proportional to the rate of emissions in any given year, whereas carbon dioxide's impact is proportional to its cumulative emissions over time. On that basis, a higher annual rate of methane emissions leads to more short-term warming, whereas a lower rate of methane emissions would counteract its historical warming over time.

This oversized and near-term impact of methane on warming is the motivation for seeking immediate reductions in methane emissions. Doing so would shave off peak temperatures. Because global warming is reported as a long-term average, the average temperature of individual years deviates from the overall trend, both above and below that broader average. As global warming approaches the 1.5°C mark, it would be expected for individual years to exceed this dangerous threshold. In fact, according to a 2021 report by the World Meteorological Organization, there is a 40 percent chance that one of the next five years (2021–25) is above 1.5°C, which is twice the likelihood stated in the report a year prior.[18] It is therefore critical to reduce methane emissions in the immediate term to shave off peak temperatures and stay below the 1.5°C threshold.

Under the 2015 Paris Agreement, governments agreed to an objective of limiting warming to well below 2.0°C—and preferably to 1.5°C—by 2050. In 2018, the IPCC estimated that the world's remaining carbon budget to keep warming below 1.5°C was 570 $GtCO_2$ with parallel reductions in methane emissions of more than 2 percent a year.[19] Failure to hit these targets would effectively put the 1.5°C objective beyond reach. Exceeding the IPCC's targets for methane emissions, on the other hand, would increase the remaining CO_2 budget before the 1.5°C threshold is crossed and thereby support a more gradual and less disruptive transition to zero net greenhouse gas emissions. The following analysis[20] shows the impact of various methane trajectories on the entire remaining carbon budget under three scenarios (Exhibit 3).[21]

The first scenario sees methane emissions growing at the current projected rate of 0.4 percent per year, totaling growth of 15.0 percent by 2050. Here, methane would cause so much warming that it would consume the entire budget, requiring net-negative CO_2 emissions to offset its impact.

The second scenario keeps emissions constant at today's levels through 2050. This would effectively reduce the remaining carbon budget from 570 $GtCO_2$ to 110 $GtCO_2$ (from 2018), which society would be expected to exceed in 2022, given the current trajectory of CO_2 emissions.

The final scenario posits a 37 percent decline in emissions by 2030 and a 55 percent decline by 2050, in line with a 1.5°C trajectory, based on IPCC data.[22] This report finds that these pathways would require swift adoption of technical solutions, alongside a reduction in demand for methane-emitting commodities. The targets up to 2030 are particularly challenging.[23] They would be contingent on rapid adoption of technical solutions across

[18] *WMO global annual to decadal climate update*, World Meteorological Organization, 2020, hadleyserver.metoffice.gov.uk.

[19] Given in chapter 2 of the IPCC's SR1.5, figures 2.6 and 2.7. The 37 percent and 55 percent reduction in methane emissions by 2030 and 2050, respectively, are based on ten underlying 1.5°C scenarios (no overshoot) which yield a simple average methane reduction required on this pathway. The scenarios for 2030 have a reduction range of 20 percent to 60 percent in magnitude, the average being 37 percent. As with the requirements for CO_2 budgets, these estimates are averages of several possible scenarios within the parameters of a 1.5°C pathway.

[20] This analysis used GWP*, a calculation that equates a change in ongoing methane emissions with a pulse of carbon dioxide emissions and a smaller long-term effect over 100 years. More details about the functionality and design of these calculations can be found in the section "CO_2 equivalents offer convenience at a cost" on page 16.

[21] Michelle Cain et al., "Improved calculation of warming-equivalent emissions for short-lived climate pollutants," *Climate and Atmospheric Science*, September 2019, Volume 2, Number 29, nature.com.

[22] IPCC, chapter 2 of SR1.5, figures 2.6 and 2.7.

[23] Scenario modeling for 2030 and 2050 was done by taking the maximum potential adoption across all sectors of technical solutions by 2030 and 2050, respectively, as modeled in this report (based on cost, feasibility, technical readiness, regulation and policy, and other barriers to implementation), and combining the resulting impact with abatement potential for different demand scenarios for fossil fuel and beef reduction.

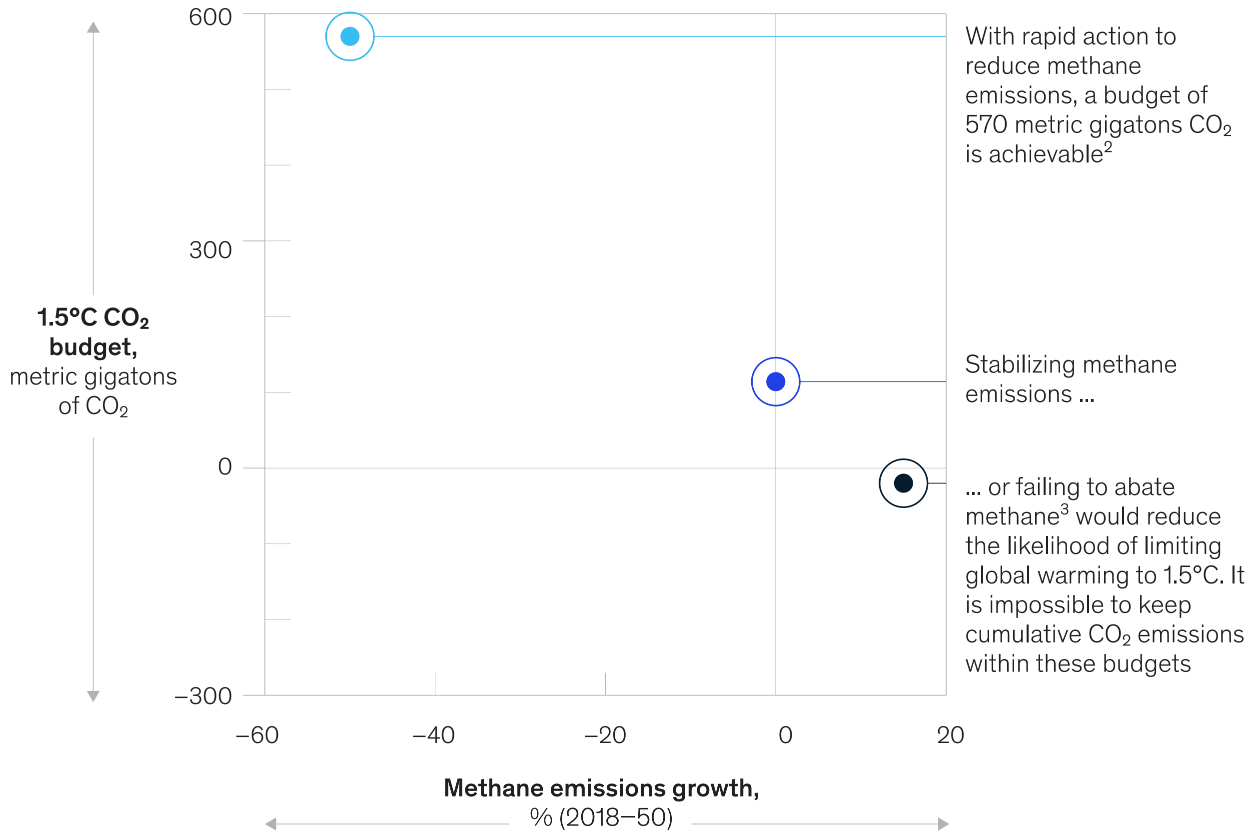
sectors, declines in fossil fuel demand in line with a 1.5°C pathway (for CO_2 reduction), and an approximately 15 percent reduction in beef demand versus today's levels.[24]

Importantly, the analysis shows that both technical solutions and shifts in consumption patterns would be required to achieve the pace of a 1.5°C pathway, as illustrated in Exhibit 4.

Exhibit 3

The trajectory of methane emissions has a significant impact on the remaining 1.5°C budget for CO_2 emissions.

Impact of methane emissions scenarios on the remaining 1.5°C CO_2 budget[1]



1. The 1.5°C CO_2 budget is a limit on cumulative CO_2 emissions from 2018 onward, established as 570 metric gigatons CO_2 (66% chance of keeping warming below 1.5°C) in the Intergovernmental Panel on Climate Change's (IPCC's) *Special report: Global warming of 1.5°C* (2018). Impact on the carbon budget was calculated using the global warming potential* (GWP*) formula published in Cain et al (2019).
2. Assuming non-CO_2 gases are reduced according to the average of 1.5°C no-overshoot scenarios published in the IPCC SR1.5 report, including a 73 percent reduction of nitrous oxide emissions and 55 percent reduction of methane emissions by 2050.
3. Current trajectory of methane emissions according to energy and population projections from McKinsey's Global Energy Perspective and agricultural projects from the Food and Agriculture Organization (FAO) of the United Nations.

Source: Michelle Cain et al., "Improved calculation of warming-equivalent emissions for short-lived climate pollutants," *Climate and Atmospheric Science*, September 2019, Volume 2, Number 29, nature.com; E.G. Nisbet et al., "Very strong atmospheric methane growth in the 4 years 2014–2017: Implications for the Paris Agreement," *Global Biogeochemical Cycles*, February 5, 2019, Volume 33, Number 3, agupubs.onlinelibrary.wiley.com; J. Rogelj et al., *Special report: Global warming of 1.5°C*, Intergovernmental Panel on Climate Change, 2018, ipcc.ch; McKinsey analysis

[24] This drop in cattle demand would be the equivalent of 50 percent of high- and upper-middle-income country residents limiting their beef and lamb consumption to 35g per week by 2030. Demand for pork, dairy, eggs, and poultry would remain unchanged, as would all meat and dairy consumption in lower- and lower-middle income countries. See Marco Springmann et al., "Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: A global modelling analysis with country-level data," *Lancet Planet Health*, October 2018, Volume 2, Number 10, pp. e451–e461, pubmed.ncbi.nlm.nih.gov.

Exhibit 4

To meet methane-reduction goals consistent with a 1.5°C pathway, significant changes would be required by 2030, setting a precedent for meeting methane-reduction goals in 2050.

Reduction in annual methane emissions, 2030, % change from 2017 baseline

Bovine livestock demand scenarios

Meets IPCC 1.5°C scenario[6]

Fossil fuel demand scenarios	Continued demand growth of beef/dairy (+11% by 2030)[4]	Flat demand of beef/dairy (fixed 2017 level)	Reduced demand of beef/dairy (–15% by 2030)[5]
Current trajectory for fossil fuel demand (+1% by 2030)[1]	17	20	28
Accelerated energy transition away from fossil fuels (–6% by 2030)[2]	19	22	29
1.5°C pathway energy transition away from fossil fuels (–43% by 2030)[3]	27	30	37

A **~37%** reduction in methane by 2030, consistent with a 1.5°C pathway, would require rapid technology deployment and shifts in commodity demand.

Reduction in annual methane emissions, 2050, % change from 2017 baseline

Fossil fuel demand scenarios	(+23% by 2050)[4]	(fixed 2017 level)	(–30% by 2050)[5]
Current trajectory for fossil fuel demand (–15% by 2050)[1]	44	49	58
Accelerated energy transition away from fossil fuels (–29% by 2050)[2]	46	51	61
1.5°C pathway energy transition away from fossil fuels (–81% by 2050)[3]	58	58	68

A **~55%** reduction in methane by 2050, consistent with a 1.5°C pathway, would require a mix of technology deployment and demand shifts.

1. McKinsey Global Energy Perspective (GEP) models a Reference Case, which shows gradual increase in oil and gas and slow decline in coal according to business-as-usual activities by 2030 (1% overall), and an Accelerated Case, which assumes significant action taken towards an energy transition, with the resulting decarbonization causing some decline in oil, gas, and coal (6%).
2. Oil and gas demand reduction required in a 1.5°C scenario as given in the McKinsey report, "Climate math: What a 1.5-degree pathway would take" (43% by 2030).
3. The fullest extent technical potential by 2030 as modeled by McKinsey is based on feasibility characteristics of each lever and sector, including cost, regulatory and policy standards, incentives, company targets, technological readiness, and other barriers to implementation.
4. Based on Food and Agriculture Organization of the United Nations (FAO) projections for increased enteric fermentation globally in a business-as-usual forecast (11%).
5. Decline in enteric fermentation of ~15% by 2030 is possible through a wide variety of scenarios, such as most high- and middle-income countries cutting beef demand in the EAT-Lancet diet, most countries substituting most beef demand for chicken or fish, or other combinations of diet shifts. There will be several important cultural and socioeconomic components to shift in demand patterns globally.
6. According to Intergovernmental Panel on Climate Change (IPCC) chapter 2 of *Special report: Global warming of 1.5°C*, 37% reduction in annual methane emissions by 2030 is required for a 1.5°C pathway in parallel with a 570 metric gigatons CO_2 carbon budget. This percentage reduction is the average of no-overshoot scenarios (full range is 20% to 60% decrease required).

Source: J. Rogelj et al., *Special report: Global warming of 1.5°C*, Intergovernmental Panel on Climate Change, 2018, ipcc.ch; McKinsey analysis

CO_2 equivalents offer convenience at a cost

Many organizations use a single common method to measure emissions of both methane and carbon dioxide, known as Global Warming Potential (GWP). The GWP method converts greenhouse gas emissions into carbon dioxide equivalents (CO_2e).

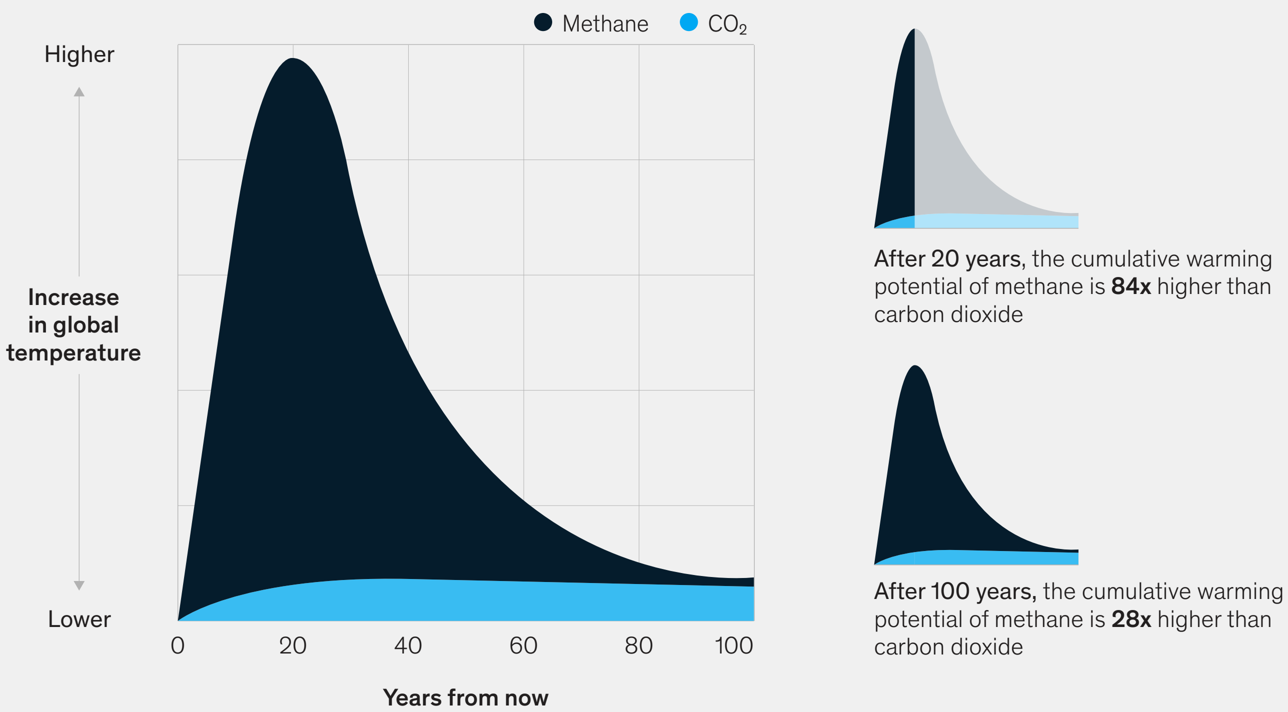
The GWP of a gas can be set for different lengths of time (Exhibit 5). GWP100, for example, assesses the warming impact of a gas over 100 years relative to that of CO_2. Methane's warming effect occurs mostly in the decade after it is emitted. As a result, GWP100 understates methane's short-term warming effect from existing sources of emissions. This is particularly concerning given that postindustrial warming—currently 1.1°C—is only 0.4°C below the 1.5°C objective[25]. Given the short lifetime of methane and the fact that nonlinear climate change is a short-term risk, a more useful metric to measure its impact would be GWP20, converting methane to CO_2e on a 20-year timeframe. (For more on an alternative method of measuring GWP, see sidebar, "Other approaches to methane measurement.")

The motivation for using CO_2e is that it is convenient, allowing methane to be combined with carbon dioxide for analytical purposes. Still, the simple conversion of methane into CO_2e can lead to inaccuracy and misunderstandings. Each molecule of methane has a greater warming impact than carbon dioxide but exists for a much shorter time in the atmosphere, creating a different warming trajectory than carbon dioxide, depending on whether global emissions are rising or falling (Exhibit 6). This scientific nuance is not captured in the common methods of greenhouse equivalency, GWP100 and GWP20.

Exhibit 5

Ton for ton, rising methane emissions contribute much more warming in the near term than carbon dioxide.

Warming potential of one incremental metric ton of carbon dioxide and methane over time (illustrative)



Source: Michelle Cain et al., "Improved calculation of warming-equivalent emissions for short-lived climate pollutants," *Climate and Atmospheric Science*, September 2019, Volume 2, Number 29, nature.com.

