THE GAS INDEX

THE UNITED STATES' NATURAL GAS SYSTEM HAS A SERIOUS PROBLEM

IT LEAKS

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THE GAS INDEX PROJECT TEAM

PROJECT LEAD

Mason Inman is the Program Director for Gas at Global Energy Monitor, a nonprofit data and research organization. He was responsible for reviewing the scientific literature on methane leakage and building The Gas Index Model. He received his bachelor's in physics from the University of California, Santa Barbara, and a graduate certificate in science writing from the University of California, Santa Cruz. He worked as a science journalist for about a decade, writing for *Science*, *Nature*, National Geographic News, and other outlets, with a focus on climate and energy issues. He then joined the nonprofit research organization Near Zero, affiliated with the Carnegie Institution for Science on the Stanford University campus, working mainly on California climate policy. At Near Zero, he designed and built a model of California's cap-and-trade program, and was lead author of a study using the model that was published in the journal Climate Policy.

ADVISERS

Emily Grubert, an Assistant Professor of Civil and Environmental Engineering at Georgia Tech, is a civil engineer and environmental sociologist. She focuses on ways to make decision making about infrastructure systems more just, effective, and informed. Specifically, she studies how community and societal priorities can be better incorporated into multicriteria policy and project decisions, mainly related to energy and water. She has published research studies on methane leakage from the gas system, including from renewable gas systems, showing how leakage can make a substantial contribution to life cycle emissions from gas, and how past studies have often under-estimated methane leakage. She reviewed the Gas Index model methodology and report.

Zach Weller, an Assistant Professor at Colorado State University, holds a PhD in statistics and does applied statistical research, collaborating with researchers from a variety of scientific domains. A part of Zach's research has focused on the use of advanced mobile leak detection for managing local natural gas distribution systems. He has published several peer-reviewed research papers on this topic, focusing on algorithm development, leak size estimation, uncertainty quantification, and integration of multiple data sources. He reviewed the Gas Index model methodology and report.

INTRODUCTION

The United States' natural gas system has a serious problem: It leaks.

Natural gas is also known as fossil gas, because natural gas is a fossil fuel. We burn it to heat buildings and to drive power plants. Natural gas is mostly composed of methane, which is a much more powerful greenhouse gas than carbon dioxide (CO_2).

Whenever natural gas leaks, it adds significantly to global warming and climate change. Methane from gas leaks also contributes to local air pollution, which has been linked to respiratory problems and premature death (West 2006, Lelieveld 2015).

The Gas Index ranks cities by how leaky their fossil gas supply chains are, based on a model that evaluates where each state's gas supplies come from, and also estimates how much leakage occurs within each city. By highlighting which cities have the leakiest gas supplies, and which parts of the system are most responsible for gas leaks, the Gas Index suggests where efforts can best be directed for fixing the gas system—and which cities would cut emissions the most by electrifying buildings so that they're not reliant on gas.

The model incorporates data from dozens of studies that have measured methane leakage in oil and gas production areas, along gas transmission pipelines, and within cities—including inside homes and businesses. In this way, the model evaluates the full life cycle to estimate a gas leakage rate for each city's gas supply. As far as we aware, these estimates are more comprehensive and up-to-date than prior independent life cycle analyses of the natural gas supply chain. Also, we believe the Gas Index is the first life cycle analysis of the U.S. natural gas supply chain to provide granular estimates for a large number of cities.

This report presents the Gas Index results for 71 cities across the U.S., with details on the contributions to methane leakage from different stages of the gas system, such as gas production areas or pipelines within cities (Figure 1). The report then provides a brief description of the main components of the gas system and how they contribute to gas leaks.

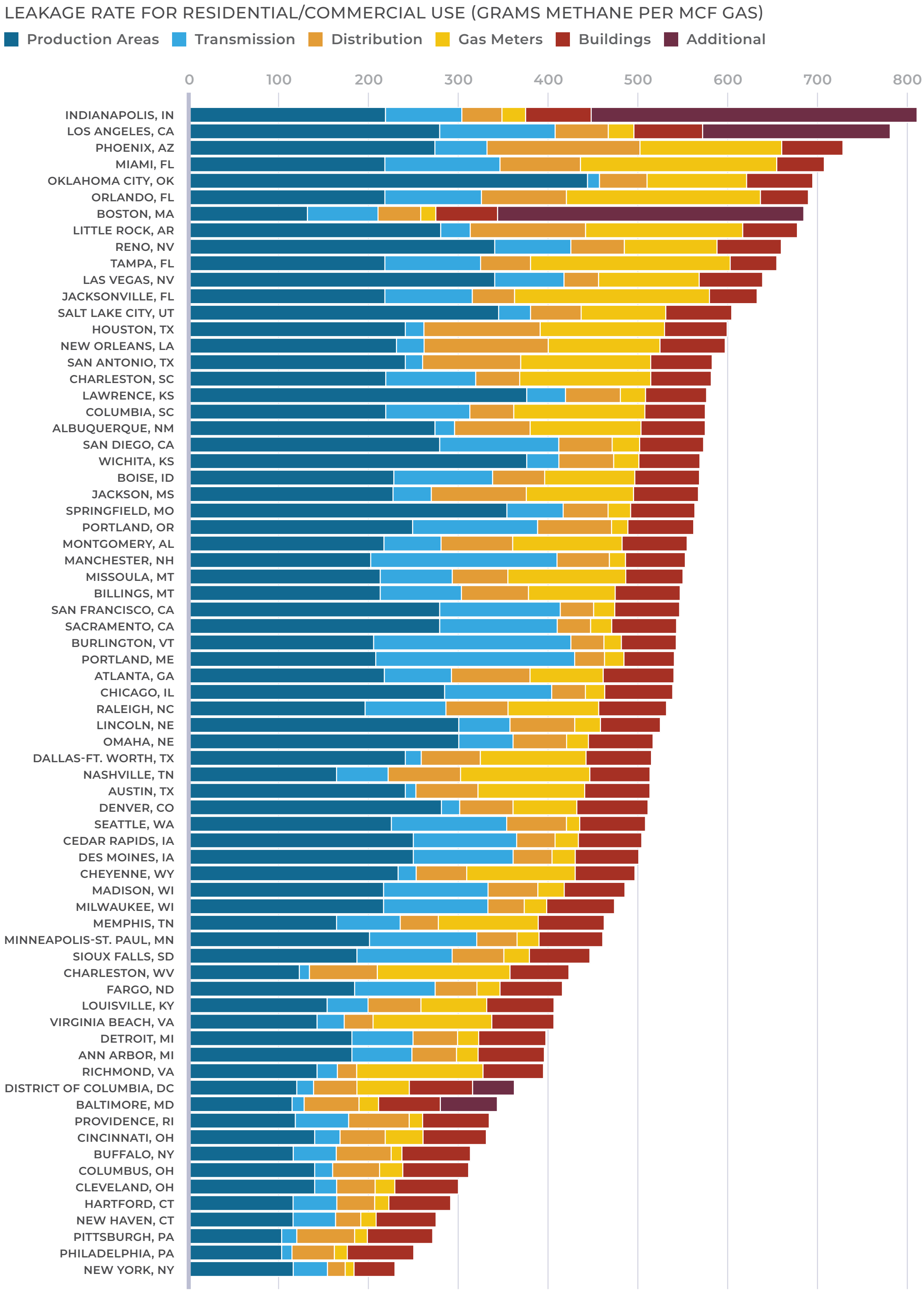
This report also discusses the implications of gas leakage. First, by drawing together results from many studies of leakage across the fossil gas system, the Gas Index results show that methane leakage is more extensive across the system than in many previous estimates. Also, the Gas Index estimates the changes in emissions from switching building heating from gas heaters to electric heaters, indicating the circumstances in which electrifying heating could lead to substantial emissions reductions.

