MEETING THE METHANE CHALLENGE:

How the U.S. Can Reach Its 2030 Goal

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ENERGY VISION

Table of Contents

Cover image sources: Buffalo Regional Digester (top), Bureau of Land Management (bottom)

Foreword

Methane is a big part of the climate problem. It has already caused a third of modern global warming, and is projected to increase climate change at the same rate as carbon dioxide over the next decade.

Cutting methane emissions is the best mechanism we have for reducing near-term global temperature rise and keeping warming within 1.5 degrees Celsius. That's why the US and 154 other countries signed the Global Methane Pledge to cut methane emissions 30% by 2030 ("30x30").

But we aren't on track to meet that goal, either domestically or globally. Atmospheric methane concentrations are at record highs, and are tracking with record high global temperatures, which highlights the urgency of cutting methane emissions faster than we have done so far.

We only have a few years left to bend the curve sharply on methane emissions. The biggest factors in human-caused emissions are methane leakage and flaring from oil and gas operations, methane released from enteric fermentation (i.e., cow belches), and methane outgassing from organic wastes such as food and farm waste. We need to attack methane emissions on all fronts.

The US government is working on oil and gas sector emissions, but at best, its new measures can only get us a little over halfway to the goal of cutting methane emissions at least 30% by 2030. Meanwhile, possible ways to cut methane from enteric fermentation are still largely experimental and won't be ready to scale up by 2030. So to get the rest of the way to 30x30 we need to find and rapidly scale up solutions for cutting methane emissions from organic waste immediately, starting yesterday.

As it turns out, the building of anaerobic digestors, systems that capture methane produced by food waste and utilize it for local energy purposes, is ramping up.

Energy Vision has put together a thoroughly researched, evidence-based blueprint for how to scale anaerobic digesters and get the rest of the way to the critical goal of 30x30. For the first time, this report offers actual data and credible numbers quantifying: how big the potential for building ADs in the US is; how much they will cost; what benefits they will provide; how the costs and benefits compare to oil and gas sector methane reduction measures; and what is most likely to achieve the most cost-effective methane abatement in the near term.

It's unique information and analysis you won't find anywhere else and should be an invaluable resource for policymakers, industry, investors, advocates, and anyone who wants to understand this burning climate issue, and what we can do about it now.

Ron Gonen
Founder & CEO, Closed Loop Partners

Executive Summary

- According to the international scientific community, it is essential to cut methane emissions at least 30% by 2030 to avoid runaway climate change. Otherwise, increasingly severe wildfires, storms, droughts, glacial melting, and sea rise will threaten to destroy life as we know it.

- Methane (CH_4) is a much more potent greenhouse gas (GHG) than carbon dioxide (CO_2) and is already responsible for a third of global warming since the Industrial Revolution began. 155 countries including the U.S. have signed on to the Global Methane Pledge, committing to cut methane emissions at least 30% from 2020 levels by 2030.

- It will be a major challenge for the U.S. to cut methane emissions 30% by 2030, and there has been no consensus on how to reach that goal. **In this report, Energy Vision has calculated that meeting the U.S. potential to process food waste and manure in airless tanks called anaerobic digesters (ADs) would cut total net U.S. methane 13.6%.**

- Building more ADs is an essential, affordable climate strategy for the U.S. based on proven technology. ADs turn organic wastes from liabilities into assets. Rather than release methane into the atmosphere as these wastes decompose, the methane is captured in ADs and subsequently used to generate electricity and heat buildings. It can also be upgraded to renewable natural gas (RNG), a sustainable fuel that requires no drilling and can displace fossil fuels.

- **Energy Vision found that the single largest opportunity for organic waste, with the biggest bang for the buck (greatest impact at the lowest cost) nationwide, is to divert food waste from landfills to ADs.** Half of all food that is currently discarded is edible and should be redistributed. Our analysis is thus only based on diverting the other, inedible half of food waste to ADs. (Community composting is an important complementary option but could only handle a small portion of the country's inedible food waste, while large commercial-scale composting facilities emit much more methane than ADs.)

- Building ~570 municipal food waste ADs (at an average capacity of 50,000 tons per year) would cut total net U.S. methane ~6.8% annually at an estimated capital expenditure (capex) of $28.4 billion. Adding another 110 ADs for industrial food and beverage processing waste would deepen the cumulative cut to 7.5% of total net U.S. methane per year at a combined total capex of ~$31.7 billion.

- The second-most impactful category is manure ADs. Energy Vision calculated that building ~4,000 additional ADs to process dairy and swine manure would cut total net U.S. methane ~6.1% annually at an estimated capex of $42.5 billion.

- **The grand total is ~$74 billion in capex for ~4,700 digesters for food waste and animal manure, which would annually reduce half of landfill methane emissions (by keeping food waste out of landfills) and three quarters of dairy and swine manure methane emissions. Together this would cut 13.6% of total U.S. methane per year. On average, each project would take roughly 2-6 years to build.**

- Those ~4,700 ADs would reduce over 12 times the amount of methane than could be achieved by plugging all 2.1 million abandoned oil and gas wells in the U.S., at roughly half the estimated cost. Other methane mitigation measures in the oil and gas sector have more bang for the buck than building ADs, but they are not competitors. Both can and should be pursued simultaneously, providing a path to reach the 30% by 2030 goal.

- The 4,700 ADs can be constructed across the country, using domestic feedstocks (food waste and manure) that will continually be generated locally. ADs are not dependent on foreign energy sources. With such positive impacts in cutting methane, reducing waste going to landfills and creating jobs, facilitating the buildout of these 4,700 ADs deserves to be an urgent non-partisan priority – one that's equal in importance to pursuing methane mitigation measures in the oil and gas sector.

- ***Without both accelerated AD development and methane mitigation measures in the oil and gas sector, the U.S. path to achieving the Global Methane Pledge would be nearly impossible. If both can be prioritized and implemented in parallel over the next six years, however, the 30% methane reduction goal by 2030 is well within reach.***

See table on page 12 for the climate impact and cost of all these methane mitigation measures.

I. Introduction: The Imperative of Cutting Methane Emissions 30% by 2030

According to the international scientific community, ***it is essential to cut global methane emissions at least 30% by 2030*** in order to avoid runaway climate change.[1] Otherwise, increasingly severe wildfires, storms, droughts, glacial melting, and sea level rise would threaten to destroy life as we know it. Methane (CH_4) is 84-87 times as potent a greenhouse gas (GHG) as carbon dioxide (CO_2) over a 20-year period, and it has been responsible for a third of global warming since the Industrial Revolution began.[2] 155 countries including the U.S. have signed on to the Global Methane Pledge, committing to meet this critical goal.[3]

It will be a major challenge for the U.S. to cut methane emissions 30% by 2030 – less than six years from now – and there has been no consensus on how to reach that goal. The three main sources of methane emissions are the oil and gas industry, agriculture, and organic waste – and all can make cuts. Increasingly, policymakers seek to reduce methane emissions from the oil and gas sector, and options for doing so are summarized later in this report.

To date, far less attention has been paid to organic waste and agriculture. In this report, Energy Vision has calculated the major national methane reduction potential of treating waste products from both categories – specifically, food scraps and manure – in airless tanks called anaerobic digesters (ADs).

II. How Building Anaerobic Digesters (ADs) Could Cut U.S. Methane Emissions 13.6% Annually

Building more ADs to cut methane emissions from organic wastes is an essential, affordable climate strategy for the U.S. based on proven technology. ADs turn organic wastes from environmental and economic liabilities into assets. Rather than release methane into the atmosphere as these wastes decompose, the methane is captured in ADs and then can be put to productive use. Meanwhile, the leftover nutrient-rich liquid in the ADs (called digestate) can be used as a soil amendment, displacing the need for synthetic fertilizer.

The methane captured in ADs can be used to generate electricity and heat buildings. It can also be upgraded to renewable natural gas (RNG), a sustainable fuel which requires no drilling and can displace fossil fuels. When it is made food scraps or manure, RNG captures more greenhouse gases (in the form of potent methane) in its production than it emits (as less potent carbon dioxide) when combusted, making it what is called "net carbon negative" on a lifecycle carbon accounting basis. This is a big win for the climate. RNG is a commercially viable strategy for displacing fossil fuels in hard to decarbonize sectors, namely heating some older buildings, powering various heavy industries, and fueling heavy-duty buses and trucks.

A refuse truck powered by clean-burning renewable natural gas (RNG) made from organic waste (source).

Energy Vision has conservatively calculated the total feasible potential for ADs in the U.S., including by number of facilities, percentage of total U.S. methane emissions avoided, and estimated capital ex-

1 International Energy Agency, United Nations Environment Programme, and Climate and Clean Air Coalition, The Imperative of Cutting Methane from Fossil Fuels, October 2023. https://www.iea.org/reports/the-imperative-of-cutting-methane-from-fossil-fuels

2 Global Methane Pledge. https://www.globalmethanepledge.org

3 Ibid.

penditure (capex). We have also introduced a simple metric to compare various types of ADs and other methane mitigation measures: metric tons of methane reduction per million dollars of capex invested, or simply "bang for the buck."

For consistency throughout this report, we use data from 2020, including revised 2020 data from the 2023 EPA "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021"[4] as the baseline for all emissions and methane reduction potential. For details on our methodology and calculations, please see Appendix I: Technical Annex.

Food Waste Anaerobic Digesters – The Top AD Target

With regard to organic waste, the single largest opportunity with the biggest climate benefit nationwide is to divert food waste from landfills, which often leak significant amounts of methane, to ADs. The US government categorizes half of all food that is currently discarded as edible and which should instead be redistributed to feed people and animals. Accordingly, in 2015 it set a goal of halving the nation's food waste by 2030. While very little progress has been made in achieving this important goal, our analysis focuses solely on the other half of food waste which is deemed inedible and should be processed in ADs. Energy Vision's calculations are based on 2020 data from both the October 2023 EPA report "Food Waste Management: Quantifying Methane Emissions from Landfilled Food Waste"[5] and the 2023 EPA GHG Inventory.

Energy Vision research found that building ~570 municipal food waste ADs (at an average capacity of 50,000 tons per year, recognizing food waste digesters can be built on a larger scale) would cut total net U.S. methane ~6.8% per year at an estimated capex of $28.4 billion. (Note: "municipal" in this context is just a reference to food waste being diverted from the municipal solid waste stream; it does not imply anything about what entity owns/operates the ADs or where they are located.)