[25] The 1.5°C objective is defined as increase in global average temperatures over a multi-decade period, rather than an individual year. Although warming in 2021 has reached 1.2°C, the current decadal average (2011-2020) is reported as 1.1°C. *Sixth assessment report* (AR6), Intergovernmental Panel on Climate Change (IPCC), August 2021, ipcc.ch.

Exhibit 6

Due to methane's short lifetime, its impact on warming depends on the global context—whether emissions are rising or declining.

Two types of greenhouse gases (GHG) and their impact on warming

Stock gases

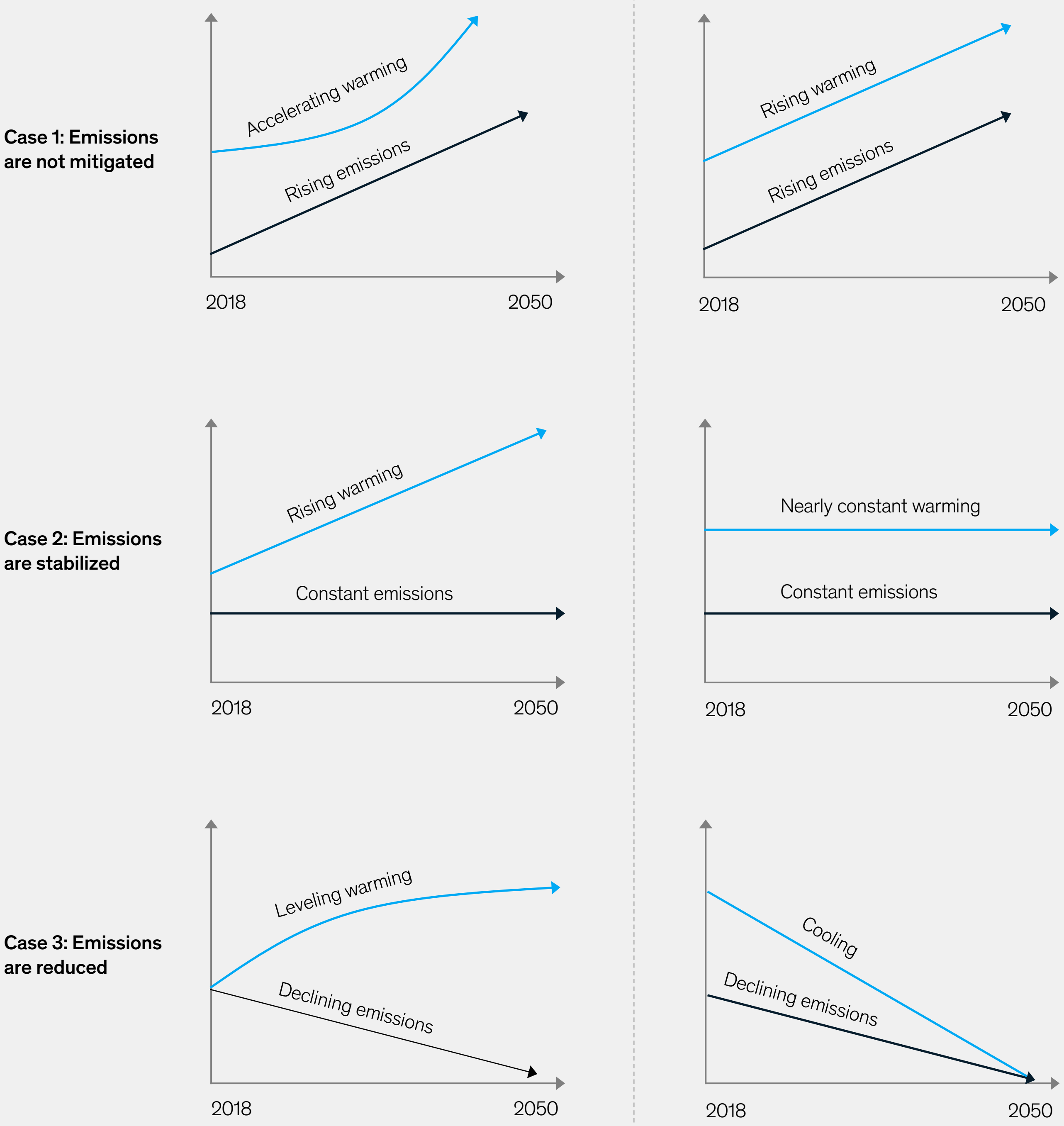
Carbon dioxide (CO_2) and nitrous oxide (N_2O)

Long-lived gases that accumulate in the atmosphere

Flow gases

Methane (CH_4) and HFCs[1]

Short-lived gases that decay more quickly in the atmosphere



1. Hydrofluorocarbons, eg, HFC-134a and HFC-152a.

Source: Carbon Dioxide Information Analysis Center (CDIAC); Intergovernmental Panel on Climate Change (IPCC); National Oceanic and Atmospheric Administration (NOAA); McKinsey analysis

Methane-emitting climate feedbacks

Global warming triggers natural feedbacks that add even more methane (and carbon dioxide) to the atmosphere. The potential scale of these feedbacks is still being developed under scientific research. Two powerful feedback loops currently playing out are the loss of permafrost and of arctic forests. As warmer temperatures melt permafrost, trapped organic matter is decaying into carbon dioxide and methane. These additional GHG emissions raise temperatures, creating an accelerating loop of melting and warming. On society's current emissions trajectory, climate models estimate that permafrost release could add an incremental 5 to 20 percent to annual anthropogenic methane and carbon dioxide emissions.[26]

Methane feedbacks could also be triggered in arctic forests in northern Canada, Russia, and Scandinavia. Increased precipitation, evaporation, and transpiration, as well as greater subsurface drainage, could emit large amounts of methane from saturated soil, inundation, or organic carbon releases into existing water bodies.

In addition, higher temperatures generally increase the recurrence of wildfires and rate of decomposition in wetlands and landfills, which would increase methane emissions from these sources.[27]

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26 T. Gasser et al., "Path-dependent reductions in CO_2 emission budgets caused by permafrost carbon release," *Nature Geoscience*, September 2018, Volume 11, pp. 830–5, nature.com; T. Schuur, "Permafrost and the global carbon cycle," The National Oceanic and Atmospheric Administration (NOAA) Arctic Program, 2019, arctic.noaa.gov; Merritt Turetsky et al., "Carbon release through abrupt permafrost thaw," *Nature Geoscience*, February 2020, Volume 13, pp. 138–43, nature.com.

27 According to the Intergovernmental Panel on Climate Change's S*ixth assessment report* (AR6).

Other approaches to methane measurement

An alternative usage of GWP, called GWP*, overcomes the scientific challenges associated with GWP20 and GWP100—that they do not accurately describe the warming impact of methane when emissions are stable or declining—by using a formula that considers the relative lifetime of methane compared to CO_2. However, while the method is more accurate than GWP20 and GWP100 at a global level, it is not useful to analyze the emissions footprint of individual products, companies, sectors, or regions. For instance, using GWP*, a growing livestock farm of 100 head of cattle would show much worse climate impact than an ongoing operation with 1,000 head (Exhibit 7). This is because of the approach's focus on incremental warming from emissions growth, rather than existing warming from current emissions. For that reason, GWP20 is used in this report when modeling single sources.

Another option would be to measure unconverted units of methane emissions in metric tons. This simple method may be most relevant to sectors where methane emissions are a majority of emissions (for example, agriculture or coal mining). Keeping methane separate would allow companies to commit to methane-reduction goals and design methane-reduction strategies that would act as a complement to carbon dioxide abatement strategies. However, reporting carbon dioxide and methane separately could create challenges in assessing trade-offs between the two gases because the volume of methane would appear small compared to that of CO_2.

Exhibit 7

Global Warming Potentials can misrepresent the emissions footprint of large, consistent methane emitters.

	Stable, large livestock farm • 15,000 cows • No change in herd size	**New, moderate-size livestock farm** • No cows in year 1 • 5,000 cows in year 2
Year 2 emissions, tCH_4/year	3	1
Change in emissions from year 1 to year 2, tCH_4/year	0	1
GWP100, tCO_2e	76	28
GWP20, tCO_2e	252	84
GWP*, tCO_2e	0	28

GWP* distorts emissions reporting by making it seem as though the new farm is emitting much more than the existing, larger farm, despite having one-third the annual emissions.

Source: McKinsey analysis

2. Barriers to addressing methane emissions

Methane emitters face significant challenges in abating emissions—originating from a range of regulatory, financial, and structural factors. Awareness is low compared with CO_2, and methane emissions are tough to measure and track. Abatement costs vary, and the stakeholder community, comprising millions of farmers—as well as governments, companies, and the public—is diverse and fragmented. Moreover, there is often no strong business case for action. Among these many impediments, three barriers to effective decision making stand out.

1. Methane emissions are individually minor, sporadic, and highly dispersed

Methane emits quietly from diverse sources that include 600,000 oil wells in the United States, close to 1.5 billion head of cattle globally,[28] and more than 6,000 abandoned[29] coal mines.[30] Many sources emit episodically, making quantification difficult and abatement uneconomic on a source-by-source basis. In addition, emissions are rarely tracked—real-time or even regular monitoring is routinely absent. Emissions inventories, meanwhile, tend to be unreliable; oil and gas emissions measured by site and aerial survey could be understated by 60 percent (compared to Environmental Protection Agency (EPA) estimates).[31]

On a more positive note, tracking technologies are increasingly available at commercially reasonable prices. These range from earth-based observation using fixed and mobile sensors to light aircraft and drone-based solutions. Satellites and drones are well adapted to the challenges of measuring gas emissions, which tend to disperse chaotically. In addition, the technology is advancing rapidly, especially for monitoring large emitting sources. That said, a winning combination of equipment, analytics, and work practices has yet to materialize.

2. Abatement costs and feasibility vary significantly

Across sectors, abatement measures vary widely in terms of cost per metric ton of methane abated, feasibility, and ease of implementation. The oil and gas industry is probably best positioned to implement abatement measures, reflecting its relatively consolidated structure and deep resources. In natural gas markets, the infrastructure required for monetization is often established (for example, preventing methane leaks also leads to less gas lost along the pipeline), and the industry has many routes to financing. Still, individual players may struggle to fund projects, and there are asset-level challenges that vary. The coal mining industry is relatively consolidated as well, creating economies of scale. However, the cost of abatement is four to five times higher than that of leak detection and repair (LDAR) in oil and gas, because the concentration of methane released from coal mines is much lower.

The fragmentation of emissions in farming means that solution scaling is exceptionally challenging. Furthermore, abatement costs vary. Rice interventions are relatively inexpensive and can generate net savings for farmers. In the beef and dairy industries, on the other hand, the most effective interventions are pure costs; they create zero productivity benefits.

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28 "World Cattle Inventory," Food and Agriculture Organization (FAO) of the United Nations, 2019, fao.org.
29 Shengyong Hu et al., "Methane extraction from abandoned mines by surface vertical wells: A case study in China," *Geofluids*, March 2018, Volume 2018, hindwai.com.
30 "Coal mine methane developments in the United States," US Environmental Protection Agency (EPA) Coalbed Methane Outreach Program, updated July 2019, epa.gov.
31 Ramón Alvarez et al., "Assessment of methane emissions from the U.S. oil and gas supply chain," *Science*, July 2018, Volume 361, Number 6398, pp. 186–8, science.sciencemag.org.

3. There are numerous trade-offs

Some measures to reduce methane require significant investment but bring positive benefits in terms of health and employment. Modern waste and wastewater infrastructure falls under this umbrella. Other measures, however, carry risks. Dry seeding in rice farming, for instance, may boost emissions of nitrous oxide, another greenhouse gas. To achieve a reduction of both methane and nitrous oxide by 60 to 90 percent,[32] the US-based Environmental Defense Fund (EDF) proposes shallow flooding as a substitute for continuous or intense irrigation techniques.

[32] K. Kritee et al., *Global risk assessment of high nitrous oxide emissions from rice production: Incorporating the discovery of high N_2O fluxes under intermittent flooding*, The Environmental Defense Fund (EDF), September 2018, edf.org.

3. Methane abatement: The numbers

Across sectors, there are a variety of potential technical solutions to reduce methane emissions—each of which comes with a unique business case and set of implementation challenges. This report models the maximum potential for application of technical solutions by 2030 and 2050 across sectors and solution types, taking into account a variety of feasibility considerations.

Across the industries considered here, 20 percent of methane emissions could be abated (versus 2017 levels) by 2030 and 46 percent of emissions could be abated by 2050. The 2030 potential falls significantly short of the estimated IPCC average of 37 percent required for a 1.5°C pathway. Demand shifts would be needed to close the gap. The 2050 goals are easier to meet; the technical potential of 46 percent by 2050 gets quite close to the 55 percent emissions reduction required, as shown by calculations for this report.[33]

Abatement by sector

Distinct characteristics across sectors and levers could jointly impact rates of solution adoption and methane abatement potential. Calculations made for this report show the maximum potential, per sector, would be as follows.

Agriculture
Accounting for 40 to 50 percent of anthropogenic methane, agriculture could achieve a 12 percent reduction in methane emissions by 2030 and a 30 percent reduction by 2050 with known solutions.

In livestock farming, the adoption rates of current technical levers, including animal feed-mix optimization, feed additives, and anerobic digestors, are assumed to have the potential to scale to between 15 and 54 percent across geographies by 2050. This would reduce sector emissions by 10 to 20 percent. In total, existing technologies for livestock could achieve ten percentage points of the 37 percent abatement total. Emerging solutions, such as direct methane capture, methane inhibitors, and gene editing are assumed to have an adoption rate of 10 percent by 2050. These solutions would have higher abatement potential (for example, 30 percent from methane inhibitors and 100 percent from direct methane capture).

In rice production, the calculation assumes variable adoption of rice paddy water management across regions, ranging from 4 percent in Africa to 37 percent in North America and Europe by 2030—and double that by 2050. Straw management, sulfate fertilizers, and dry direct seeding are assumed to see adoption potential across regions ranging from 22 to 28 percent in 2030 and 35 to 53 percent in 2050. These levers have been proven to reduce emissions by 40 to 50 percent per unit (except for straw management, which has an emissions-reduction potential of 16 percent).

Oil and gas
Accounting for 20 to 25 percent of anthropogenic methane, oil and gas could achieve a 40 percent reduction in methane emissions by 2030 and a 73 percent reduction by 2050.

This report assumes full adoption of technical levers set out in the International Energy Agency (IEA) Methane Tracker, with regional variances in adoption of levers ranging between 50 and 85 percent. The levers include LDAR (for facilities with high volumes of equipment),

[33] IPCC targets based on chapter 2 of SR1.5, as noted elsewhere in this report.

electrification, instrument air systems, and vapor recovery units (VRU). The IEA does not make any estimate of adoption rates. Roughly 25 percent of emissions are considered "unavoidable." This is due to the operating procedures involved in the ramp-up and ramp-down periods of oil and gas assets and the limits of current technology to completely prevent fugitive emissions.

Coal mining

Accounting for 10 to 15 percent of anthropogenic methane, coal mining could achieve a 2 percent reduction in methane emissions by 2030 and a 13 percent reduction by 2050.

Levers such as full ventilation and degasification of underground mines are standard coal mine methane (CMM) abatement technology but would likely see adoption rates of only 0.5 to 1.0 percent by 2030 and 2 to 4 percent by 2050. Other levers—such as ventilation air methane (VAM) capture and utilization, capture of abandoned mine gas, degasification of surface mines, and predrainage of surface mine—are less technically challenging but are expensive. They could see 2 to 16 percent adoption rates in 2030, growing to 20 to 30 percent adoption rates by 2050.

Solid waste

Accounting for 7 to 10 percent of anthropogenic methane, solid waste could achieve a 39 percent reduction in methane emissions by 2030 and a 91 percent reduction by 2050.

This analysis considers abatement through diversion of organic waste from landfills and retrofitting for methane capture or recovery. On a country-by-country level, it assumes that adoption would rise to 30 percent by 2030 and 69 percent globally for diverting organic waste to compost and to 15 percent by 2030 and 31 percent by 2050 for retrofitting existing landfills (adoption benchmarked to current top-quartile performance by region according to the World Bank Index, with all countries in a region achieving third-quartile performance by 2030 and top-country performance by 2050).

Wastewater

Accounting for 7 to 10 percent of anthropogenic methane, wastewater could achieve a 27 percent reduction in methane emissions by 2030 and a 77 percent reduction by 2050.