Finally, the report includes an Appendix with a summary of the methodology for the estimates underlying the Gas Index. The full description of the methodology is provided in the model documentation available on the Gas Index website ***downloads page***.

Figure 1 shows the Gas Index results for each city evaluated, with methane leakage estimated for separate components:

- **Production:** Leakage from production areas includes leakage from well sites, from gathering pipelines, and from gas processing plants
- **Transmission:** Leakage from long-distance transmission pipelines
- **Distribution:** Leakage from distribution pipelines, including distribution mains and service lines, and miscellaneous processes including mishaps
- **Gas meters:** Leakage from customers' gas meters that measure gas consumption
- **Buildings:** Leakage from "behind-the-meter" processes, including from gas pipes in buildings and from appliances.
- **Additional leakage:** Citywide leakage based on measurements of methane emissions from the whole city, and which cannot be attributed to particular processes.

FIGURE 1. *Gas Index results for the rate of life cycle methane leakage for the gas supplies for the 71 cities evaluated.*



WHERE GAS LEAKS OCCUR

Gas leaks occur throughout the natural gas supply chain, due to a multitude of diverse processes.

Across the country—from North Dakota to Texas, and from California to Pennsylvania—there is leakage in oil and gas fields, where fossil gas is extracted from rock deep underground. There's leakage along the network of transmission pipelines that carries gas to cities. And there's leakage in the cities, from distribution pipelines that snake under the streets and up to buildings, and from appliances inside buildings.

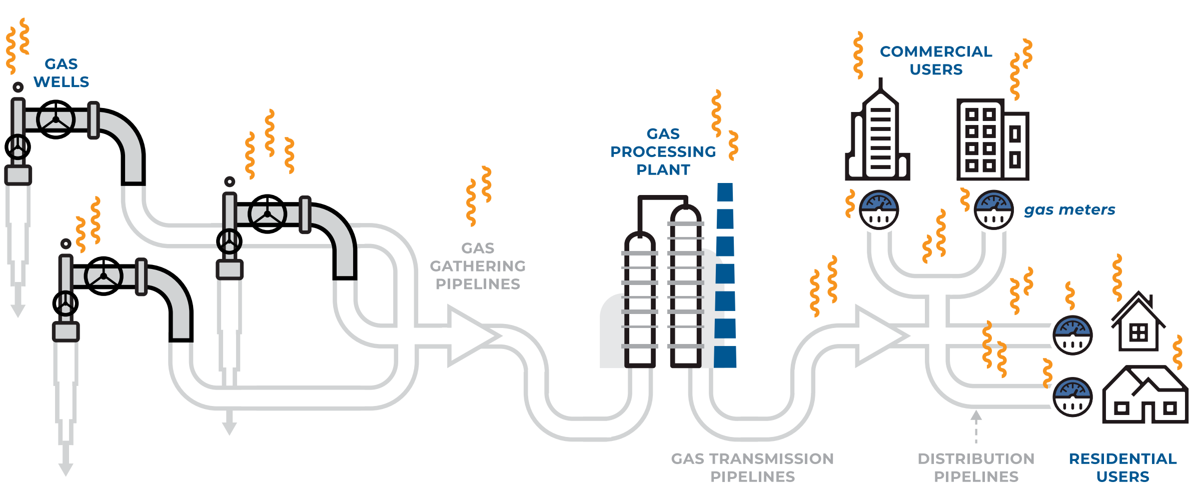
Recent research has filled many gaps in our knowledge, showing that the U.S. gas system is significantly leakier than had been thought. (See the section "More extensive methane leakage.")

There are seven main stages in the process of extracting gas from rock deep underground and ultimately delivering it to customers (Figure 2). All these stages are responsible for some methane leakage, but the leakage rates vary between the different stages, and from region to region. Adding up the leakage from all of these stages provides an estimate of the full life cycle leakage for gas.

Leakage from production areas—from well sites, and also gathering and processing steps described below—is the single largest contributor to methane leakage from the oil and gas system. But for many cities, leakage within the cities adds substantially to the life cycle emissions from use of gas, particularly in the residential and commercial sectors.

The seven main stages in the natural gas supply chain are described below.