Anaerobic Digestion and Composting: Both Have Roles to Play

In addition to ADs, composting can play an essential complementary role. Community composting provides important local benefits such as improved soil health, incremental progress in landfill diversion, and greater citizen engagement. But community compost programs can typically only take fruits, vegetables, and yard wastes, and overall could handle just a small fraction of the enormous volume of inedible food waste that the U.S. produces. That said, if the sites are well aerated, they can cut methane emissions significantly compared to the baseline of landfilling food waste.

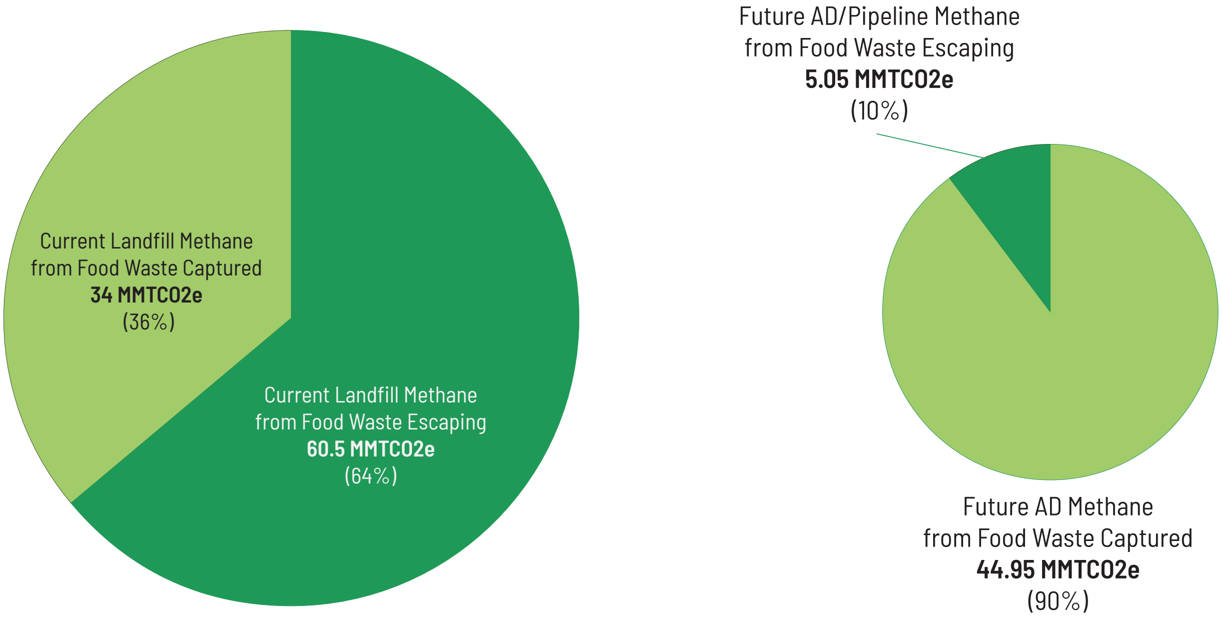
Larger, commercial-scale compost sites also have a role to play. However, empirical data on conventional commercial compost sites indicate they often produce as much methane as average landfills, which is far more than ADs (see Technical Annex Section I for details). Our research concludes that the optimal solution is diverting the majority of food waste to ADs, complemented by well-aerated community and commercial compost facilities that can properly and sustainably manage food and yard waste.

Adding in another 110 ADs for industrial food and beverage processing waste, bringing the total to approximately 680 food waste ADs, would deepen the cumulative cut to 7.5% of total net U.S. methane per year at a total capex of ~$31.7 billion. Building these ~680 food waste ADs would annually cut about half of landfill methane emissions from 2020 levels. We calculated the collective bang for the buck of building these ~680 municipal and industrial food waste ADs to be 1,752 metric tons of methane reduction per million dollars of infrastructure investment. (See Technical Annex Sections II-IV for more.)

4 U.S. Environmental Protection Agency, 2023 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021. EPA 430-R-23-002. https://www.epa.gov/system/files/documents/2023-04/US-GHG-Inventory-2023-Main-Text.pdf

5 EPA, Food Waste Management: Quantifying Methane Emissions from Landfilled Food Waste. October 2023. EPA-600-R-23-064. https://www.epa.gov/system/files/documents/2023-10/food-waste-landfill-methane-10-8-23-final_508-compliant.pdf

Total Food Waste Emissions, Million Metric Tons of CO2 Equivalent (MMTCO2e), at Landfills Currently, (Left) and Future, After Edible Half Redistributed and Inedible Half Diverted to ADs (Right)



Source: Energy Vision based on EPA data[6]

Manure Anaerobic Digesters – The Number Two AD Target

Our analysis concluded that the second-most impactful segment of organic waste – where anaerobic digestion can play an important role in mitigating methane emissions – is livestock manure. This is subdivided into dairy, the largest source, and swine, the second-largest source. Our calculations are based on 2020 data from the 2023 EPA GHG Inventory and 2022 data (the closest available to 2020) from the U.S. Department of Agriculture Census of Agriculture 2022, released in February 2024.[7]

Energy Vision used a minimum threshold of 500 dairy cows for a dairy manure AD project, with capex rising as herd sizes increase. We calculated that building ~3,180 dairy manure ADs would cut total net U.S. methane 3.6% per year at a total capital investment of approximately $34.2 billion. Meanwhile, we used 20,000 pigs (whether at a single farm or a cluster of farms) as the minimum threshold for a swine manure AD project.[8] We found that building ~850 ADs to process swine manure would cut total net U.S. methane 2.5% per year at an estimated capex of ~$8.3 billion.

All told, building ~4,030 ADs to process dairy and

6 Note: "CO2 equivalent" is a widely used metric for assessing the global warming impact of methane (and other potent greenhouses gases) relative to carbon dioxide. EPA counts 1 metric ton of methane as being equivalent to 28 metric tons of CO2 over a 100-year period. Source: EPA, 2023 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021.

7 U.S. Department of Agriculture, Census of Agriculture 2022. February 2024. AC-22-A-51. https://www.nass.usda.gov/Publications/AgCensus/2022/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf

8 It is clear that large "factory farms" are opposed by many advocates because of their treatment of the animals and because of their contamination of nearby water sources with manure. However, thousands of these operations exist and are entrenched across the country, with millions of dollars in sunk investments per farm. Furthermore, both the dairy and swine industries have been on paths of increasing consolidation into a smaller number of bigger farms over the past two decades based on market dynamics and economies of scale. However, since large dairy and swine farms' concentrated manure produces a lot of methane, it is better to capture that potent greenhouse gas in ADs as soon as possible rather than let it escape into the atmosphere. Whether or not protests against the factory farming model result in basic changes, ADs are needed. Their operation will not materially impact the broader challenges to the factory farming industry.

Climate Impact and Cost of Meeting U.S. Anaerobic Digester Potential

Strategy	Number of ADs	Total U.S. Methane Reduction (compared to 2020)	Total Capex
Food Waste ADs (Municipal and Industrial)	~680 ADs	7.5%	$31.7 billion
Manure ADs (Dairy and Swine)	~4,030 ADs	6.1%	$42.5 billion
Total Food Waste and Manure ADs	**~4,700 ADs**	**13.6%**	**$74.2 billion**

Source: Energy Vision calculations

swine manure would reduce total net U.S. methane ~6.1% annually at an estimated capex of $42.5 billion. Building these manure ADs would cut three quarters of dairy and swine manure methane emissions per year.[9] We calculated the collective bang for the buck of building these 4,030 dairy and swine manure ADs to be approximately 1,068 metric tons of methane reduction per million dollars of investment. (See Technical Annex Sections V-VIII for more.)

Total Cost and Methane Reductions from Food Waste and Manure Anaerobic Digesters

The estimated total capex is therefore $74.2 billion for ~4,700 ADs to process food waste and animal manure, which would annually reduce half of landfill methane emissions (by keeping food waste out of landfills) and three quarters of dairy and swine manure methane emissions. Together, this mass deployment of ADs would cut approximately 13.6% of total U.S. methane per year (see table above). On average, each project takes roughly 2-6 years to build. We calculated the collective bang for the buck of building these 4,700 food waste and manure ADs to be 1,360 metric tons of methane reduction per million dollars of investment.

III. Honorable Mentions: Other Feedstocks for Anaerobic Digesters, Better Gas Collection at Landfills, and Methane Reduction Potential in Sectors Besides Oil and Gas

Other Feedstocks for Anaerobic Digesters

Other types of organic waste are worth mentioning as AD feedstock but have far lower cost-effectiveness or cumulative impact (bang for the buck) in methane reduction than food waste or dairy and swine manure. These include sewage from wastewater treatment plants (both publicly owned and industrial), yard waste, and other types of animal manure (such as poultry). Successful AD projects can be developed in these subsectors, especially at large wastewater treatment plants that "co-digest" food waste, such as the recent case of the Newtown Creek facility in Brooklyn, New York (as highlighted in Energy Vision's report *Gotham Gas Goes Green*).

9 Positive results are also emerging from other options to reduce methane from manure lagoons, such as mixing in biochar or acids. See for example, Institute for Governance & Sustainable Development, "A Primer on Cutting Methane: The Best Strategy for Slowing Warming in the Decade to 2030," April 12, 2024. https://www.igsd.org/wp-content/uploads/2024/01/IGSD-Methane-Primer.pdf. The methane reductions compared to ADs (see Technical Annex section IX for details), but they may be great solutions for the many farms that are too small to consider ADs, such as those with fewer than 500 dairy cows or fewer than 5,000 swine. Our emphasis on building ADs to process food waste and manure is rooted in the efficiency, relative cost-effectiveness, and scalability of this solution. Plus, building manure ADs brings in a new revenue source to the farmers from producing electricity or RNG.

Source: EPA

Landfills

Landfills are largely excluded from this report, because organic waste – especially food waste – increasingly can and should be diverted from landfills. As the organic portion of landfilled waste decomposes, methane is released, and landfill gas collection systems are inherently less efficient than ADs; they typically also aren't installed on "active cells" where waste is still being deposited daily. In line with the EPA's Wasted Food Scale (see above), we don't favor an expansion of landfills but rather of ADs, which both efficiently capture methane emissions and allow nutrients (especially nitrogen and phosphorous) to be recycled via the digestate back into the soil.

Nonetheless, landfills are currently the third largest source of U.S. methane emissions. And even as we make additional progress in diverting organics from landfills, they will continue to generate methane while active and for decades after closure. In the meantime, there is significant potential for greater methane collection efficiency at many landfills. This includes through tighter regulations that come into effect soon after waste is deposited (rather than the current EPA rule that the landfill operator must install and run a gas collection system within 30 months after non-methane organic compounds reach a certain threshold,[10] which has meant that a lot of methane typically escapes in the early years, especially from food waste[11]). More advanced methane monitoring and capture technology could also be implemented at many landfills, which could make a very big difference in the sector's emissions in the near term.

