Methane Math: How Cities Can Rethink Emissions from Natural Gas

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Abbreviations

°C	Degrees Celsius
°F	Degrees Fahrenheit
BTEX	Benzene, Toluene, Ethyl-Benzene, and Xylene
CARB	California Air Resources Board
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CH_4	Methane
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
COGCC	Colorado Oil and Gas Conservation Commission
CPP	Clean Power Plan
CPUC	California Public Utilities Commission
CWA	Clean Water Act
EDF	Environmental Defense Fund
EIA	US Energy Information Administration
EPA	Environmental Protection Agency
FRAC Act	Fracking Responsibility and Awareness of Chemicals Act
GHG	Greenhouse Gas
GWP	Global Warming Potential
GWP_{100}	Global Warming Potential over 100 Years
GWP_{20}	Global Warming Potential over 20 Years
HFCs	Hydrocarbons
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LBNL	Lawrence Berkeley National Lab
lbs	Pounds
mmbtu	Million British Thermal Units
$MMTCO_2e$	Million Metric Tonnes Carbon Dioxide Equivalent
$MTCO_2e$	Metric Tonnes Carbon Dioxide Equivalent
NO_2	Nitrogen Dioxide
NOAA	National Oceanic and Atmospheric Administration
NSPS	New Source Performance Standards
PG&E	Pacific Gas and Electric
PHMSA	Pipeline and Hazardous Material Safety Administration
RCRA	Resource Conservation and Recovery Act
SDWA	Safe Drinking Water Act
SLCP	Short-Lived Climate Pollutants
TRI	Toxic Release Inventory
UIC	Underground Injection Control
UNEP	United Nations Environmental Programme
US DOE	United States Department of Energy
US GHGI	US Greenhouse Gas Inventory
VOC	Volatile Organic Compounds

Executive Summary

This report represents the first multi-city meta-analysis of how we account for the global warming impact of the natural gas system.

Natural gas, which is primarily composed of methane, has long been touted as an environmentally friendly bridge fuel for the United States that could aid with a longer-term transition to renewable energy sources, including wind, solar and water. Policymaker support for natural gas, combined with the fracking revolution, has led to a 53 percent growth in natural gas production since 1990.[1]

But there is growing evidence that policymakers and operators are underestimating climate and health risks associated with the natural gas system, especially when it comes to accounting for the heat-trapping power of methane emissions from extracting, transporting and using natural gas. This is due to both how we calculate the global warming impact of short-lived climate pollutants, especially methane, as well as the estimated rate at which natural gas leaks from extraction sites and the distribution system. These studies have serious implications for city-level and national-level carbon accounting, including the U.S. Greenhouse Gas Inventory (USGHGI), which the Environmental Protection Agency uses to report U.S. emissions to the United Nations.

For instance, while methane traps more than 80 times the heat carbon dioxide does during its 12-year atmospheric lifetime, it is standard carbon accounting practice to use a 100-year timeframe for measuring methane's impact. Artificially extending the accounting timeline basis to 100-years reduces the magnitude of global warming from shorter-lived gases such as methane. In fact, the current 100-year accounting practice underestimates methane's heat-trapping power by 67 percent compared to accounting over a 20-year time frame. This choice has downstream effects on cap-and-trade allowance and auction values as well as the long-term accuracy of local, state and national carbon inventories when tracking progress toward climate goals.

Further, this report finds that independent studies have estimated methane leakage rates industry-wide averaging 4.52 percent, with individual estimates as high as 12 percent. However, the USGHGI

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[1] "U.S. Natural Gas Marketed Production." *U.S. Energy Information Administration Independent Statistics and Analysis*, 30 Dec 2016.

methodology assumes a relatively low leak rate of just 1.4 percent. Because methane is such a powerful heat-trapping gas, higher rates of leakage will effectively cancel out any emissions reduction benefits assumed from switching to natural gas from coal.

Overall, the report finds that the short-term global warming potential of methane coupled with higher than previously estimated natural gas leak rates means that sunny assumptions about coal-to-gas switching should not serve as the basis for climate policy. The good news is that cities and states are already experimenting with ways to reduce gas leaks while the costs for renewable energy generation from wind and solar as well as battery energy storage continue to drop. Below is a list of ten priority actions cities can take to address methane leaks from the natural gas system:

1. Change carbon accounting practices. Switch to a shorter time frame for methane emissions (GWP_{20}), use updated leak rate estimates, and advocate for these changes to become the new standard of practice, including in emissions trading systems.
2. Communicate the importance of leaks. Highlight the impact of natural gas leaks and include leak reduction goals in climate action plans.
3. Disclose leaks. Require utilities provide public data that details leaks, including number, location, pipeline, component type, volume leaked, estimated greenhouse gas emissions, and past or planned repairs.
4. Collect more local data on natural gas leak rates. Partner with local or state governments, non-profits, private sector, local universities, utilities, or other entities to conduct bottom-up emissions that quantify city-level leaks.
5. Reduce leaks in local distribution. Require utilities to detect and repair leaks during municipal street or sidewalk construction projects and encourage the prioritization of "super-emitter" sites that account for a large portion of leaks in cities.
6. Incentivize leak repair. Create a carbon emission abatement metric for fixing leaks to incentivize utilities to prioritize non-emergency leak repairs.
7. Prioritize decarbonization. Eliminate code barriers to electrification and require electric-only new construction while phasing in retrofits of other types of buildings, including single family, small multifamily, and municipal operations.
8. Support fuel switching. Fund homeowners at the end of a natural gas distribution line to switch to electricity rather than repairing or replacing natural gas pipelines.

9. Switch to renewable natural gas. Where electrification is not feasible, switch to renewable natural gas sources such as bio-methane from landfills and dairy producers.
10. Create an investment plan. Develop a long-term energy investment plan that considers together aging natural gas infrastructure replacement costs, emission-reduction goals, and climate change adaptation.

The U.S. natural gas system

Natural gas is largely comprised of methane, which forms when plants, animals and microorganisms that lived millions of years ago, are covered by layers of soil and subjected to high temperatures and pressures. Overall, natural gas comprises 29 percent of the United States' energy use. The U.S. natural gas system is vast. More than 175 million end users – including homes and businesses – receive natural gas through 3 million miles of underground pipeline, which laid end to end would reach the moon and back more than six times. The nation's production system includes 285,000 producing wells, 125 pipeline companies, and 1,200 distribution companies.[2]

Fifty-five percent of natural gas is used in buildings to provide heating, cooling, lighting and cooking. Meanwhile, 36 percent is used to generate electric power. And the remaining 9 percent is used for powering equipment in gas wells and power plants.[3]

All told, the United States used 27.49 trillion standard cubic feet of natural gas in 2015. By 2040, consumption is expected to increase 30 percent, and production is expected to increase 52 percent from 2015 levels.[4] *(See Appendix A for more information).*

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[2] "Natural Gas Explained: Natural Gas Pipelines." *U.S. Energy Information Administration Independent Statistics and Analysis.*

[3] "Natural Gas Consumption by End Use - Date Series." *Natural Gas, U.S. Energy Information Administration Independent Statistics and Analysis,* 2016.

[4] "Table: Total Energy Supply, Disposition, and Price Summary." *Annual Energy Outlook, U.S. Energy Information Administration Independent Statistics and Analysis,* 2016.

Risks from the Natural Gas System

Natural gas is a non-renewable combustible fuel that supplies energy to buildings and transportation systems. As with all energy sources, natural gas comes with a set of risks that policymakers, managers and users try to mitigate. Leaks in the natural gas systems threaten public health and safety, impact environmental and air quality, and result in carbon emissions that exacerbate global climate change.

Public Health

Natural gas is extracted from the earth using conventional and unconventional drilling methods, both of which can present risks to local communities. Conventional methods include drilling into relatively accessible pockets of natural gas. As known conventional reservoirs have been depleted, the natural gas industry has developed unconventional methods generally referred to as hydraulic fracturing – or fracking – that use a series of underground explosions and high-pressure fluid injection to release trapped gas.

Extraction involves the use of more than 1,000 chemical products, many of which can be harmful to workers or anyone exposed to them.[5] Water quality is also a concern, with one study finding contamination around extraction sites at 250 areas in Pennsylvania. In Colorado, researchers found 77 surface spills in a one-year period, with 62 including benzene, toluene, ethylbenzene and xylene, most in excess of federal standards. Other studies have found heavy metals in water in the Texas Barnett Region as well as increased fish mortality and toxic levels of heavy metals after fracking fluid was released into a Knox County stream in Kentucky. [6]

Residents living near production sites can be exposed to carcinogenic compounds such as benzenes, xylenes and hydrocarbons, and one study has found a 40 percent increase in the risk for developing

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[5] Elliott, Elise G., et al. "A systematic evaluation of chemicals in hydraulic-fracturing fluids and wastewater for reproductive and developmental toxicity" *Journal of Exposure Science and Environmental Epidemiology*. 27, 90-99 Nature America Inc. 16 Jan 2016

[6] "Surface and groundwater contamination association with modern natural gas development." *Science Summary*. PSE Healthy Energy, Oct 2014.

cancer for residents living within a half mile of a production site compared to those living further away.[7] *(See Appendix C for more information).*

Fracking poses additional public health risks, including: contamination of drinking water, earthquakes, reduced local air quality and problems related to industrial development generally, such as increased heavy truck traffic. Policies regarding fracking vary widely by locality, both in terms of whether the practice is allowed, as well as how environmental data is collected, if at all, and whether the public or operators bear responsibility for environmental risks. Additionally, a federal law passed in 2005 – the so-called "Halliburton loophole" – exempts fracking operations from clean water laws. Much of the regulatory framework for fracking is built at the state and municipal level. A number of states including Vermont[8], New York[9], and Maryland[10] have already taken the lead on banning this fossil-fuel extraction method due to the costly health risks associated with it.

Public Safety

Natural gas is highly flammable and safety issues arise when it's transported across the United States through aging pipeline infrastructure. On average since 2010, the natural gas system has annually caused 236 safety incidents, 14 fatalities, 66 injuries, and $198 million in damages.

In 2005, the local gas distribution company in New Orleans, Entergy New Orleans, Inc., reported a total cost to repair the natural gas system of $470 million[11] after Hurricane Katrina.[12] In 2010, a 30-inch carbon-coated transmission pipe ruptured in San Bruno, California, resulting in eight fatalities, 51 injuries, and $560 million in reported total costs.[13] The Aliso Canyon Disaster was the most

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[7] McKensie, LM., et al. "Human health risk assessment of air emissions from development of unconventional natural gas resources." *Science of the Total Environment*, Vol 424, pg. 79-87 ScienceDirect, 1 May 2012.

[8] NewsCore. "Vermont becomes first state to ban fracking". *Fox News*. 17 May 2012.

[9] Thomas Kaplan. "Citing Health Risks, Cuomo Bans Fracking in New York". *The New York Times*. 17 December 2014.

[10] Pamela Wood. "Maryland General Assembly approves fracking ban". *The Baltimore Sun*. 27 March 2017.

[11] Daly, Erin Marie. "Entergy Rises Out of Bankruptcy." *Law 360*. 9 May 2007.

[12] Larino, Jennifer. "Entergy learns Katrina lessons, but damage prevention is still in question." *Nola.com*, The Times-Picayune. 25 Aug 2015.

[13] "Distribution, Transmission & Gathering, LGN, and Liquid Accident and Incident Data." *Pipeline and Hazardous Materials Safety Administration*. U.S. Department of Transportation.

environmentally detrimental natural gas leak ever recorded. Thousands of residents were evacuated due to the health risks they faced after the release of more than 100,000 tons of methane, equivalent to having an additional 2.2 million cars on the road. *(See Appendix D for more information).*

Leak costs are often passed on to the ratepayer. For the cost of only the lost natural gas commodity, $37.9 million was lost due to incidents from 2010 to 2015. Total costs for damage and emergency responders totaled $1.2 billion in that time frame. Additionally, the EPA Inspector General estimates that $192 million is passed on to customers for non-incident distribution line leaks annually.[14]

Fatalities and injuries from pipeline incidents have not declined significantly during the most recent five years compared to a baseline of the past 20 years. Newer, more ductile material has not proven to be a cure-all either. Since 2010, 19 percent of incidents occurred in pipelines installed post-2000, and 20 percent occurred in plastic pipelines. A third occurred in pipelines installed between 1980 and 2000 and almost half occurred in steel pipelines.

Safety is currently the only metric by which pipeline repairs are regulated. The Department of Transportation (DOT) is the regulating authority for pipeline transportation of flammable, toxic, or corrosive gases - including natural gas. They provide the minimal federal regulations and enforce safety through the DOT's Pipeline and Hazardous Material Safety Administration (PHMSA). The PHMSA requires that leaks are surveyed every five years and state authorities and utilities are tasked with monitoring leaks for safety. PHMSA requires that leaks are fixed "as soon as feasible" unless they create a pipeline integrity issue and there are currently no national standards for when leaks need to be fixed due to environmental reasons. Additionally, the EPA has no regulatory authority over pipeline leaks.[15]

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[14] "Improvements Needed in EPA Efforts to Address Methane Emissions from Natural Gas Distribution Pipelines." *U.S. Environmental Protection Agency*, Office of Inspector General, Report No. 14-P-0324, 25 Jul 2014.

[15] "Improvements Needed in EPA Efforts to Address Methane Emissions from Natural Gas Distribution Pipelines." *U.S. Environmental Protection Agency*, Office of Inspector General, Report No. 14-P-0324, 25 Jul 2014.

Environmental Injustice

Climate change is one of the greatest sources of global environmental injustice, with less developed countries contributing the least to the problem but suffering the most from its consequences. This disparity also holds true within countries, as not all people will suffer the impacts of climate change equally. The degree to which different populations and communities are vulnerable depends largely on established social, political, environmental, and economic inequalities. Referred to as the Climate Gap, there are several factors affecting the magnitude of climate change impacts on people's lives and health outcomes. These include socioeconomic and demographic indicators such as age, race, and income, as well as environmental factors such as tree cover and air pollution, exposure to hazards including flooding and extreme heat, as well as infrastructure factors including housing quality, overcrowding, access to air conditioning, access to neighborhood goods and services, and transportation. Pre-existing health conditions also influence vulnerability to climate impacts.[16]

Local air quality is affected by climate change due to its varied and complex effects on global and regional atmospheric patterns. Even cities that are on the lower end of the pollution spectrum, could see both short-term spikes and longer-term small increases in smog – also referred to as ground-level ozone – as a direct result of climate change. Additionally, while the effect of climate change on particulate matter (PM2.5) is less certain because PM levels are strongly affected by local weather, a reduction in wind and vertical mixing due to climate change could result in increased PM levels.[17]

Leaks from the natural gas system could compound these climate injustices. For example, methane and volatile organic compounds leaked at production sites have been found to result in higher levels of smog.[18] Leaks in the natural gas distribution system, located throughout communities including existing areas of environmental injustice and communities of color, could also increase ground-level ozone. A visual inspection of EPA Environmental Justice Screen maps [19] overlaid with natural gas leak maps

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[16] "The Climate Gap: Inequalities in How Climate Change Hurts Americans & How to Close the Gap." By Rachel Morello Frosch, Manuel Pastor, Jim Sadd, and Seth Shonkoff. May 2009.