FIGURE 2. *Stages of the natural gas supply chain responsible for methane leakage. Methane is a colorless gas, but for purposes of illustration, methane leakage is represented in orange.*



Production: The U.S. extracts more fossil gas than any other country—more than one-fifth of all the gas extracted worldwide. There are nearly one million active oil and gas wells in the country (EIA 2020a). Some wells produce only gas, but more often they produce a mix of gas, oil, and other compounds known as natural gas liquids. The extraction process involves drilling a well, and often fracking it (using hydraulic fracturing) to open paths for the oil and gas to escape the rock. Methane leakage can occur from the well itself, or from other equipment on the well site.

Gathering: Pipelines known as gathering lines run from each well site, carrying gas away, usually to gas processing facilities. Gathering pipelines can leak methane due to damage to pipelines. But most of the leakage from gathering is estimated to occur from equipment along the pipelines, such as compressors that boost the pressure of the gas to move it along the pipelines. In the Gas Index results, leakage from gathering pipelines is included within the category of production, since the pipelines are located within production areas.

Processing: Natural gas is composed mostly of methane, the simplest hydrocarbon molecule, with only one carbon atom. But most gas at the wellhead contains other hydrocarbon molecules known as natural gas liquids, such as ethane (with two carbon atoms) and propane (with three carbon atoms). Much of the gas extracted in the U.S. contains around 10-20% natural gas liquids, so it is sent to processing facilities, where most of the natural gas liquids are removed and sold separately. Gas processing facilities then output consumer-grade natural gas, which is composed nearly entirely (about 95%) of methane. Gas processing facilities also leak some methane, but their leakage is estimated to be much smaller than leakage from extraction sites and gathering pipelines (Alvarez 2018). In the Gas Index results, leakage from gas processing plants is included within the category of production, since the plants are generally located within production areas.

Transmission: Consumer-grade gas is sent over long distances through transmission pipelines, which form an extensive network nationwide. As with gathering lines, transmission pipelines themselves can leak some methane, but most of the leakage is from equipment that is part of the pipeline system, primarily compressors. In the U.S., about half of gas is sold directly from transmission lines, primarily to large industrial plants or power plants. The remaining gas is sold in cities, where it enters the distribution pipeline system to reach various consumers.

Distribution: The gas distribution pipeline system is made up of distribution mains, which typically run under city streets, and service lines, which branch off of distribution mains, and run up to each building that receives gas. A new study using extensive measurements of methane leakage in cities shows that distribution mains leak substantial amounts of methane, about five times more than previously recognized. Distribution pipelines can leak due to damage from natural processes, such as earthquakes, or due to pipeline corrosion. Distribution pipelines are also often damaged by people digging, such as for construction projects, and accidentally hitting a pipeline (PHMSA 2018).

Customer gas meters: For consumers, gas meters are one of the more visible parts of the gas system, since they are one of the few parts of the system that is above ground. Every building with gas service has at least one gas meter, and large buildings with many customers can have many gas meters. Customers' gas meters can leak a substantial amount of methane. A recent major study found commercial sector gas meters were leaking about 6 times more than EPA had estimated, and also found large differences in the leakage rate between regions of the country (Moore 2019).

Buildings: Any leakage that occurs after gas passes through the meter as "behind-the-meter" leakage, or "beyond-the-meter" leakage. Such leakage has been found from pipelines that carry gas within buildings, as well as from appliances that burn gas, such as furnaces, water heaters, and ovens (Fischer 2018, Johnston 2020, Lebel 2020, Sweeney 2020). For example, when a stove or other appliance is starting up, there can be a moment when a pulse of gas leaks out before it ignites. Also, when turning off appliances, there can be leakage of unburned gas.

In addition to the seven stages above, researchers have measured methane emissions from whole cities, using flights overhead and measurements from towers located in and around the cities. They have also estimated how much of the methane emissions come from natural gas, as opposed to other sources such as landfills or other biological decomposition. These citywide methane emissions can't be attributed to a specific stage of the gas system; the methane could be coming from leakage of distribution pipelines, customer gas meters, and/or buildings (behind-the-meter leakage).

If these citywide measurements indicate that there is more methane leakage from a city's gas system than the Gas Index estimated, then these additional emissions are also included in the total for the city. For the cities with such measurements, the measured leakage rates are all similar to or much higher than the Gas Index model estimates for those cities.

MORE EXTENSIVE METHANE LEAKAGE

Estimates from the Gas Index model indicate that substantially more methane leakage is occurring from the U.S. natural gas supply chain than is currently estimated by the Environmental Protection Agency's Greenhouse Gas Inventory (EPA 2020a). The Gas Index estimates are higher because they are based on new studies of methane leakage across the gas system, including in production areas and within cities. These new studies often show that components of the system are leaking at a higher rate than previously estimated.

As researchers continue to study natural gas supply chains, they are often finding more methane leakage from the natural gas system than previously estimated. These findings have come from more extensive surveys, as well as use of new methane sensors and leak detection technologies.

Gas leakage from production areas was evaluated in a high-profile study published in Science in 2018, which found that about 2% of the gas produced in the U.S. leaked (Alvarez 2018). The Gas Index estimates somewhat higher leakage within production areas, with a leakage rate of 2.3% on average, based on new studies that weren't available at the time of the earlier assessment. Whereas the earlier assessment drew on measurements from oil and gas production areas responsible for about one-third of the nation's gas production, the Gas Index includes new studies to cover production area responsible for about 90% of gas production in the contiguous U.S.

The study by Alvarez and colleagues focused primarily on leakage that occurs within oil and gas extraction areas, and did not make a new evaluation of leakage that occurs within cities; in lieu of its own estimates, the study used EPA results. However, more recent measurements in cities have found much more leakage than EPA estimates.

For example, a new study estimated that, nationwide, the major gas pipelines within cities, known as distribution mains, are leaking nearly five times as much gas as the EPA estimates (Weller 2020). This was based on extensive data gathered in a partnership between the Environmental Defense Fund (EDF) and Google, in which cars drove through many U.S. cities with methane sensors mounted on them, collecting far more extensive measurements of individual gas leaks than were available before. Detailed analysis of those measurements by researchers at Colorado State University attributed more than 4,000 detected methane enhancements to leakage from distribution mains of particular materials and ages—for example, plastic pipelines installed 30 years ago. In this way, the study was provided a much stronger basis for estimating how much leakage occurs from pipelines of specific types and ages.