Enteric Fermentation (Methane from Cows' Digestion)

It is also worth mentioning some other non-AD methane mitigation solutions in sectors besides oil

10 EPA, "Federal Plan Requirements for Municipal Solid Waste Landfills That Commenced Construction On or Before July 17, 2014, and Have Not Been Modified or Reconstructed Since July 17, 2014." Federal Register. May 21, 2021. https://www.federalregister.gov/documents/2021/05/21/2021-10109/federal-plan-requirements-for-municipal-solid-waste-landfills-that-commenced-construction-on-or

11 EPA estimates that in 2020, food waste accounted for 58% of the fugitive methane emissions from municipal solid waste landfills. Source: EPA, Food Waste Management: Quantifying Methane Emissions from Landfilled Food Waste. October 2023.

and gas, although it was beyond the scope of this report to estimate their specific percentages of feasible methane contributions or cost estimates. Within agriculture, a gigantic source of methane (about triple[12] that of manure methane) is called "enteric fermentation" – otherwise known as animal burps, predominantly from cows. There is not yet a proven, cost-effective, scalable solution akin to ADs that could significantly cut enteric fermentation emissions. Several ways to cut enteric fermentation emissions are still early stage and mostly experimental but have promising prospects, like altering animal feed, and selective breeding to produce cows that emit less methane.[13] (See Technical Annex Section IX for more.) Similarly, new approaches to scale "methane eating microbes" to produce biofertilizers are encouraging but not yet commercial.[14]

Coal Mining

Additional reductions in methane emissions could come from coal mining (an industry that produces fewer methane emissions than the natural gas and oil industries).[15] Methane is generated at both active and abandoned coal mines, and much of it leaks or is deliberately vented into the atmosphere. But that methane could instead be captured and used productively (for example to generate electricity) or flared. Flooding abandoned coal mines is another option to limit methane emissions.[16]

Rice Cultivation

Lastly, rice cultivation is a small contributor to total U.S. methane[17], but there's room for improvement. Reducing the total time that rice fields are flooded (which produces methane) by alternate flooding and drainage methods would reduce methane emissions.[18]

All told, broader recognition that methane is a major short-term challenge and opportunity – driven by findings of the global scientific community – has fostered innovation and investment in a wide range of emerging technologies, solutions, and market-based mechanisms. This is a great development, and there is no doubt potential in many of these applications. Our focus on anaerobic digestion is by no means a suggestion that it is the *only* methane mitigation strategy, but it is among the most established and illustrates an important, broader point: much of the technology we need to adequately address the climate challenge is commercial but under-deployed.

IV. Methane Mitigation Measures in the Oil and Gas Industry and How They Compare to ADs

Plugging Abandoned Oil and Gas Wells – Worthwhile but Less Impactful

Energy Vision also analyzed how building ADs compares to several methane mitigation measures in the oil and gas industry. Our calculations show that building ~4,700 food waste and manure ADs would mitigate over 12 times the amount of methane that plugging all 2.1 million abandoned oil and gas wells in the U.S. would, at roughly half the cost (based on a conservative average plugging cost of $60,000/well due to the challenges involved).

We calculated the bang for the buck of plugging these abandoned oil and gas wells to be just 63 metric tons of methane reduction per million dollars of

12 EPA, 2023 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021.

13 Institute for Governance & Sustainable Development, "A Primer on Cutting Methane: The Best Strategy for Slowing Warming in the Decade to 2030."

14 BusinessWire, "Windfall Bio Raises $28 Million Series A to Scale Methane Capture & Transformation Solution," April 8, 2024. https://www.businesswire.com/news/home/20240408846147/en/Windfall-Bio-Raises-28-Million-Series-A-to-Scale-Methane-Capture-Transformation-Solution

15 EPA, 2023 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021.

16 Institute for Governance & Sustainable Development, "A Primer on Cutting Methane: The Best Strategy for Slowing Warming in the Decade to 2030."

17 EPA, 2023 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021.

18 Ibid.

capex invested. Plugging these abandoned wells is certainly a worthy long-term endeavor[19], and data is very patchy and scarce about their emissions (and in many cases their precise locations), but the EPA's estimate of their cumulative methane emissions equates to just 1.1% of the country's total net methane emissions.[20] (See Technical Annex Section X for more.)

Compliance with EPA's New Source Performance Standards for Oil and Gas Sector Emissions – The Largest Benefit if Fully Realized

A more impactful development for oil and gas industry methane is the EPA's latest New Source Performance Standards (NSPS) for oil and gas sector emissions, which formally came into effect on May 7, 2024, pending any delays due to litigation. The Clean Air Act gives the EPA the authority and obligation to regulate new stationary sources of dangerous air pollutants and to issue legally binding minimum emissions guidelines for states to regulate existing "designated facilities."

The revised NSPS are meant to make a massive reduction in the methane emissions from operating oil and gas facilities. They entail mandatory equipment upgrades (for example, swapping out very leaky gas-powered pneumatic controllers at the vast majority of oil and gas wellheads with zero-emission ones within a year); very tight restrictions on gas flaring; new requirements for regular emissions monitoring and reporting at infrastructure throughout the industry; and the incorporation of new monitoring technology like third-party satellites to detect super-emitter events (which must then be quickly investigated by the owner/operator and reported back to the EPA).

The EPA has stipulated various phase-in periods for compliance with the new rules. It accordingly foresees methane reductions from the NSPS slowly ramping up from 2024-2027, before dramatically accelerating in 2028 and reaching the full level in 2029 and beyond.[21] The full methane abatement per year, as estimated by the EPA, would equal 86% of the nationwide methane emissions from oil and gas production in 2020, or 54% of total oil and gas industry methane emissions in 2020. The EPA meanwhile projects the total number of oil and gas wells to remain largely stable (just a very slight decrease) through 2038, as new ones roughly replace retired ones. Full compliance with the revised NSPS, from 2029 onwards, would annually cut 17.5% from the 2020 level of total net U.S. methane.

Once in full effect, EPA's new rules would cut 86% of the nationwide methane emissions from oil and gas production compared to 2020. Source: Tim Evanson

The cumulative capital cost of compliance with the NSPS regulations from 2024-2029 is expected to be $20.7 billion,[22] to be largely borne by the industry

19 Of note, there's an emerging market for credits to offset methane emissions that might help direct funding for efforts like plugging abandoned oil and gas wells. See for example: Keaton Peters, "Carbon Credit Market Seizes On a New Opportunity: Plugging Oil and Gas Wells," Inside Climate News, June 23, 2023. https://insideclimatenews.org/news/23062023/carbon-credit-oil-gas-plugging/

20 2020 data from EPA, 2023 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021.

21 EPA, Regulatory Impact Analysis of the Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review. December 2023. EPA-452/R-23-013. https://www.epa.gov/system/files/documents/2023-12/eo12866_oil-and-gas-nsps-eg-climate-review-2060-av16-ria-20231130.pdf

22 Note that the NSPS calculations do not double-count any emissions potential with the EPA's separate proposed Waste Emissions Charge and vice versa. This "methane fee," as it's known in shorthand, is expressly ordered in the Inflation Reduction Act and is mainly meant to accelerate compliance with the NSPS. Once affected facilities are in compliance with the NSPS, they're no longer subject to the methane fee. As a result, expected government revenue from the Waste Emissions

(with some federal funding available, such as through the Methane Emissions Reduction Program). But if spread out per year (~$3 billion per year) and among the producers according to their emissions, these compliance costs are fairly minor for an industry whose annual capex has recently ranged from $79 billion in 2021 to $156 billion in 2019. Furthermore, some of that incremental cost of compliance can be defrayed by greater amounts of gas being recovered and sold instead of leaking into the atmosphere. The EPA estimates that from 2024-2029, the cumulative amount of additional recovered gas would be worth $3.6 billion – more than covering the cumulative operational expenses of approximately $3.3 billion and thus helping to recoup a little of the capex of compliance.

We calculated that fully complying with the NSPS has even more bang for the buck (6,280 metric tons of methane reduction per million dollars of capex invested) than building ADs, but both need to be pursued simultaneously and aggressively this decade. Together, they provide a path to reach the 30% by 2030 goal – even possibly to exceed it. The 17.5% reduction in net U.S. methane from oil and gas industry NSPS compliance plus the 13.6% reduction in net U.S. methane from building food waste and manure ADs equals a 31.1% decrease per year from 2020 levels. And doing so is feasible by 2030 if we start acting soon. As noted above, ADs typically take 2-6 years to build, so much of this infrastructure could be deployed by 2030, and the EPA is projecting the full NSPS compliance impact by 2029. (See Technical Annex Section XI for more.)

Lawsuits, such as those filed by oil and gas producing states, may delay implementation of parts of the NSPS or weaken certain provisions. But given the urgency of tackling methane NOW, we are cautiously optimistic that emissions will start coming down significantly in the oil and gas sector as a result of the NSPS. ADs, meanwhile, do not face the same kind of legal/regulatory challenges, although local opposition and pushback from certain segments of the environmental community can derail projects and progress. Regardless of whether the new oil and gas regulations are suspended pending the outcome of legal action, ADs can and should proceed at full speed with design, permitting, construction, and commissioning.

Nearly 80% of all U.S. oil and gas wells are "stripper wells," and they produce only 6% of oil and gas but half of all methane emissions from U.S. oil and gas production.
Source: NatalieMaynor

Plugging All "Stripper Wells" – Major Methane Reduction

If the revised NSPS for oil and gas production are suspended/repealed by court order, then another useful comparison for building ADs is with plugging marginal conventional oil and gas wells. Known as "stripper wells," these produce 0-15 barrels of oil equivalent per day. Nearly 80% of all active oil and gas wells in the country are stripper wells, but they produce only about 6% of the oil and gas – as well as half of all methane emissions from oil and gas production.[23] (The EPA estimates that about half of the NSPS methane emissions reduction would come from improvements at stripper wells.)

Relative to building the 4,700 ADs, we found that there is more bang for the buck in plugging all 703,000 stripper wells24 (2,830 metric tons of methane reduction per million dollars of capex invested, based on a lower average plugging cost

Charge drops 98% from the peak of $770 million in 2025 to just $13 million starting in 2027. Source: EPA, Regulatory Impact Analysis of the Proposed Waste Emissions Charge, January 2024. EPA-430/R-23-005. https://www.epa.gov/system/files/documents/2024-01/wec_ria.pdf

23 U.S. Energy Information Administration, The Distribution of U.S. Oil and Natural Gas Wells by Production Rate with data through 2022. December 2023. https://www.eia.gov/petroleum/wells/pdf/Well_Distributions_report_2023_full_report.pdf

24 This is the most up to date official statistic available on the total number of stripper wells, as per the EIA. Source: Ibid.