[17] "**San Francisco's Climate and Health Adaptation Framework**". *San Francisco Department of Public Health.* 2017.

[18] "EPA Needs to Improve Air Emissions Data for the Oil and Natural Gas Production Sector." U.S. Environmental Protection Agency, Office of Inspector General, Report No. 13-P-0161 20 Feb 2013.

[19] 165 "EJ Screen: Environmental Justice Screening and Mapping Tool." *U.S. Environmental Protection Agency.*

created by EDF / Google revealed no distinct correlation between census blocks of low-income and minority populations and leak locations. *(See Appendix E for more information).* The EPA Environmental Justice Screen is, however, a national tool that does not reflect the complex social, political, environmental, and economic factors that result in environmental justice inequalities, especially at the local level.

While further investigation into the potential impact of leaks in the natural gas system on environmental justice and communities of color may be warranted, to eliminate disparities in exposure to air pollution and promote health equity, special emphasis should be placed on protecting communities and populations most vulnerable to the effects of air pollution from the impact of a changing climate.

Climate Change

Climate change from burning fossil fuels and destroying tropical forests poses several extant and long-term threats to our built and natural environment as well as to human well-being. These impacts range from sea-level rise, heat stress, longer wildfire seasons, disruptions to agricultural production, loss of snowpack, and concentrating rainfall in more intense downpours.[20] Scientists agree that the extent of future climate change is largely a function of decisions we are currently making about our energy system. To fully address climate change, we must reduce emissions to zero or net-negative, which will require converting all of our energy using systems to renewable and non-carbon-emitting sources.

Global levels of carbon dioxide stand at 406 parts per million, 30 percent higher than pre-industrial levels. Methane concentrations, meanwhile, are more than 125 percent higher than historic levels. As a result of industrial greenhouse gas emissions global temperatures have risen by nearly a degree Celsius, worsening extreme heat, causing sea-levels to rise, and disrupting a variety of human and natural systems. Scientists warn that as the Earth warms, changes to natural systems could make the problem harder to solve, for example, if methane currently frozen in northern tundras were to be

[20] "Climate Change Impacts in the United States: The Third National Climate Assessment." *U.S. Global Change Research Program*, 841 pp. doi:10.7930/J0Z31WJ2.

released as the tundra thaws.[21]

Because methane is such a powerful heat-trapping gas, the climate system is more immediately responsive to methane emissions than carbon dioxide emissions. Indeed, unless emissions from methane are reduced immediately, the earth is still expected to warm by 1.5 degrees Celsius by 2030 and 2 degrees Celsius by 2050.[22] This would mean exceeding the temperature reduction goals that have long served as the basis for international policymaking, U.S. emissions reduction goals, and local climate commitments. The outsized impact of short-lived climate pollutants such has methane has prompted an increased focus among scientists and policymakers. Tackling short-lived climate pollutant emissions can buy the world more time to decarbonize our energy systems and make the switch to 100 percent renewable fuels.

A stronger focus on short-lived climate pollutants can be integrated into policy responses to climate change, which vary significantly by city, state and country. Currently, at least 20 states and the District of Columbia have adopted similar targets. In the absence of national climate legislation, federal policymakers have worked to reduce emissions under the Clean Air Act. Internationally, nearly every country in the world is party to the 2015 Paris Agreement, which aims to dramatically limit emissions and requires countries to transparently share emissions data with one another. At the same time, some state and federal policymakers have suppressed climate research and publicly rejected the scientific realities of climate change. Further, the current U.S. presidential administration has planned to roll back emissions reduction policies and withdraw the U.S. from the Paris Climate Agreement. In response, hundreds of states and cities - along with major businesses, renewed their pledge to work together to fulfill America's promise to reduce emissions.[23]

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[21] "Methane emissions proportional to permafrost carbon thawed in Arctic lakes since the 1950s." *Nature Geoscience*. 9. 679-682. 10.1038/ngeo2795.

[22] Schindell, Drew, et al. "Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security." Science Magazine. Vol 335, 13 Jan 2012.

[23] https://www.bloomberg.org/program/environment/americas-pledge/

Rethinking Emissions Accounting

Current methods for quantifying methane emissions are outdated and underestimate the global warming power of methane as a short-lived climate pollutant as well as the magnitude of system wide leaks. Cities and states have an opportunity to both reassess the timeline basis on which they account for methane emissions, as well as the rate of methane leaks in the natural gas system. These two accounting changes can help cities and states better understand the opportunities for high impact and targeted actions to mitigate the near-term rate of global warming while developing longer-term strategies to achieve carbon neutrality.

A 20-year vs 100-year timeframe for short-live climate pollutants

Scientists and policymakers have been devoting increased attention to short-lived climate pollutants, including black carbon, methane, tropospheric ozone and hydrofluoro-carbons. These pollutants vary in how much heat they trap, but they all have relatively short atmospheric lifetimes ranging from days to weeks to several years. Methane is both extremely potent and has a short, but significant atmospheric lifetime of 12 years, making the climate system more immediately responsive to changes in methane emissions than carbon dioxide emissions.

Due to the long atmospheric life span of carbon dioxide, reductions of this pollutant will not dramatically affect global temperatures before 2040. While reducing carbon dioxide levels will continue to be necessary to protect the climate in the long term, policymakers have an opportunity to focus on powerful, short-term damage to the climate from methane and other pollutants.[24] For instance, a 2011 study found that immediate mitigation of short-lived climate pollutants might constrain temperature increases for the next 40 years, a time during which we can expect to transition over most of our energy infrastructure and reduce our dependence on fossil fuels entirely.[25]

However, this reality is not reflected in how we account for emission at the local, state, federal or international level. Greenhouse gases are evaluated using a global warming potential (GWP), or the

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[24] United Nations Environment Programme and World Meteorological Organization. "Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers." UNON, 2011 Nairobi, Kenya.

[25] Schindell, Drew, et al. "Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security." Science Magazine. Vol 335, 13 Jan 2012.

relative measure of how much heat the gas traps within the atmosphere compared to carbon dioxide, which is given a GWP value of 1. The Intergovernmental Panel on Climate Change (IPCC), the main body through which scientists advise policymakers on climate change, provides global warming potential values for both 100-year (GWP_{100}) and 20-year (GWP_{20}) timeframes. But, emissions inventory methodologies typically use a global warming potential of 100 years, even for short-lived climate pollutants such as methane.

Using a GWP_{100} for methane means the warming potency of the natural life span of this gas in the atmosphere – which is 12 years – is spread out over 100 years, diminishing its true impact. In the IPCC 5th Assessment Report, the GWP_{100} value for methane was estimated to be 28, while the GWP_{20} value was estimated to be 86, meaning the GWP_{100} framework effectively dilutes the value of reducing methane emissions by 67 percent.

The timeline over which policymakers count emissions is entirely at their discretion. The IPCC states that there is no scientific reason to rely exclusively on GWP_{100} values.[26] Additionally, IPCC GWP values have been increasing over the past several assessments as scientists learn more about the effect of methane on our climate system. As an example, methane GWP_{20} values have increased 19 percent since the 2007 Assessment Report[27] and 50 percent since the 1995 Assessment Report.[28] Further, a 2011 study noted that previously unaccounted-for interactions between methane and aerosols in the atmosphere may significantly increase these global warming potentials up to 33 times on a 100-year time frame and up to 105 times on a 20-year time frame when compared to carbon dioxide.[29]

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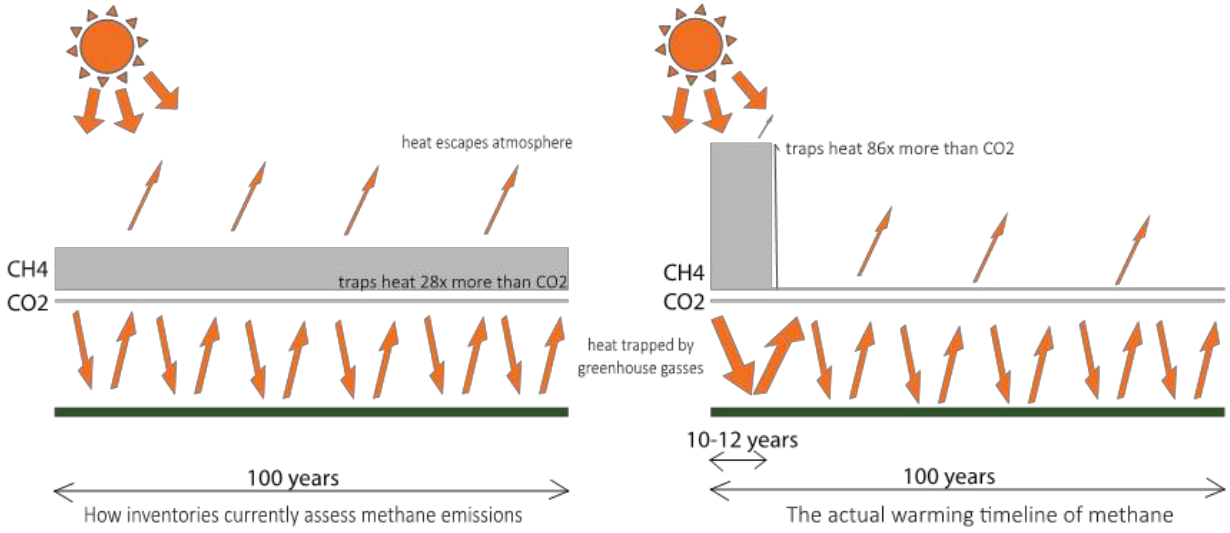
[26] Intergovernmental Panel on Climate Change. "Climate Change 2014: Synthesis Report". Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Fifth Assessment, Intergovernmental Panel on Climate Change, 2014 Geneva, Switzerland

[27] Pachauri, R.K. and A. Reisinger. "Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change." Intergovernmental Panel on Climate Change, 2007. Geneva, Switzerland.

[28] "Contribution of Working Group 1 to the Second Assessment Report of the Intergovernmental Panel on Climate Change" UNEP, WMO. 1995. Geneva, Switzerland.

[29] Howarth, Robert W. "Methane and the greenhouse-gas footprint of natural gas from shale formations." Climatic Change. DOI 10.1077/s10584-011-0061-5 13 Mar 2011

FIGURE 1: SHORT-TERM POWER OF METHANE



Natural Gas Leaks Historically Underestimated

Evidence continues to accumulate that natural gas leaks are more prevalent than policymakers have previously assumed. Leaks can occur at every point of extraction, distribution and use. For instance, leaks occur at fracking sites where gas fails to get captured, in large pipelines, and at the municipal level, ranging from leaks in main city lines under streets to leaks at the individual building level. Leaks can result from changes in pressure, weather conditions, temperature, mechanical stresses, wear and tear, and construction and operator error. Additionally, seismic activity can also disrupt systems and cause leaks.

This complexity makes finding and quantifying leaks challenging. Fortunately, new technologies and increased resources are helping scientists and local governments find and address leaks. Typically, one of two study methodologies: (1) bottom-up or (2) top-down – is used in these efforts.

In bottom-up studies, a specific geographic area is monitored, and the activity rate, meaning the number of leaks per mile of pipeline, is estimated. A limited number of leaks are typically monitored to understand the flow rate, or volume of gas, that escapes per hour or day. Based on the leaks measured – which can vary depending on time and budget – researchers calculate the average flow rate and in some cases, quantify leaks by pipe material and classification, such as transmission lines, distribution mains, and distribution services. The average flow rate and activity rate are then multiplied

to determine the emission factor, or tons of carbon, that escape per mile on an annual basis. Inventory estimations can then be scaled up based on these emission factors to reflect the potential amount of natural gas leaks.

In a joint project conducted by the Environmental Defense Fund (EDF) and Google Earth Outreach, Google Street View cars were equipped with methane sensors and surveyed representative areas in various U.S. cities. These bottom-up studies located and estimated the flow rate of natural gas leaks from local distribution systems to help local governments and utilities prioritize the largest leaks or most leak-prone pipes for repair and replacement. *(See Appendix B).*

The other type of study is a top-down study. In these studies, atmospheric methane measurements are taken, and a portion is traced back to natural gas by either isotopic tracers or trace elements. Natural gas can also be allocated through the simultaneous testing of trace elements, such as propane and ethane, to discriminate natural gas methane from biological methane, from landfills or dairy production.

Top-down studies are particularly important at the national level. While USGHGI estimations indicate only a 1 percent increase in methane emissions from all sectors, and a 4 percent decrease in methane from the natural gas sector between 2004 and 2012[30], atmospheric measurements suggest U.S. emissions have increased 35 percent over that same period. This discrepancy could be due to increased natural gas extraction; at least one study found increasing methane concentrations were largely seen in the central part of the country, where oil and gas drilling activity is primarily located.[31]

A Range of Leak Rates

The EPA currently estimates the overall natural gas system leak rate at 1.4 percent based on a 2014 EPA GHGI study, though the agency acknowledges that natural gas leaks are a widely unknown

[30] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 2014." U.S. Environmental Protection Agency, 15 Apr 2016.

[31] Turner, A.J., et al. "A large increase in U.S. methane emissions over the past decade inferred from satellite data and surface observations." Geophysical Research Letters. Volume 43, Issue 5, 16 Mar 2016.

source of emissions.[32] But leak rate estimates from other studies range from 1 to 12 percent (*see Table 1).* This is because natural gas leak rates vary due to local conditions, production type, natural gas source, method of extraction, and study type. For the purposes of evaluating how natural gas leaks impact current carbon accounting, this report calculated unweighted, average leak rates across the nine studies considered. This resulted in an average percent leak rate of 4.52, which is three times greater than the current leak rate used by the EPA in the U.S. Greenhouse Gas Inventory (USGHGI), which is produced at the federal level to comply with reporting under the United Nations Framework Convention on Climate Change.