Customers' gas meters have also been found to be leaking much more than the EPA estimates. The Department of Energy commissioned the Gas Technology Institute to take measurements of leakage from hundreds of customers' gas meters across the country. Their study, published in 2019, found that for the commercial sector, the meters were leaking about half a percent of all the gas that passes through them—a rate 6 times higher than the EPA estimated (Moore 2019).

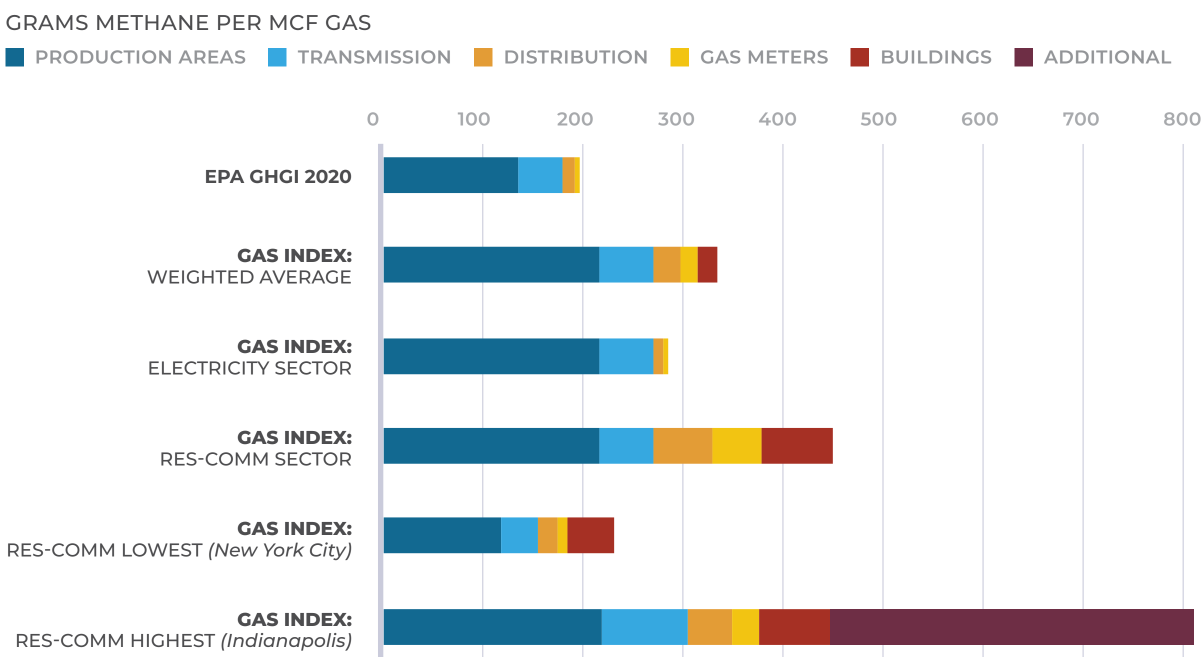
Most greenhouse gas inventories, including the EPA's Greenhouse Gas Inventory, do not include "behind-the-meter" leakage (Saint-Vincent and Pekney 2019). This is gas leakage that occurs within buildings, from pipes within buildings and from appliances such as furnaces and water heaters. Recent studies commissioned by the California Energy Commission showed that residential buildings are leaking around half a percent of the gas consumed, and commercial buildings about a quarter of a percent. As a result of that research, in 2019 California began including behind-the-meter leakage from the residential sector in the state's greenhouse gas inventory (CARB 2019).

Measurements of citywide methane emissions have indicated that some cities are leaking much more methane than EPA estimated, and also more than the Gas Index's estimates based on the properties of each city's gas system. For such cities, the Gas Index shows "additional" leakage occurring in the cities. The sources of these additional emissions are not known; the leakage may be from pipelines, customer gas meters, and/or behind-the meter leakage.

COMPARISON WITH EPA ESTIMATES

All 71 cities evaluated in the Gas Index have life cycle leakage rates higher than estimated in the EPA's Greenhouse Gas Inventory, and some cities have leakage rates more than four times higher than the EPA estimate (Figure 3). Estimates in the Gas Index are higher than EPA's estimates because the Gas Index draws on additional new studies of methane leakage across the gas system.

FIGURE 3. *Comparison of Gas Index results with EPA's Greenhouse Gas Inventory.*



The bars in Figure 3 are described below:

- **EPA GHGI 2020:** Methane leakage rate based on methane emissions from the natural gas system estimated in EPA's Greenhouse Gas Inventory (EPA 2020a).
- **Gas Index weighted average:** The Gas Index methane leakage rate for a the contiguous U.S., for gas delivered to all sectors.
- **Gas Index electricity sector:** The Gas Index methane leakage rate for gas delivered to the electricity sector (power plants).
- **Gas Index res-comm sector:** The Gas Index methane leakage rate for gas delivered to the residential and commercial sectors.
- **Gas Index res-comm lowest and highest:** The Gas Index methane leakage rate for gas delivered to the residential and commercial sectors for the city with the lowest leakage rate of those evaluated (New York City) and for the city with the highest leakage rate (Indianapolis, IN).

EMISSIONS FROM ELECTRIC HEATING VERSUS GAS HEATING

The Gas Index results show significant emissions cuts that can result from buildings switching from using natural gas to using electricity. In residential and commercial buildings, the largest use of gas—and largest use of energy overall—is for space heating (EIA 2018). Switching from gas heating to electric heating would cut greenhouse gas emissions in many situations—although not in every case.

The upper-left panel of Figure 4 shows the emissions reductions if buildings are switched from natural gas furnaces to traditional electric heaters, in a scenario in which the electricity system only gets a bit cleaner—that is, if the electric sector follows a "business-as-usual" scenario. (For more information on the scenarios, see the "Summary of methodology" section below.) Cities are shown on the map if the Gas Index model estimates that switching to traditional electric heaters would cut emissions.