Climate Impact and Cost of Meeting U.S. Anaerobic Digester Potential and Oil and Gas Sector Methane Reduction Measures

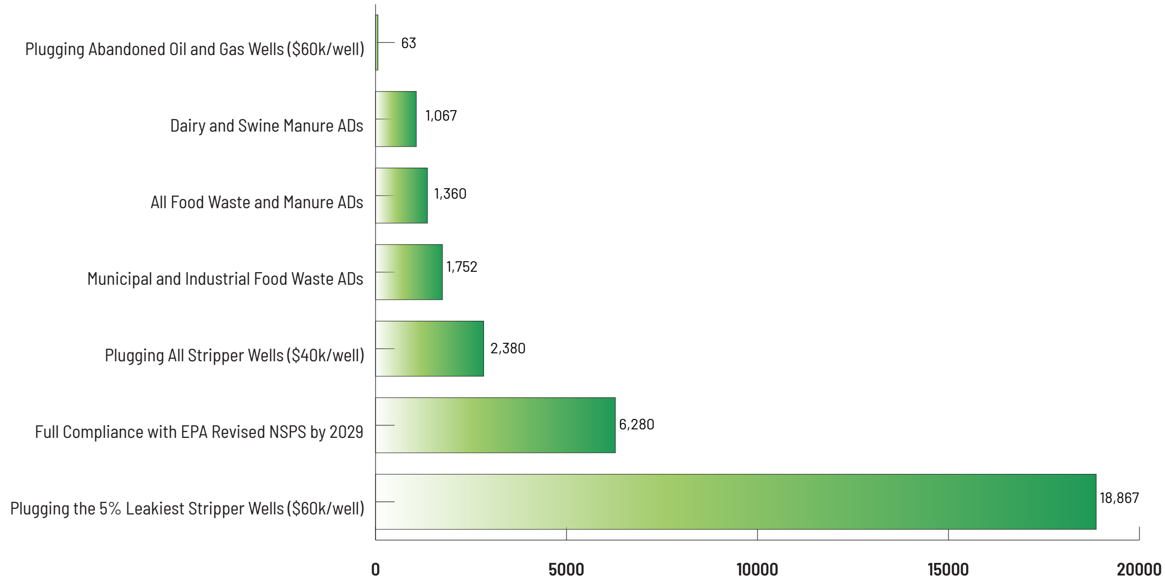
Strategy	Number of ADs or Oil and Gas Wells	Total U.S. Methane Reduction (compared to 2020)	Total Capex
Food Waste ADs (Municipal and Industrial)	~680 ADs	7.5%	$31.7 billion
Manure ADs (Dairy and Swine)	~4,030 ADs	6.1%	$42.5 billion
Total Food Waste and Manure ADs	**~4,700 ADs**	**13.6%**	**$74.2 billion**
Full Compliance with EPA Revised NSPS by 2029 (predominantly based on improving rather than shutting down operations)	Millions of pieces of equipment plus different procedures	17.5%	$20.7 billion
Plugging All Stripper Wells	703,000 wells	10.7%	$28.1 billion
Plugging the Leakiest 5% of Stripper Wells	35,150 wells	5.4%	$2.1 billion
Plugging Abandoned Oil and Gas Wells	2.1 million wells	1.1%	$130.7 billion

Source: Energy Vision calculations, based on EPA, USDA, EIA, and other scientific data[25]

of $40,000/well due to more economies of scale available). However, the aggregate potential methane cut is lower: plugging all stripper wells would yield a maximum 10.7% drop in total U.S. net methane per year, which is less than the 13.6% from food waste and manure ADs. But they are not rivals and both could be done, yielding a combined 24.3% annual reduction in net U.S. methane (if the revised NSPS for oil and gas production were to be suspended/repealed and have no impact). That would still represent huge progress towards the U.S. goal of cutting methane 30% by 2030. (See Technical Annex Section XII for more.)

25 The sources for these calculations, as cited throughout this report, are:
- EPA, 2023 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021. https://www.epa.gov/system/files/documents/2023-04/US-GHG-Inventory-2023-Main-Text.pdf
- EPA, Food Waste Management: Quantifying Methane Emissions from Landfilled Food Waste. October 2023. https://www.epa.gov/system/files/documents/2023-10/food-waste-landfill-methane-10-8-23-final_508-compliant.pdf
- USDA, Census of Agriculture 2022. February 2024. https://www.nass.usda.gov/Publications/AgCensus/2022/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf
- EPA, Regulatory Impact Analysis of the Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review. December 2023. https://www.epa.gov/system/files/documents/2023-12/eo12866_oil-and-gas-nsps-eg-climate-review-2060-av16-ria-20231130.pdf
- EIA, The Distribution of U.S. Oil and Natural Gas Wells by Production Rate with data through 2022. December 2023. https://www.eia.gov/petroleum/wells/pdf/Well_Distributions_report_2023_full_report.pdf
- Omara, M., Zavala-Araiza, D., Lyon, D.R. et al. Methane emissions from US low production oil and natural gas well sites. Nature Communications 13, 2085 (2022). https://doi.org/10.1038/s41467-022-29709-3

Methane Reduction (Metric Tons of Methane as CO2 Equivalent) Per Million Dollars of Capex Invested in Different Types of ADs or Methane Abatement Solutions



Source: Energy Vision calculations

Plugging Just the Leakiest 5% of Stripper Wells – The Most Bang for the Buck

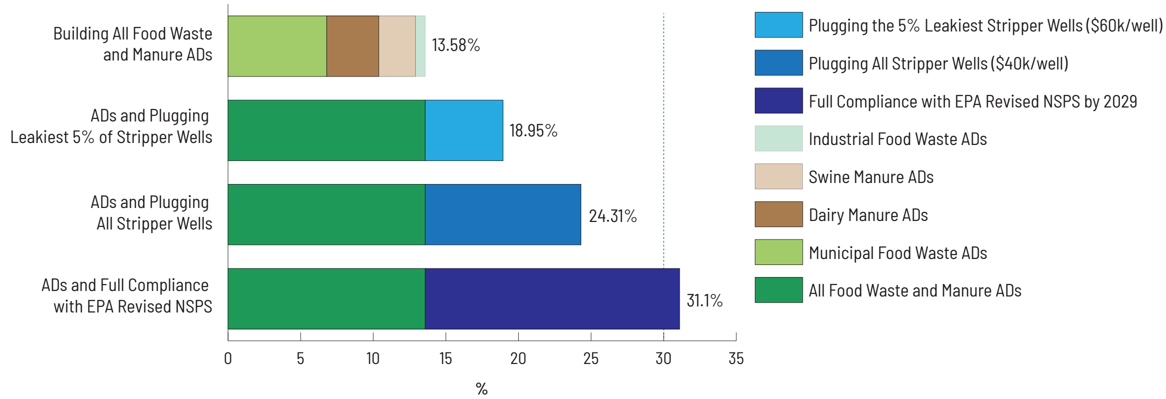
If attempting to plug all stripper wells is politically unfeasible or logistically impractical, then a more targeted approach would be to identify and plug the leakiest 5% of stripper wells, some 35,000. This subset is estimated to produce half of all stripper well methane emissions, or a quarter of all methane emissions from U.S. oil and gas production.[26] Plugging these leakiest 5% of stripper wells has far more bang for the buck than any other methane mitigation option we examined: 18,887 metric tons of methane reduction per million dollars of capex invested (based on an average plugging cost of $60,000/well due to the challenges involved). That's not to imply that the other options are inefficient, but rather it reflects the massive amounts of methane that are spewing into the atmosphere from these leakiest of stripper wells and that plugging them is incredibly cost-effective.

Plugging the leakiest 5% of stripper wells would yield a 5.4% cut in net U.S. methane per year. That's less than the 10.7% from plugging all stripper wells, but still significant. If that 5.4% from plugging the leakiest 5% of stripper wells were paired with the 13.6% from building the 4,700 ADs, the total net U.S. methane reduction per year would be 19%: a large and achievable step on the way to the goal of 30% reduction by 2030. (See Technical Annex Section XIII for more.)

The table on page 12 summarizes the climate impacts and costs of meeting the U.S. AD potential as well as the oil and gas sector methane reduction options. The chart above compares the bang for the buck or cost-effectiveness in methane reduction for all of these strategies.

26 Omara, M., Zavala-Araiza, D., Lyon, D.R. et al. Methane emissions from US low production oil and natural gas well sites. Nature Communications 13, 2085 (2022). https://doi.org/10.1038/s41467-022-29709-3

Progress of Various Combinations Toward the 30% Methane Reduction by 2030 Goal (%)



Source: Energy Vision calculations

V. How Policy Can Further Accelerate the Buildout of Anaerobic Digesters

In direct response to favorable state and federal policy put in place over the past decade, the recent expansion of AD infrastructure in the U.S. has largely been funded by private sector dollars. Private companies and private investment play indispensable roles at all stages of AD development, from initial feasibility studies all the way through construction and operations.

The role of public policy – at the federal, state, and local levels – has been to facilitate this private sector-led buildout of AD infrastructure so as to maximize climate and job creation benefits while keeping costs to taxpayers at acceptable levels, primarily through incentives. Historically (to date), valuable credits earned by producers of RNG that's used to replace fossil fuel consumption in transportation – via the federal Renewable Fuel Standard and Low Carbon Fuel Standards in California, Oregon, and Washington – have been the biggest drivers in the nationwide growth of ADs and RNG production. (Through our work in collaboration with Argonne National Laboratory, Energy Vision has documented the nationwide growth in RNG projects from 60 operational projects in 2017 to 275 in 2022, with the figures of continued expansion since then still being finalized.)[27] Landfill diversion mandates as well as other state and local regulation/policy are important, but the economic incentives have been the primary driver.

Getting to 30x30: The Bottom Line

The buildout of AD infrastructure needs to be supercharged in order to reach its full potential in meeting the country's climate goals. The 2022 Inflation Reduction Act (IRA) contains tax credits and other support mechanisms that can do so. However, nearly two years after the passage of this landmark federal climate legislation, concerns and confusion persist when it comes to anaerobic digester projects. Treasury (the IRS) is still working to finalize the specifics for certain aspects of the law, including a variety of often complex eligibility requirements directly and indirectly related to ADs. With clarity and certainty, the private sector appears poised to lead.