The EPA's national emission factors for natural gas systems have been disputed. Many experts, including the EPA's Inspector General, think they are significantly underestimated. In a 2013 report, the Inspector General outlined data improvement needs for the oil and gas sector, including direct emissions measurements for several important gas production processes, including well completions and evaporative ponds. Approximately half of the EPA's oil and gas emission factors were rated "below average" or went unrated because they are based on insufficient or low-quality data. The Inspector General concluded that this limited data or lack of data could affect decision-making and negatively impact both human health and the environment.[33]

It is worth noting that some of the studies considered in this report evaluated all production types while others chose a specific type of production - conventional or shale, which is primarily extracted using fracking - on which to base their analysis. This is of interest as the three shale studies noted below each found high leak rates, and a shale study has the highest maximum rate of 11.7 percent. As the share of shale production increases as projected by the Energy Information Administration, the overall system wide leak rate could increase as the portion of leaks from production will likely increase.[34]

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[32] Intergovernmental Panel on Climate Change "Climate Change 2014: Synthesis Report". Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Fifth Assessment, IPCC, 2014 Geneva, Switzerland.

[33] Howarth, Robert. "Still a Bridge to Nowhere: Methane Emissions and the Greenhouse Gas Footprint of Natural Gas." Cornell University Lecture, 14 Apr 2015

[34] "Natural gas production from shale gas and tight oil plays leads growth in U.S. natural gas supply." Market Trends, Natural Gas Annual Energy Outlook 2016, 15 Sep 2016.

TABLE 1: LITERATURE REVIEW ON METHANE LEAKS FROM NATURAL GAS SYSTEMS

Study	Percent Leak	Min Leak	Max Leak	Production Type	Analysis Type	Year
EPA GHGI*[i]	1.37%	1.11%	1.78%	All production	Bottom-Up	2014
Brandt*[ii]	2.35%	1.96%	2.75%	All production	Top-Down	2014
Miller*[iii]	3.57%	2.74%	4.40%	All production	Top-Down	2013
Caulton et al[iv]	7.00%	2.30%	11.70%	All production	Lit Review	2014
Burnham[v]	2.75%	0.97%	5.47%	Conventional	Lit Review	2011
Howarth[vi]	3.80%	1.70%	6.00%	Conventional	Lit Review	2011
Burnham[vii]	2.01%	0.71%	5.23%	Shale	Lit Review	2011
Howarth[viii]	5.80%	3.60%	7.90%	Shale	Lit Review	2011
Howarth[ix]	12.00%	4.30%*	19.70%*	Shale	Lit Review	2015
Averages	*4.52%*	*2.15%*	*7.21%*			

**Additional data points were estimated by the San Francisco Department of the Environment*

The Carbon Cost of Leaks

Accounting for the short-term (20 year) global warming potential of methane coupled with an average percent leak rate based on the nine studies considered in this report has significant impacts on emissions inventories at all scales - from national to local. Below, the figures and analysis presented exemplify the yet unaccounted for carbon costs at the national (U.S.), state (California) and local (San Francisco) levels. These conclusions would naturally apply at the global level, too, though such analysis was beyond the scope of this report.

United States

The difference between GWP_{100} and GWP_{20} values at the inventory level is significant and growing more so. United States emissions were analyzed through 4 different scenarios to show how the impact on methane emissions when (1) switching to a GWP_{20} and (2) using a higher leak rate for the natural gas systems.

- The first scenario (GWP_{100} / 1.4%) serves as reference to the other scenarios and is based on emissions inventory data for 2014[35]. The US emissions inventory uses a 100-year GWP for all greenhouse gases and an estimated 1.4% leak rate.[36]
- The second scenario (GWP_{20} / 1.4%) uses a 20-year GWP, while maintaining a 1.4% leak rate.
- The third scenario (GWP_{20} / 4.5%) uses to a 20-year GWP, and changes natural gas leak rate to the average rate of 4.5%.
- The fourth scenario (GWP_{20} / 12%) uses a 20-year GWP and uses the maximum leak rate estimated by Howarth's 2015 analysis[37] *(see Table 1).*

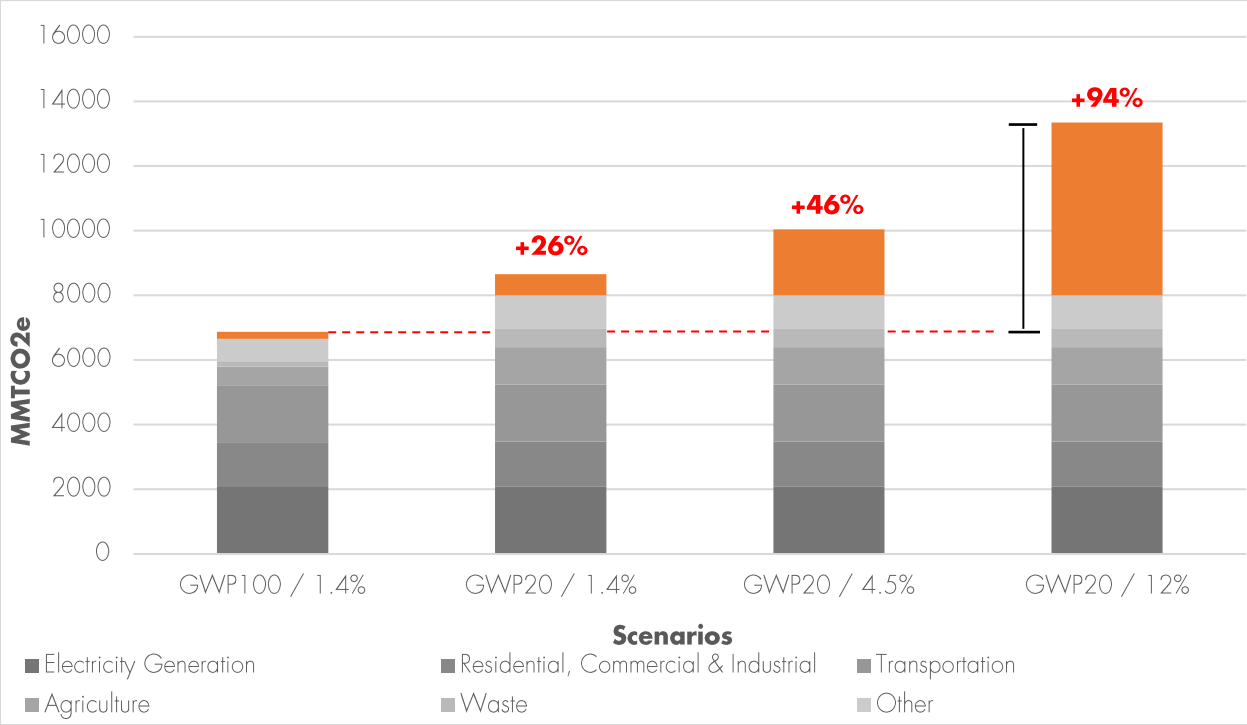
The following figures show how our current accounting practices are underestimating emissions from the natural gas system. Changes to the overall U.S. greenhouse gas emissions inventory may be underestimated by as little as 26 percent to as much as 94 percent. When evaluating these changes by greenhouse gas, the analysis shows an increase in methane emissions ranging from 3 to 10 times higher than what is currently reported.

[35] Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014 (published 2016)

[36] Leak rate was estimated by the research team based on the EPA's GHG emissions inventory data and US natural gas production numbers.

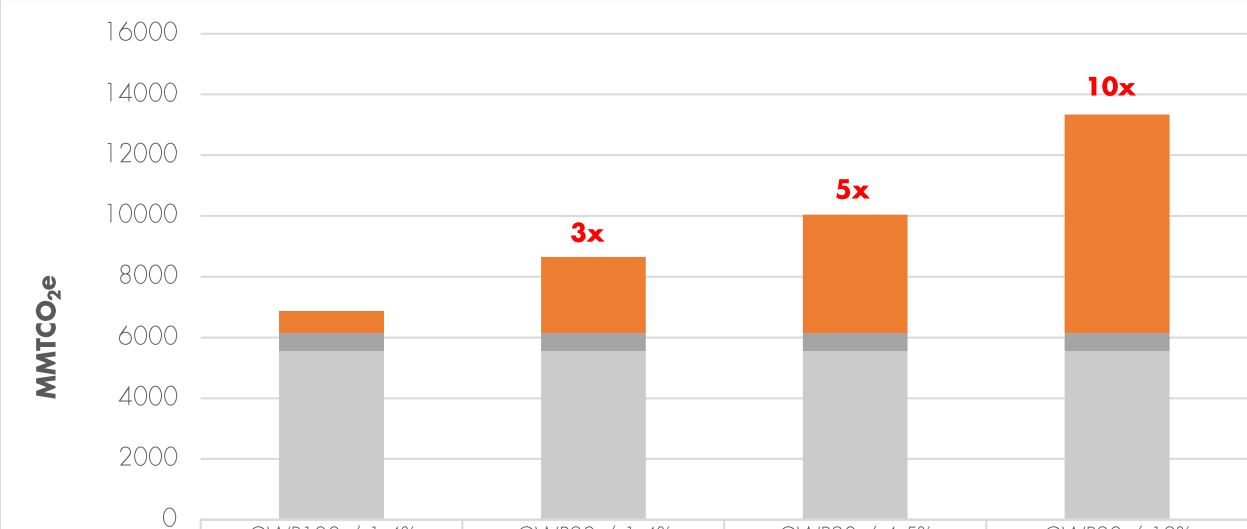
[37] Howarth, Robert W. "Methane emissions and climatic warming risk from hydraulic fracturing and shale gas development: implications for policy." *Energy and Emission Control Technologies,* 2015. Dovepress 8 Oct 2015

FIGURE 2: CHANGES IN US OVERALL GHG EMISSIONS WITH DIFFERENT GWP AND LEAK RATE SCENARIOS



Source: Based on EPA data for USGHGI 2014 (published in 2016)

FIGURE 3: CHANGES IN US METHANE EMISSIONS WITH DIFFERENT GWP AND LEAK RATE SCENARIOS



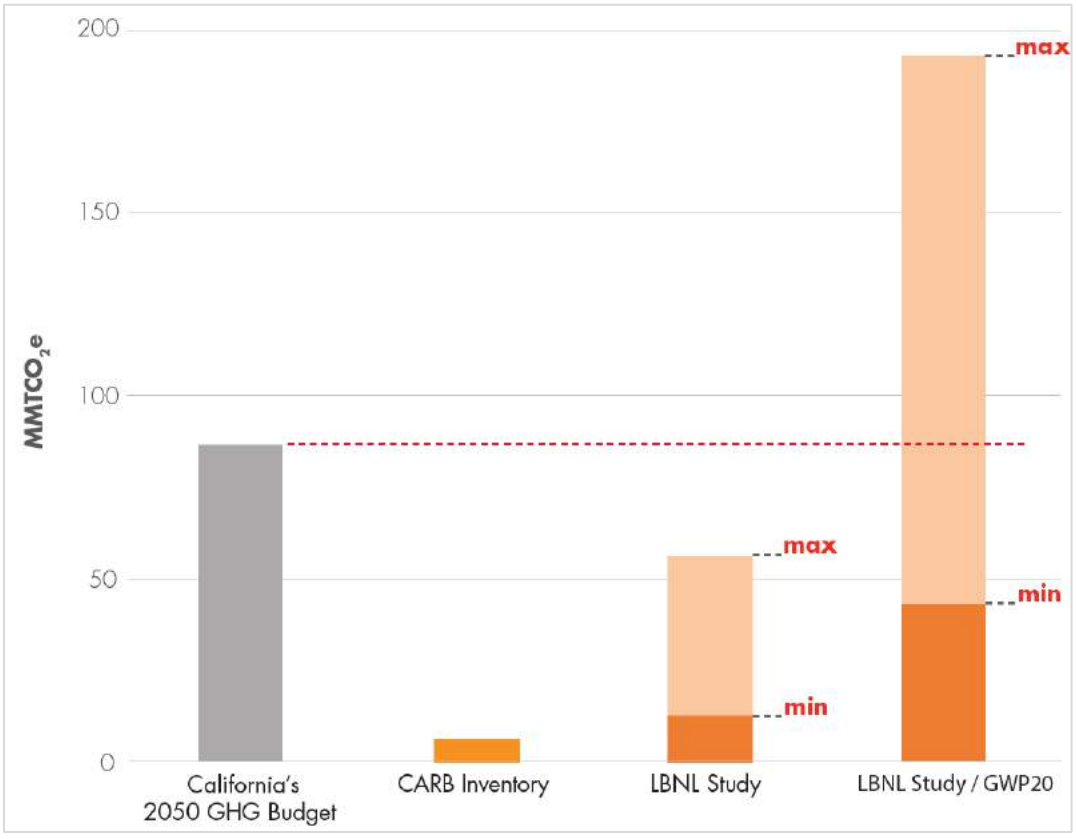
	GWP100 / 1.4%	GWP20 / 1.4%	GWP20 / 4.5%	GWP20 / 12%
CH4 Emissions	731	2514	3903	7206
Other GHGs	584	584	584	584
CO2 Emissions	5556	5556	5556	5556

Source: Based on EPA data for USGHGI 2014 (published in 2016)

State of California

Methane emissions from all sources are likely underestimated in the California Air Resources Board (CARB) inventory. A 2016 study completed by the Lawrence Berkeley National Laboratory (LBNL) estimated that statewide methane emissions were 1.2 to 1.8 times greater than the current inventory estimate.[38] California has set a long-term goal of achieving 80 percent carbon emissions reductions below 1990 emissions levels by 2050, with a total emissions budget of 86.4 million metric tons of carbon dioxide equivalent ($MMTCO_2e$). Currently, CARB estimates approximately 5.9 $MMTCO_2e$ of the state's emissions is from natural gas systems, while the LBNL study estimates natural gas emissions fall within a range of 12.5 $MMTCO_2e$ to 43.7 $MMTCO_2e$.