The upper-right panel of Figure 4 shows the emissions reductions if buildings are switched from natural gas furnaces to electric heat pumps, a much more efficient type of heating, and the electricity sector follows the business-as-usual scenario. In this scenario, electrifying heating would cut emissions in every city evaluated in the Gas Index.

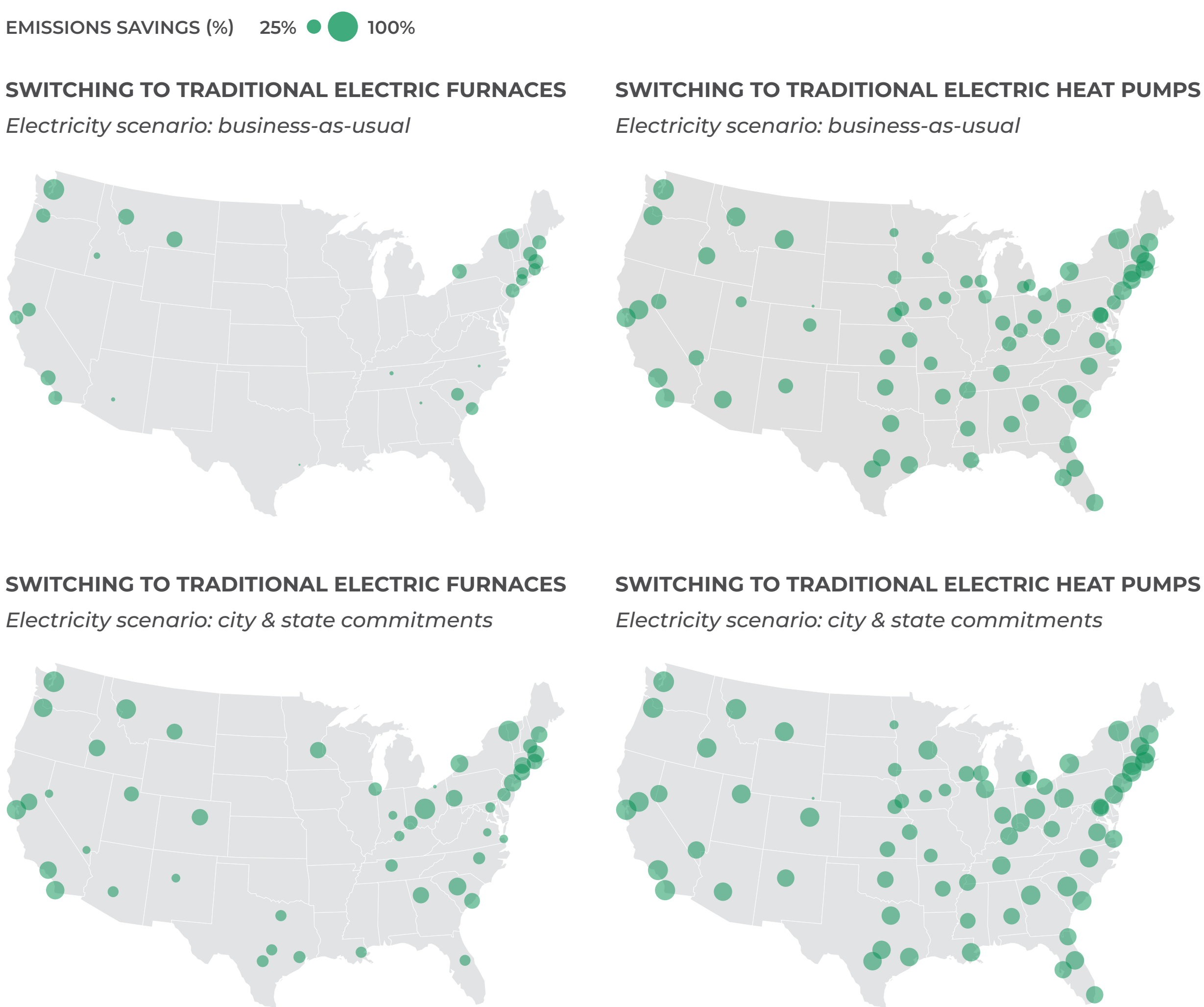
Many cities and states have requirements or targets for switching to 100% clean electricity by a certain date. For example, legislation in California mandates that the whole state will achieve 100% clean electricity by 2045. Meanwhile, San Diego has committed to achieving 100% clean electricity earlier, in 2035. If cities and states remain on track to meet these targets for cleaner electricity, then electrifying building heating now leads to much greater emissions cuts.

The lower-left panel of Figure 4 shows the emissions reductions if cities and states remain on track to meet their commitments for clean electricity, and if they switch from gas furnaces to traditional electric heaters.

The lower-right panel of Figure 4 shows the emissions reductions if cities and states remain on track to meet their commitments for 100% clean electricity, and if they switch from gas heating to more efficient electric heat pumps. In this case, switching to electric heat pumps leads to emissions reductions in every city evaluated, and achieves the largest emissions reductions of any of the scenarios, benefitting from using both efficient appliances and cleaner electricity.

Interactive versions of the graphs, showing values for each city, are available on the Gas Index website, at ***https://thegasindex.org/electrification***.

FIGURE 4. *Emissions savings from switching residential and commercial buildings from natural gas heating to electric heating.*



These results from the Gas Index model are based on a method similar to a recent analysis by the Rocky Mountain Institute (RMI 2020). However, in the Gas Index model, for nearly all cities the benefits of electrifying homes are larger in the Gas Index estimates than in the RMI analysis. The Gas Index shows larger benefits of electrification in part because the Gas Index model factors in methane leakage—both for gas burned directly in buildings, and for gas burned in power plants to supply electricity. The RMI analysis did not factor in methane leakage.