Barring unforeseen setbacks, the good news is that many of the pieces are in place for the buildout of 4,700 ADs across the country, using domestic feedstocks (food waste and manure) that will continually be generated locally. With such positive impacts in cutting methane, reducing waste going to landfills and creating jobs, facilitating the buildout of these 4,700 ADs deserves to be an urgent non-partisan priority – one that's equal in importance to pursuing methane mitigation measures in the oil and gas sector. This is especially the case as new empirical sat-

27 Mintz, M. and Lerner, M. Database of Renewable Natural Gas (RNG) Projects: 2022 Update, Argonne National Laboratory, December 2023, https://www.anl.gov/es/reference/renewable-natural-gas-database

ellite data emerges[28] on the scale of landfill methane emissions being above and beyond long-held estimates, and with the EPA having recently calculated that 58% of landfills' fugitive methane emissions come from food waste.[29]

Oil and gas sector methane mitigation measures are critically important. But even if those efforts get delayed or weakened, AD development doesn't face the same legal/regulatory challenges and could proceed regardless. Without both, the U.S. path to achieving the Global Methane Pledge would be nearly impossible. If both can be prioritized and implemented in parallel (see chart on page 14) over the next six years, however, the 30% methane reduction goal by 2030 is well within reach.

The Regional Digester in Buffalo, New York State's second-largest city, processes 45,000 tons of food waste per year from farms, food processors, restaurants, and grocery stores. By early 2025 it will be producing RNG from the captured methane biogas. Meanwhile, the "digestate" is turned into soil amendments that enrich more than 1,000 acres of local farmland.

(Source: Buffalo Regional Digester)

28 Will Sullivan, "More Than Half of U.S. Landfills May Be Methane 'Super-Emitters,' Study Finds." Smithsonian Magazine. April 3, 2024. https://www.smithsonianmag.com/smart-news/more-than-half-of-us-landfills-may-be-methane-super-emitters-study-finds-180984071/

29 EPA, Food Waste Management: Quantifying Methane Emissions from Landfilled Food Waste. October 2023.

Appendix I: Technical Annex

This Technical Annex describes the methodologies, assumptions, and calculations used in Energy Vision's report, ***Meeting the Methane Challenge: How the U.S. Can Reach Its 2030 Goal.*** As noted for consistency throughout the report, we use data from 2020, including revised 2020 data from the 2023 EPA "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021"[30] as the baseline for all emissions and methane reduction potential calculations.

I. Emissions from Commercial-Scale Compost Sites Relative to Landfills and ADs

According to 2021 NASA Jet Propulsion Laboratory methane-monitoring satellite data from California, commercial-scale compost production facilities emit, on average, nearly as much methane to the atmosphere as landfills. Specifically, the average California commercial compost facility emits less than the 10 leakiest landfills measured, but more than almost all the other 25+ landfills measured.[31]

Landfills with no gas collection systems leak all their methane into the atmosphere, but even landfills with gas collection systems often leak 30% of their methane, in some cases even 50%. The EPA's voluntary goal is for all landfills across the country to capture 70% of their methane emissions by 2030, meaning 30% is being written off as unattainable/unrealistic.[32] It's also important to note that a growing body of empirical satellite data[33] clearly shows that landfill methane is often being under-reported by 40% on average, meaning that EPA assumptions and data on landfills are likely undershooting the mark.

By contrast, anaerobic digesters capture almost all the methane from the organic wastes they process. A 2021 UK study found the average amount of methane leakage from digesters is 3.7%, with well-operated modern facilities as low as 0.2%.[34] Similar data from US facilities does not yet appear to exist, although this type of assessment would be invaluable.

Lastly, a literature review conducted for the Oregon Department of Environmental Quality[35] looked at 148 separate studies and concluded that anaerobic digestion plus composting the digestate provides 3.5 times the carbon reductions that compost alone provides. And that is when the organic waste is converted to electricity. If it's used to produce hydrogen and/or upgraded to renewable natural gas (RNG) and used to replace

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30 U.S. Environmental Protection Agency, 2023 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021. EPA 430-R-23-002. https://www.epa.gov/system/files/documents/2023-04/US-GHG-Inventory-2023-Main-Text.pdf

31 National Aeronautics and Space Administration Jet Propulsion Laboratory, Greenhouse Gas Mapping. https://methane.jpl.nasa.gov Screenshots of charts of California 2021 methane emissions as measured by NASA JPL satellites in 2021 are available at https://drive.google.com/file/d/1DnCqksjPO9n4w6s6rj5K1MsycEP1CBSP/view . See also: https://www.jpl.nasa.gov/news/a-third-of-california-methane-traced-to-a-few-super-emitters

32 The White House, U.S. Methane Emissions Reduction Action Plan. November 2021. https://www.whitehouse.gov/wp-content/uploads/2021/11/US-Methane-Emissions-Reduction-Action-Plan-1.pdf

33 Will Sullivan, "More Than Half of U.S. Landfills May Be Methane 'Super-Emitters,' Study Finds." Smithsonian Magazine. April 3, 2024. https://www.smithsonianmag.com/smart-news/more-than-half-of-us-landfills-may-be-methane-super-emitters-study-finds-180984071/

34 Bakkaloglu, Semra et al, "Quantification of methane emissions from UK biogas plants," Waste Management, Volume 124, 2021, Pages 82-93, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2021.01.011.

35 Morris, Jeffrey, "Evaluation of Climate, Energy, and Soils Impacts of Selected Food Discards Management Systems." Prepared for the State of Oregon Department of Environmental Quality, October 2014. https://www.oregon.gov/deq/FilterDocs/FoodWasteStudyReport.pdf

diesel, then the carbon benefits of anaerobic digestion are even greater (and the difference between anaerobic digestion and compost is even bigger). More research into this latter aspect would be very useful.

II. Number and Cost of Municipal Food Waste ADs

56.7 million metric tons of food waste were disposed of in municipal solid waste (MSW) landfills in 2020 (according to the 2023 EPA report, Food Waste Management: Quantifying Methane Emissions from Landfilled Food Waste.)[36]

Despite marginal progress to date, we assume that the edible half of that will eventually be redistributed, as per the U.S. government's 2030 goal (set in 2015).[37]

So the inedible half, 28.35 million metric tons, is the potential for municipal food waste ADs. (As noted in the report, "municipal" in this context is just a reference to food waste being diverted from municipal solid waste; it does not imply anything about what entity owns/operates the ADs or where they are located.)

We assume an average food waste AD processes 50,000 tons per year (although they can be and often are built on larger scales with proportionally higher costs).

= 28,350,000 / 50,000 = 567 food waste ADs

At an assumed average of $50 million per food waste AD = ~$28.4 billion

Factored into this $50 million average cost are all related infrastructure and equipment, including combined heat and power, gas upgrading, and pipeline interconnection where applicable.

Note: a few food waste ADs have come online since 2020, but the amount of food waste in landfills and the methane emissions from that food waste have been on the rise and increased since then. EPA's 2023 landfilled food waste methane report notes that from 1990-2020, methane emissions from landfilled food waste increased steadily by 295% even as total landfill methane emissions decreased by 43% because of expanded federal and state regulations for gas collection requirements and more local/state yard waste diversion. And according to the national non-profit ReFED (which has a large quantitative discrepancy from EPA's data on total food waste sent to landfill in 2020 but at least has consistent data available after 2020), the amount of surplus food disposed of in landfills went from 30.8 million tons in 2020 to 32.4 million tons in 2021 and 32.6 million tons in 2022.[38] Given this sustained increase in food waste being landfilled (even as overall landfill methane emissions continue to slightly drop due to the aforementioned reasons), we are not counting any existing operational municipal food waste ADs against the calculated total of 567 additional ones needed.

III. Number and Cost of Industrial Food Waste ADs

Food processing and beverage industry food waste sent 5.5 million metric tons to landfill in 2020 (the indus-

36 EPA, Food Waste Management: Quantifying Methane Emissions from Landfilled Food Waste. October 2023. EPA-600-R-23-064. https://www.epa.gov/system/files/documents/2023-10/food-waste-landfill-methane-10-8-23-final_508-compliant.pdf

37 EPA, USDA, and FDA, Draft National Strategy for Reducing Food Loss and Waste and Recycling Organics. December 2023. https://www.epa.gov/system/files/documents/2023-12/draft_national_strategy_for_reducing_food_loss_and_waste_and_recycling-organics.pdf

38 ReFED, Insights Engine, https://insights-engine.refed.org/food-waste-monitor?break_by=destination&indicator=tons-surplus&view=detail&year=2022 Last updated November 2, 2023.

try is already repurposing 94% so this number should remain steady – and it indeed was in 2021, the latest reporting year.)[39]

Divided by 50,000 tons per AD = 110 more ADs for industrial food waste

We estimate that a 50,000 ton per year industrial food waste AD would cost approximately $30 million (generally less expensive than municipal food waste AD given that it would be receiving uncontaminated, more concentrated feedstock and could be built onsite next to the food & beverage processing plant, with reliable supply). Factored into this $30 million average cost are all related infrastructure and equipment, including combined heat and power, gas upgrading, and pipeline interconnection where applicable.

110 X an average cost of $30 million = $3.3 billion

IV. Emissions Reductions from Municipal and Industrial Food Waste ADs

According to the 2023 EPA report on methane from landfilled food waste, municipal food waste generated 89 MMT CO2e (at Global Warming Potential 100) of methane in 2020; of which 55 MMT escaped.

For the purposes of this assessment, we assume that the appropriate policies and regulations to separate food waste will be in place and will be complied with (including separating edible food for redistribution and separating food waste from non-recyclable and inorganic materials) to meet the U.S. government's 2030 goal of redistributing the edible half of food that is currently discarded – recognizing full well that this is not currently the case in many jurisdictions.

We then conservatively assume that AD systems are 95% efficient in capturing methane and that pipelines are similarly 95% effective at minimizing leakage in subsequently transporting the biogas and, if applicable, any upgraded renewable natural gas (RNG). We therefore conclude that 90% of the total methane generated from inedible food waste could be prevented using AD, allowing for a 6-7% buffer as compared to empirical UK AD leakage data (see Section I). We likewise assume that redistributing food that would otherwise be landfilled leads to a 90% net reduction in methane, factoring in any secondary wastage of redistributed food plus the inevitable food scraps generated, which then ideally go to ADs. So we conservatively take 90% off the total methane generated from all food waste in landfills, which would be 80.1 out of 89 MMT CO2e.