FIGURE 4: CHANGES TO CALIFORNIA'S GHG INVENTORY WITH LBNL STUDY AND GWP_{20} SCENARIOS



Source: Based on EPA data for LBNL Study

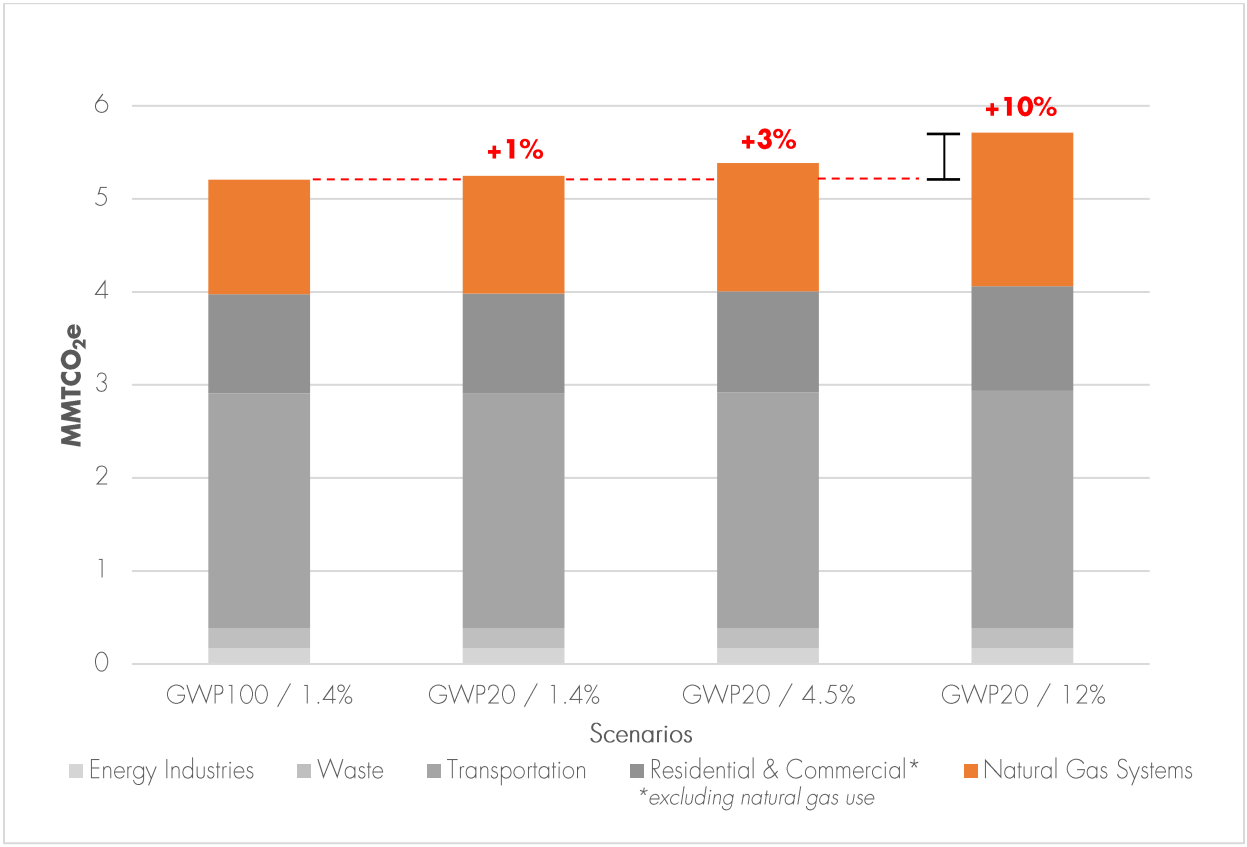
[38] Jeong, Seongeun et al. "Estimating methane emissions in California's urban and rural regions using multitower observations." Journal of Geophysical Research: Atmospheres. doi:10.1002/2016JD025404. AGU Publications. 15 Sep 2016.

For California to reach its 2050 reduction goals, significant efforts will need to be made across all sectors, including the natural gas sector. As California's Scoping Plan relies heavily on the cap-and-trade program to achieve greenhouse gas reductions, it would prove helpful to value methane using GWP_{20}, which would create stronger incentives to reduce methane emissions.

City of San Francisco

Using San Francisco's 2015 emissions of 5.3 $MMTCO_2e$ and the same scenarios used to evaluate national emissions, the following figure shows how previously unaccounted for natural gas leaks in the distribution system alone would add an additional 3 to 10 percent to citywide emissions, depending on the leak rate and under GWP_{20}.

FIGURE 5: CHANGES IN SAN FRANCISCO'S NATURAL GAS SYSTEM EMISSIONS WITH DIFFERENT GWP AND LEAK RATE SCENARIOS



Source: Based on EPA data for USGHGI 2014 (published in 2016)

Proposed Policy Solutions

While the conclusions in this report are troubling, they underscore a clear set of priority actions that cities and states can take, namely, accurately reflecting the global warming potential of methane and other short-lived climate pollutants through new accounting practices, adopting or advocating for stronger leak detection and management policies, and accelerating the transition to 100 percent carbon-free renewable energy for systems that currently run on natural gas.

Importantly, these goals are achievable. Cities and states have flexibility in how they account for short-lived climate pollutants, and as natural gas production and the amount of methane in the atmosphere increase, policymakers would be justified in counting methane and other short-lived climate pollutants based on their GWP_{20} values. This new standard accounting practice could have important effects on cap-and-trade allowance and auction values, increasing the value of immediate emissions reduction from methane and other-short lived gases.

In addition, cities and states should account for leaks more accurately to better understand when, and if, switching from coal to natural gas will provide a climate benefit. If leak rates were zero, the benefits of natural gas would start to be felt in 2040. But if leak rates are 10 percent, there would be no benefits until 2140. Based on analysis in the Clean Power Plan, half of all U.S. emissions reduction are expected to come from coal-to-gas switching. But this is only achievable if leaks are kept below 1.5 percent. At a leak rate of just 4 percent, which is lower than the average of all studies considered in this report, the Clean Power Plan goals could only be met by the most aggressive renewable energy scenario the EPA examined, equivalent to a national 26.3 percent renewable electricity standard.[39] This suggests that substituting natural gas for coal is not an effective climate strategy, and policymakers should emphasize switching from coal to carbon-free renewable energy sources.

Policymakers should also embrace electrifying gas systems, whether for heating, cooling, cooking, electricity generation or transportation. We can think ahead to a system in which we rely largely on renewable sources and energy storage, including renewable sources of biogas, and work backwards from there. Electrification is becoming a greater reality every day as the cost of renewable energy is

[39] "What is U.S. electricity generation by source?" Frequently Asked Questions, U.S. Energy Information Administration. 1 Apr 2016.

declining and availability is increasing through new technologies and market transformation. Cities can play an important role as incubators, and innovators, developing new systems and exporting clean technology domestically and globally.

Priority actions for state and local governments include revisiting assumptions in our own emissions inventories, supporting accurate quantification of leaks, requiring utility reporting of leaks, creating repair ordinances to address leaks during municipal street construction, and working toward city-wide electrification through municipal staff training on heat-pump technologies and all-electric new construction ordinances. A number of these priority actions are detailed below and in *Appendix F* , which contains numerous policy options, including recommend actions for production-oriented local governments.

Ten Priority Action Steps for City Climate Leadership on Methane

1. Change carbon accounting practices. Switch to a shorter time frame for methane emissions (GWP_{20}), use updated leak rate estimates, and advocate for these changes to become the new standard of practice, including in emissions trading systems.

2. Communicate the importance of leaks. Highlight the impact of natural gas leaks and include leak reduction goals in climate action plans.

3. Disclose leaks. Require utilities provide public data that details leaks, including number, location, pipeline, component type, volume leaked, estimated greenhouse gas emissions, and past or planned repairs.

4. Collect more local data on natural gas leak rates. Partner with local or state governments, non-profits, private sector, local universities, utilities, or other entities to conduct bottom-up emissions that quantify city-level leaks.

5. Reduce leaks in local distribution. Require utilities to detect and repair leaks during municipal street or sidewalk construction projects and encourage the prioritization of "super-emitter" sites that account for a large portion of leaks in cities.

6. Incentivize leak repair. Create a carbon emission abatement metric for fixing leaks to incentivize utilities to prioritize non-emergency leak repairs.

7. Prioritize decarbonization. Eliminate code barriers to electrification and require electric-only new construction while phasing in retrofits of other types of buildings, including single family, small multifamily, and municipal operations.

8. Support fuel switching. Fund homeowners at the end of a natural gas distribution line to switch to electricity rather than repairing or replacing natural gas pipelines.[x]

9. Switch to renewable natural gas. Where electrification is not feasible, switch to renewable natural gas sources such as bio-methane from landfills and dairy producers.

10. Create an investment plan. Develop a long-term energy investment plan that considers together aging natural gas infrastructure replacement costs, emission-reduction goals, and climate change adaptation.

In Conclusion

In keeping with the adage that what gets measured gets managed, perhaps one of the most immediate and impactful recommendations in this report is that local governments can, and should, change the way they account for methane. In addition to updating their own practices, local governments can encourage and advocate to those responsible for developing global carbon accounting methodologies to also change their practices to incorporate the full impact of methane. This could have widespread consequences on our shared understanding of the impact methane is having on global warming, and could result in accelerated action in support of fuel switching to renewable, non-carbon emitting sources. In addition, having more accurate and locally specific information about leaks in the natural gas system will help local governments and states advance policies, programs and incentives to aggressively repair leaks while working towards their decarbonization goals.

References

[i] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 2014." *U.S. Environmental Protection Agency*, 15 Apr 2016. https://www3.epa. gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2016-Main-Text.pdf

[ii] Brandt. A.R., et al. "Methane Leaks from North American Natural Gas Systems." *Science Magazine*. Vol 343. Issue 6172 14 Feb 2014 http://science.sciencemag.org/content/343/6172/733

[iii] Miller, Scot M., et al. "Anthropogenic emissions from methane in the United States." *Proceedings of the National Academy of Sciences of the United States of America*. PNAS 2013 110 (50) 20018-20022, http://www.pnas.org/content/110/50/20018.abstract

[iv] Caulton, Dana et al. "Toward a better understanding and quantification of methane emissions from shale gas development." *Environmental Sciences Proceedings of the National Academy of Sciences*, Vol 111 No. 17

[v] Burnham, Andrew, et al. "Lifecycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal, and Petroleum." *Environmental Science and Technology*. 22 Nov 2011. http://pubs.acs.org/doi/abs/10.1021/es201942m

[vi] Howarth, Robert, et al. "Methane Emissions from Natural Gas Systems: Background Paper Prepared for the National Climate Assessment." *Cornell University*, 25 Feb 2012. http://www.eeb.cornell.edu/howarth/publications/Howarth_et_al_2012_National_Climate_Assessment.pdf

[vii] Burnham, Andrew, et al. "Lifecycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal, and Petroleum." *Environmental Science and Technology*. 22 Nov 2011. http://pubs.acs.org/doi/abs/10.1021/es201942m

[viii] Howarth, Robert, et al. "Methane Emissions from Natural Gas Systems: Background Paper Prepared for the National Climate Assessment." *Cornell University*, 25 Feb 2012. http://www.eeb.cornell.edu/howarth/publications/Howarth_et_al_2012_National_Climate_Assessment. pdf

[ix] Howarth, Robert W. "Methane emissions and climatic warming risk from hydraulic fracturing and shale gas development: implications for policy." *Energy and Emission Control Technologies*, 2015. Dovepress 8 Oct 2015

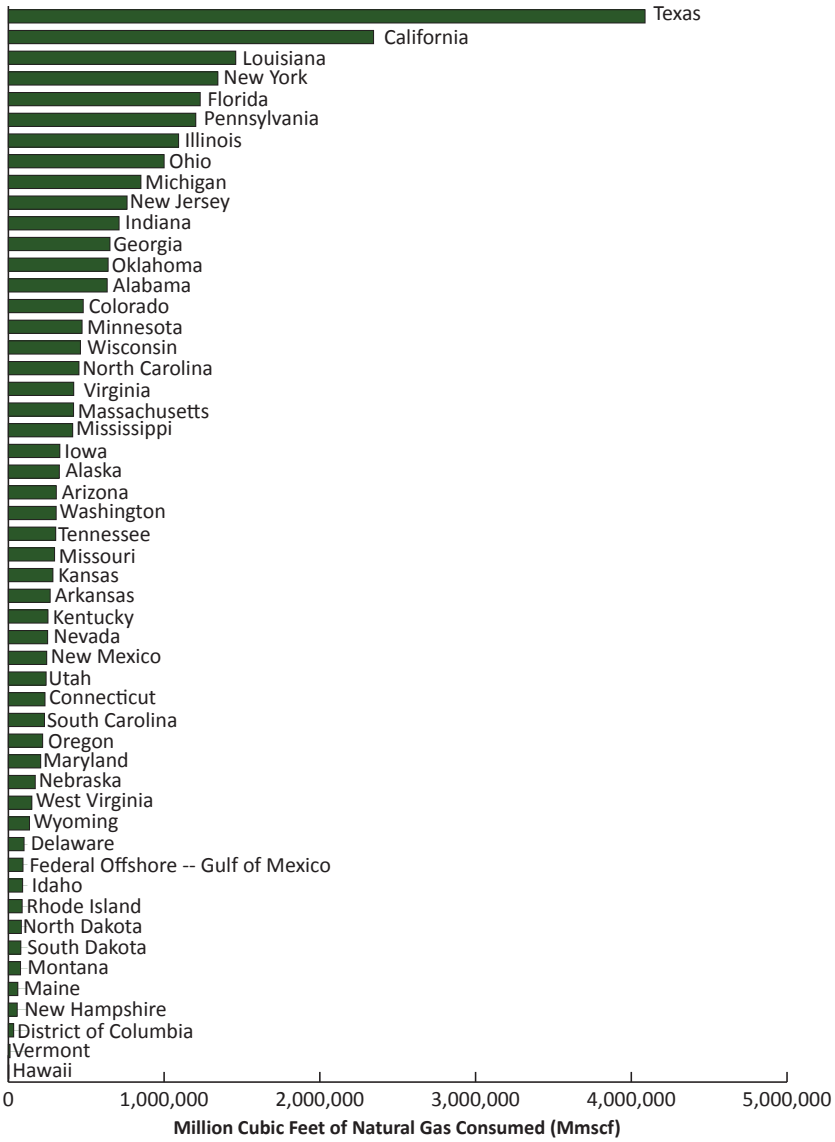
[x] "Pruning the Gas "Tree". *Home Energy Efficiency Team*, 2017. https://www.heetma.org/#

Appendix A: Background on the US Natural Gas System

United States' Natural Gas Consumption

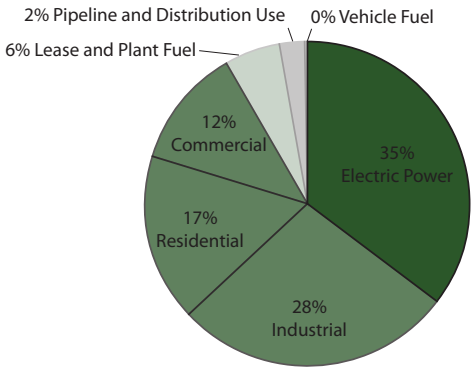
Natural gas is one of the major sources of fuel in the United States. It is distributed to more than 175 million end users through 3 million miles of underground pipelines. Consumption by state varies as demonstrated in Figure A-1.[1] Natural gas is used primarily to heat buildings, cook, heat water, dry clothes, and light outdoor areas.[2] Fifty-six percent of natural gas usage is for building end-use, while 35 percent is used for electric power generation. The remaining 9 percent is used within plants and distribution lines as shown in **Figure A-2.**[3]

Figure A-1: Natural Gas Consumption by State



Source: EIA

Figure A-2: 2015 Natural Gas Consumption by Sector



Source: EIA

In 2015, natural gas comprised 29 percent of the nation's energy usage;[4] the U.S. used 27.3 trillion standard cubic feet of natural gas, an increase by 3 percent since 2014. By 2040, consumption is expected to increase 30 percent, and production is expected to increase 52 percent from 2015 levels **(Figure A-3)**.[5] Natural gas exports are expected to increase as Mexico's domestic natural gas production is declining, while their consumption is increasing[6] To accommodate the increased consumption and exports, shale and tight gas oil plays are becoming an increasing share of our natural gas supply **(Figure A-4)**. This type of extraction typically has a higher rate of leakage, as will be discussed in Part 5.