Another reason for larger benefits in the Gas Index estimates is that Gas Index model differentiates between gas supplied to buildings in cities, and gas supplied to power plants. To use gas in city buildings, the gas has to pass through distribution pipelines and customer meters, both of which leak a much larger share of gas for residential and commercial customers than for electricity sector customers. Also, for residential and commercial gas use, there is additional leakage within buildings themselves, including from appliances such as furnaces and water heaters. In the Gas Index model, natural gas burned in power plants suffers much less leakage, per unit of gas delivered.

CONCLUSION

The Gas Index draws on dozens of studies that measured methane leakage across the U.S., from most components of the natural gas supply chain. Compared with EPA estimates, these studies often found much more extensive methane leakage throughout the gas supply chain. This extensive methane leakage has important implications for the future of natural gas use in the U.S., indicating that natural gas use contributes more to climate change than EPA has estimated, in particular for natural gas used in the residential and commercial sectors.

With granular estimates at the level of individual cities, the Gas Index estimates can suggest where efforts can best be directed for fixing the gas system, and which cities would cut emissions the most by electrifying buildings so that they're not reliant on gas. The Gas Index estimates indicate that electrifying building heating would lead to emissions reductions in many cases—and that replacing gas heaters with efficient electric heat pumps would lead to emissions cuts in every city evaluated in the Gas Index. Switching building heating from gas to electric heat pumps, while also continuing efforts to make the electricity system cleaner, would lead to even greater emissions cuts.

APPENDIX | SUMMARY OF METHODOLOGY

The Gas Index is based on a new open-source model of the U.S. natural gas system, from extraction of gas to its consumption in cities. The model draws on dozens of recent studies to provide a more up-to-date and detailed picture of methane leakage across the country.

A full methodology for the Gas Index model is available on the Gas Index website, at ***https://thegasindex.org/downloads***. The model code is also published on Github at ***https://github.com/masoninman/The-Gas-Index***.

OIL AND GAS PRODUCTION AREA LEAKAGE

Gas is extracted in various areas across the country, most of it now through fracking, such as in the Marcellus shale in Pennsylvania and West Virginia, and the Permian basin in west Texas and New Mexico. Gas leaks at the well sites, but also at other equipment in these large production areas, for example from “gathering” pipelines that carry the gas away from wells.

U.S. production areas have been extensively measured for methane leakage, with measurements now covering areas responsible for 89% of gas production in the contiguous U.S. These measurements are typically taken by flights over production areas, including studies sponsored by NASA and NOAA; some newer studies draw on satellites that can detect methane. The Gas Index model draws on 17 studies of methane leakage in production areas, all of which have all been published in peer-reviewed journals (Barkley 2017, Barkley 2019, Cui 2019, Foster 2019, Karion 2013, Karion 2015, Negron 2020, Omara 2018, Peischl 2015, Peischl 2016, Peischl 2018, Pétron 2014, Ren 2019, Schneising 2020, Schwietzke 2017, Smith 2017, Zhang 2020). More details on these results are in Table 1 and in the Gas Index model documentation.

A significant portion of methane leakage from production areas comes from wells that produce two different products: gross natural gas and crude oil. Often, gross natural gas is processed to separate out natural gas liquids, which are sold separately, and the remaining gas is consumer-grade natural gas, also known as dry gas.

Also, many wells produce oil, which is sold, but the gas produced is burned off at the well site, a process known as flaring. Some flares malfunction or simply aren’t lit, studies have found, so not all the gas is burned and much of it is simply released into the air, contributing much more to global warming (EDF 2020). Storage tanks for oil can also leak methane that is carried along with the oil (Lavoie 2017, Lyon 2016).

There have not been sufficient studies of methane leakage from different processes in production areas to estimate with precision how much methane should be attributed to oil that is produced, and how much to natural gas. Therefore, the Gas Index model uses an approach common in the life cycle assessment literature, allocating leakage across the different products (e.g., natural gas and oil), based on the energy content of the different products. The model uses EIA data on production by state to estimate how much of the energy is from consumer-grade natural gas, as opposed to crude oil and/or natural gas liquids, and allocates methane leakage across these products. These values are applied to calculate the leakage allocated to consumer-grade gas in each state. Across the contiguous U.S., consumer-grade natural gas makes up 53% of the total energy content of produced oil and gross natural gas. Thus, the Gas Index model attributes, on average, 53% of the methane leaked from oil and gas production areas to the consumer-grade natural gas that ultimately flows to customers.

TABLE 1. *Measured leakage rates for gas production areas in the contiguous U.S. used as inputs for the Gas Index model. Gross production volumes, and percent of contiguous U.S. gas volume, are based on gross withdrawals ("raw gas") in 2018, reported by the U.S. Energy Information Administration (EIA) as of October 30, 2020. Methane leakage rates are calculated on a volume basis, for methane leaked from oil and gas production areas, compared with the methane content of gross gas produced. For more information, see the Gas Index methodology document, Table 3-2 and Appendix A.*

PRODUCTION AREA	GROSS GAS PRODUCTION (BCF/YEAR)	PERCENT OF CONTIGUOUS U.S. GAS PRODUCTION	METHANE LEAKAGE RATE (% of CH_4 in gross gas produced that leaked)
Appalachia region (outside northeast PA)	7,086	20.8%	0.88%
Appalachia region (northeast PA)	3,368	9.9%	0.33%
Permian region	4,213	12.4%	3.7%
Haynesville region	3,338	9.8%	1.3%
Anadarko region	2,632	7.7%	5.7%
Eagle Ford region – east	1,385	4.1%	3.2%
Eagle Ford region – west	735	2.1%	2.0%
Greater Green River region	1,323	3.9%	1.3%
San Juan region	1,293	3.8%	3.4%
Offshore Gulf of Mexico	1,079	3.2%	2.9%
Barnett region	1,203	3.5%	1.5%
Denver-Julesburg region	923	2.7%	3.1%
Bakken region	871	2.6%	5.9%
Fayetteville region	519	1.5%	1.3%
Uintah region	230	0.7%	9.7%
San Joaquin Valley	142	0.4%	10%
Total	**30,346**	**89.1%**	
Weighted average			2.3%

The Gas Index model then estimates where each state obtains its gas supplies from, based on EIA data for gas flows across state boundaries. For example, natural gas consumed in Massachusetts mostly comes from Pennsylvania, whereas in neighboring New Hampshire, most of the gas supply is from Canada.