The assumed levels would require comprehensive modernization of global water-treatment infrastructure. For many regions, such as Europe, the Middle East, and North America, the analysis assumes that 79 to 84 percent of emissions can be abated by 2030 and 100 percent of emissions can be abated by 2050. This is predicated on all water systems matching current best-in-region systems. Europe, the Middle East, and North America account for slightly less than half of total reduction potential. In Asia, Latin America, and sub-Saharan Africa, 25 to 39 percent of emissions could be abated by 2030 (consistent with achieving regional third-quartile performance) and 66 percent of emissions could be reduced by 2050 by every country in a region achieving the regional top performance benchmark.[34]

The economics of abatement

The economics of technical methane abatement are driven by two factors—cost and the quantum of potential revenues. The good news is that roughly 30 percent of methane abatement potential would come from levers that save costs or create a revenue opportunity greater than the total cost (Exhibit 8).[35] These would include most levers in the oil and gas industry and in rice production. Beyond these:

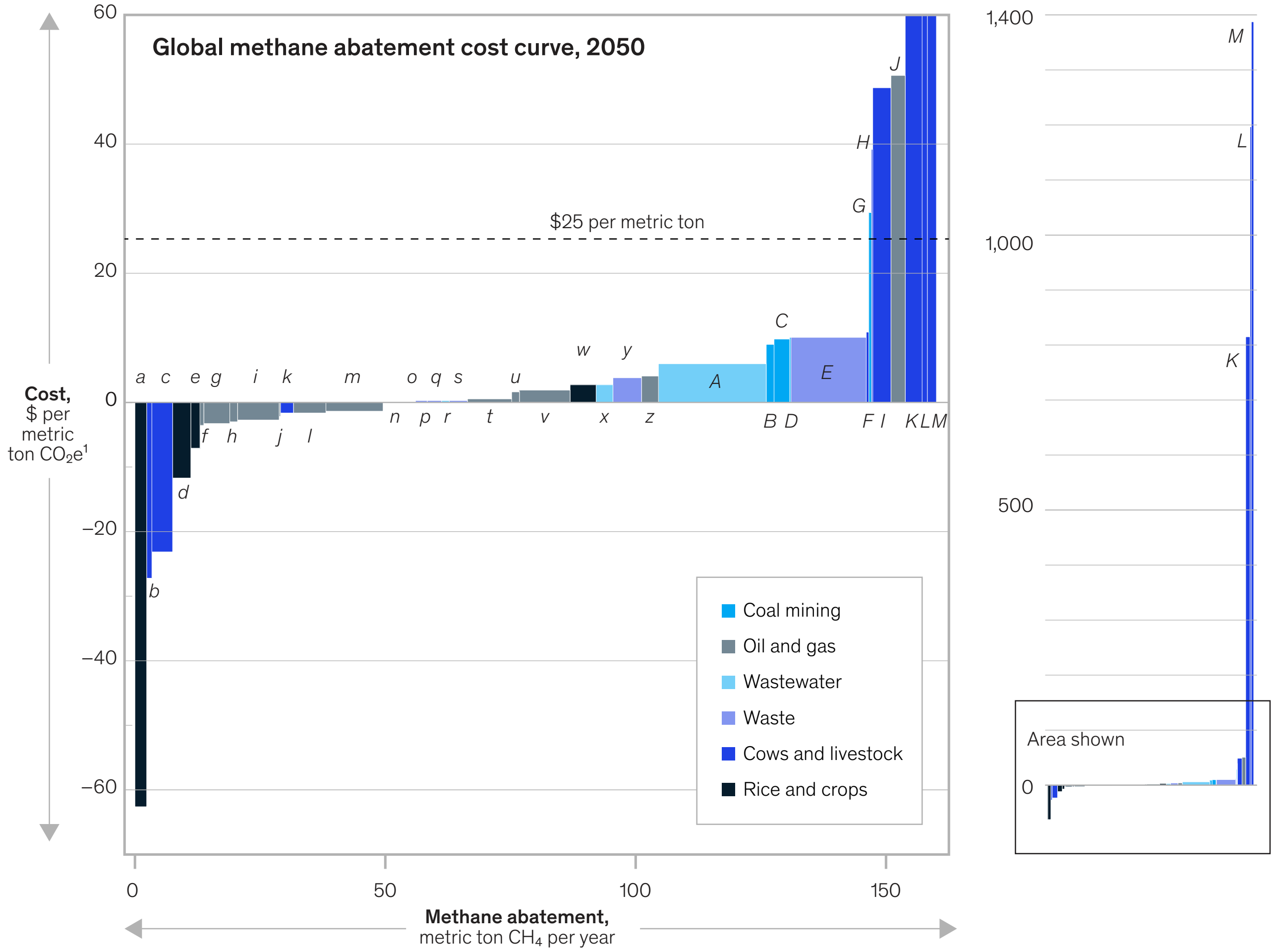
— A further 50 percent would be possible at between $0 and $10 per metric ton of carbon dioxide equivalent (tCO_2e), including retrofitting landfills and downstream LDAR for oil and gas.

[34] Top-down methodology assumes that each country in a given region will be able to achieve the equivalent of today's upper-quartile players for percentage of new water treatment performed in that region by 2030 and of today's top performers by 2050. For example, if Greece is currently at 64 percent treatment, upper-quartile European players are at 84 percent, and top players are at 100 percent, it is assumed that Greece achieves 84 percent by 2030 and 100 percent by 2050, resulting in a corresponding amount of emissions abatement.

[35] Abatement costs are indicative for global average. In reality, costs will vary widely by region. Additional sensitivities include oil and gas costs, which are sensitive to natural gas spot-price volatility; coal and waste costs, which are sensitive to the cost of infrastructure necessary to create a market for recovered methane; waste costs, which are sensitive to the maturity of existing waste management systems; and agricultural costs, which are sensitive to regional climate and farming conditions.

Exhibit 8

About 90 percent of methane emissions tracking to these levers could be abated at a cost of less than $25 per metric ton of CO_2e, according to our analysis.



Global methane abatement cost, 2050, $ per metric ton CO_2e[1]

a. Dry direct seeding	–$62	*n. Genetic selection and breeding*	$0	*A. New treatment connection*	$6
b. Anaerobic manure digestion	–$27	*o. Varietal rice selection*	$0	*B. Coal methane to flare*	$9
c. Animal health monitoring	–$23	*p. Landfill gas to feedstock*	<$1	*C. Coal methane to heat*	$10
d. Rice paddy water management	–$12	*q. Landfill gas to power*	<$1	*D. Coal methane to power*	$10
e. Straw management in rice	–$7	*r. Operational improvement*	<$1	*E. Mechanical biological treatment*	$10
f. Blowdown capture	–$3	*s. Landfill gas to flare*	<$1	*F. Plug flow digestors*	$11
g. Replace pumps	–$3	*t. Downstream leak detection and repair*	<$1	*G. Coal methane to feedstock*	$29
h. Replace compressor seal or rod	–$3	*u. Early replacement of devices*	$2	*H. Small scale dome digestors*	$39
i. Replace with instrument air systems	–$3	*v. Replace with electric motor*	$2	*I. Animal feed-mix optimization*	$49
j. Install plunger	–$2	*w. Sulfate fertilizers*	$3	*J. Other*	$50
k. Feed grain processing	–$2	*x. Advanced technologies*	$3	*K. Animal feed additives*	$88
l. Vapour recovery units	–$2	*y. Composting*	$4	*L. Covered lagoon and anaerobic digesters*	$205
m. Upstream leak detection and repair	–$1	*z. Install flares*	$4	*M. Animal growth promoters*	$1378

Note: Some levers are not depicted on cost curve due to the lack of cost data and the skew of the chart due to high cost.
1. Carbon dioxide equivalent. Cost is based on 20-year global warming potential where 1 metric ton of methane is equivalent to 84 metric ton of carbon dioxide.
Source: McKinsey analysis

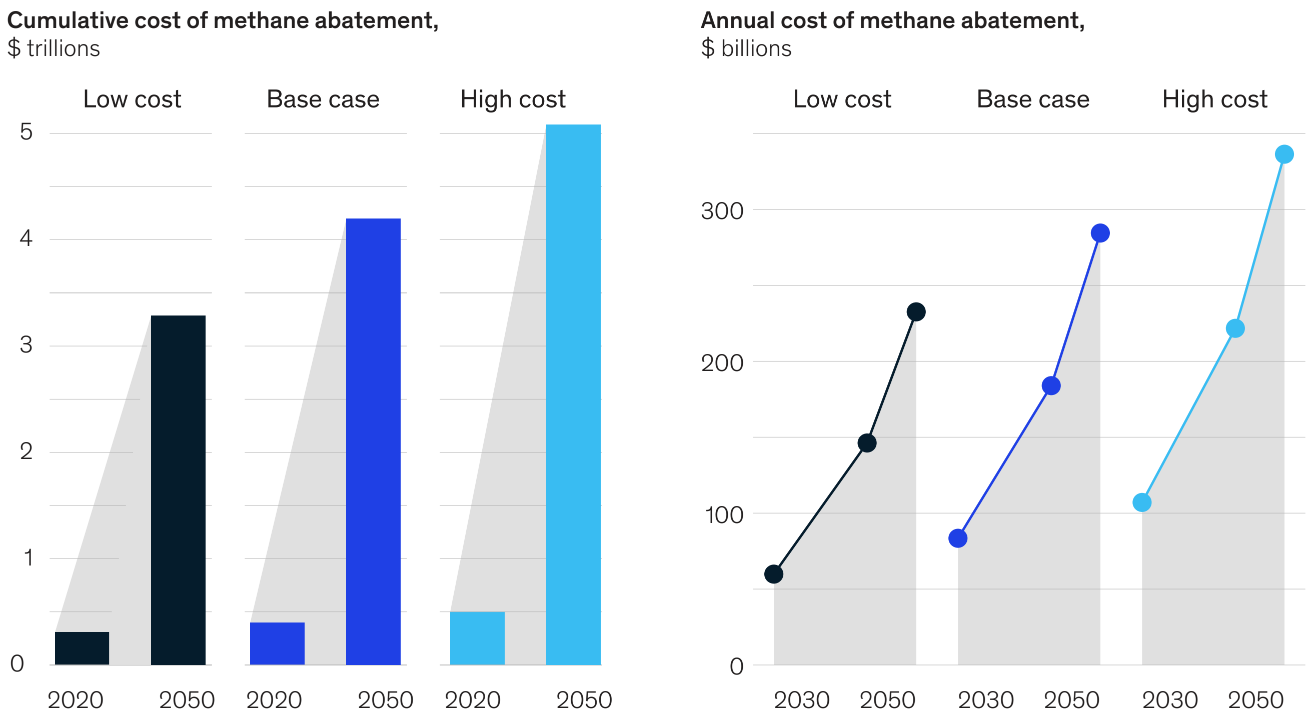
- Ten percent would cost between $10 and $25 per tCO_2e and would include mechanical biological treatment of solid waste and VAM capture for coal mines.
- Three percent would cost between $25 and $50 per tCO_2e and would include plug flow and small-scale dome digestors for livestock.
- The remaining 6 to 7 percent would cost more than $50 per tCO_2e and would include animal feed additives and covered lagoon or anerobic digestors for animal farms.

Cost modeling accounts for technical levers that could abate 80 Mt of methane (or 6.7 $GtCO_2e$)[36] by 2030 and 160 Mt of methane (or 13.4 $GtCO_2e$) by 2050. It does not account for "next horizon" technologies, such as methane inhibitors or direct methane capture from ruminants.

Full deployment of the abatement measures described here would cost an estimated $60 billion to $110 billion annually up to 2030, $150 billion to $220 billion annually by 2040, and $230 billion to $340 billion annually by 2050. These estimates include the capital investments, operational costs and savings, and potential revenues from recovered methane (Exhibit 9). Cumulatively, the cost of adopting all technical levers would amount to $3.3 trillion to $5.1 trillion over a 30-year period. For reference, the total economic stimulus announced by governments in 2020 was $12 trillion dollars. On the basis of converting methane into CO_2e, the estimates equate to an average cost of around $21 per tCO_2e using GWP20 or $63 per tCO_2e using GWP100.

Exhibit 9

Deploying technical solutions to reduce methane at the scale required to limit warming to 1.5°C would cost $3.3 trillion–$5.1 trillion in total by 2050.



Source: McKinsey analysis

[36] Calculated using GWP20 (1 metric ton of methane equals 84 metric tons of carbon dioxide). Using GWP100, this figure would be 2.2 $GtCO_2e$.

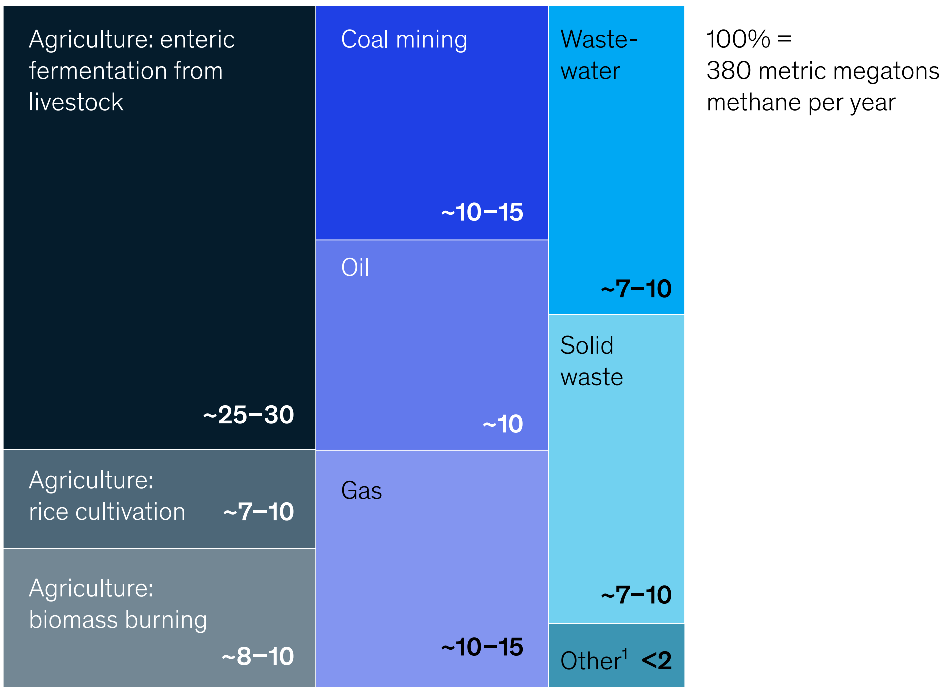
4. Industry solutions

Agriculture, oil and gas, coal mining, solid waste, and wastewater produce 380 Mt per year of methane emissions, accounting for around 98 percent of such emissions from human activity (Exhibit 10). These industries, therefore, are vital to the abatement required to align with a 1.5°C pathway. Given their diverse circumstances, however, there is no single type of solution that can be applied across the board. Instead, decision makers must solve a complex optimization problem, developing tailored responses in the context of what is economically and practically feasible—both of which are evolving over time. At a minimum, they will need to find a balance between strategy, practicality, regulatory alignment, and urgency while managing the interests and expectations of a broad range of stakeholders.

Exhibit 10

Methane from human activity is emitted by five key industries: oil and gas, coal, agriculture, solid waste, and wastewater.

Global methane emissions from human activities, % share



1. "Other" includes industry and vehicle transport emissions.

Source: Marielle Saunois et al., "The global methane budget 2000–2017," *Earth System Science Data*, 2020.

Agriculture

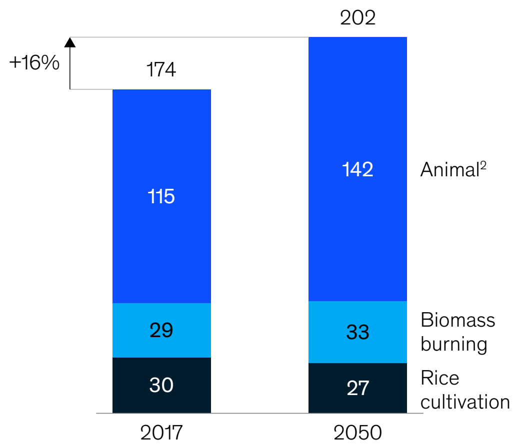
The agricultural sector is the largest single emitter of methane, accounting for 174 Mt per year from sources that include enteric fermentation (64 percent), rice cultivation (17 percent), and biomass burning (17 percent).[37] The magnitude of emissions varies considerably across regions and millions of individual farms.[38]

Methane footprint and trajectory
The Food and Agriculture Organization and McKinsey Food Models project methane emissions from agriculture will rise by 16 percent by 2050, based on current trends. Methane from cattle alone is projected to grow by 23 percent by 2050, mainly driven by a rise of 0.8 to 1.0 percent per year in per capita consumption in low-income countries and by a global annual population growth of 0.8 percent (Exhibit 11). Even after that growth, on a per capita basis, lower-income countries will still predominantly trail higher-income countries in protein consumption, indicating the significance of the change required—both in developed and developing countries.

Exhibit 11

Methane emissions from agriculture mostly result from ruminant animals and could increase 16 percent by 2050.

Methane emissions from agriculture, by segment, current and projected, $MtCH_4$/year[1]



1. Current emissions (2017) based on Marielle Saunois et al., "The global methane budget 2000–2017," *Earth System Science Data*, 2020, Volume 12, Number 3, pp. 1561–1623, essd.copernicus.org; emission projections based on Food and Agriculture Organization (FAO) global numbers scaled to 2017 baseline.
2. Some research groups challenge the attribution of methane emissions to ruminant animals, including the Oxford Martin Programme on Climate Pollutants (Myles Allen et al., "Climate metrics for ruminant livestock," Oxford Martin School, July 2018, oxfordmartin.ox.ac.uk) and the Beef Board ("Is beef to blame for climate change?," Beef Board, September 19, 2019, beefboard.org).