In 2014, the Energy Information Administration (EIA) estimates that approximately 2,474 trillion cubic feet of technically recoverable resources of dry natural gas are in the United States; at the 2014 rate of consumption, the gas will last approximately 93 years.[7] However, taking into account the expected increase in consumption and exports, that reserve could last only 43 years.

Figure A-3: Natural Gas Production and Consumption - Historical and Projected [8] [9]

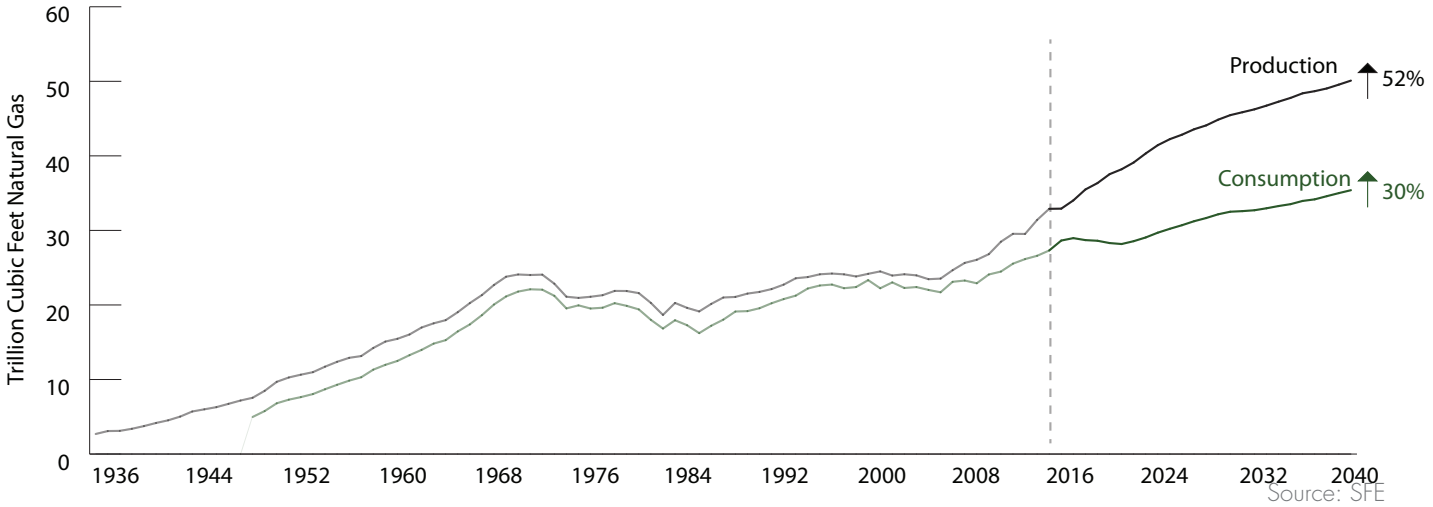
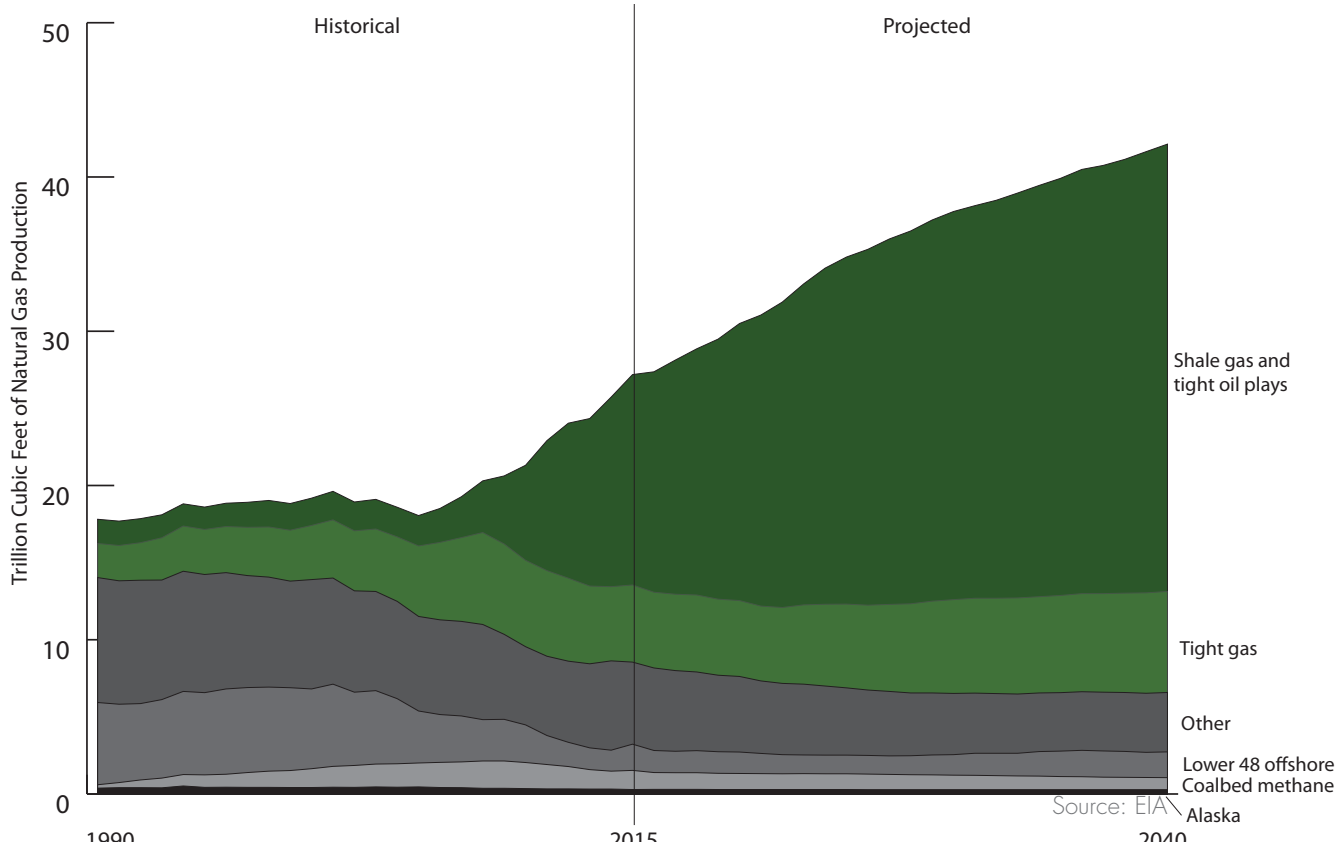


Figure A-4: Historical and Projected Sources of Natural Gas Production [10]



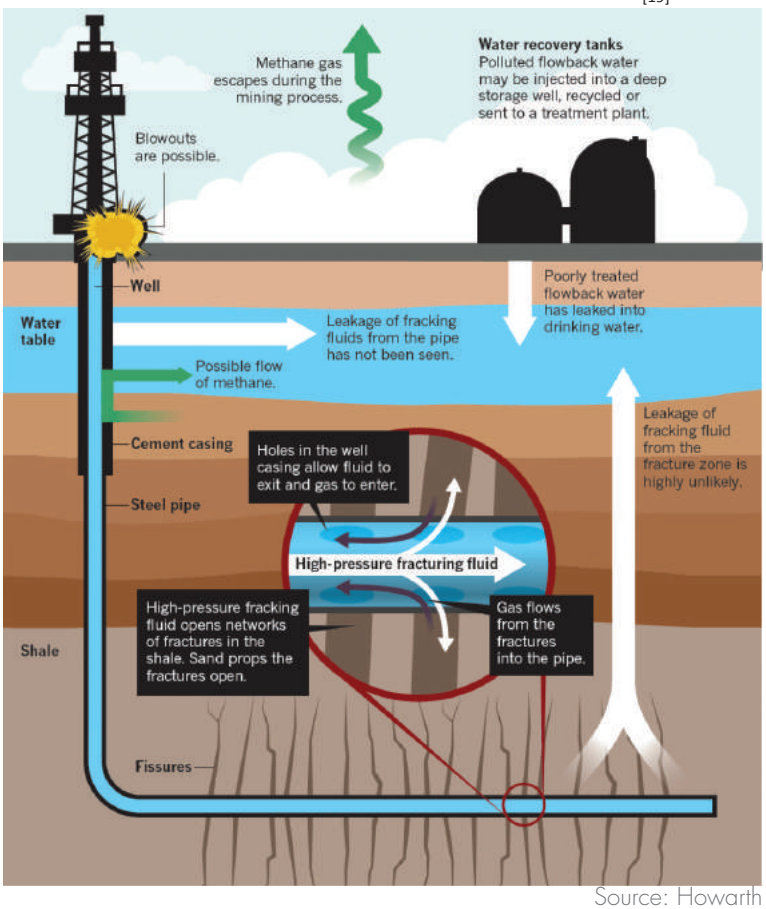
Extraction of Natural Gas

Natural gas is extracted from the earth using either "conventional" or "unconventional" drilling methods. Conventional methods are used to extract gas that has migrated to a reservoir or in areas of low pressure, where gas is relatively simple to extract.[11] As known resources in conventional reservoirs deplete, industry has developed methods to extract gas that has not yet migrated into a reservoir. This gas is, instead, trapped within its source rock in tight pockets. A process called "hydraulic fracturing" ("fracking") uses a series of underground explosions and high-pressure fluid injection to release the gas in these tight pockets. This unconventional process has been applied to 90 percent of the oil and gas wells in the United States to simulate production, often multiple times per well,[12] and it is expected to be the main extraction methodology employed to increase production in the coming years.[13]

The first phase of fracking sometimes involves injecting acidic or basic fluid into the well to break down any natural cements and migrate any mineral deposits that may block access to the gas. Fracturing fluid, a mixture of water and chemicals,[3] is then injected into the well at high pressure to fracture the tight rock. More fracturing fluid mixed with proppants (usually sand or man-made ceramic materials) are then forced into the fractures to elongate and hold them open to allow the gas to flow out of the formation and into the production well. Lastly, the well is flushed out to remove excess fracturing fluid. However, in the case of the Marcellus Shale formation, only 9–35 percent of the final fracturing fluid returned to the surface in the final flush-out phase.[14]

Hydraulic fracturing has been linked to contamination in drinking water,[15][16] earthquakes,[17] and reduction in air quality linked to adverse health effects.[18] **Figure A-5** details the process and some of the areas that contamination can occur. These issues will be discussed in more detail in **Appendix C**.

Figure A-5: Process of Hydraulic Fracturing[19]

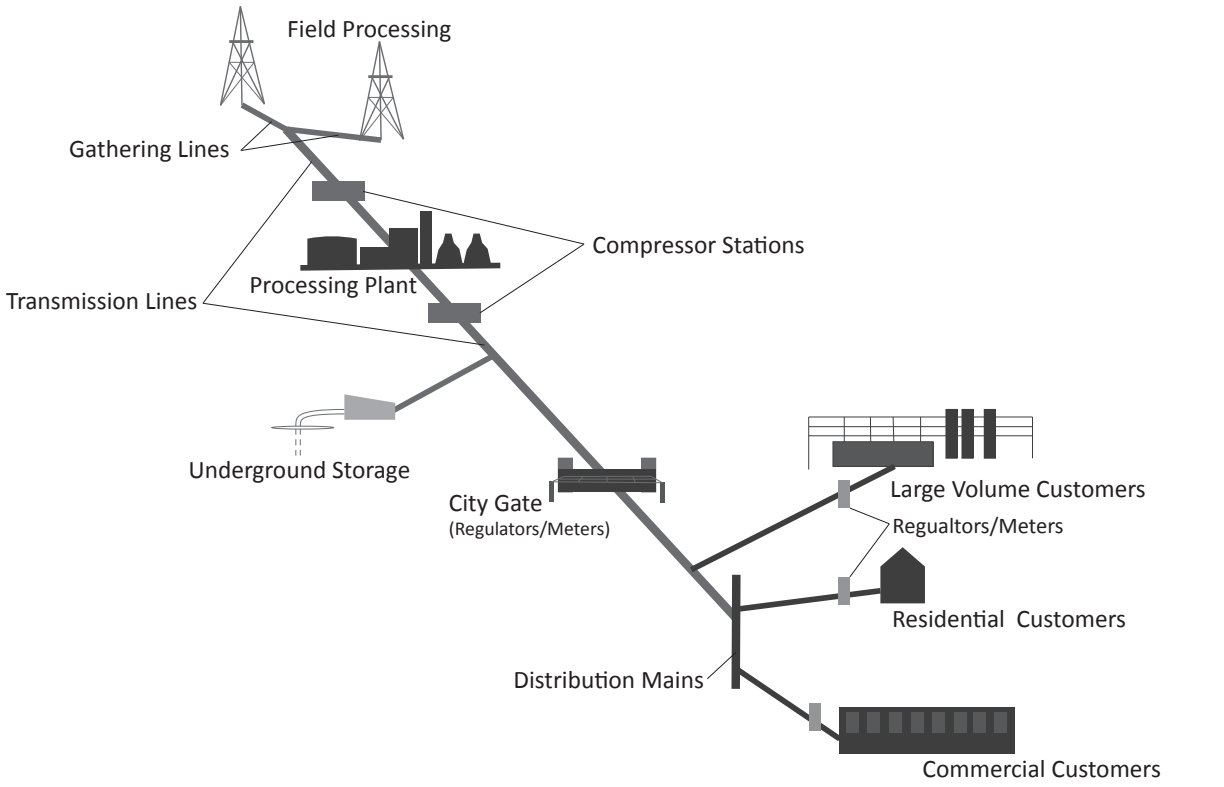


Source: Howarth

Wells are connected to downstream processing and treatment facilities through small-diameter pipes termed "gathering pipes." In instances in which pipeline-quality natural gas is produced directly at the wellhead, the natural gas is moved directly to receipt points along the pipeline grid. Non-pipeline quality natural gas is piped to processing facilities at which oil, water, and elements such as sulfur, helium, and carbon dioxide are removed to create pipeline-quality natural gas. The gas is then transported to customers through larger transmission pipelines and distributed to individual end users through smaller-diameter distribution pipelines. **Figure A-6** illustrates this process.