Based on where each state obtains its gas from, then the Gas Index model calculates a weighted average value for how much methane leakage occurs in production areas to extract, gather, and process that gas.

TRANSMISSION PIPELINE LEAKAGE

There is also leakage from the long-distance transmission pipelines that crisscross the country. The farther the gas has to travel through transmission pipelines to reach consumers, the more leakage occurs along the way. To estimate leakage from transmission pipelines, the Gas Index model draws on a major study of transmission pipeline leakage, which the U.S. Environmental Protection Agency (EPA) also uses for its official Greenhouse Gas Inventory. This means the Gas Index model's results are similar to EPA's for the national total leakage from transmission pipelines.

However, the Gas Index model provides estimates tailored to each city, based on how far the gas has to travel from production areas to reach consumers in cities. The Gas Index model estimates that gas travels on average 1056 miles through transmission lines. (This is an average across the 71 cities included in the Gas Index, weighted by the quantity they gas each city consumes.) But there is wide variation between cities, with some, such as Philadelphia, mainly sourcing gas from production nearby in Pennsylvania, so the estimated distance gas travels to that city is about 100 miles. Whereas to reach Los Angeles, CA, the model estimates that gas travels on average about 1,200 miles, 12 times farther than for Philadelphia.

DISTRIBUTION PIPELINE LEAKAGE

When gas reaches each city, it enters the distribution system, a network of pipelines that snake underneath city streets, and branch off to supply buildings, such as houses and offices. These distribution pipelines leak as well.

The larger pipelines in the distribution system are known as mains, and a major study published this year has found that distribution mains are leaking nearly 5 times more than EPA estimated (Weller 2020). This study was based on extensive measurements from a partnership between the Environmental Defense Fund (EDF) and Google, in which methane sensors were mounted on cars as they drove through cities taking images for Google Street View.

Methane leakage from smaller pipelines that run up to buildings, known as service lines, have not yet been as extensively measured in scientific studies. Therefore, for service lines, the Gas Index model defaults to using leakage rates from the EPA's Greenhouse Gas

Inventory (EPA 2020a). This is an example of how the model uses standard values where there is a lack of newer scientific studies to update the estimates.

The Gas Index Model uses detailed data on each gas utility's distribution mains and service lines that utilities self-report annually to the Pipeline and Hazardous Materials Safety Administration, or PHMSA, part of the U.S. Department of Transportation (PHMSA 2020). These data include information about pipeline age and material. This data shows which utilities have very long pipeline systems, for example, and which have many pipelines made of older types of pipes, such as cast-iron pipes, that tend to leak more methane. The Gas Index model also draws on data that gas companies report to the Energy Information Administration on the quantity of gas they sell to consumers in each sector, such as residential, commercial, and electric power.

Using this data, the Gas Index model estimates leakage from distribution systems for each city, based on data specific to the utilities that serve them. For example, the Boston urban area is served by three major utilities—National Grid, Eversource, and Columbia Gas of Massachusetts—as well as five smaller utilities, such as Middleborough Gas and Electric Department. All of these report data annually to federal agencies, PHMSA and EIA, about the status of their pipeline systems and how much gas they have sold.

The Gas Index Model uses a geographical analysis to estimate how many people live within each urban area and within each gas company's service territory. Thus, it is able to estimate how much gas is delivered by each local distribution company to each urban area. This analysis is based on local distribution company service territories published by the Department of Homeland Security (DHS 2019), as well as boundaries of urban areas defined by the U.S. Census (U.S. Census 2018) and populations at the census tract level (U.S. Census 2019).

In this way, gas leakage in each city can be estimated based on which gas companies supply the city, and the properties of each gas company's pipeline system. As an example, Figure 5 shows the Atlanta, Georgia, urban area and two of the main utilities serving the area.

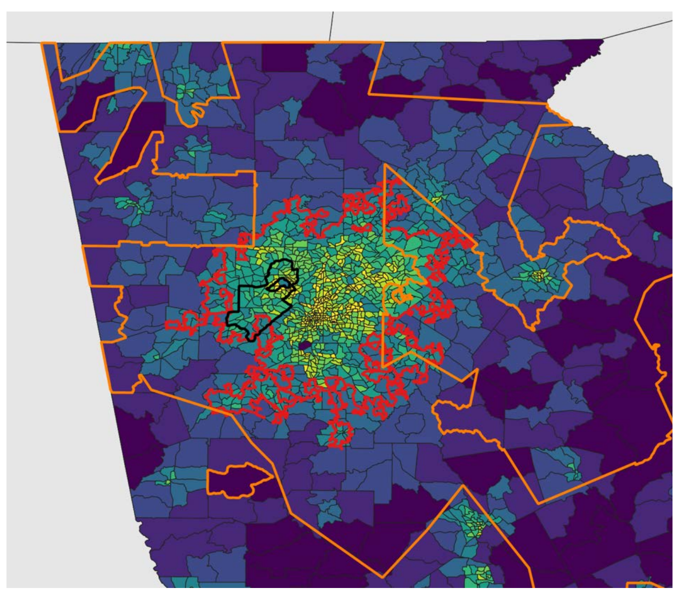


FIGURE 5. *Map of northern Georgia showing the Atlanta urban area, gas utility service territories, and population density. The Atlanta urban area is outlined in red (U.S. Census 2018). The service territory of Atlanta Gas Light is outlined in orange, and of Austell Gas is outlined in black (DHS 2019). The underlying layer is the population density for each census tract, based on U.S. Census population (U.S. Census 2019); yellow is most dense and dark blue is least dense.*

CUSTOMER GAS METER LEAKAGE

Each building that consumes natural gas has at least one gas meter that measures how much gas the building uses. These customer gas meters leak natural gas as well.

For gas meters on commercial buildings—such as office buildings or stores—the Gas Index model draws on a 2019 study by the Gas Technology Institute, which was commissioned by the Department of Energy (Moore 2019). The study found that commercial meters were leaking about 6 times more than in EPA estimates. The study also found large variations in the leakage rates between different regions of the country, which was attributed in part to the predominant gas meter technologies used in each region.