Source: The Food and Agriculture Organization (FAO);

Technical solutions
Methane emissions from agriculture could be abated up to 12 percent by 2030 and 30 percent by 2050 through technical levers (Exhibit 12). The following conditions would need to be met:

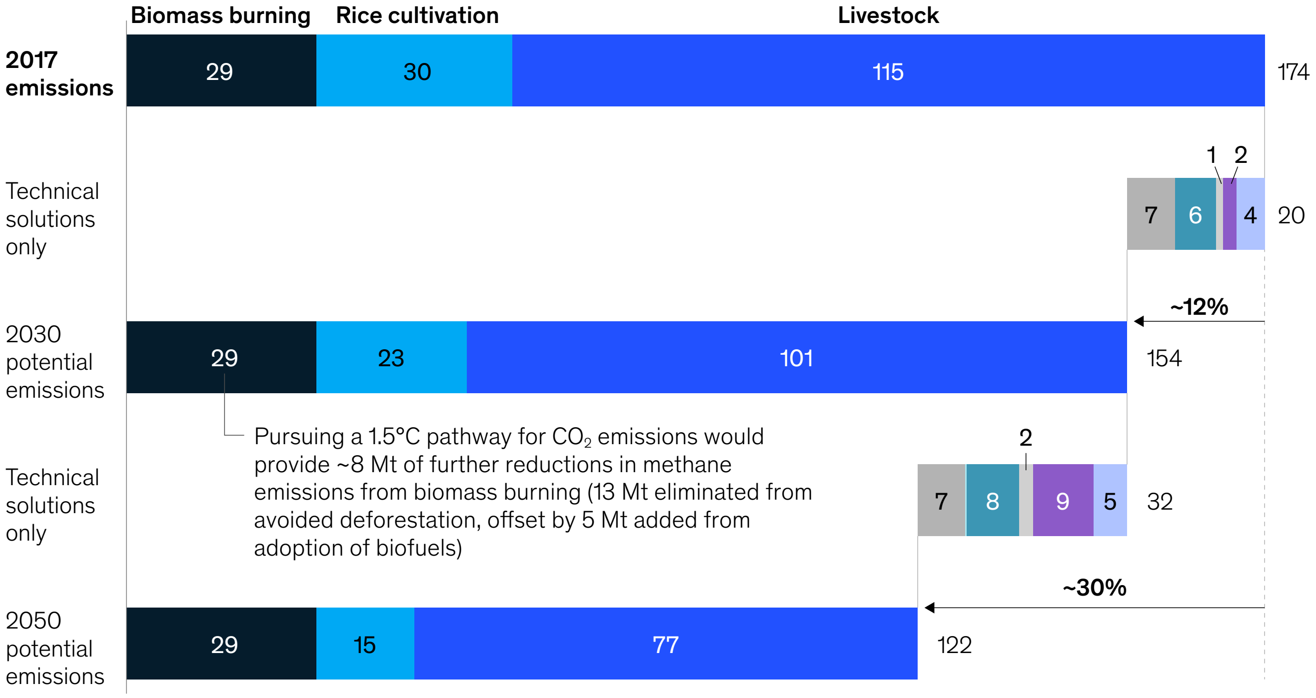
Rice growers would need to change long-established farming practices, including adopting new fertilization and water-management techniques, planting seeds directly in dry soil instead of transplanting young crops into flooded fields, and using aerobic rice varieties that can be grown without flooding and are more tolerant to droughts. At the same time, farmers would need to carefully manage water, nitrogen, and organic matter and avoid triggering releases of other greenhouse gases trapped in the soil, such as nitrous oxide and carbon.[39] Dry direct seeding has the potential to reduce methane emissions from rice by 40 to 60 percent,[40] but it increases nitrous oxide emissions by 30 to 40 percent (from a minimal baseline). Still, when considered in terms of CO_2e, this results in a net reduction

[37] Biomass burning emits methane under incomplete combustion conditions (that is, when oxygen availability is insufficient for complete combustion), for example in smoldering fires. The amount of methane emitted during the burning of biomass depends primarily on the quantity of biomass, the burning conditions, and the specific material burned. The efficient burning of dry savannah, for example, releases relatively small amounts of methane compared with smoldering forest or peat fires.
[38] Marielle Saunois et al., "The global methane budget 2000–2017," *Earth System Science Data*, 2020, Volume 12, Number 3, pp. 1561–1623, essd.copernicus.org.
[39] *Global risk assessment,* 2018.
[40] For our modeling, we assume a 43.0 percent reduction in methane emission. Multiple studies indicate different reduction levels: for instance, J.Y. Ko and H.W. Kang ("The effects of cultural practices on methane emission from rice fields," *Nutrient Cycling in Agroecosystems*, November 2000, Volume 58, pp. 311–14, link.springer.com) estimate a 37.0 percent reduction, while Debashis Chakraborty et al. ("A global analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production," *Scientific Reports*, August 2017, Volume 7, Number 9342, nature.com) estimate a reduction of 43.9 percent from dry direct seeding.

Exhibit 12

Technical solutions could reduce methane emissions from agriculture by 30 percent by 2050.

Methane emissions abatement potential by solution type, $MtCH_4$/year



Implementation considerations

Biomass burning

~80%
Reduction in deforestation globally would be required by 2030 and would need to be maintained through 2050

30–40%
Increase in biomass as fuel to displace coal and fossil fuels in a 1.5°C scenario could marginally increase agriculture methane emissions up to 3–4%

Rice cultivation

200M+
Farms would need to implement technical solutions, with most farms less than **2 hectares in size**

Livestock

40%
Emissions from top 3 regions, where only 20% of beef and 33% of dairy is consumed

400M+
Rural, poor livestock keepers supported by farming

Technical solution	Top abatement levers
Deploy next-horizon technologies	Methane inhibitors; direct methane capture aerobic rice; gene editing; microbiome
Boost crop efficiency	Pressurized irrigation and electrification of on-site machinery
Change rice planting[1]	Dry direct seed; rice paddy water; straw, sulfate fertilizers; varietal rice selection
Improve manure management	Plug flow, covered lagoon, and anaerobic; small-scale dome and complete mix anaerobic digestors
Change breeding	Genetic selection and breeding; growth promoters; health monitoring
Change feeding	Feed-mix optimization; feed grain processing; feed additives

1. Note that some solutions focused on reducing methane from rice planting do have a net positive increase on nitrous oxide emissions that would need to be taken into account.

Source: Daniel Aminetzah, Nicolas Denis, Kimberly Henderson, Joshua Katz, and Peter Mannion, "Reducing agriculture emissions through improved farming practices," May 6, 2020, McKinsey.com.

of 49 to 56 percent.[41] These measures could collectively reduce rice-related methane emissions by 50 percent and overall agricultural methane by 9 percent.

Beef and dairy producers would need to adopt alternative practices and technologies, such as feed additives or mixes, different breeding practices, and methane inhibitors. These could reduce methane from cattle by 29 percent and from agriculture by 19 percent.

Although not considered a technical lever, reducing agriculture-driven deforestation—for example, for the planting of soybeans (used mainly in cattle feed)—in line with a 1.5°C pathway would also cut methane emissions from biomass burning by an estimated 42 percent and from overall agriculture by 7 percent.[42]

Example technologies for methane mitigation in cattle

Reducing methane emissions from cattle through the development and deployment of technologies would lessen the need for massive shifts in consumption. Several promising technologies are highlighted here.

Feed additives
Additives such as seaweed and propionate precursors can inhibit the formation of methane in the animal's gut.[1] DSM, a company that develops food and feed ingredients and additives, has developed an additive to reduce methane emissions from enteric fermentation in dairy cows. Adding a tablespoon of the additive to every 250 pounds of dry feed reduces methane emissions by 30 percent without impacting milk production.[2] DSM submitted its additive for approval for sale in the European Union in 2022. Additionally, the use of seaweed as an additive has attracted the attention of multiple startups, such as Volta Greentech and Blue Ocean Barns, seeking to scale up options for farmers.

Genetic breeding
Breeding can address the 20 percent of a ruminant's methane emissions rate that stem from genetics alone.[1] Some commercial genetics products reduce emissions by 5 percent or more per head, and in single herds, intentional breeding for methane efficiency has achieved variation in methane production of about 20 percent. New breeding techniques, such as those using CRISPR/Cas9 gene-editing technology, could lower barriers to entry for innovators and allow for more specificity in genetics programs. Synomics, a company based in Europe, is currently working on an analytics-driven selective breeding solution as a cost-effective way for farmers to cut emissions.

Feed-mix optimization
Feed-mix optimization is a widely applicable approach to transitioning ruminant animals to a higher-fat diet, which is an effective means of reducing enteric fermentation, the digestive process that produces methane emissions. There is growing interest in using larger amounts of whole seeds, plant oils, or fat supplements in animal feed.[1] The content of dry matter (DM) in a traditional ruminant diet is about 1.5 to 3.0 percent fat and could safely be increased up to 6.0 percent fat. Each percentage point would reduce methane emissions by 4 percent per head.

1 Daniel Aminetzah, Nicolas Denis, Kimberly Henderson, Joshua Katz, and Peter Mannion, "Reducing agriculture emissions through improved farming practices," May 2020, McKinsey.com.
2 A. Melgar et al., "Dose-response effect of 3-nitrooxypropanol on enteric methane emissions in dairy cows," *Journal of Dairy Science*, July 2020, Volume 103, Number 7, pp. 6145–56, sciencedirect.com.

Abatement economics and challenges

Around half of agriculture solutions realize costs savings. However, the cost curve is variable, ranging from savings of \$41 per tCO_2e to costs of \$1,378 per tCO_2e (including some CO_2 reduction as well).[43] In rice farming, dry direct seeding cuts both labor costs and water usage and therefore could generate significant savings. By contrast, the economics of proven technologies

41 GWP20 indicates a 56 percent decrease using an 84:1 ratio of methane to carbon dioxide and a 265:1 ratio of nitrous oxide to carbon dioxide, while GWP100 indicates a 49 percent decrease using a 28:1 ratio for methane and a 264:1 ratio for nitrous oxide.
42 Additionally, burning conditions (smolder) of biomass in agricultural clearing, as well as building heating and cooking, release methane. On a 1.5°C pathway, it is projected that biomass usage will increase in the buildings sector. Increased biomass burning could cause a marginal increase in methane emissions, heavily offset by the abatement benefit of reduced CO_2 emissions from fossil fuels being displaced by biomass.
43 GWP20 is used to convert methane into carbon dioxide equivalents (1 metric ton of methane equals 84 metric tons of carbon dioxide) for the sole purpose of calculating abatement costs.

to reduce methane emissions from cattle tend to be relatively costly, running from a savings of $27 per tCO_2e to a cost of $88 per tCO_2e abated. While there is proven efficacy in lowering methane production through feed additives, the business model is currently unproven. With that in mind, adoption at scale would likely require incentives, driven by policy or increased customer demand for low-methane beef.

Based on McKinsey analysis, implementation of these technical solutions in aggregate would require $250 billion in capital but could lead to savings of $20 billion to $40 billion in annual operating costs.[44]

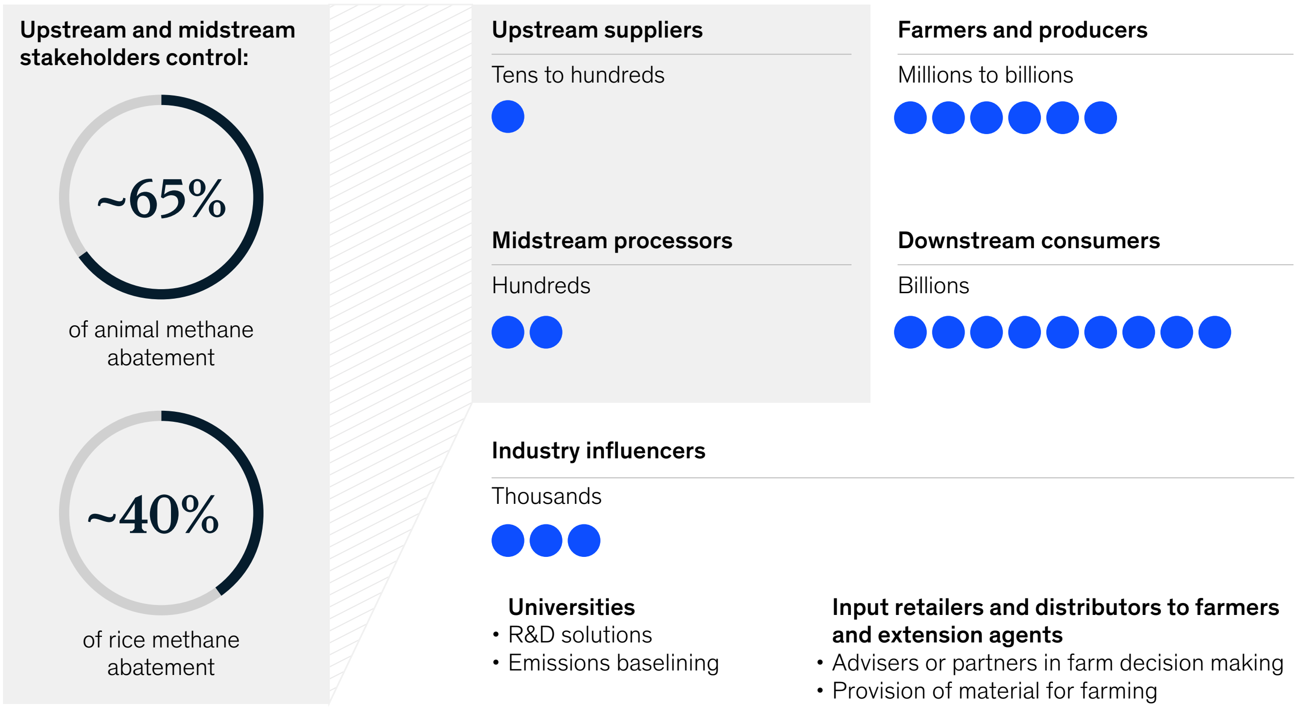
There are significant practical challenges in implementing methane abatement in agriculture. These include stakeholder fragmentation, a lack of financial and regulatory incentives, animal welfare considerations, a generally low level of awareness, and poor industry monitoring in many countries. Agriculture is also central to sustaining livelihoods and reinforcing economic development, supporting 65 percent of low-income working adults globally. The risk of failure or lower yields in the short term—even for the sake of longer-term gains—is therefore a potential barrier to change.[45]

Given the distributed nature of agriculture production and the length of the value chain, the most optimal bet for reducing methane would likely be to target concentrated segments. Upstream and midstream stakeholders, including distributors, seed cultivators, and cattle breeders, could implement roughly two-thirds of animal-methane abatement solutions and about two-fifths of rice-methane abatement solutions (Exhibit 13). It may be easier to instigate change among these groups than among the millions of smaller or subsistence farming operations.

Major players in the space have the key role of incentivizing and aiding growers or producers to adopt existing technologies (for example, financing schemes to help growers buy dry rice planters or premiums for low-methane dairy to encourage feed additives) or of innovating to provide tools to help growers (for example, digital animal-health trackers for lower animal mortality).

Exhibit 13

Because agricultural suppliers and processors are few, it could be easier for them to achieve high adoption of abatement solutions.



Source: McKinsey analysis

44 Daniel Aminetzah, Nicolas Denis, Kimberly Henderson, Joshua Katz, and Peter Mannion, "Reducing agriculture emissions through improved farming practices," May 2020, McKinsey.com.
45 Ibid.

Oil and gas

The oil and gas industry emits nearly 84 Mt of methane annually, which would be worth $11 billion to $18 billion on the open market, valued at the average 2019–20 Henry Hub price of $2.5 per million British thermal units (MMBtu).[46] While the industry accounts for just 9 percent of global anthropogenic GHG emissions, it is responsible for 20 to 25 percent of methane emissions.[47] In addition, the industry flares approximately 90 Mt of methane per year, losing an additional $12 billion to $19 billion in value.

Methane footprint and trajectory

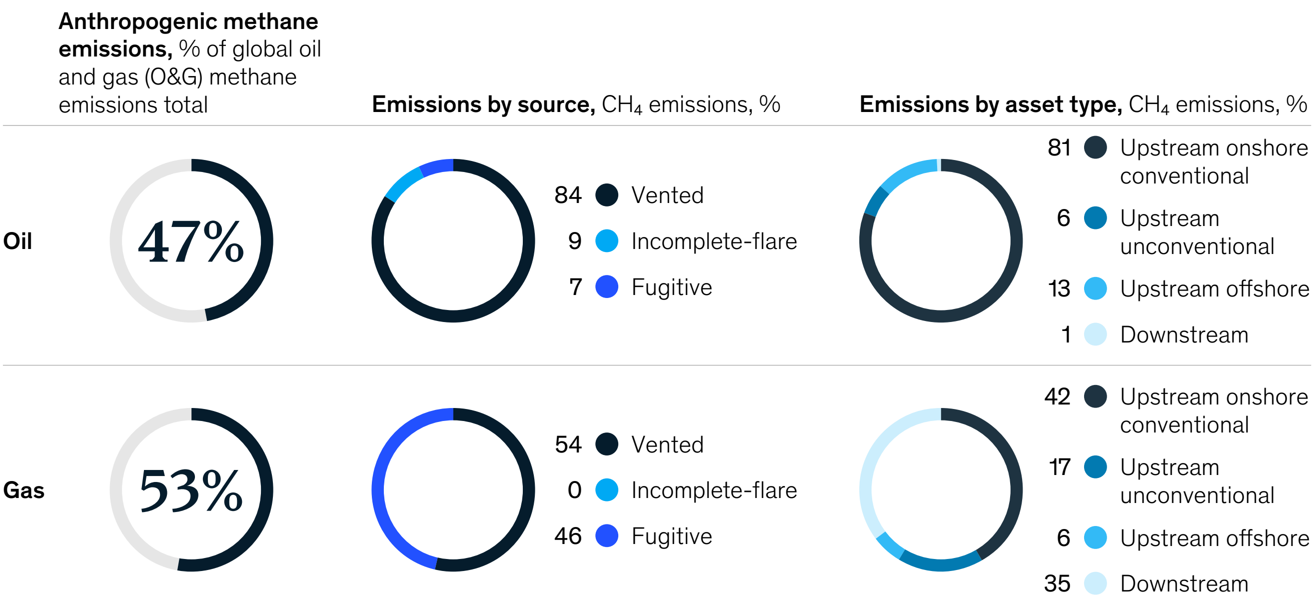
Almost all (93 percent) of oil and gas emissions are associated with one of five segments: onshore oil (38 percent), conventional onshore gas (22 percent), downstream gas (19 percent), unconventional gas (9 percent), and offshore oil (5 percent).[48] There can be wide performance differentials within and across segments, and the lowest emitters in onshore oil can have a similar footprint to some offshore oil producers.