Once the existing food waste has rotted away in landfills (which will take a few years – and the landfill gas could be collected more efficiently in the meantime) and is not being replaced with new food waste, then in the long term we are looking at a vast improvement in food waste emissions. Instead of 55 MMT CO2e escaping out of 89 MMT (58%) in landfilled food waste, which may well be an underestimate (in part based on dated default landfill methane emissions values applied rather than empirical measurements taken[40]), there could be 4.5 MMT CO2e escaping out of 44.5 MMT (10%), which is very likely an overestimate since our assumptions on AD and pipeline efficiency are conservative. Compared to the situation today of a patchwork of MSW landfills with largely inefficient gas collection systems, that would be a 91.8% drop in MSW landfill methane emissions from food waste specifically, and a 53.6% drop in total net MSW landfill methane emissions.

39 Table A-203 in EPA, Annexes to the Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2021. 2023. https://www.epa.gov/system/files/documents/2023-04/US-GHG-Inventory-2023-Annexes.pdf

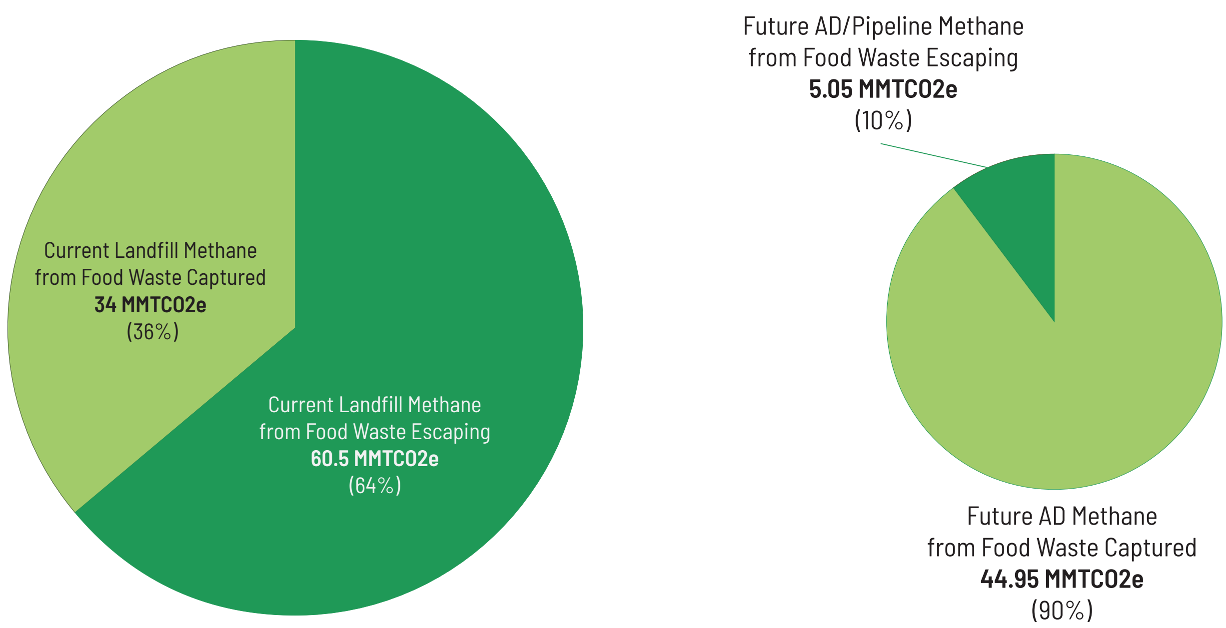
40 Brown, Sally. "Connections: Food Waste And Landfill Methane Report — A Giant Step On A Long Road." BioCycle. January 16, 2024. https://www.biocycle.net/connections-food-waste-and-landfill-methane-report-a-giant-step-on-a-long-road/

The same assumptions hold for diverting industrial landfills' food waste to ADs, meaning a 90% reduction in their total generated methane from the food and beverage industry from 5.5 MMT to .55 MMT. Again, the 10% of methane escaping is very likely an overestimate. This compares enormously favorably to the current situation of virtually 100% of industrial landfills' methane emissions escaping to the atmosphere (the EPA notes that only 1 out of 167 industrial landfills in the US that reported in a GHG monitoring program has an active gas collection and control system).[41]

Together, the MSW and industrial landfill figures mean that establishing policies to divert the edible half of food waste to redistribution and the inedible half to ADs would equate to a 90% reduction in gross methane generated by landfilled food waste. Instead of 60.5 [55+5.5] MMT CO2e escaping from a larger pool (94.5 [89+5.5] MMT CO2e gross emissions from food waste in both MSW and industrial landfills in 2020), there would be 5.05 [4.5+.55] MMT CO2e escaping from a smaller pool (50 [44.5+5.5] MMT CO2e gross emissions from municipal and industrial food waste ADs). See charts below.

Going from 60.5 MMT CO2e to 5.05 MMT CO2e is a 91.7% reduction (a 55.45 MMT CO2e drop in absolute terms) in net methane from food waste (aggregating both municipal and industrial). Granted, halving food waste by redistributing the edible half is a huge undertaking and would be responsible for almost half of that reduction (27.5 MMT, or 49.6% of the 55.45 MMT reduction), but diverting the inedible half to ADs is an even larger component, accounting for slightly over half (50.4%) of the reduction.

Total Food Waste Emissions, Million Metric Tons of CO2 Equivalent (MMTCO2e), at Landfills Currently (Left) and in Future After Edible Half Redistributed and Inedible Half Diverted to ADs (Right)



Sources: Energy Vision based on EPA data[42]

41 EPA, 2023 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021.

42 Note: "CO2 equivalent" is a widely used metric for assessing the global warming impact of methane (and other potent greenhouses gases) relative to carbon dioxide. EPA counts 1 metric ton of methane as being equivalent to 28 metric tons of CO2 over a 100-year period. Source: EPA, 2023 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021.

Total US methane emissions in 2020 were 742.2 MMT CO2e. A 55.45 MMT CO2e drop from diverting food waste to ADs would be a 44.5% drop in net landfill emissions from the 2020 level and a 7.47% drop in total US net methane emissions per year from the 2020 level.

(To give an example of the upside of our calculations, we could raise the methane capture rate from 90% to 95% – if for instance well-maintained ADs and/or pipelines leak less; or if the biogas is used to generate electricity on-site and does not travel through off-site pipelines; or if the biogas is upgraded to RNG and dispensed in on-site vehicle fueling station, meaning not traveling through off-site pipelines. A 95% methane capture rate would mean a 57.7 MMT CO2e drop from diverting the inedible half of food waste to ADs, which would be a 46.3% drop in net landfill emissions and a 7.77% drop in total US net methane emissions per year. But we stick with the more conservative figures above to play it safe and have ample margin to cover other real-world inefficiencies that may occur, such as during routine maintenance.)

V. Number and Cost of Dairy Manure ADs

Our calculations are based on 2020 data from the 2023 EPA GHG Inventory and 2022 data (the closest available to 2020) from the U.S. Department of Agriculture Census of Agriculture 2022, released in February 2024.[43]

Based on empirical industry practice, we used a minimum threshold of 500 dairy cows for a dairy manure AD project, with capex rising as herd sizes increase. Also based on empirical industry practice, we assumed the following costs for ADs (factoring in all related infrastructure and equipment, including combined heat and power, gas upgrading, and pipeline interconnection where applicable):

An AD at a dairy farm with 500-999 cows would cost $4 million on average.
An AD at a dairy farm with 1,000-2,499 cows would cost $10 million on average.
An AD at a dairy farm with 2,500-4,999 cows would cost $20 million on average.
An AD at a dairy farm with 5,000 or more cows would cost $50 million on average.

USDA Census of Agriculture 2022 data:

# of dairy farms with herd size 500-999: 1,438
At avg cost of $4 million = ~$5.75 billion

# of dairy farms with herd size 1,000-2,499: 1,179
At avg cost of $10 million = ~$11.8 billion

# of dairy farms with herd size at least 2,500-4,999: 625
At avg cost of $20 million = $12.5 billion

# of dairy farms with herd size at least 5,000: 209
At avg cost of $50 million = $10.45 billion

Subtotal: $40.5 billion for 3,451 dairy ADs

43 U.S. Department of Agriculture, Census of Agriculture 2022. February 2024. AC-22-A-51. https://www.nass.usda.gov/Publications/AgCensus/2022/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf

Cost estimates for the 268 existing dairy ADs as of 2022 (of at least 500 dairy cows), based on EPA AgSTAR database (January 2023)[44]

500-999: 43 x $4 million = $172 million
1,000-2,499: 73 x $10 million = $730 million
2,500-4,999: 52 x $20 million = $1.04 billion
5,000+: 83 x $50 million = $4.15 billion
Number not specified: 14 x $15 million (a mid-level approximation) = 210 million

268 existing dairy ADs subtotal: ~$6.3 billion

$40.5 billion – $6.3 billion = $34.2 billion more for 3,183 dairy farm ADs

VI. Emissions Reductions from Dairy ADs

2022 USDA Census of Agriculture data: dairy farms with 500+ cows accounted for ~7 million (6,997,538) cows out of 9,309,855 cows total (75.16%). Large dairy operations account for more methane per cow due to the use of lagoons for manure storage, whereas small dairies often apply manure directly to the land, where it mostly decomposes aerobically. But we conservatively leave the dairy manure methane reduction potential at 75% for ADs at all farms with at least 500 dairy cows, which allows for various minor inefficiencies in the process. We calculated that building ~3,180 dairy manure ADs would cut total net U.S. methane 3.6% at a total capital investment of approximately $34.2 billion.

Note on emissions year data: as mentioned before, we use 2020 emissions levels as the baseline throughout the report for consistency across all sectors. The closest farm data available is from 2022, and it's not a perfect fit with 2020 figures. There has been some minimal incremental progress since 2020 in trimming dairy manure methane emissions, largely due to slight overall reductions in nationwide herd sizes, even as the long-running industry trend of consolidation into a smaller number of larger farms continued. Additionally, over 70 new dairy manure ADs were built in 2021 and 2022, according to AgSTAR.

Our macro analysis concludes that ~3,180 dairy manure ADs are needed to reduce dairy manure emissions by 75% from 2022, but it's hard to back-date that to 2020 with the same level of accuracy. There were greater methane emissions in 2020 since there were both more dairy cows and fewer dairy manure ADs, so in theory more ADs than the 3,180 would have been needed then. Yet over 70 were built and herd sizes also declined since then. As such, it's far more useful to take the metric of 75% reduction from the sector's methane from 2022 and apply that to 2020 USDA data. This is an imperfect solution, but it gives an approximate answer as to the impact of building these ADs: cutting 75% of the 35.5 MMT of CO2 equivalent of dairy manure methane in 2020 equates to 26.6 MMT of CO2e, or roughly 3.6% of the 2020 level of U.S. net methane per year.