The Gas Index Model uses regional values from this Gas Technology Institute study to estimate how leaky each meter is. Utility-level data from the EIA that states how many customers there are in each sector—such as commercial, residential, and electricity sectors (EIA 2020b). Thus, the model estimates the leakage for each city based on data specific to the utilities that serve each city.

For residential customer meters, there is a lack of newer studies to update estimates, so the Gas Index model uses standard values from EPA's Greenhouse Gas Inventory.

BEHIND-THE-METER LEAKAGE

Gas-fueled appliances in homes and offices—such as furnaces, water heaters, and stoves—also leak natural gas. Gas leaks from pipes in buildings that carry the gas to appliances, and there is additional leakage from the appliances themselves, when some of the gas escapes unburned.

Behind-the-meter leakage has generally been left out of assessments of life cycle emissions from using gas; for example, this leakage isn't counted in the EPA's Greenhouse Gas Inventory. But this is starting to change. In 2019, the California Air Resources Board (CARB) started counting behind-the-meter leakage from residential buildings in their official state greenhouse gas inventory (CARB 2019); their estimates are based on one of the same studies that the Gas Index Model draws on (Fischer 2018). The Gas Index model also draws on two newer studies, published in the summer of 2020, on behind-the-meter leakage in commercial buildings (Sweeney 2020, Johnston 2020).

The studies cited above were commissioned by the California Energy Commission and were conducted by research teams at the Lawrence Berkeley National Laboratory (part of the Department of Energy), the Gas Technology Institute, and the consultancy ICF.

ADDITIONAL CITYWIDE LEAKAGE

Researchers have conducted measurements of citywide methane leakage for some U.S. cities, and some studies have further estimated the portion of methane emissions that originated from natural gas. For those studies, the Gas Index model draws on estimates of the leakage rate reported in the studies (e.g., the percentage of gas leaked out of the total natural gas delivered to the city). The urban areas with such estimates, and the studies used as inputs for the Gas Index, are: Boston, MA (Sargent 2020); Washington, DC, and Baltimore, MD (Ren 2018); San Francisco, CA (Jeong 2017); Los Angeles, CA (Peischl 2013, Wunch 2016).

For one city—Indianapolis, IN—methane emissions have been measured and the percentage originating from natural gas has been estimated, but the studies did not calculate a percentage leakage for the natural gas delivered to the city (Cambaliza 2015, Lamb 2016). For Indianapolis, IN, the Gas Index estimates the percentage leakage based on its modeling of the gas delivered to the city.

CHANGE IN EMISSIONS FROM SWITCHING TO ELECTRIC HEATING

In the Gas Index model's calculations, the change in greenhouse gas emissions due to switching from gas heating to electric heating has four key components:

- The heating technology
- The sources of electricity
- The methane leakage rate for the gas supply (both for direct use in buildings, and for power plants)
- The global warming potential of methane, which is used to convert methane leakage into CO_2 equivalent emissions.

For electric heaters, the calculations consider two types of heaters: Traditional electric heaters, which are assumed to be 100% efficient at converting electricity into heat, and highly efficient heat pumps, which can move heat into or out of buildings, allowing them to heat or cool more than the quantity of energy they expend.

For gas heaters, the efficiency is lower than electric heaters. In southern states, gas heaters are assumed to have an efficiency of 90%, and in northern states an efficiency of 95%, based on EPA Energy Star ratings for efficient heaters; the EPA lists the states that are in each region (EPA 2020b).

For calculating emissions from switching to electric heating, it is important to recognize that the electric grid is getting cleaner over time. These improvements in environmental impact should be factored in when estimating the emissions over the lifetime of a new appliance, such as a furnace. In the Gas Index model's calculations for electrification, the business-as-usual projection for the electricity sector is from a model by the National

Renewable Energy Laboratory (NREL), called the Regional Energy Deployment System, or ReEDS (Brown 2020). From the ReEDS 2019 Standard Scenarios, we chose the scenario called "Low natural gas prices and Low RE cost," to represent a case in which natural gas prices remain low and renewable energy costs continue to fall. This is the same scenario used in RMI's recent building electrification analysis (McKenna 2020). ReEDS results state the mix of electricity generation in each state, with projections through 2050.

For the cleaner electricity scenario, Many U.S. states and cities have targets to achieve 100% clean electricity by a specified date, set either by legislation, executive order, or other frameworks. For a clean electricity scenario, we assume that all cities and states that have such targets or mandated requirements will remain on track, with a linear ramp-down of non-clean electricity between 2018 and the year specified for achieving 100% clean electricity. We attempted to find all city and state clean electricity commitments as of November 29, 2020, drawing on a variety of sources (ACEEE 2020, Clean Air Task Force 2020, Sierra Club 2020, WRI 2019).

The calculations also factor in methane leakage—both for gas supplies used directly in buildings, and gas used in power plants. The Gas Index model estimates methane leakage for residential and commercial sector gas use for each city, as well as leakage from gas use for generating electricity in each state. As shown in Figure 3, gas delivered to residential and commercial buildings can suffer much more leakage than gas delivered to power plants. The Gas Index model factors in the share of electricity from natural gas in each of the scenarios described above, then calculates methane leakage accordingly.

Finally, to calculate the total emissions—both CO_2 and methane—from use of either electric heating or gas heating, it is necessary to convert the methane emissions into CO_2 equivalents. This conversion uses a 20-year global warming potential of 84 from the IPCC Fifth Assessment Report (IPCC 2013). Although this value is much higher than the 100-year global warming potential of 28 from the IPCC Fifth Assessment Report, we believe that the 20-year global warming potential better represents the impact of methane emissions. In 2019, New York State adopted a 20-year global warming potential in its state greenhouse gas inventory (Howarth 2020), and California also uses a 20-year global warming potential for methane in its Short-Lived Climate Pollutants program, which includes efforts to reduce methane emissions (CARB 2015).

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