In the oil value chain, 99 percent of methane emissions are released during upstream production (Exhibit 14). The separation process divides oil, water, and methane soon after extraction. Some fields reinject the gas or use it for power, but at others, these options may have been seen as uneconomic at the time of developing the asset.

In the gas value chain, 65 percent of methane emissions are upstream, caused by venting from pressurized vessels, pipelines, or other infrastructure. The remainder are downstream, mainly due to fugitive leaks in pipelines, seals, and other equipment. Leaks occur throughout

Exhibit 14

Most methane emissions from oil and gas assets are released from venting during midstream or upstream production.



Note: Figures may not sum to 100%, because of rounding.
Source: Emissions Database for Global Atmospheric Research (EDGAR), 2015; International Energy Agency (IEA) methane tracker, 2020; Wood Mackenzie; McKinsey analysis

the gas value chain, right up until gas is delivered to the customer (Exhibit 14).

46 Estimate is highly dependent on gas prices. Average Henry Hub prices are now under $3 per MMBtu since 2018, but the maximum price was $4 in 2018. Note that prices in Asia and Europe are higher than at Henry Hub.
47 Nine percent of carbon emissions are from oil and gas operations (Scope 1 and 2); however, end customers of oil and gas contribute 33 percent of total emissions.
48 Remaining emissions are contributed by unconventional oil, offshore gas, and downstream oil.

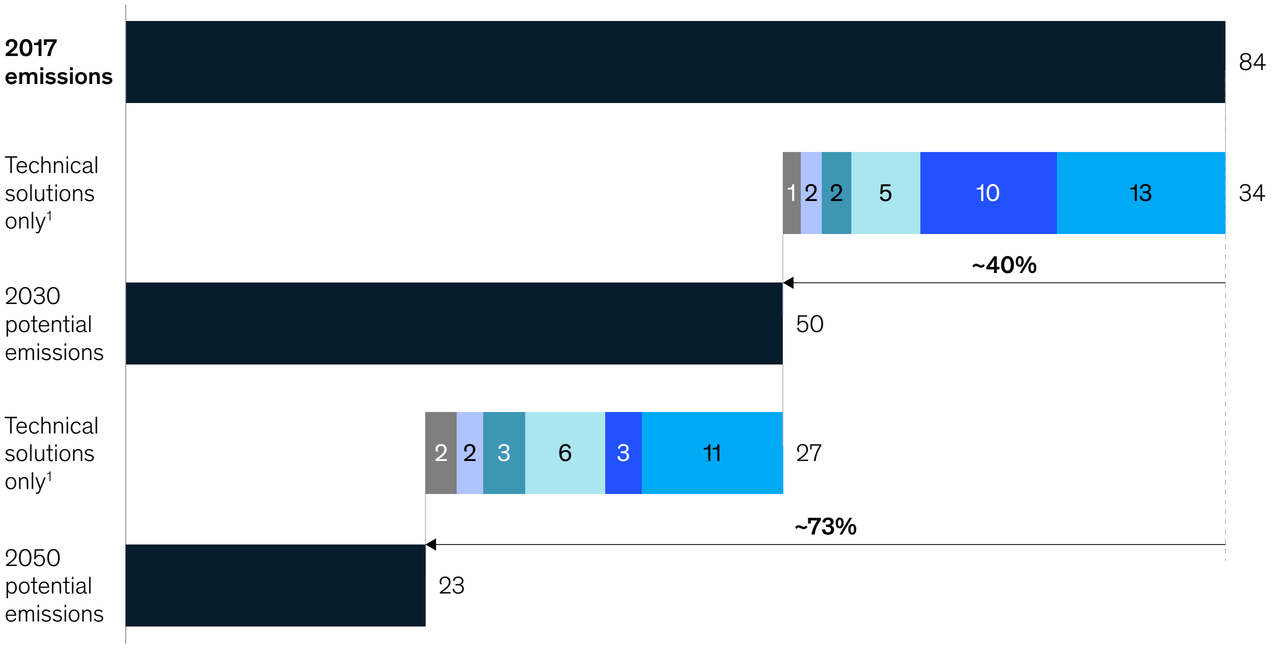
Technical solutions

Methane emissions from oil and gas could be abated by 40 percent by 2030 and 73 percent by 2050 via technical levers alone. Indeed, large volumes of methane emissions that are now treated as a waste could be recovered and sold as natural gas. Upstream production represents 75 percent of abatement potential, with key abatement options including LDAR for facilities with high volumes of equipment, electrification, instrument air systems, and VRUs. Downstream has fewer emissions and therefore represents just 18 percent of abatement potential. Abatement options include LDAR (long transmission pipelines and facilities with less equipment), replacing compressor seals, and flaring (oil processing) (Exhibit 15).

Exhibit 15

Technical solutions could reduce methane emissions from oil and gas by nearly three-quarters by 2050.

Methane emissions abatement potential, metric megatons of anthropogenic methane emissions per year



Asset type	Top abatement levers
Onshore conventional oil	Electric motor replacement of pneumatics; vapor recovery units; pump replacement
Onshore conventional gas	Leakage detection and repair; replace pumps with instrument air systems
Downstream gas	Leakage detection and repair; replace compressor seals and rods
Unconventional gas	Leakage detection and repair; replace pumps; instrument air systems
Offshore oil	Install flares; vapor recovery units
Other	Install flares; replace pneumatics with electric motor; upstream leakage detection and repair

Note: Figures may not sum, because of rounding.
1. Applied to 100% of production, as given by the International Energy Agency (IEA). All options deployed across oil and gas value chain.
Source: International Energy Agency (IEA) methane tracker, 2020; McKinsey analysis

By 2030, the oil and gas industry could feasibly adopt technical solutions that have a net negative cost. By 2050, the fullest extent of technical solutions could be deployed across assets, including both solutions with positive and negative cost. The remaining emissions are considered "unavoidable," as they are the result of standard start-up, shutdown, safety, and other operating characteristics that are currently an inevitable part of oil and gas operations.[49] Further technical advancements would be required to address the remaining emissions, or fossil fuel production would need to fall.

Abatement economics and challenges

Many of these levers could generate operating-expenditure savings by reducing energy or maintenance costs and create revenues from gases that otherwise would be lost into the atmosphere.[50] The IEA estimates that around 40 percent of abatement measures in the oil and gas industry are possible at zero or negative net cost.[51] The most cost-efficient solutions are in conventional upstream production rather than downstream, where the upgrading of thousands of miles of pipeline would be both resource-intensive and costly. Potential solutions include replacing pneumatic or chemical injection pumps with electric pumps in conventional onshore oil and replacing gas-fed pumps with solar chemical pumps in conventional onshore gas. These could improve both operational integrity and efficiency and are therefore no-regret moves.

The economics of abatement for individual assets are highly variable and depend on the type, scale, complexity, and integrity of the asset. Consider the example of an onshore conventional producer of gas and natural gas liquids. The asset has an emissions intensity of less than 15 $kgCO_2e$ per barrel of oil equivalent (BOE), 40 percent of which is methane lost as fugitives or through venting. The majority of methane abatement comes at a cost of less than $20 per tCO_2e before regional carbon benefits are considered.[52] This translates into a total cost of $15 to $24 per billion cubic feet (bcf) of lifetime gas production, a minor cost burden relative to the total production costs of $1 million to $2 million per bcf (Exhibit 16). Primary levers and their economics for this onshore conventional asset include the following:

— Early replacement of devices (high-to-low bleed instruments) typically costs $1,000 to $1,200 per well, which nets out to $2.50 to $3.50 per bcf of production.

— Improving LDAR through a fugitive-emissions management program can be implemented at operational costs of $7 to $8 per bcf and may save $1 per bcf of production.

— Replacing gas-fired pumps with solar chemical pumps typically costs $11,000 to $13,000 per well, which nets out to $18 to $22 per bcf in capital costs and can save an additional $5 to $6 per bcf of gas production. With drilling and completion costs of a well in the range of $6 million to $8 million, the cost of methane abatement is approximately 0.1 percent of total capital expenditures. Likewise, replacing air instrumentation systems can cost $80,000 per facility, netting out to less than $1 per bcf and a relatively small fraction of overall capital costs.

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49 *Methane tracker 2020*, International Energy Agency (IEA), 2020, iea.org.

50 Energy operating-expenditure savings come from increased efficiency (for example, replacing gas pumps with electric) or maintenance from increased asset lifetimes (for example, replacing a compressor seal, thereby increasing the rod's lifetime). Further revenue comes from additional gas throughput (for example, installing plungers to increase production). See *Methane tracker 2020*, 2020.

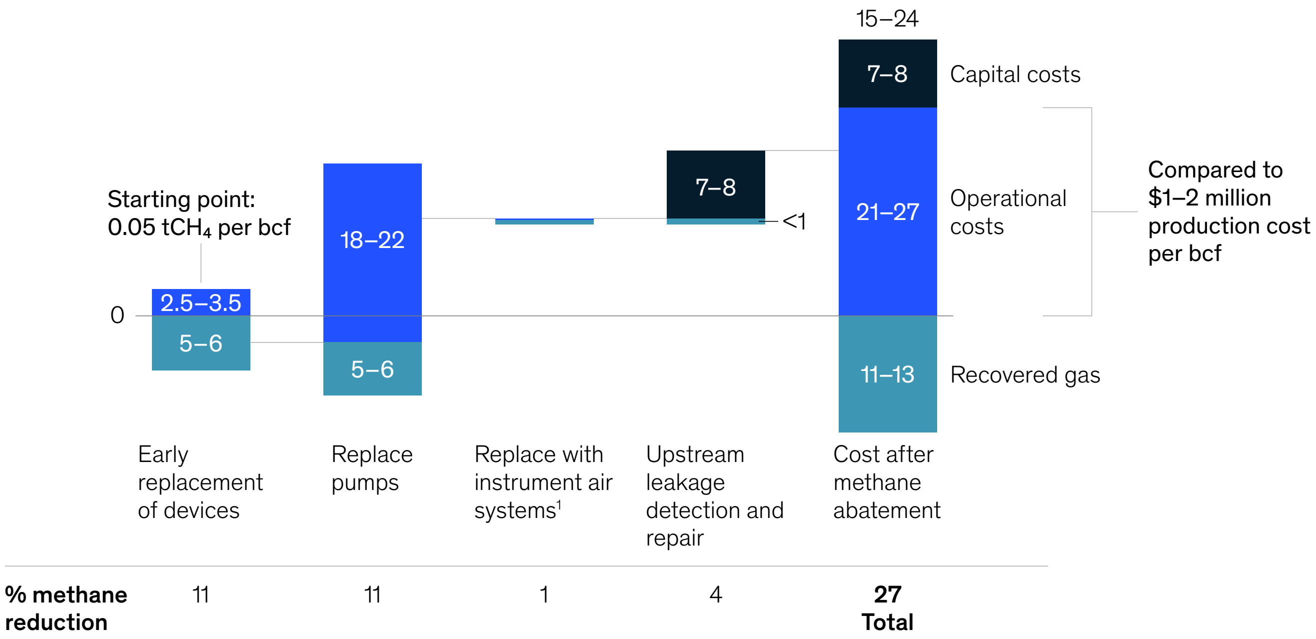
51 *Methane tracker 2020*, 2020.

52 GWP20 is used to convert methane into carbon dioxide equivalents (1 metric ton of methane equals 84 metric tons of carbon dioxide) for the sole purpose of calculating abatement costs.

Exhibit 16

The cost of methane abatement for conventional gas assets is minor compared with the production cost of gas.

Cost of methane reduction levers, $/billion cubic feet (bcf)
Indicative



1. Capital costs = <$1/bcf; operational costs, <$1/bcf; recovered gas, –$0.1/bcf.

Source: McKinsey analysis

Operator capabilities, balance sheets, and execution approaches further influence the overall abatement economics and speed of execution:

— Deployment of some abatement options could impede ongoing operations because installation requires a shutdown—in the normal course of business, done once every two to four years. Business leaders, therefore, face a value dilemma if they decide to implement outside of the normal cycle.

— Where producers have strong balance sheets and advanced operational capabilities, methane abatement projects may be easier to implement—both economically and operationally. As these projects will require additional operator interventions in delivering capital projects and in regular maintenance operations, advanced change-management approaches may be required.

— The economics of cross-operator solutions, such as adding gas-export infrastructure, might be more attractive as a basin-wide initiative, rather than a stand-alone effort to address the evacuation of gas from a single asset.

Products that can be shown to be responsible for lower emissions could command an advantage with customers looking to decarbonize their supply chains. The International Group of Liquefied Natural Gas Importers (GIIGNL) has said that carbon-neutral LNG can be viewed as a premium product and a competitive differentiator.[53] In the United States, Cheniere Energy has announced plans to combine public data from value-chain participants and operational data from its Sabine Pass and Corpus Christi LNG facilities in a proprietary life cycle analysis model to measure GHG emissions of its cargoes. The intent is to quantify emissions data from wellhead to delivery point and offer each cargo with a carbon emissions

[53] Vincent Demoury, *LNG carbon offsetting: Fleeting trend or sustainable practice?*, The International Group of Liquefied Natural Gas Importers (GIIGNL), June 18, 2020, giignl.org.

tag (CE Tag). Cheniere Energy also cofounded the Collaboratory to Advance Methane Science (CAMS) with Chevron, Equinor, ExxonMobil, and Pioneer Natural Resources to improve scientific understanding of methane emissions across the entire natural gas value chain.[54] In Asia, Qatar Petroleum and Pavilion Energy are collaborating on establishing an emissions transparency standard; in October 2020, they signed a ten-year supply agreement for which each cargo delivered will come with a statement of its well-to-port GHG emissions.[55] Noncommercial efforts to measure, track, and certify cleaner products also continue. RMI and SYSTEMIQ have launched a market-based gas certification system to develop greener products and distinguish cleaner producers.

Implications of alignment with the 1.5°C pathway

An aggressive transition away from fossil fuels will be a necessary part of achieving the 2030 target for methane reduction on a 1.5°C pathway. However, even in a fully decarbonized economy, oil and natural gas will continue to play a role in the energy system (and for other uses, such as chemical production). If all sectors acted to reach net-zero emissions by 2050, natural gas would continue to service 20 percent of total energy demand in 2030 and 7 percent by 2050. Oil would transition from 33 percent today to 25 percent in 2030 and to 10 percent in 2050, with remaining demand residing in hard-to-abate sectors.

With these trajectories in mind, deploying solutions to recover methane could offer existing oil producers a near-term revenue opportunity. In addition, companies that continue to operate assets through 2030 or 2050 would likely cut methane emissions as much as possible to sustain their future attractiveness to investors.

[54] "Cheneire to provide cargo emissions data to LNG customers," Cheniere, February 24, 2021, cheniere.com; "Cheniere announces publication of greenhouse gas life cycle assessment," Cheniere, August 5, 2021, cheniere.com

[55] Jessica Jaganathan, "Singapore's Pavilion inks first long-term LNG deal with Qatar," Reuters, November 9, 2020, reuters.com.

Companies shaping their abatement responses

Leading companies have already responded to the methane challenge by cutting emissions. In fact, the majority of recent emissions reductions in oil and gas have been due to methane abatement and present opportunities to define higher operating standards for the industry. ExxonMobil, for example, is formulating methane abatement standards and techniques to help achieve its 2025 goal to reduce methane intensity by 40 to 50 percent, and it operates a network of sensors to monitor emissions in the West Texas Permian Basin. The project, a partnership with the Environmental Defense Fund, The University of Texas at Austin, and the Gas Technology Institute, will evaluate monitoring technologies and help regulators understand onshore oil and gas emissions.

In March 2021, Neptune Energy, in partnership with the Environmental Defense Fund, announced plans to pilot novel methane measurement solutions at its offshore oil and gas facilities. It will deploy drones, aircraft, and remote monitoring at its Cygnus platform in the United Kingdom's North Sea to provide a close-up view of operations typical of a North Sea offshore facility, such as gas separation, drying and compression technology, and flaring and venting.[1] A key research objective is to establish a reliable benchmark for assessing total oil and gas methane emissions in an offshore environment.

Another leader in the field is Pioneer Natural Resources, which is differentiating itself among Permian Basin producers through operations with lower methane emissions. The company has set a target to reduce methane intensity by 40 percent by 2030.[2] Pioneer has committed to ensuring that 100 percent of its new wells are tied to gas-gathering infrastructure before going into production, a first in the Permian Basin. The company currently maintains a vented or flared methane rate of 0.6 percent, compared with an average of 2.0 percent across the basin. To achieve this, it uses flares as backup to VRUs for emergencies, where methane would otherwise be vented. It has installed a low-pressure stack system in case a VRU goes down. All of its tanks have multiple VRUs, regardless of the economics of recovered gas, to ensure 100 percent VRU capture efficiency. In 2019, it also advocated to the Texas Railroad Commission licensing body that methane flaring and emissions in the Permian be limited to 2 percent.

1 "Nepture Energy, EDF to pilot novel method to measure offshore methane emissions," Neptune Energy, March 5, 2021, neptuneenergy.com.
2 "Pioneer Natural Resources releases 2020 sustainability report, incorporates emission reduction targets," Pioneer Natural Resources, December 2, 2020, pxd.com

Coal mining

Coal mining around the world is responsible for around 44 Mt of methane emissions a year, or 10 to 15 percent of the global total. Coal seams contain pockets of methane that are exposed and released during normal mining operations underground and at the surface. In addition, methane can seep out of abandoned mines.