VII. Number and Cost of Swine Manure ADs

Like with our dairy manure AD calculations, our swine manure calculations are based on 2020 data from the 2023 EPA GHG Inventory and 2022 data (the closest available to 2020) from the USDA Census of Agriculture 2022.

We only realistically see potential for AD at swine farms with at least 5,000 head, and even that may be low. But we assume a single swine manure digester would use manure from at least 4 such farms (20,000 swine)

44 EPA, AgSTAR Livestock Anaerobic Digester Database, based on data available through January 2023. https://www.epa.gov/agstar/livestock-anaerobic-digester-database

as the lowest feasible threshold for a swine manure AD project. Based on empirical industry practice, we assumed that the average cost of a swine manure AD is $10 million per 20,000 head, and this rate generally holds proportionally as herd size increases. Factored into this $10 million average cost are all related infrastructure and equipment, including combined heat and power, gas upgrading, and pipeline interconnection where applicable.

2022 USDA Census of Agriculture data:

# of hog farms with herd size 5,000+: 3,540 farms

Assume four farms per AD (20,000 hogs) = 885 ADs

At average cost of $10 million per 20,000 hogs = 8.85 billion

33 ADs as of 2022 (of at least 5,000 hogs), as per AgSTAR 2022 data.

Their herd sum is 1,030,975 + 1 project of unspecified herd size, so we round up to 1,040,000.
X ($10 million/20,000 hogs) = $520 million already invested for the existing 33 ADs

$8.85 billion – $520 million = $8.33 billion for 852 more swine manure ADs

VIII. Emissions Reductions from Swine ADs

According to 2022 USDA Census of Agriculture data, swine farms with over 5,000 head account for 55,528,543 out of 73,817,751 (75.2)% of all swine. Similar to the dairy sector, large swine operations account for more methane per hog than small operations due to their use of manure lagoons, which often apply manure to the land, where it mostly decomposes aerobically. Nevertheless, we conservatively estimate swine manure methane reduction potential at 75% for ADs at all farms with at least 5,000 swine, which allows for various minor inefficiencies in the process. We found that building ~850 ADs to process swine manure would cut total net U.S. methane 2.5% at an estimated capex of ~$8.3 billion.

Note on emissions year data: as mentioned before, we use 2020 emissions levels as the baseline throughout the report for consistency across all sectors. The closest farm data available is from 2022, and it's not a perfect fit with 2020 figures. There has been some minimal incremental progress since 2020 in trimming manure methane emissions, largely due to slight overall reductions in nationwide herd sizes, even as the long-running industry trend of consolidation into a smaller number of larger farms continued. Additionally, 4 large swine manure ADs were built in 2021, according to AgSTAR. Our macro analysis concludes that ~850 swine manure ADs are needed to take 75% off the level of swine manure emissions from 2022, but it's hard to back-date that to 2020 with the same level of accuracy. There were greater methane emissions in 2020 since there were both more hogs and fewer swine manure ADs, so in theory more ADs than the 850 would have been needed then. Yet 4 were built and herd sizes also declined since then. As such, it's far more useful to take the metric of 75% reduction from the sector's methane from 2022 and apply that to 2020. This is an imperfect solution, but it gives an approximate answer as to the impact of building these ADs: cutting 75% of the 25.1 MMT of CO_2 equivalent of swine manure methane in 2020 equates to 18.8 MMT of CO_2e, or roughly 2.5% of the 2020 level of U.S. net methane per year.

All told, building ~4,030 ADs to process dairy and swine manure would reduce total net U.S. methane ~6.1% per year at an estimated capex of $42.5 billion. Building these manure ADs would cut three quarters of dairy and swine manure methane emissions per year.

IX. Emerging Non-AD Methane Reduction Technologies for Manure Management and Enteric Fermentation

Manure Management

Positive results are also emerging from other options to reduce methane from manure lagoons, such as mixing in biochar or acids. A study prepared for the California Air Resources Board in 2021 found that adding biochar, acids, and straw to manure could mitigate methane emissions by 82.4%, 78.1%, and 47.7%, respectively (although it cautioned that "the data for straw is quite small so it should not be taken out of context as it may introduce a source of carbon into lagoons").[45]

These are very encouraging figures, yet they are still smaller methane reductions than what ADs entail, albeit at much lower cost. As detailed previously, we use conservative estimates of 95% methane capture at ADs and 95% transmission efficiency afterwards, leading to an overall 90% reduction in methane by using ADs (compared to the default baseline of all methane escaping into the atmosphere). Even if more methane is generated by the manure in the optimal conditions inside an AD (whether a covered lagoon or a closed tank) compared to an open-air lagoon, almost all of that methane is captured, making it far better than the default baseline and still more effective than the aforementioned manure additives.

Nevertheless, adding in biochar or acids to manure lagoons may be great solutions, especially for the many farms that are too small to consider ADs, such as those with fewer than 500 dairy cows or fewer than 5,000 swine. Our emphasis on building ADs to process food waste and manure is rooted in the efficiency, relative cost-effectiveness, commercial readiness, and scalability of this solution. Plus, building manure ADs brings in a new incremental revenue source to the farmers from electricity or RNG production. By contrast, manure additives are further expenses that don't necessarily generate additional revenue (although they benefit the climate and might qualify for government grants to cut agricultural methane emissions) absent new voluntary markets for those willing to pay for these reductions in methane.

Enteric Fermentation

Within agriculture, a gigantic source of methane (approximately triple[46] that of manure methane) is called "enteric fermentation" – otherwise known as animal burps, predominantly from cows. There is not yet a proven, cost-effective, scalable solution akin to ADs that could significantly cut enteric fermentation emissions. Several ways to cut enteric fermentation emissions are still early stage and mostly experimental but have promising prospects, like altering animal feed, and selective breeding to produce cows that emit less methane (although there are a range of other challenges and questions related to genetic engineering).[47] For example, the aforementioned study for the California Air Resources Board found that among feed additives, "3-nitrooxypropanol (3NOP)" had the greatest methane reductions in enteric fermentation: 41% for dairy cows and 22% for beef cattle (although this percentage dropped to an average 11.7% reduction when all lifecycle emissions of producing and transporting 3NOP were taken into account).[48]

Strategies like altering animal feed and selective breeding to reduce enteric fermentation emissions may be

45 Kebreab E. & Feng X., Strategies to Reduce Methane Emissions from Enteric and Lagoon Sources. January 8, 2021. Prepared for State of California Air Resources Board. https://ww2.arb.ca.gov/sites/default/files/2020-12/17RD018.pdf

46 EPA, 2023 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021.

47 Institute for Governance & Sustainable Development, "A Primer on Cutting Methane: The Best Strategy for Slowing Warming in the Decade to 2030," April 12, 2024. https://www.igsd.org/wp-content/uploads/2024/01/IGSD-Methane-Primer.pdf.

48 Kebreab E. & Feng X., Strategies to Reduce Methane Emissions from Enteric and Lagoon Sources.

positive climate options for farms of any size. However, further research needs to be done on scalability and any unintended ripple effects, for instance on livestock production (such as dairy milk output), animal health and longevity, and so on.

It was beyond the scope of this report to estimate the costs of these non-AD technologies for cutting methane in manure management and enteric fermentation or what percentages they could feasibly reduce from the country's net total methane emissions, given their relative early stages and limited empirical track records. Further research and data-backed projections would be very useful as these technologies develop.

X. Plugging Abandoned Oil and Gas Wells

According to the 2021 EPA GHG Inventory, there are approximately 2.1 million abandoned oil and gas wells nationwide that are unplugged (1,739,533 oil + 439,407 gas = 2,178,940 total). The crucial distinction is that this is the subset of abandoned oil and gas wells that are unplugged. There are another ~1.5 million abandoned oil and gas wells (1,192,907 oil and 358,871 gas) that have already been plugged and emit virtually zero methane. Energy Vision's analysis is only concerned with the unplugged 2.1 million.

The EPA calculated that the total methane emissions from these wells was 8.2 MMT CO2e in 2020, which amounted to 1.1% of the country's total methane emissions.

Real world data is rather scarce about these unplugged abandoned wells' emissions (and in many cases their precise locations). Compared to a known well that goes straight from operating to being plugged, these abandoned wells can be much more complicated, with many challenges involved. Some may have been abandoned over 50 years ago, and their infrastructure may have deteriorated so much that it is much harder to plug than a recent well shaft. (A subset of these 2.1 million are orphaned wells, which have no identifiable or financially solvent entity responsible for them and are thus the responsibility of the state or, if on federal lands, then the federal government. Documented orphaned wells number at least 126,000 and estimates of undocumented orphaned wells range from 310,000 and 800,000 – and potentially much more.[49])

The capital costs of plugging these unplugged abandoned oil and gas wells also vary considerably based on numerous factors: characteristics of the well itself, accessibility, location (plugging can be much more expensive in some states compared to others), availability of workers to carry out the tasks, and supply chain/inflation issues, among others. Energy Vision researched many sources, recognizing that estimates from before 2022 now largely undershoot the mark for two main reasons. One is that high inflation since then has increased nominal costs across the board. Second is that there is greater demand for companies and workers to plug abandoned oil and gas wells, in part because of the $4.7 billion authorized for plugging orphaned oil and gas wells by the 2021 federal Bipartisan Infrastructure Law. That competition has also driven up prices. Citing the rising wages and greater demand for well plugging workers, a July 2023 article in E&E News noted that the cost of plugging wells rose by over 50% in Ohio in the past year.[50]

For demonstrative purposes, we assumed that all 2.1 million of these abandoned oil and gas wells could be found and plugged (even though that is an extremely tall order and may not be logistically feasible). We calculated a range of average capital costs per well for doing so, from an unrealistic rock-bottom $20,000/well to

49 US Department of the Interior, Orphaned Wells Program Office. Orphaned Oil and Gas Wells 101: Understanding the Basics and Discovering How the Bipartisan Infrastructure Law Addresses Legacy Pollution. November 15, 2023. https://storymaps.arcgis.com/stories/92cf4a914be240bb9d72b2351b8d9960;
Interstate Oil and Gas Compact Commission, Idle and Orphan Oil and Gas Wells: State and Provincial Regulatory Strategies. 2021. https://iogcc.ok.gov/sites/g/files/gmc836/f/iogcc_idle_and_orphan_wells_2021_final_web.pdf

50 Webb, Shelby. "States struggle to plug oil wells with infrastructure law cash," E&E News, July 14, 2023. https://www.eenews.net/articles/states-struggle-to-plug-oil-wells-with-infrastructure-law-cash/

a higher-end $80,000/well. The total price tag for plugging these wells, which would trim that 1.1% from total U.S. methane, ranged accordingly from $43.6 billion to $174.3 billion. We selected a conservative $60,000/well as the comparative example in the report to measure the "bang for the buck" against building ADs and other methane mitigation measures. This is less than what several states like Louisiana are budgeting for their abandoned oil and gas well plugging programs (Louisiana estimated it would cost more than $401 million to plug the 4,605 orphaned wells in its territory, which comes out to about $87,000/well).[51] It is less than the 2022 figure that plugging a well in California costs an average of $111,000, according to the California Geologic Energy Management Division (CalGEM).[52] It is also less than the $71,000 that the federal Bureau of Land Management estimates the cost of plugging and remediating an average abandoned oil and gas well on federal lands to be.[53]

And as always with averages in a very large data set, some wells may be fairly simple to plug and thus be at the low end of the cost range, while other, particularly challenging ones have been documented at over $1 million to plug.[54] The total cost of plugging the 2.1 million wells at $60,000/well would be $130.7 billion. But no matter the cost per well, these pale in comparison to building ADs to treat organic waste. Recall that building those ~680 food waste ADs would reduce total U.S. methane emissions by 7.5% at a cost of $31.7 billion – this is vastly more bang for the buck than plugging abandoned oil and gas wells.