The nation's production system includes 285,000 producing wells, 125 pipeline companies, and 1,200 distribution companies.[20] Maps of the gas wells, processing facilities, underground storage facilities, and transmission pipeline system can be seen in **Figures A-7, A-8, A-9 and A-10,** respectively.[20][21]

Figure A-6: Diagram of Natural Gas Production to Distribution[22]

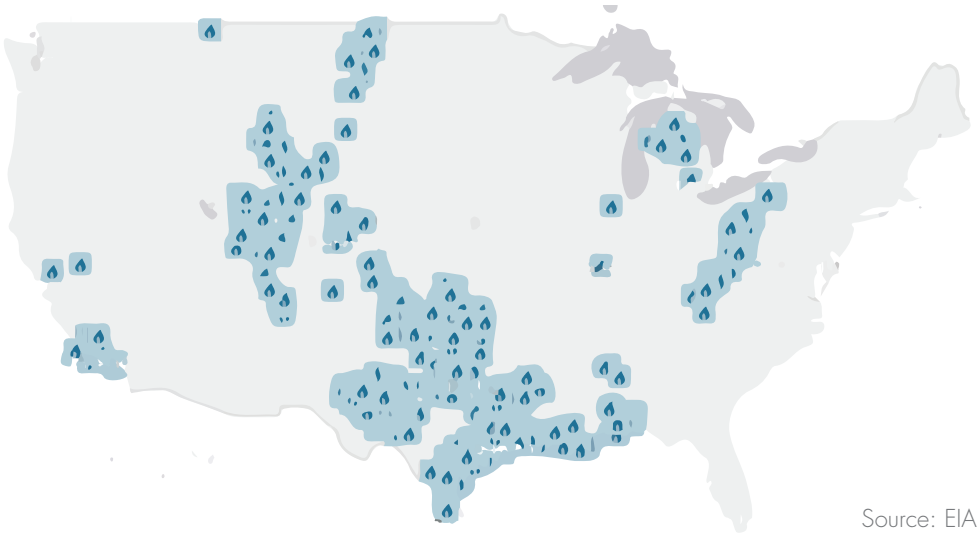


Source: EPA

Figure A-7: Map of U.S. Natural Gas Wells

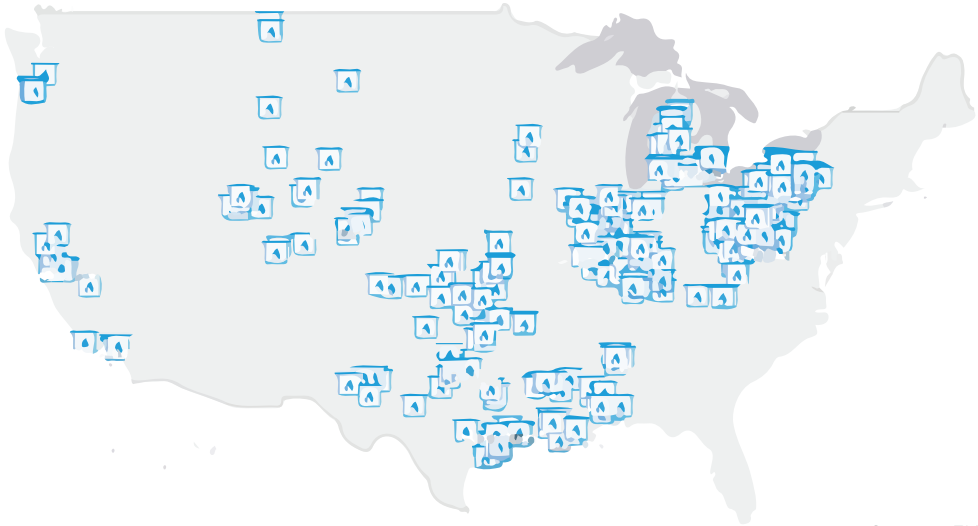
Source: EIA

Figure A-8: Map of U.S. Processing Facilities



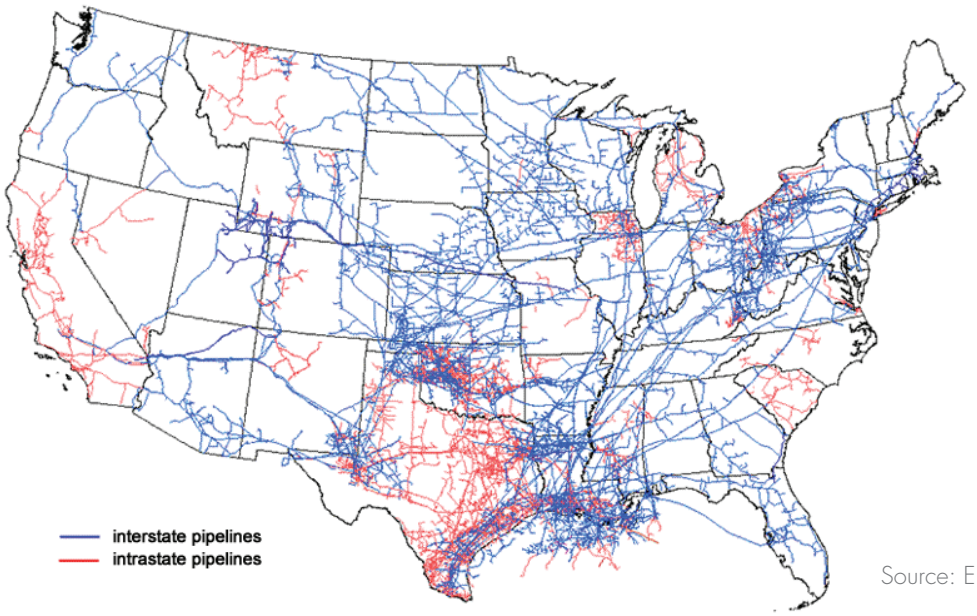
Source: EIA

Figure A-9: Map of U.S. Underground Storage Facilities



Source: EIA

Figure A-10: Map of Natural Gas Transmission Lines



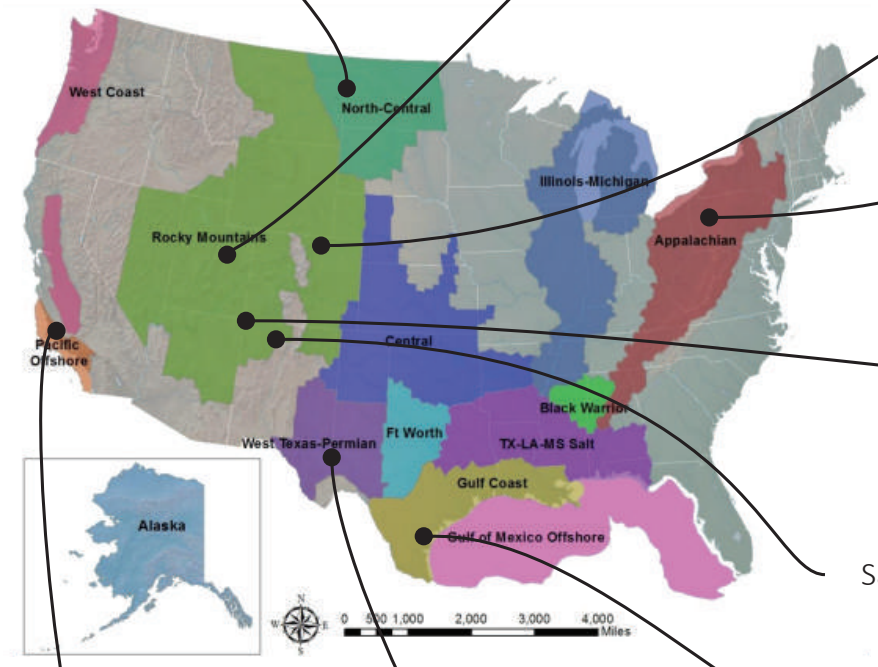
Source: EIA

Field Production

Production Regions

With the rise of unconventional extraction of natural gas and the expected production growth rate of 52 percent by 2040, it is important to understand the emissions from these sites. A summary of the study results by production zone can be seen in **Figure A-11** below.

Figure A-11: Emissions from Production Zones Map



Bakken Shale, North Central
10.10% leak [2.80 - 17.20%]
Schneising et al 2014

Unita Basin, Utah
6.20 - 11.70% leak
Karion et al 2013

Denver - Julesburg Basin
4.0% leak [2.30 - 7.70%]
Petron et al 2012

Marcellus Shale, Appalachian
2.80 - 17.30% leak
Caulton et al 2014

4-Corners Region
14.7% leak [12.5 - 16.7%]
Kort et al 2014

San Juan Basin, Rocky Mountains
31.0% leak
Frankenberg et al 2014

Eagle Ford Shale, Gulf Coast
9.10% leak [2.90 - 15.30%]
Schneising et al 2014

Los Angeles Basin
17.0% leak [13.0- 17.0%]
Peischel et al 2013

Texas, Oklahoma, Kansas Region
2.2% leak [1.0% - 3.4%]
Miller et al 2013

Official U.S. GHGI Estimate: EPA, 2016
0.9% leaked throughout production

USGHGI versus Independent Studies

Leak rates from specific production sites vary, depending on the type of gas and the stage of extraction. Independent studies have measured a leakage rate at specific production zones of 2.2 percent–30.1 percent as shown in **Figure A-12** and **Table 4**.

The low outlier is a bottom-up estimate by Allen et al. showing a 0.42 percent leakage on a national scale. Unfortunately, the study has been shown to exhibit systematic underestimation through the use of equipment with known sensor failures.[23] [24] Allen et al. also declared a conflict of interest, including competing financial interests by the authors of the paper, authors that serve as consultants, are on advisory boards with oil and gas companies, and paper sponsorship by oil and gas companies.