Methane footprint and trajectory
According to McKinsey's Basic Materials Insights (BMI), thermal coal demand will likely fall by 1.4 percent a year over the next 20 years and faster after 2040. Metallurgical coal demand will decline 0.4 percent over the same period. As a result, CMM emissions will drop 38 percent by 2050.[56]

Underground mining accounts for more than approximately 85 percent of CMM emissions, released primarily from ventilation, postmining activities, degasification, and fugitive emissions from abandoned but vented mines.[57] Put simply, the deeper the mine, the greater the amount of methane release, reinforcing the primary role underground mining plays in coal methane emissions.[58] Surface mining operations are responsible for the remaining approximately 15 percent of emissions, amid periodic releases of methane from open-pit drilling and blasting, exposed seams, stockpiled overburden (earth and rock removed to access coal seams), and emissions from coal transport.[59] These occasional releases are challenging to determine from current methodologies and data, suggesting that the share of surface emissions could be higher than current estimates.

Methane release from abandoned and decommissioned mines is a significant challenge. The coal abandonment rate is roughly 5 percent globally,[60] and around ten percentage points of the more than 85 percent of underground CMM release is from hundreds of abandoned underground mines in the United States.[61] Thousands of abandoned coal mines in China could present a similar risk,[62] though there have been considerable efforts to identify and drive capture of abandoned mine methane (AMM).[63] Longer-term AMM presents a significant challenge, as fugitive emissions could continue until the end of the century.[64] There are several factors that will affect AMM over the next three decades:

— **Measurement and tracking.** A global audit is required to confirm the 5 percent abandonment number, which is based on information from China, Russia, and the United States.

— **Depth of mines.** If mines are excavated more extensively and deeply in a search for metallurgical coal, then gassiness will increase, along with emissions now and the risk of abandonment in the future.[65]

— **Share of surface versus underground mining.** More surface mines as a share of production volume would reduce both CMM and AMM, given a lower emissions rate and reduced gassiness, plus the greater ease of rehabilitation.

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56 The 38 percent drop in emissions by 2050 is based on predicted energy demand for coal from McKinsey's 1.5C business-as-usual (BAU) energy scenario.
57 "Coal Mine Methane Developments in the United States," EPA, 2018, epa.gov.
58 Nazar Kholod et al., "Global methane emissions from coal mining to continue growing even with declining coal production," *Journal of Cleaner Production*, May 2020, Volume 256, sciencedirect.com.
59 "The global methane budget," 2020; "Coal mine methane developments," updated 2019; Kyle Swanson, George Sugihara, and Anastasios Tsonis, "Long-term natural variability and 20th century climate change," *Proceedings of the National Academy of Sciences of the United States of America* (PNAS), September 2009, Volume 106, Number 38, pnas.org.
60 "Global methane emissions from coal mining to continue growing even with declining coal production," 2020.
61 "Coal Mine Methane Developments in the United States," 2018; *Abandoned coal mine methane opportunities database*, US Environmental Protection Agency (EPA) Coalbed Methane Outreach Program, July 2017, epa.gov.
62 Ron Collings, Kevin Doran, and Robin Murray, *Methane emissions from abandoned coal mines in China*, Ruby Canyon Engineering, 2014, understandchinaenergy.org; Junlian Gao, ChengHe Guan, and Bo Zhang, "China's CH4 emissions from coal mining: A review of current bottom-up inventories," *Science of the Total Environment*, July 2020, Volume 725, sciencedirect.com.
63 Zhao-ping Meng et al., "Evaluation model of CBM resources in abandoned coal mine and its application," *Meitan Xuebao/Journal of the China Coal Society*, 2016, Volume 3, pp. 537–44.
64 "Global methane emissions from coal mining to continue growing even with declining coal production," 2020, p. 7.
65 Ibid., p. 3: "Generally, pressure on a coal seam increases with depth, as does the volume of methane contained by the coal."

— **Rate of coal production.** If coal production falls, the risk of further AMM goes up, as there will be fewer operating mines and more abandonment, especially if precipitated by bankruptcy.[66]

Technical solutions

It is standard practice for coal miners to keep methane at dilute concentrations (less than 1 percent) by circulating large volumes of air via ventilation systems. However, the low concentration level makes it technically challenging and expensive to recover, capture, or reuse methane. To recover methane, a mine would need to be equipped with gas drainage systems (drilled boreholes augmented by pumps) and capture technology (pipes that transport the gas to surface tanks, usually via water).[67] Finally, a mine would need to deploy VAM utilization tools to either employ the methane for energy on-site or transport it to an end user. Additional VAM use cases include producing ammonia and vehicle fuel, but these are not widely deployed.[68]

There are a handful of mines globally that capture methane, but the number is small, and the technology requires significant capital expenditures, particularly in an industry in which there are limited capital-development opportunities. Ensuring that a mine with high methane emissions has sufficient ventilation and is able to capture fugitive methane alone requires more than $25 million in capital expenditures.[69] Capture, therefore, is feasible only for major mining companies with sufficient resources, where there are state subsidies, or if other energy sources are scarce, making VAM utilization economic. If recovery is impossible, capturing methane to destroy it through a flare is an option, but it would release carbon dioxide into the atmosphere.

Given the reality of emissions from closed mines, sealing is critical, particularly for subsurface operations. For surface mines, the challenge is less acute—particularly given requirements in some jurisdictions that land be returned to an approximation of its premined state. In addition, as long as the closed surface mine does not leave exposed walls, there will be little to no emissions in any event. Abandoned mines that have flooded (due to proximate surface- or groundwater) drop to zero methane emissions in 15 years but create the secondary risk of potential water contamination.[70]

Given these challenges, it would make sense to compose or update global inventories of abandoned and closed mines. The inventories should include information on whether mines were successfully sealed or are still emitting methane. The US EPA conducted an extensive survey through 2015, which contained a useful methodology for abandoned or closed CMM release.[71] In addition, previously abandoned mines would need to be properly checked to ensure that methane does not continue to vent through wells, shafts, or fissures.[72]

Given that Canada and the United States together are the third biggest source of CMM emissions, the need to update the US inventory is acute. Other parts of the world, including the European Union and the United Kingdom, have tracked their abandoned coal mines, but some of the data are also old and need updating. These regions are moving away from coal mining in almost all instances (an exception being Poland).[73] However, there have been

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66 Nazar Kholod et al., "Global methane emissions from coal mining to continue growing even with declining coal production," *Journal of Cleaner Production*, May 2020, Volume 256, sciencedirect.com.

67 *Coal mine methane recovery: A primer*, US Environmental Protection Agency (EPA) Coalbed Methane Outreach Program, July 2019, epa.gov.

68 C. Özgen Karacan et al., "Coal mine methane: A review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction," Centers for Disease Control and Prevention (CDC), cdc.gov.

69 Assumes an underground mine producing 1,000 metric tons of coal and capturing 17,000 m^3 per day of methane. Unit capital cost is $45,000 per 1,000 metric tons of run of mine coal.

70 "Coal Mine Methane Developments in the United States," EPA, 2018, epa.gov.

71 *Abandoned coal mine methane*, 2017. The Office of Surface Mining Reclamation and Enforcement (OMSRE) also tracks the disposition of the Abandoned Mine Land (AML) Reclamation Program, including environmental issues; for more, see osmre.gov.

72 Nazar Kholod et al., "Global methane emissions from coal mining to continue growing even with declining coal production," *Journal of Cleaner Production*, May 2020, Volume 256, sciencedirect.com.

73 For example, the United Kingdom has multiple abandoned mine efforts (see Hugh Potter and Dave Johnston, *Inventory of closed mining facilities*, Environment Agency, January 2014, assets.publishing.service.gov.uk). However, from a peak of more than 2,000 coal mines, the United Kingdom now has approximately ten operating surface mines and one proposed deep mine (versus 240 in 1970 and about 500 in the mid-20th century) (see Terry Macalister et al., "The demise of UK deep coal mining: Decades of decline," *The Guardian*, December 18, 2015, theguardian.com). The European Union has strict requirements for mine closure and cleanup since 2004; however, many EU coal mine owners have not been able to comply with the expected actions.

challenges in compliance with abandoned-mine closure and reclamation requirements to ensure AMM abatement.[74] Other coal mining nations around the world may consider similar initiatives, especially where there is a history of extensive underground production.

Following drafting of inventories, it will be critical to assess the probability of future emissions from abandoned and closed mines and the means to seal the mines—often as simple as applying cement. Finally, tracking will be required to ensure sealing measures are maintained. With any local or regional decline in coal mining, the work will benefit from the experience and knowledge of former miners.

In the United States, finance for sealing is available from the Abandoned Mine Land (AML) Fund,[75] which has collected and distributed significant grants to states and tribes. In addition, the Biden Administration's American Jobs Plan offers funds to address abandoned mines.[76] However, without a clear understanding of the rapidly changing landscape, funds alone will not solve AMM challenges.

More broadly, given the paucity of coal mines that are capturing and utilizing methane, it is unlikely that these technical levers alone will significantly impact emissions. To make the steep reductions in methane emissions (and CO_2) needed for a 1.5°C pathway, rapid reduction in coal demand in line with current market movements would be the fastest and most likely solution.

Economics and challenges of abatement

While the economics for VAM utilization are challenging, they improve if the gas can be used for energy, either via microturbines (for example, 30.0 kilowatts) or full-size turbines (more than 0.5 megawatts).[77] Indeed, the relevant technologies have been deployed for decades.

Among stakeholders, coal miners themselves have made the biggest strides in reducing CMM, leveraging degasification, capture, utilization, and sometimes exchange for carbon credits. There are examples in Australia, Poland, Russia and the United States—four of the top nine countries for estimated global CMM emissions.[78]

The VAM option is more attractive for high-cost energy markets—markets such as the United States, which have cheaper sources of energy than coal, may have little use for the approach. Even where there is an economic driver, the market context has often forced coal miners to operate with much less invested capital, inhibiting large-scale methane abatement. Many coal miners have ceased operations, resulting in abandoned mine methane release. At the same time, profit pools are shifting toward East and South Asia. This means financing in some geographies is becoming restricted, with many banks cutting exposure to carbon-producing industries. Less capital to deploy means it is more difficult to commit to methane recovery beyond local minimum safety requirements.

Chinese exception

A notable exception to the challenges around coal industry abatement may be companies in China, which account for nearly 50 percent of global production and close to 70 percent of emissions (Exhibit 17). China has the scale and infrastructure from coal gasification (for the production of chemicals such as ammonia and methanol) to make methane capture more economically attractive.[79] This supply chain could be expanded to connect recovered methane from coal mines to industrial customers, including chemical and metal producers.

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[74] Patricia Alves Dias et al., "EU coal regions: Opportunities and challenges ahead," The European Commission Joint Research Council, 2018, publications.jrc.ec.europa.eu.

[75] The OMSRE AML fee collection has disbursed $6.064 billion and has $2.213 billion still unappropriated as of September 30, 2020 (see "Status of the abandoned mine land reclamation fund (AML fund)," OMSRE, September 2020, osmre.gov).

[76] Up to $16 billion is proposed as a preliminary amount for orphan oil and gas wells and abandoned mines. See "Fact sheet: The American jobs plan," The White House, March 31, 2021, whitehouse.gov.

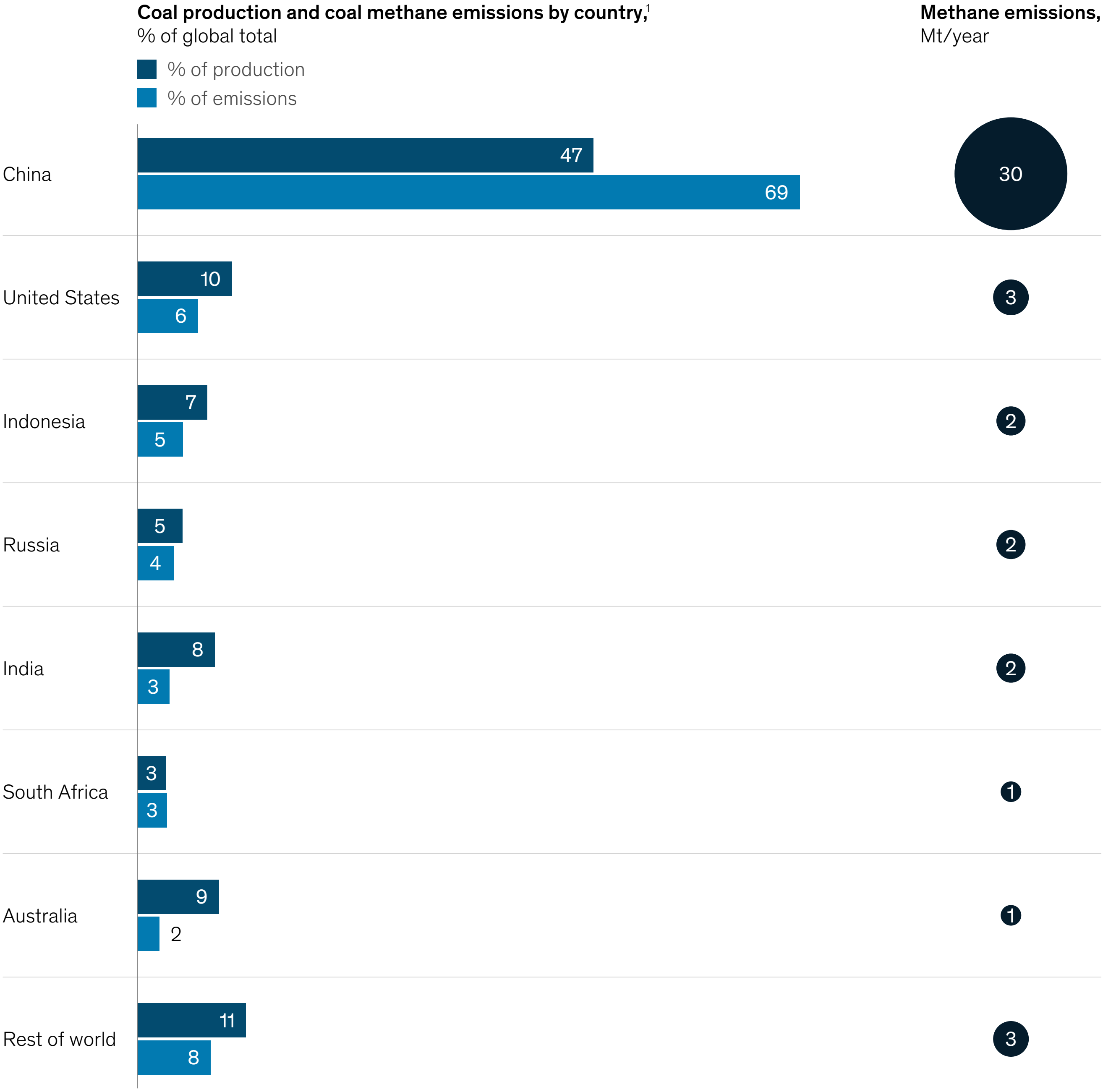
[77] "Ventilation air methane (VAM) utilization technologies," US Environmental Protection Agency (EPA) Coalbed Methane Outreach Program, updated July 2019, epa.gov.

[78] "Estimated global CMM emissions, 2020," using US Environmental Protection Agency's Global Anthropogenic Emissions of Non-CO_2 Greenhouse Gases: 1990–2030 data, 2020, epa.gov.

[79] Less than 5 percent of syngas produced from coal gasification facilities is currently used to generate electricity, and over 70 percent is used to generate methanol and ammonia. See "China gasification database," The Department of Energy's (DOE) Office of Fossil Energy (FE) and the National Energy Technology Laboratory (NETL), 2014, netl.doe.gov.

Exhibit 17

Coal methane emissions are concentrated in China.



1. Top 7 countries in coal mining production, accounting for 98% of production and 97% of methane emissions (Intergovernmental Panel on Climate Change methodology).
Source: Global Methane Initiative, Coal Mine Methane Country Profiles, 2015; McKinsey MineSpans database

Furthermore, there are powerful government incentives to produce higher-quality coal and reduce pollution. And the country has a track record of deploying large capital projects quickly. These factors combined mean there could be significant abatement progress in the country that matters most to emissions reduction. The 14th five-year plan will likely lead to new CMM emissions reductions targets later this year.[80]

[80] Jiang Yifan, "14th five year plan: China's carbon-centered environmental blueprint," China Dialogue, March 25, 2021, chinadialogue.net; Scott Vaughan, "A new plan ahead," International Institute for Sustainable Development (IISD), March 10, 2021, sdg.iisd.org.

Existing industry efforts to address methane

Drilling down into specific examples and geographies, there are large numbers of companies that have made significant efforts to abate methane:

— **Australia.** There are at least 25 CMM recovery projects in Australia, of which nine use methane to generate more than 215 MW of electricity (enough to power 90,000 to 190,000 homes).[81] Anglo American, BHP, and Glencore/Xstrata have made investments at multiple mines to generate power from fugitive methane. Australia also conducts public-sector research into VAM capture and abatement and incorporates CMM emissions reductions into national GHG reduction targets.[82]

— **China.** China has more than 50 projects for VAM capture and utilization[83] and captures more than 12 bcm of CMM annually as of 2017.[84] It is home to one of the world's largest VAM-to-power conversion power plants, capable of producing 30MW.[85] In addition, the infrastructure for CMM tracking is probably the most advanced outside of Australia.