Our calculations show that building all ~4,700 food waste and manure ADs would mitigate over 12 times the amount of methane that plugging all 2.1 million abandoned oil and gas wells in the U.S. would, at roughly half the cost (based on $60,000/well), ignoring the additional job creation and economic impacts of bolstering our domestic AD industry. We calculated the bang for the buck of plugging these abandoned oil and gas wells to be just 62.7 metric tons of methane reduction per million dollars of capex invested. Nevertheless, plugging these abandoned wells is certainly a worthy long-term endeavor, not just for the methane reduction but also to minimize groundwater contamination from these wells and to clean up the surrounding despoiled environments. Ultimately, we need to do both – plugging wells and building out AD infrastructure.

XI. Compliance with EPA's New Source Performance Standards for Oil and Gas Sector Emissions

This section is based on EPA's Regulatory Impact Analysis of the Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review, published in December 2023,[55] as well as the EPA's 2021 GHG Inventory.

In the Regulatory Impact Analysis (RIA), the EPA estimates that the full methane abatement per year of compliance with the NSPS, 130 MMT CO2e, would be reached in 2029 and beyond. 130 MMT CO2e would equal 86% of the nationwide methane emissions from oil and gas production in 2020 (150.3 MMT CO2e), or 54% of

51 Ibid.

52 Legislative Analyst's Office, The 2022-23 Budget: Oil Well Abandonment and Remediation. January 31, 2022. https://lao.ca.gov/Publications/Report/4508

53 Bureau of Land Management, Proposed Rule on Fluid Mineral Leases and Leasing Process. [BLM_HQ_FRN_MO4500172196] RIN 1004-AE80. 47562 Federal Register/Vol. 88, No. 140/Monday, July 24, 2023 https://www.govinfo.gov/content/pkg/FR-2023-07-24/pdf/2023-14287.pdf

54 Raimi, Daniel, et al, Decommissioning Orphaned and Abandoned Oil and Gas Wells: New Estimates and Cost Drivers. Environmental Science & Technology 2021 55 (15), 10224-10230. DOI: 10.1021/acs.est.1c02234 https://pubs.acs.org/doi/10.1021/acs.est.1c02234

55 EPA, Regulatory Impact Analysis of the Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review. December 2023. EPA-452/R-23-013. https://www.epa.gov/system/files/documents/2023-12/eo12866_oil-and-gas-nsps-eg-climate-review-2060-av16-ria-20231130.pdf

total oil and gas industry methane emissions in 2020 (239.8 MMT CO2e). The RIA meanwhile projects the total number of oil and gas wells to remain largely stable (just a very slight decrease) through 2038, as new ones roughly replace retired ones. So we can assume that the no-changes baseline would remain ~150 MMT CO2e from oil and production. Full compliance with the revised NSPS, from 2029 onwards, would cut 17.5% from the 2020 level of total net U.S. methane (130/742.2 MMT CO2e).

The cumulative capital cost of compliance with the NSPS regulations from 2024-2029 is expected to be $20.7 billion,[56] to be largely borne by the industry (with some federal funding available, such as through the Methane Emissions Reduction Program). Energy Vision calculated this from RIA "Table 2-12: Undiscounted Projected Compliance Costs under the Final NSPS OOOOb and EG OOOOc, 2024–2038 (millions 2019$)," on page 2-62. We summed the capital costs of the years 2024 through 2029, excluding annual operating costs and revenue from product recovery.

But if spread out per year (~$3 billion per year) and among the producers according to their emissions, that amount is fairly minor for an industry whose annual capex has recently ranged from $79 billion in 2021 to $156 billion in 2019, according to the EPA. Furthermore, a small amount of that incremental cost of compliance can be defrayed by greater amounts of gas being recovered and sold instead of leaking into the atmosphere, as Table 2-12 details. The EPA estimates that from 2024-2029, the cumulative amount of additional recovered gas would be worth $3.6 billion – more than covering the cumulative annual operational costs of approximately $3.3 billion and thus helping to recoup some of the capex of compliance.

XII. Plugging "Stripper" Wells

This section is based on:

- U.S. Energy Information Administration, The Distribution of U.S. Oil and Natural Gas Wells by Production Rate with data through 2022 (published December 2023).[57]
- Omara, M., et al. Methane emissions from US low production oil and natural gas well sites (published 2022).[58]
- GSI Environmental Inc., Quantification of Methane Emissions from Marginal (Low Production Rate) Oil and Natural Gas Wells, Prepared for U.S. Department of Energy National Energy Technology Laboratory (published 28 April 2022).[59]

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56 Note that the NSPS calculations do not double-count any emissions potential with the EPA's separate proposed Waste Emissions Charge and vice versa. This "methane fee," as it's known in shorthand, is expressly ordered in the Inflation Reduction Act and is mainly meant to accelerate compliance with the NSPS. Once affected facilities are in compliance with the NSPS, they're no longer subject to the methane fee. As a result, expected government revenue from the Waste Emissions Charge drops 98% from the peak of $770 million in 2025 to just $13 million starting in 2027. Source: EPA, Regulatory Impact Analysis of the Proposed Waste Emissions Charge, January 2024. EPA-430/R-23-005. https://www.epa.gov/system/files/documents/2024-01/wec_ria.pdf

57 U.S. Energy Information Administration, The Distribution of U.S. Oil and Natural Gas Wells by Production Rate with data through 2022. December 2023. https://www.eia.gov/petroleum/wells/pdf/Well_Distributions_report_2023_full_report.pdf

58 Omara, M., Zavala-Araiza, D., Lyon, D.R. et al. Methane emissions from US low production oil and natural gas well sites. Nature Communications 13, 2085 (2022). https://doi.org/10.1038/s41467-022-29709-3

59 GSI Environmental Inc., Quantification of Methane Emissions from Marginal (Low Production Rate) Oil and Natural Gas Wells. Prepared for U.S. Department of Energy National Energy Technology Laboratory. 28 April 2022. Available for download at https://www.osti.gov/biblio/1865859

- The EPA 2021 GHG Inventory (published April 2023).

According to both EIA and the 2022 Omara study, stripper wells account for almost 80% of all operational wells in the U.S. but only about 6% of the country's oil and gas production by volume. There are approximately 703,000 stripper wells in the U.S. (also known as marginal conventional wells), as per the EIA (2022 data published in December 2023).

The Omara study concluded that stripper wells account for roughly half of all oil and gas production emissions. The 2022 study by GSI Environmental similarly concluded that marginal gas production accounts for an estimated 60% (±10%) of emissions from U.S. natural gas production, and that marginal oil production accounts for an estimated 40% (±10%) of emissions from U.S. oil production. We use the more detailed emissions estimates from the GSI study (60% of natural gas production emissions and 40% of oil production emissions), which totals 79.58 MMT CO2e based on the 2020 emissions from the EPA GHG Inventory.

Similar to our approach with plugging abandoned oil and gas wells, we calculated the cost for plugging stripper wells with a range of average costs per well, since there is large variation due to multiple variables: characteristics of the well itself, accessibility, location (plugging can be much more expensive in some states compared to others), availability of workers to carry out the tasks, and supply chain/inflation issues, among others. And just as with cost estimates for plugging abandoned oil and gas wells, estimates from before 2022 for plugging stripper wells now largely undershoot the mark for two main reasons. One is that high inflation since then has increased nominal costs across the board. Second is that there is greater demand for companies and workers to plug oil and gas wells, given the aforementioned multibillion-dollar federal funding for plugging abandoned oil and gas wells.

In general, though, stripper wells are more straightforward to plug than abandoned oil and gas wells (and especially compared to the latter's subset of orphaned wells) for the simple reason that their locations are known and their operational details (including what infrastructure is on site and when they were built) is accessible – at least to the owner/operator. The fact that they have owners/operators also means that action could be taken faster by those responsible entities than if these wells first had to be discovered and then were deemed orphan wells and wards of the state.

We calculated the total capital cost of plugging all stripper wells by using a conservative range between \$20,000 and \$60,000/well. The cumulative totals accordingly ranged from \$14.1 billion to \$42.2 billion. For comparative purposes in the report, we selected the mid-point of \$40,000/well (with a cumulative capital cost of \$28.1 billion), since there are more economies of scale available than in plugging abandoned oil and gas wells. Many stripper wells are owned by the same company and located in the same general area, meaning that a skilled crew could plug several stripper wells in a single excursion on a single contract. The Omara study documented that 77% of stripper well sites, accounting for 83% of oil and gas production from stripper wells, are owned by 770 medium-to-large operators with over 100 stripper well sites apiece. A significant portion of the ~700,000 stripper wells would likely be straightforward to plug at a reasonably low cost.

Moreover, the Omara study concluded that the leakiest 5% of stripper wells account for half of all methane emissions from stripper wells. That means that 35,150 stripper wells (the leakiest 5%) accounted for 39.79 MMT CO2e in 2020. We calculated the total capital cost of plugging the leakiest 5% of stripper wells by using a conservative range between \$20,000 and \$60,000/well. The cumulative capital totals accordingly ranged from \$703 million to \$2.1 billion. We assumed that these leakiest 5% would have more challenges and complications than the overall pool of stripper wells and would thus cost more. Hence, we selected an average plugging cost of \$60,000/well for these ~35,000 leakiest stripper wells, with a cumulative cost of \$2.1 billion. Even at that higher per well cost, plugging the leakiest 5% of stripper wells has by far the most bang for the buck in reducing methane than any other methane mitigation option we surveyed in this report.

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