Figure A-12: Percent Leakage from Production Sites

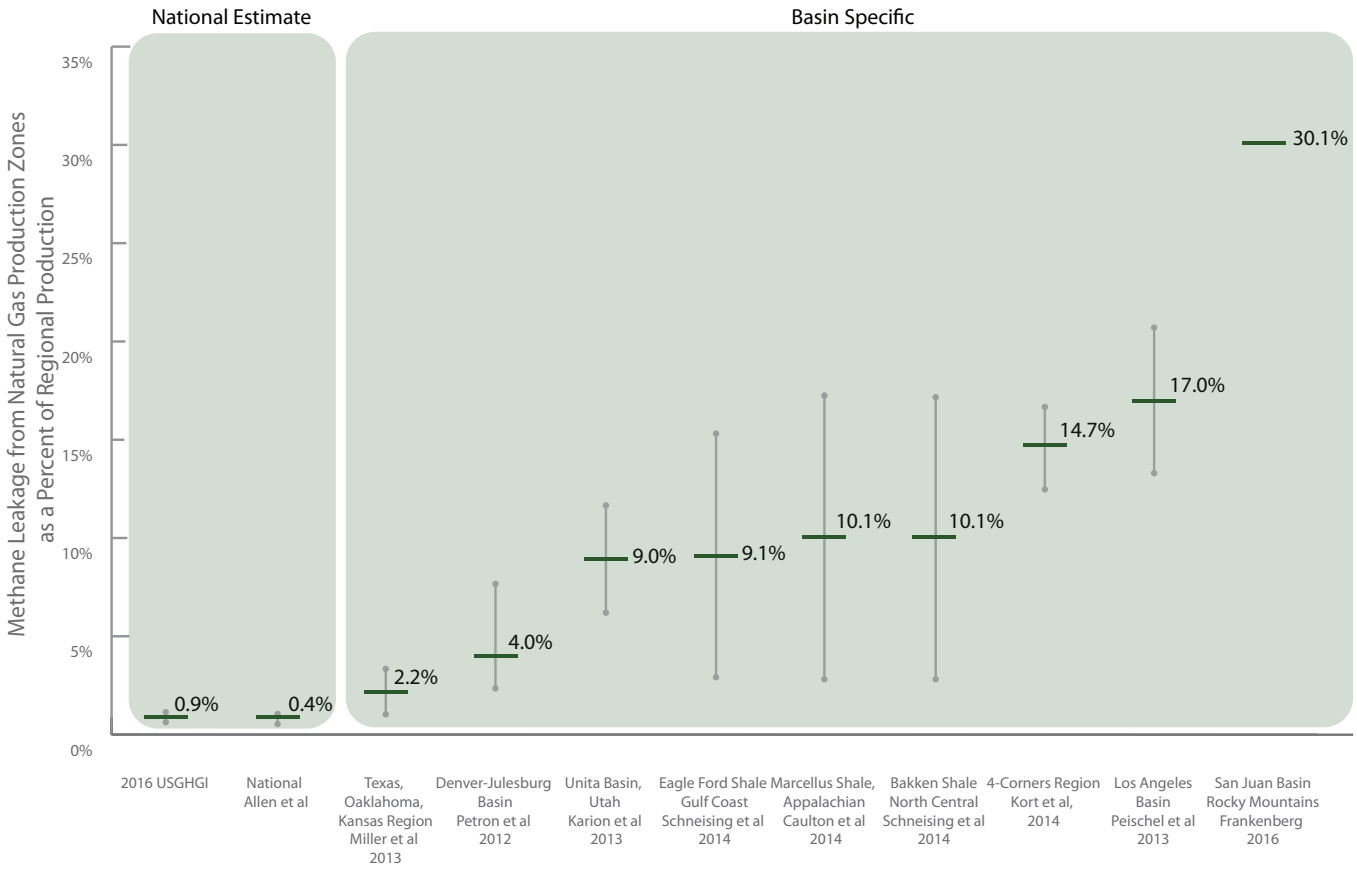


Table 4: Leakage from Production Sites								
Study Area	**Citation**	**Year Measured**	**Study Type**	**Percent Leak Mean** [min - max]	**MMTCO2e Leak (GWP20)**	**MMTCO2e Leak Low Error**	**MMTCO2e Leak High Error**	**Equivalent # of Annual Aliso Canyon Disasters**
National Estimate	EPA GHGI, 2016 [25]	2014	Bottom-Up	0.9%	375			45
National Estimate	Allen et al [3] [26]	2011	Bottom-Up	0.4% [0.6% - 0.8%]	198	181	215	24 [22-26]
Texas, Oklahoma, Kansas Region	Miller et al, 2013, [8] [27]	2007	Top-Down	2.2% [1.0% - 3.4%]	318	146	490	38 [17-59]
Denver - Julesburg Basin	Petron et al, 2012 [28]	2008	Top-Down	4.0% [2.3% - 7.7%]	11	6.2	21.7	1 [1-3]
Uinita Basin Utah	Karion et al, 2013 [29]	2012	Top-Down	9.0% [6.2% - 11.7%]	41	30	52.7	5 [4-6]
Eagle Ford Site Shale	Schneising et al, 2014 [30]	2011	Top-Down	9.1% [2.9% - 15.3%]	46	17	74.0	6 [2-9]
Marcellus Shale	Caulton et al 2014 [31]	2012	Top-Down	10.1% [2.8% - 17.3%]	--	--	--	--
Bakken Basin Shale	Schneising et al, 2014 [32]	2011	Top-Down	10.1% [2.8% - 17.2%]	85	29	141	10 [3-17]
4-Corners Region	Kort et al, 2014,[9] [33]	2003 - 2009	Top-Down	14.7% [12.5% - 16.7%]	507	430	576	61 [51-69]
Los Angeles Basin	Peischel et al, 2013 [34]	2010	Top-Down	17.0% [13.0% - 21.0%]	2.7	2.2	3.3	0.3 [0.2-0.4]
San Juan Basin	Frankenberg, 2016 [35]	2015	Top-Down	31%	507			61

8. Official Allen et al. estimate used for general estimate. As estimate was based on scale of production, uncertainty values scaled up to represent 2014 production metrics.
9. No official estimate given, only range. Midpoint used for general estimate.

Distribution Lines

Of the 3 million miles of underground pipeline within the gathering, transmission, and distribution sectors, almost half were installed during the 1950-60's as consumer demand for natural gas doubled post-World War II. Approximately 0.3 million miles of these pipelines make up the transmission system, and 1.3 million miles comprise the distribution system. The remainder of pipelines are in the gathering system.[36]

Leaks can occur at the many connection points in the system; within the moving parts of equipment when those parts are not fitted property; when changes occur in pressure, weather conditions, or temperature; mechanical stresses; when an improperly fitted connection point starts to wear over time; or when equipment is not operated correctly.[37] Additionally, disturbances resulting from earth movement can result in leaks.[38] The breakdown of leak per the USGHGI can be seen in **Table 3** below.[39] According to the USGHGI, leaks in the mains and service lines make up only 48 percent of the leaks along the distribution lines. The remainder of the leaks can be attributed to metering and regulating stations, customer meters, maintenance venting and pressure releases, and mishaps such as dig-ins.[40] Leaks at customer meters are not within the jurisdiction of local utilities and remain largely unfixed unless there is an emergency. These meters are primarily placed on the outside of homes and businesses and can impact health as discussed in **Appendix C**.

The type and age of pipe are also factors in leakage rates. The most at-risk pipelines to leaks and explosions are unprotected steel and cast iron.[41] Unprotected steel can corrode with age, and cast iron pipelines undergo a process called "graphitization," in which iron degrades over time to form softer elements, which makes the pipelines more prone to cracking.[42] The U.S. Department of Energy put together a table of the states with the most mileage of these at-risk pipelines; see **Table 4** below. These 10 states contain 73 percent of the total at-risk mains nationwide.[43] Other pipeline materials such as plastic still leak and are prone to large incidents. A breakdown of incidents by both age and material can be seen in **Appendix D**.

Table 3: Sources of Distribution Line Leaks per USGHGI

Distribution Segment	Description	Percentage
Metering & Regulating Stations	Custody transfer stations and pressure regulator stations (City Gates)	9%
Main Pipeline Leaks	Distribution pipelines usually 2" to 24" diameter that transport gas from long-distance transmission lines to local service lines	31%
Service Pipeline Leaks	Distribution pipelines usually under 2" diameter that transport gas from mains to end user	17%
Customer Meters	Connection point from service lines to natural gas end use	28%
Routine Maintenance	Maintenance procedures such as venting and pressure releases	1%
Upsets	Leaks due to digging/construction impacts	14%

Table 4: Miles of Leak Prone Iron and Steel Distribution Mains

Rank	State	Leak Prone Iron Mains (Miles)	Leak Prone Steel Mains (Miles)	Total Leak Prone Mains (Miles)	Percent of Leak Prone Mains out of All Mains in State
1	Pennsylvania	3,300	9,200	12,500	26%
2	New York	4,200	7,900	12,100	25%
3	Ohio	580	9,900	10,480	18%
4	California	29	8,400	8,429	8%
5	New Jersey	4,900	2,300	7,200	21%
6	Texas	830	6,200	7,030	7%
7	Massachusetts	3,700	2,800	6,500	31%
8	Michigan	3,000	3,100	6,100	11%
9	Kansas	89	3,400	3,489	16%
10	West Virginia	14	3,100	3,114	29%

Appendix B: Distribution Case Studies

Because EPA emission estimates have proven to lack the breadth of data needed to accurately estimate natural gas emissions, and independent studies identifying emissions exclusively from distribution lines are limited on a national scale, a series of case studies will be evaluated to better understand leaks in the distribution lines. Leaks in distribution lines disproportionately affect cities depending on the level of ratepayer consumption, local environmental conditions, pipeline material type and age, pipeline maintenance, pipeline replacement programs, local and state policies, and proactivity of local utilities and regulatory agencies. Depending on these factors, natural gas leaks could potentially undermine a city's greenhouse gas reduction efforts. Where possible, the Cities of Oakland and San Francisco have calculated a rough estimation of annual emissions from natural gas distribution line leaks.

The majority of the following studies employ bottom-up methodologies using infrared laser analyzers to detect natural gas leaks. Mobile surveyors from sensor manufactorers like Picaro, Los Gatos Research, and LiCor, have a high-precision sensor that can be driven around on a street-by-street basis to measure differences in concentrations of methane, ethane, and other air pollutants found in natural gas. While this sort of estimate and analysis cannot provide a nationwide estimate of emissions, it can provide a means to better understand the potential for leaks in different areas and provide a basic understanding for locally adjusted programmatic and policy shifts.

A series of bottom-up estimates have been carried out in a number of cities. These include small to large cities that were part of different bottom-up and top-down atmospheric studies. The Google and EDF Methane Mapping project did a study in a number of small and large cities across the US; several universities ran one for Boston and Washington DC; and the Air Resources Board-led one for California. **Figure B-1** shows a map of areas that have been studied with an overlay of the natural gas distribution system. A summary of all distribution studies in terms of greenhouse gas emissions' intensity ($MTCO_2e$ per square mile studied) and total emissions (Thousand $MTCO_2e$) is shown in **Figures B-2 and B-3**.

Figure B-1: Map of Distribution Leakage Case Studies with Distribution Pipeline Map Overlay

Figure B-2: Range of Emissions Intensity (Thousand MTCO2e/Square Mile) by Distribution Leakage Case Study

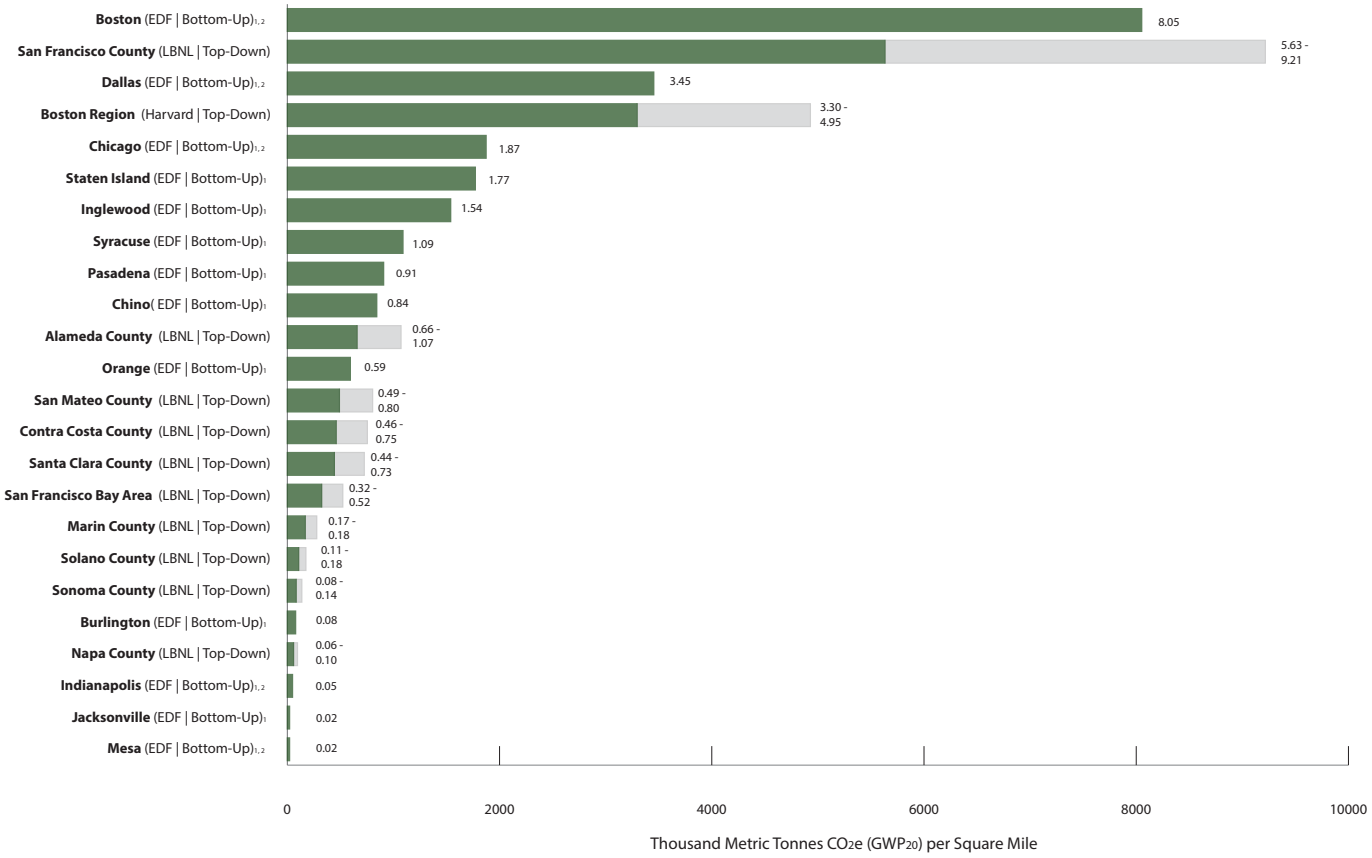
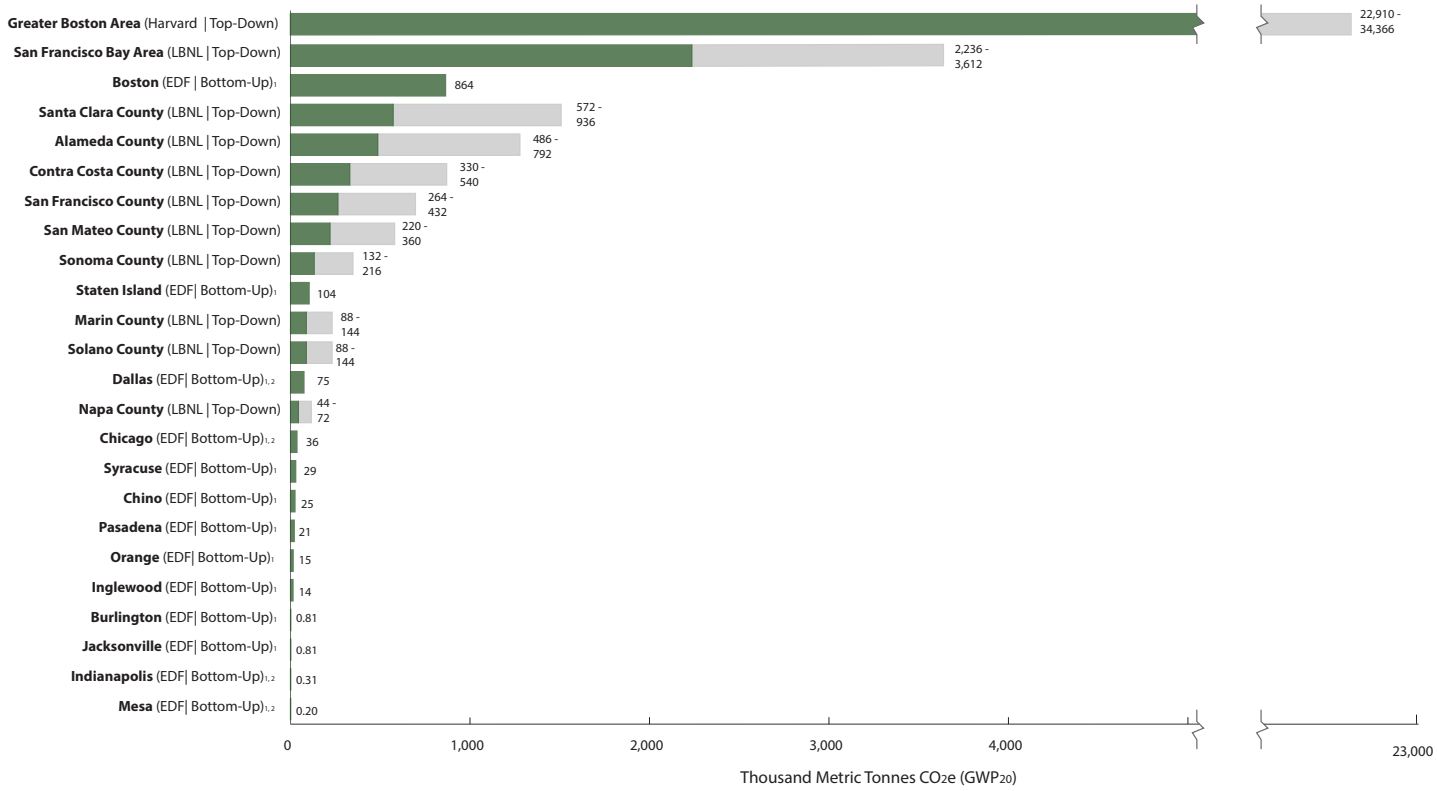


Figure B-3: Range of Total Emissions (Thousand MTCO2e) by Distribution Leakage Case Studies



[1] The Cities of San Francisco and Oakland calculated the annual emissions and emissions factor. These estimations were created using the assumption that the average liters per minute measured in this study are consistent throughout the duration of the year. This assumption and resulting calculation does not represent the view of EDF or Google.