— **Poland.** The leading coal producer, JSW, has moved decisively since 2018 on VAM tracking, capture, and utilization. The goal is to carry out premining CMM drainage and capture and radically increase methane's contribution to power and heat generation.[86]

— **The United States.** As of 2017, there were more than ten multiyear efforts to capture and use CMM. Arch, Consol, Contura, Coronado, Drummond, Murray, and Warrior were among active companies.[87] However, many projects have ceased amid switches in ownership and closure of mines. A new inventory is required to update the latest (2017).

The above analysis shows that there are practical approaches to CMM capture, recovery, and utilization that can be implemented now. That said, the challenge is much greater than current resources can address. For example, coal will account for 75 percent of China's methane emissions in 2050, despite the country's methane capture targets.[88]

Implications of alignment with the 1.5°C pathway

Should society commit to reducing emissions in line with the 1.5°C pathway, coal demand would need to fall by 63 percent by 2030 and 85 percent by 2050.[89] In parallel, coal methane emissions would need be abated by 70 percent by 2030 and 90 percent by 2050.

Achieving these goals would be dependent largely on the power and metals sectors. Thermal coal demand, for example, would need to be substituted by renewables. In some parts of the world, it is already cheaper to build wind and solar power than it is to keep an old coal plant operating.[90] In parallel, it will help to roll out carbon capture and utilization (CCU) for metallurgical coal transformed into coke and to continue the transition of steelmaking to recycled materials or alternative production methods. Momentum is already moving fast in this direction.

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81 Assuming 75 percent capacity factor, 400 to 900 kilowatt-hours (kWh) annual household electricity consumption.

82 *Anglo American – Climate change 2019*, CDP, 2019, angloamerican.com; Ben Hagemann, "Making the best of methane: The latest look at methane abatement in coal mining," Australian Mining, March 24, 2014, astralianmining.com.au; *Ventilation air methane utilization technologies*, EPA, July 2019, epa.gov

83 Global Methane Initiative publishes an index of CMM abatement projects by country, with mine-level reductions of metric tons of CO_2 equivalent (tCO_2e).

84 "China International Centre of Excellence on coal mine methane," Global Methane Initiative (GMI), 2019, globalmethane.org. The target of the 13th Five-Year Plan (2015–20) is 14 bcm^3; see "Development and utilization of coalbed methane, 13th Five-Year Plan," China National Energy Board, 2016, policy.asiapacificenergy.org.

85 "World's largest ventilation air methane/coal mine methane oxidation project goes live," Durr, September 9, 2015, durr.com.

86 "Methane in the crosshairs," JSW, December 19, 2019, jsw.pl.

87 "Identifying opportunities for methane recovery at U.S. coal mines: Profiles of selected gassy underground coal mines (2002–2016)," US Environmental Protection Agency (EPA) Coalbed Methane Outreach Program, updated July 2019, epa.gov; "Coal mine methane developments," updated 2019.

88 "China methane emissions," Global Methane Initiative, 2020, globalmethane.org; "Global non-CO_2 greenhouse gas emission projections & mitigation: 2015-2025," US Environmental Protection Agency Office of Atmospheric Programs, October 2019, p. 12, epa.gov.

89 Kimberly Henderson, Dickon Pinner, Matt Rogers, Bram Smeets, Christer Tryggstad, and Daniela Vargas, "Climate math: What a 1.5-degree pathway would take," McKinsey Quarterly, April 2020, McKinsey.com.

90 "Lazard's levelized cost of energy analysis, version 14.0," Lazard, October 2020, lazard.com.

Solid Waste

Some 20 to 30 percent of food is wasted globally every year, while 30 to 70 percent of cardboard is not recycled. Organic waste not sorted for chemical conversion to biogas or chemicals, recycled, composted, or turned into feedstock (around 30 percent) usually ends up as landfill.

Methane footprint and trajectory

Municipal solid waste (MSW) creates around 34 Mt per year of methane emissions, all of which originates from landfills or open dumps. Methane is generated from organic waste when it decays anaerobically (without access to oxygen), allowing methane-emitting bacteria to thrive. Accumulated waste creates the ideal conditions for anaerobic decay as older organic waste is buried. Therefore, most of the emissions today originate from waste produced several years ago.

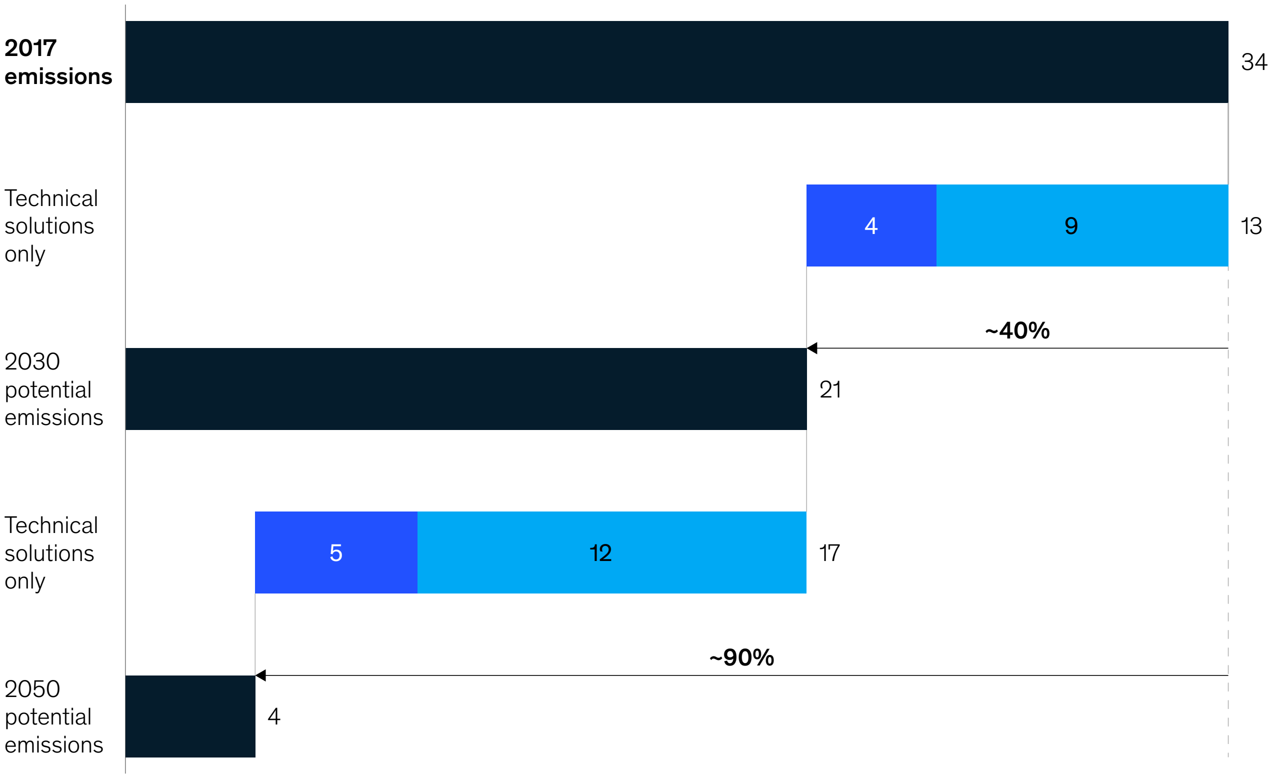
Technical solutions

Methane emissions from solid waste could be abated by about 40 percent by 2030 and 90 percent by 2050 (Exhibit 18). Almost all of the reduction would be through diversion of organic material to secondary purposes, such as composting or biogas extraction. Organic

Exhibit 18

Technical solutions could nearly eliminate methane emissions from solid waste by 2050.

Methane emissions abatement potential by solution type in solid waste, $MtCH_4$/year



Technical solutions	Top abatement levers
Change waste collection practices	Diversion of organic waste to specialized treatment for chemical conversion (biogas, chemical feedstock, etc), composting for fertilizer, or recycling
Change waste disposal practices	Retrofitting of landfills and dump sites with landfill gas capture, mechanical biological treatment, membrane reactors, etc

Source: McKinsey analysis

waste could be sorted and processed through anaerobic digestion facilities to generate feedstock, fertilizer, soil enhancer, and renewable natural gas—or incinerated for energy.

Storing organic waste in landfills is the least effective way to both prevent emissions and promote natural degradation of waste volume. In fact, organic materials trapped in anaerobic landfill conditions can persist for up to 25 years underground, leaking methane gradually as the material decays. Diverting organic waste for specialized processing is therefore the best way to prevent emissions and utilize organic material as feedstock for extracting value. Additionally, existing landfills could be retrofitted with solutions for methane mitigation, including gas capture, which could then be used for onsite power or sent back to the grid. Waste could also be mechanically or biologically reduced to biogas, though this is much more challenging with mixed waste streams. These solutions would be effective but would come at a cost. A useful rule of thumb is that disposal costs around $35 per metric ton. Finally, transformation of waste systems is unlikely to be possible without reform in the collection and processing value chain. Collection is typically the highest cost across all country income levels and presents a barrier to methane-optimized waste treatment.[91]

Economics and challenges of abatement

Municipal solid waste is often controlled by municipalities, and funding is usually from local taxes. More than 70 percent of waste services are overseen directly by local public organizations.[92] Given the global implications of methane emissions, funding for change could be shared with national governments and international organizations. There is also generally a lack of public pressure and awareness around emissions from waste, with most green initiatives focused on reducing volumes of inorganic waste, which do not emit methane. For developed nations, waste is "out of sight, out of mind," while in developing nations, there is limited public infrastructure to manage waste, resulting in weak local disposal systems.

The financial potential of transformation is generally insufficient to attract enough investment funding from financial institutions, which tend to be more focused on CO_2 carbon credits. Sometimes credits can be applied but often not enough to sufficiently offset capital expenditure for the retrofitting of landfills and treatment facilities. Additionally, there is insufficient regulation requiring methane abatement in waste management. In most countries, emissions are not regularly reported or mitigated, and accounting for organic waste volumes is poor or nonexistent.

Implications of alignment with the 1.5°C pathway

As the world accelerates its efforts to align with the 1.5°C pathway, a key lever would be to reduce the volume of organic municipal solid waste. This would mean reducing food and paper waste by changing individual behaviors (for example, broad adoption of composting) and improving efficiency in supply chains (for example, ensuring food does not rot in transit and reducing overstocking at supermarkets). Local volumes of organic waste are linked to population size, but there are actions society can take to control organic-waste volumes. Recycling of organic materials, such as paper, cardboard, and leather, as well as reduction of food waste are two effective approaches.

The most favorable path toward addressing solid waste methane will vary by country and will be dependent on local infrastructure and development goals. However, broadly, there are three archetypes:

1. **Countries with underdeveloped waste management systems.** Here, the public has limited access to centralized collection, waste streams are largely unsorted, and there is limited governance to support waste management improvements.

2. **Countries with basic waste management systems.** In these geographies, collection coverage is higher, waste streams are moderately sorted, and there are limited controls

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[91] *Global waste management outlook*, United Nations Environment Programme, 2015, unep.org.

[92] Silpa Kaza et al., *What a waste 2.0: A global snapshot of solid waste management to 2050*, The World Bank, September 20, 2018, datatopics.worldbank.org.

on methane emissions. However, actual production of waste per capita is high. Examples include the United Kingdom and the United States.

3. **Countries with advanced waste management systems.** These countries have built infrastructure to comprehensively collect, sort, and dispose of waste, creating waste-to-X markets and minimizing methane emissions. Example countries include Belgium, Germany, and Sweden.

For each archetype, there will be significant actions required to effect change in solid waste methane.

Countries with underdeveloped waste management systems

— **Increase collection and isolate organic waste where possible.** Uncollected waste leads to more methane emissions, as well as societal and environmental degradation. Waste is projected to grow fastest in low- and low-middle income countries, where waste management systems are least developed.[93] The single most powerful lever for reducing methane emissions would be to improve the number of new wastewater treatment facilities connections in these regions—and in particular in Asia and Latin America. In one case example, Morocco and the World Bank partnered to improve municipal solid waste treatment and increased coverage of professional collection from 40 percent of the population in 2008 to 66 percent in 2011. It closed or rehabilitated 21 dumpsites and increased collection in sanitary landfills from 10 percent in 2008 to 32 percent in 2011.[94]

Countries with basic waste management systems

— **Isolate organic waste.** Households and retailers could upcycle organic waste into valuable products. Municipalities and other waste management players would help ensure organic waste is separated during collection (for example, separate bins). Higher tipping fees at landfills could encourage waste management providers and consumers to produce less waste and divert organic waste to compost and anaerobic digestion. By 2050, organic-waste sorting could reduce waste emissions by 21 Mt of methane per year or 70 percent of overall waste abatement potential.

— **Retrofit landfills to recover methane.** All landfills emit methane from organic material, some of which may be decades old. Operators could retrofit their facilities to collect methane and sell it as biogas to local utilities or industrial customers.

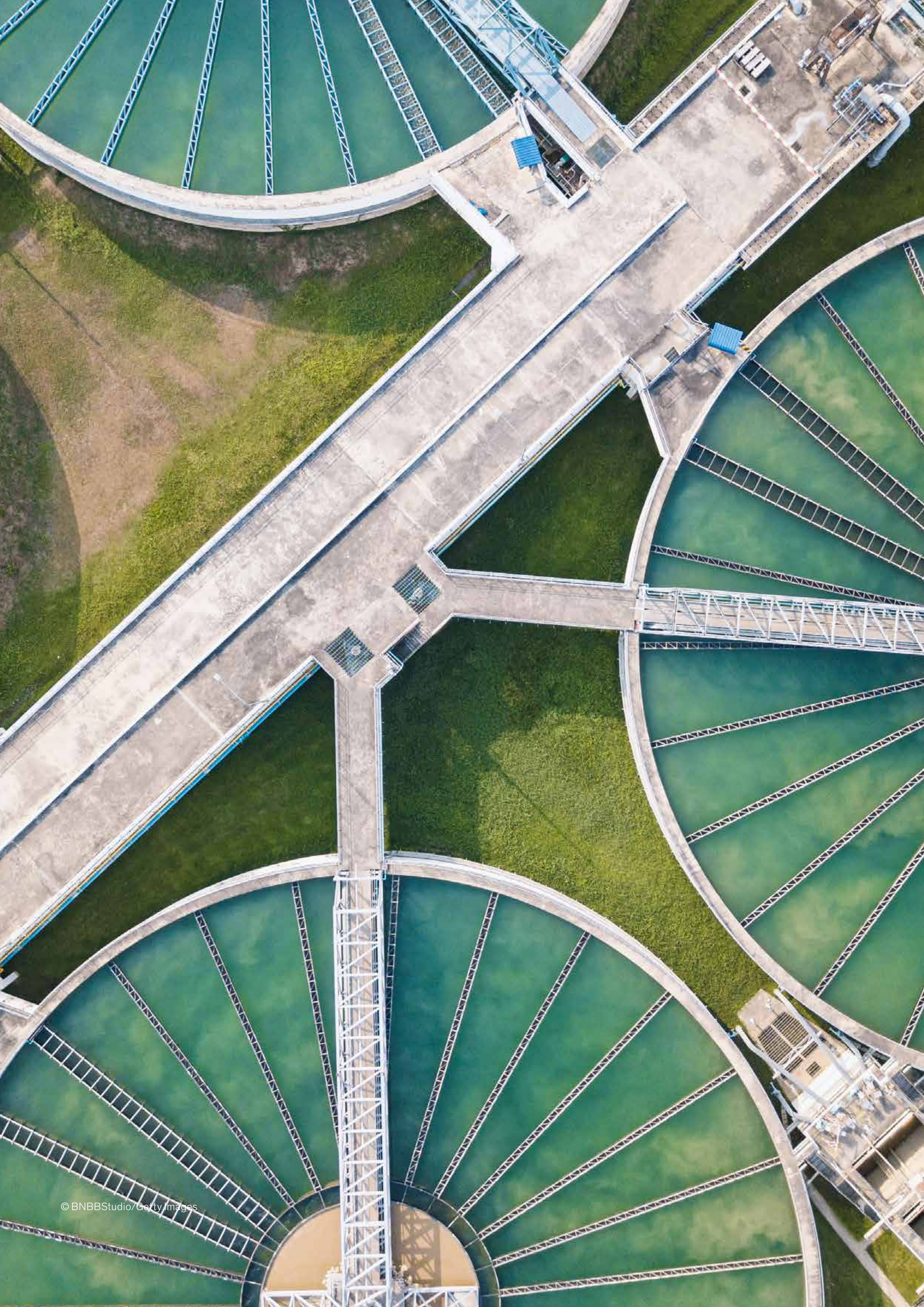
— **Increase the value of byproducts to encourage sorting.** Creating higher-value byproducts, such as biogas, would incentivize waste management players to capture more methane to sell back to the grid and drive down the cost of technology. Several jurisdictions and gas utilities have already begun to pay a premium for methane generated through waste treatment and have created blending requirements, driving up the price of biogas (for example, California's low carbon fuel standard (LCFS) market or the federal Renewable Energy Standard in the United States).

Countries with advanced waste management systems

— **Share best practices globally.** Leading waste management countries have decades of experience in fine-tuning their policies and technologies. Sharing their expertise with countries with less expertise would allow them to have a greater impact on global emissions.

— **Optimize waste management.** Leading countries could explore bio-fermentation or composting organic waste instead of burning it for power generation. This would reduce emissions and increase the end value of waste.

93 *What a waste 2.0*, 2018.
94 "Morocco: Improving municipal solid waste management through development policy operations," The World Bank, 2013, worldbank.org.



Wastewater

Methane is produced from wastewater in the same way as it is from organic solid waste—from the decay of organic matter in waste streams that are undertreated or unmanaged.

Methane footprint and trajectory

Wastewater creates around 34 Mt per year of methane emissions, mostly from the decay of biological load in continuous streams of waste. Roughly half of global wastewater is untreated, producing the bulk of emissions (90 percent). Treated wastewater is usually processed aerobically, but imperfect operating standards can lead to methane leakage (10 percent of wastewater methane emissions).

At many wastewater treatment plants, methane is a byproduct of standard processes. Some facilities use it as fuel for digestor heating, while others flare it. Incentives for gas capture are mixed, depending on location, and can drive capital investments for gas cleaning, fuel cell development, and gas line injections, among other reutilization opportunities.

Technical solutions

By 2030, methane emissions from wastewater could be abated by 27 percent, and by 2050, they could be abated by 77 percent (Exhibit 19). The most effective solution would be to increase the volume of wastewater collected and treated centrally. There is also an opportunity to widen access to modern wastewater infrastructure, which is underdeveloped in many geographies.

Mitigation potential varies by geography. Where infrastructure already exists, sewage water treatment generally involves creating aerobic chemical reactions to sanitize and collecting biosolids as sludge. This can be turned into fertilizer or biogas. Water can also be used for energy production. Newer technologies may use covered lagoons and microalgae to harvest methane and other bioproducts. Recovered methane from water treatment could become a source of renewable natural gas (RNG) and may create value through generation of heat or energy. The methane could be injected back into the gas grid or used as fuel for combined heat and power (CHP) systems, fuel cells, or other methods of on-site power generation.

Considering the stakeholders involved, municipalities have a significant role to play, with support from the public and private sectors to provide the necessary infrastructure and contracted services. In cases where water treatment is already in place, methane recovery is a matter of costs. In addition, authorities would need to consider the economic feasibility of cleaning digester gas to a standard that would allow for injection into a natural gas pipeline. Incentives such as renewable energy certificates (RECs) in the United States often provide enough cover for the capital investment required for gas purification. In other markets, the cost of buying gas from the grid is higher, so generating on-site power would be profitable enough to support the investment. Still, without economic incentives and absent regulatory requirements, action to date has tended to be slow or nonexistent.

The path forward varies by country. However, the same archetypes exist as in solid waste infrastructure—that is, countries with underdeveloped management systems, basic systems, and advanced systems.

Countries with underdeveloped wastewater management systems

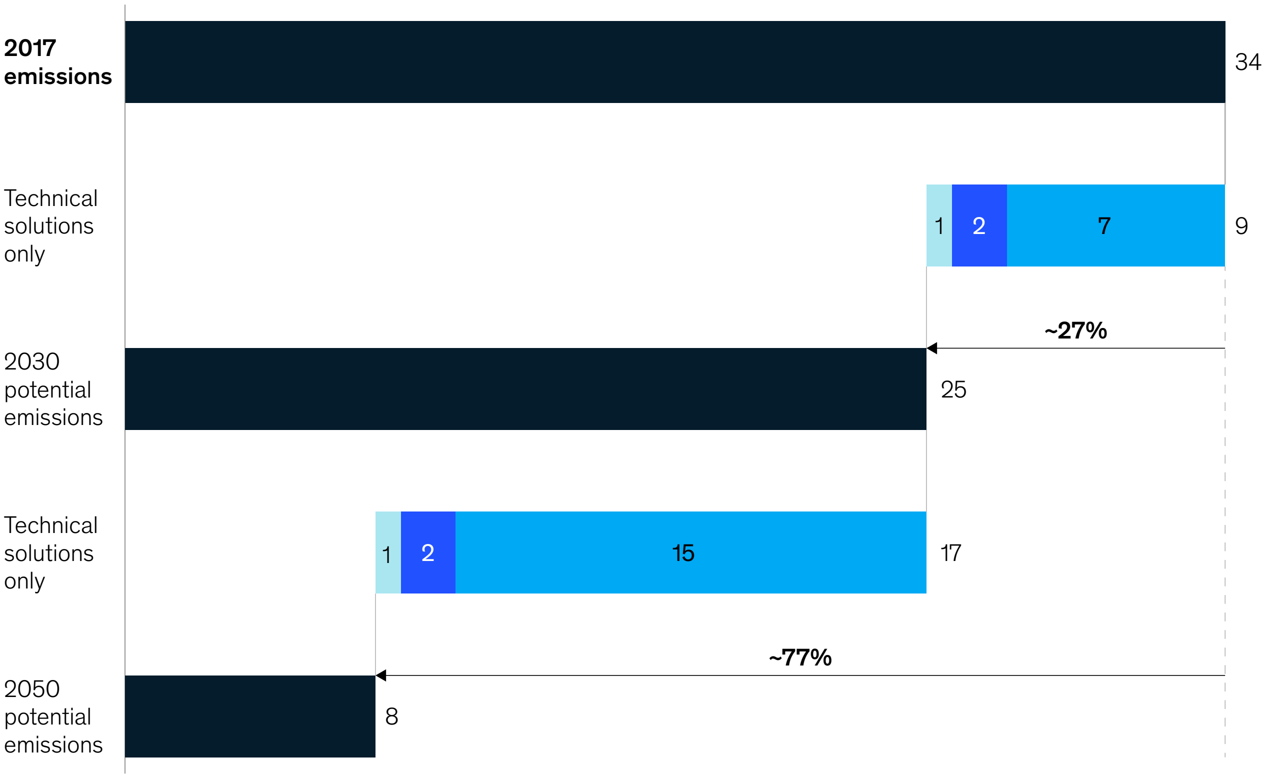
Wastewater treatment infrastructure and central treatment facilities are critical to creating effective abatement solutions. In many cases, there will also be a requirement for plumbing infrastructure and sewage systems. One country that has moved forward in recent years is Thailand. A project in the Prankatai district built out infrastructure to capture methane under two closed anaerobic wastewater treatment facilities. The methane was emitted by a local starch plant that used cascading open lagoons. The new facilities convert methane into energy, which is sold.[95] The project created 17 new jobs and improved environmental conditions in the community.

[95] "Project fact sheet: Nakhon biogas," The South Pole Group, February 2018, southpole.com.

Exhibit 19

Technical solutions could reduce methane emissions from wastewater by more than three-quarters by 2050.

Methane emissions abatement potential by solution type in wastewater, $MtCH_4$



Technical solutions	Top abatement levers
Build treatment facilities and upgrade connections	Construction of wastewater treatment facilities and connection to treatment grid in developing economies, especially in Asia and Latin America
Implement advanced technologies	Improved efficiency and operating standards, such as improved membrane filtration, pressure settings, venting, etc, to prevent anaerobic methane release
Make operational improvements	Advanced technologies, such as microalgae, covered lagoons, anaerobic sludge digestors, degassing effluent charge, etc, for biogas harvesting

Note: Figures may not sum, because of rounding.
Source: McKinsey analysis

Countries with basic wastewater management
Existing treatment facilities can explore options to invest in turning biosolids and sludge from organic matter into valuable products. Municipalities and other waste management players should cooperate to ensure efficient collection from residential and industrial sites.

Countries with advanced wastewater management systems
Research is required to improve wastewater treatment, optimize methane capture, and establish best practices. Exploring the use of microalgae, covered lagoons, and other bio-fermentation methods to increase the end value of waste could inspire the next generation of wastewater treatment.

5. Bending the methane curve: Three key enablers

This report shows that a 1.5°C warming pathway is unlikely without a 37 percent decline in methane emissions by 2030. Concerted abatement action, therefore, will be critical in the near term. The good news is that there are multiple options to shift emissions from their current pathways. These range from feed additives for livestock to modern waste management strategies in the oil and gas industry. Up to a third of these measures can be implemented at or below net-zero cost. Unfortunately, a cost-based approach may be insufficient for the scale required. Achieving these reductions will require a step change in attitudes, awareness, and economic incentives.

In the meantime, three no-regret initiatives may help support individual and collective action. These focus on increasing transparency around the impacts of methane, supporting sustainable purchasing, and encouraging innovation:

— **Expand monitoring, reporting, and verification.** Methane emissions are often not directly or comprehensively measured today.[96] To enable effective reporting, governments and industries would need to upgrade data collection, moving from estimates to observed measurements which could be validated and accessible.[97] Satellite, drone, and sensor monitoring, the costs of which are falling sharply, would be one way to help achieve this. Strong measurement programs hold the potential to create incentives for rapid methane reduction across industries. Efforts to develop global tradable goods markets that value the carbon intensity of different products along a traceable value chain depend heavily on implementing such programs. Reporting methane emissions separately from CO_2 emissions would also aid transparent target setting and benchmarking.

— **Support sustainable consumption.** Stakeholders could develop mechanisms to differentiate assets and score products based on their methane footprints. If every kilogram of rice, MMBtu of natural gas, metric ton of steel, pound of meat, barrel of oil, and metric ton of coal came with a methane intensity label, the market signals could support a more orderly decarbonization transition. With this, retailers and consumers could make more informed purchasing decisions, producers could define new foundations for competitive advantage, and investors could better understand portfolio risk.

— **Increase innovation.** Many solutions are sufficiently developed to be effective but are not adopted at scale because of excessive costs and sometimes a lack of awareness of the technology available. In the oil and gas industry, innovation in methane monitoring—for example, leveraging flyovers and on-ground detection—could help businesses pinpoint leaks and cut mitigation costs. The beef industry is in the early stages of adopting feed additives, genetic breeding, and methane capture. These technologies would benefit from support to move more speedily from lab to field. Climate change is among the biggest challenges facing humankind over the coming years. The need to address it across all five key industries will drive new ideas, encourage changes in behavior, and promote innovation. Groundbreaking solutions supported by at-scale investment will be needed throughout the value chains of methane-emitting industries.

[96] "The global methane budget," 2020. The methodology section discusses the limitations of current inventory measurements due to poor monitoring and reporting: "We acknowledge that we do not consider the uncertainty of the individual estimates, and we express uncertainty as the range of available mean estimates, i.e., differences across measurements and methodologies considered" (pg. 1566).

[97] "Global methane emissions," 2020.

This report demonstrates that abating methane emissions will be critical to achieving the 1.5°C warming pathway and avoiding the worst effects of climate change. The good news is that there are many practical solutions available. Feed additives for cattle, new rice farming techniques, advanced approaches to oil and gas leak detection, coal methane capture, and modern water and waste facilities can all be effective abatement measures. Still, each of these faces implementation challenges.

The priority, therefore, is for action where it is practical. Many of the solutions discussed in this paper can be implemented at a relatively low or net-negative cost, and these should be a priority. Where costs are prohibitive, there is a need for coordinated action to put in place the infrastructure and fiscal conditions that will support further action. Across the board, there is a need for more monitoring, reporting, and verification—and this report recommends steps to support data collection and measurement of methane emissions that do not rely on comparisons to CO_2 equivalents. Consumers, meanwhile, have a significant role to play and would benefit from being able to make more informed decisions on the sources of methane and how their choices can have an impact. Certification schemes could play a useful role, as they already do in many aspects of sustainability benchmarking. Finally, innovation must continue, both privately and in civil society, to support the rollout of solutions at scale and to educate stakeholders. Without these efforts, it is likely that current initiatives aimed at flattening the warming curve will fail, and the planet will continue on a collision course with an uncertain and dangerous future.

Appendix

Exhibit A1

Reference: Path for modeling maximum technical opportunity by 2030 and 2050

Coal			
Lever	**2030 abatement,** Mt/year	**2050 abatement,** Mt/year	**Methodology**
Ventilation air capture	0.07	0.15	Every country moves to upper-quartile performance by 2030 and best-in-class performance by 2050 based on coal mine methane project inventory across type, region, and company
Degasification of underground mines	0.28	3.18	
Capture of abandoned mine gas	0.02	0.41	
Underground mine flaring	0.17	1.40	
Degasification of surface mines	0.13	0.26	
Total coal abatement, Mt/year	**0.67**	**5.39**	
Reduction of coal emissions, % of 2017 baseline	**2%**	**12%**	

Source: BHP report on ventilation air capture efficiency; Environmental Protection Agency (EPA) 2015 coal mine methane project database for determining targets for emissions abatement by country; Intergovernmental Panel on Climate Change (IPCC) report on calculation of coal mining emissions; International Energy Agency (IEA) energy atlas for emissions by country

Exhibit A1 (continued)

Reference: Path for modeling maximum technical opportunity by 2030 and 2050 (continued)

Solid waste			
Lever	**2030 abatement,** Mt/year	**2050 abatement,** Mt/year	**Methodology**
Divert organic solid waste from landfill and dump to specialized use or treatment capture and pretreatment	8.84	21.42	Every country moves to upper-quartile performance by 2030 and best-in-class performance by 2050 based on World Bank database of 2019 solid waste treatment by country, waste type, and treatment type
Retrofitting landfill and dump emissions capture and pretreatment for solid waste	4.50	9.30	
Total solid waste abatement, Mt/year	**13.34**	**30.72**	
Reduction of solid waste emissions, % of 2017 baseline	**39%**	**90%**	

Source: Emissions Database for Global Atmospheric Research (EDGAR) 2015 emissions data for waste by country; World Bank 2019 global waste data

Exhibit A1 (continued)

Reference: Path for modeling maximum technical opportunity by 2030 and 2050 (continued)

Wastewater

Lever	**2030 abatement,** Mt/year	**2050 abatement,** Mt/year	**Methodology**
New treatment connection for wastewater	6.75	21.31	Every country moves to upper-quartile performance by 2030 and best-in-class performance by 2050 based on proportion of water treated globally by country type
Advanced technologies for wastewater	1.70	3.39	
Operational improvements for wastewater treatment	0.78	1.56	
Total wastewater abatement, Mt/year	**9.23**	**26.25**	
Reduction of wastewater emissions, % of 2017 baseline	**27%**	**77%**	

Source: IPCC method of wastewater emission calculations; Toshio Sato et al., “Global, regional, and country level need for data on wastewater generation, treatment, and use,” *Agricultural Water Management*, August 2013, Volume 130, pp. 1–13, inweh.unu.edu; Başak Taşeli, “Sustainability assessment of wastewater treatment plants,” in *Water Chemistry*, 2020.

Exhibit A1 (continued)

Reference: Path for modeling maximum technical opportunity by 2030 and 2050 (continued)

Oil & gas

Lever	**2030 abatement,** Mt/year	**2050 abatement,** Mt/year	**Methodology**
Onshore conventional oil	12.89	23.67	International Energy Agency (IEA) oil & gas methane tracker 2020 estimate for full abatement potential by asset type and lever type scaled to 2030 and 2050 based on industry expert input
Onshore conventional gas	10.46	13.26	
Downstream gas	5.24	11.33	
Unconventional gas	2.25	5.49	
Offshore oil	1.62	3.61	
Other (offshore gas, unconventional oil, downstream oil)	1.35	3.75	
Total oil & gas abatement, Mt/year	**33.81**	**61.11**	
Reduction of oil & gas emissions, % of 2017 baseline	**40%**	**73%**	

Source: International Energy Agency oil and gas methane tracker 2020

Exhibit A1 (continued)

Reference: Path for modeling maximum technical opportunity by 2030 and 2050 (continued)

Agriculture			
Lever	**2030 abatement,** Mt/year	**2050 abatement,** Mt/year	**Methodology**
Avoided deforestation	12.68	12.68	● (dark navy)
Direct methane capture	4.30	8.69	● (cyan)
Sulfate fertilizers	2.15	5.01	● (blue)
Methane inhibitors	1.54	3.12	● (cyan)
Animal-feed-mix optimization	1.54	3.63	● (light cyan)
Rice paddy water management	1.51	3.51	● (blue)
Propionate precursors—animal feed additives	1.50	3.34	● (light cyan)
Dry direct seeding	1.22	2.55	● (blue)
Feed grain processing	1.09	2.54	● (light cyan)
Genetic selection and breeding	1.00	5.42	● (light cyan)
Straw management in rice	0.73	1.71	● (blue)
Animal health monitoring and illness prevention	0.59	4.20	● (light cyan)
Aerobic rice	0.57	1.15	● (blue)
Animal growth promoters	0.43	1.82	● (light cyan)
Complete mix anaerobic manure digestion	0.43	1.00	● (light cyan)
Varietal rice selection	0.42	1.00	● (blue)
Covered lagoon and anaerobic digestors	0.42	0.97	● (light cyan)
Gene editing	0.37	0.91	● (cyan)
Microbiome	0.29	0.71	● (cyan)
Plug flow digestors	0.27	0.64	● (light cyan)
Small scale dome digestors	0.12	0.28	● (light cyan)
Pressurized irrigation	0.00	0.01	● (blue)
Electrification of on-farm machinery and equipment	–	0.18	● (blue)
Total agriculture abatement, Mt/year	**33.15**	**65.07**	
Reduction of agriculture emissions, % of 2017 baseline	**19%**	**37%**	

Methodologies

- ● (dark navy) Based on needed deforestation rate as required in a 1.5C scenario, laid out in McKinsey's "Climate math: What a 1.5-degree pathway would take" report (2020)
- ● (cyan) Using input assumptions as listed in McKinsey's *Agriculture and climate change* report (2020), based on academic literature and expert input
- ● (blue) Variable adoption and emissions impact by country, using input assumptions as listed in McKinsey's *Agriculture and climate change* report (2020), based on comprehensive academic literature
- ● (light cyan) Variable adoption and emissions impact by country and ruminant animal type, using input assumptions as listed in McKinsey's *Agriculture and climate change* report (2020), based on comprehensive academic literature

Source: McKinsey's *Agriculture and climate change* report (2020); McKinsey's "Climate math: What a 1.5-degree pathway would take" report (2020); McKinsey analysis

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