[2] Full city not surveyed in study. See EDF Methane Maps website for survey area.

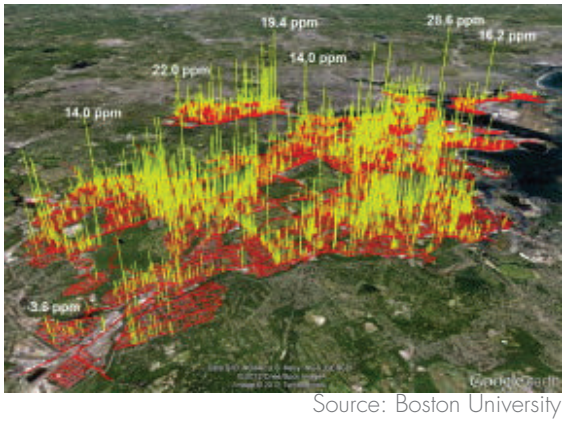
Boston

Forty-five percent of Boston's pipelines are made of corrosive materials, and 50 percent of the pipelines are more than 50 years old.

Study 1:
Researchers: Boston University, Gas Safety Inc., Picarro Inc., Duke University
Dates: August 2011 - September 2011
Study Type: Bottom-Up, Picarro Mobile Spectrometer
Study Area: Whole city
Methane Attribution to Natural Gas: Isotopic Tracers

Results: 3,356 natural gas leaks with methane concentrations up to 15 times that of the background levels were identified (4.3 leaks per mile). Four manhole locations were found with gas concentrations exceeding the explosive limit.[44] The methane plume map from this study appears in Figure B-5 below.

Figure B-4: Boston Methane Concentration Map



Source: Boston University

Study 2:
Researcher: Harvard University, Duke University, Boston University, Hofstra University, et al.
Dates: September 2012 - August 2013
Study Type: Atmospheric readings: Two background sites outside the city and two downtown sites for comparison
Study Area: 7,000 square miles of Boston and surrounding area
Methane Attribution to Natural Gas: Isotopic Tracers of Ethane

Results: 15 billion standard cubic feet of natural gas had been emitted in the area, translating into 24 $MMTCO_2e$ using GWP_{20} (or 7 $MMTCO_2e$ using GWP_{100}). This translates to a 2.7 percent +/- 0.6 percent leak rate within Boston, i.e., just within the transmission, distribution, and end-use sectors. The study determined this was valued at $90 million dollars.[45]

Washington DC

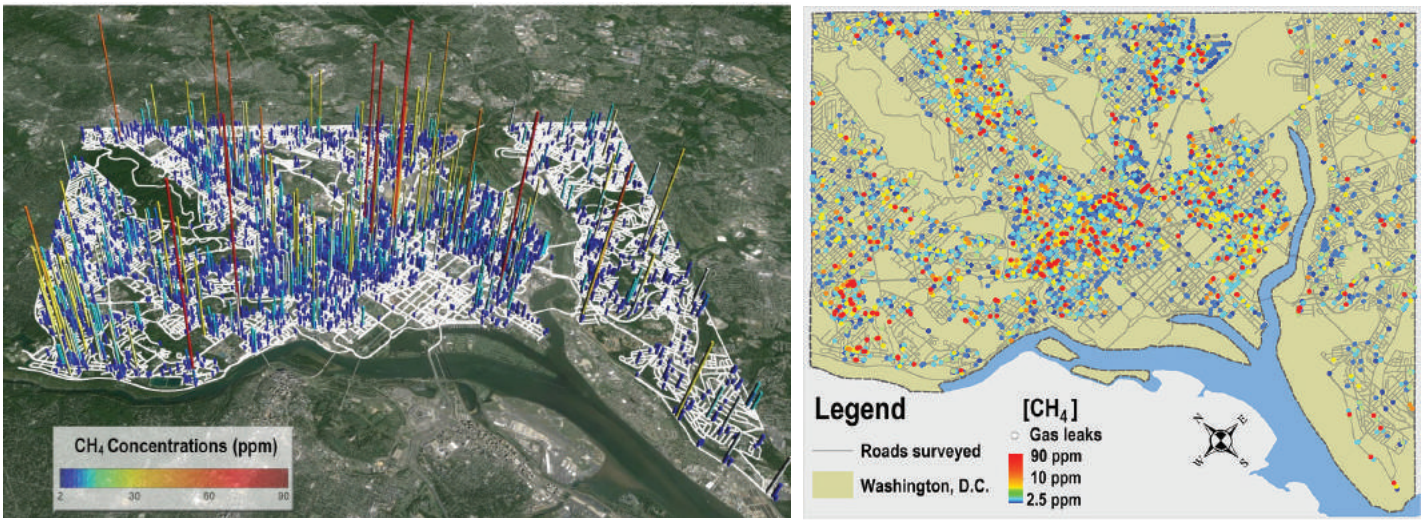
The District of Columbia has 419 miles of known cast-iron pipes, comprising 35 percent of the total pipe inventory.

Researchers: Duke University, Stanford University, Boston University, and Gas Safety Inc.
Dates: January 2013 - February 2013
Study Type: Bottom-Up, Picarro Mobile Spectrometer
Study Area: Whole city, 1,500 road miles
Methane Attribution to Natural Gas: Isotopic Tracers of Ethane and Propane

Results: Over all, 5,893 natural gas leaks were identified, which translates to a density of 3.9 leaks per mile. Additionally, 12 manhole locations were found with gas concentrations that exceeded the explosive limit.

The flow rate of natural gas from the leaks was not calculated in this study; therefore, the overall rate of emissions from the leaks is unknown. However, when compared to a similar Boston study (**See Table 5**), it was found that the density of leak profiles was very similar; however, the concentration of methane at the leaks was significantly higher in Washington, D.C. This city had 51 leaks that emitted higher concentrations of methane than the largest leak in Boston, and its maximum leak was more than three times larger than the largest leak in Boston.[46]

Figure B-5: Washington DC Methane Concentration Maps



Source: Duke University

EDF and Google Methane Maps

In a joint project conducted by the Environmental Defense Fund (EDF) and Google Earth Outreach, Google Street View cars were equipped with methane sensors and surveyed representative areas in various U.S. cities. This method locates, sizes, and estimates the flow rate of natural gas leaks from local distribution systems, which helps utilities to prioritize the larges leaks or most leak-prone pipes for repair and replacement.

Leaks in the natural gas distribution system are not typically accounted for in local greenhouse gas inventories. In an effort to estimate the amount of GHG emissions generated by leaks, this study estimated the MTCO2e from leaks for each city based on the number of leaks detected and then compared this number to the city's published greenhouse gas inventory. This estimation was created independent of EDF and Google Earth Outreach, and does not represent their views.

Throughout these studies, it is generally found that cities with older pipelines or pipelines made of leak-prone materials (i.e., cast-iron and unprotected bare steel), have higher emissions from natural gas distribution pipeline leaks than cities that use more modern materials such as plastic. While only two cities with publically owned pipelines were surveyed, the cities with city-owned utilities or public trust utilities showed less emissions from leaks in natural gas pipelines than those with private utilities. See **Table 5** for details.

Table 5: Summary of City Natural Gas Emissions Surveys

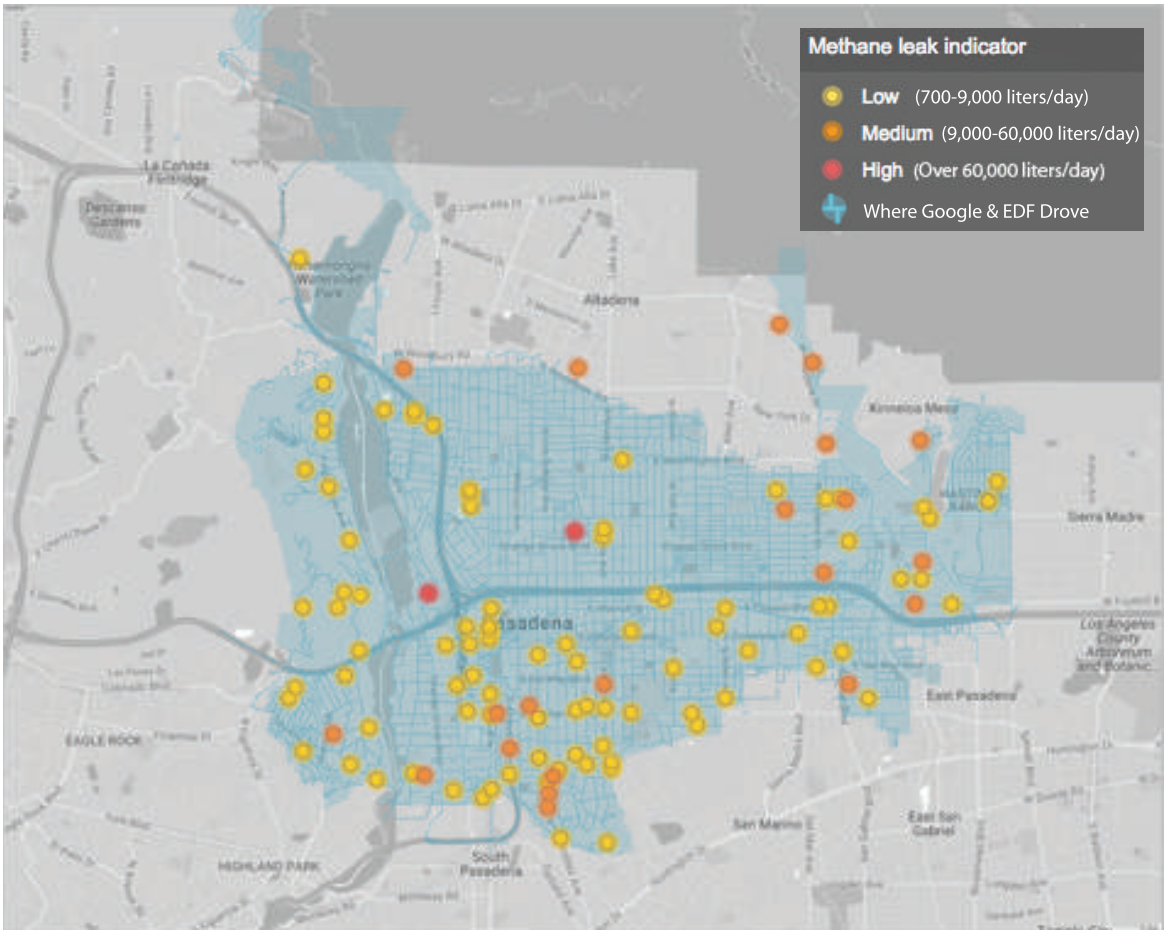
EDF Data [47]			2016 PHMSA Data		Calculated Data[3]			Utility Data	
City	# Of Leaks Detected	Leaks per Mile	Percentage of Corrosive Pipe Materials (per Utility)	Percentage of Pipes over 50 Years Old	Calculated Emission Factor (Mscf/ mile-year)	Annual Emissions (MTCO2e per year using GWP_{20})	% Addition to City's Community Greenhouse Gas Inventory	Utility Company	Utility Type
Boston	2320	1.00	45%	50%	243.6	864,208	14% (2013)	National Grid	Private
Staten Island	990	1.00	25%	Over 50%	68.7	104,015	Underest [4]	National Grid	Private
Dallas	540	0.50	13%	50%	45.6	75,297	17% (2012)	Atmos Energy, Mid-Texas	Private
Chicago	349	0.33	37%	38%	22.2	35,500	0.1% (2010)	Peoples Gas	Private
Syracuse	224	0.50	45%	Over 50%	42.3	28,980	2% (2010)	National Grid	Private
Chino	69	0.20	16%	38%	46.7	24,633	12% (2014)	Southern CA Gas Co.	Private
Pasadena	114	0.25	16%	38%	29.4	20,527	1% (2009)	Southern CA Gas Co.	Private
Orange	91	0.17	16%	38%	18.0	15,045	No Inv.	Southern CA Gas Co.	Private
Inglewood	64	0.20	16%	38%	27.6	13,514	2% (2010)	Southern CA Gas Co.	Private
Jacksonville	87	0.11	3%	20%	7.8	9,273	0.2% (2013)	Peoples Gas System	Private
Burlington	11	0.10	Not Reported	7%	4.8	809	No Inv.	Vermont Gas Systems	Private
Indianapolis	5	0.01	Less than 1%	Not Reported	0.25	380	No Inv.	Citizen's Energy Group	Public Trust
Mesa	3	0.02	Not Reported	13%	0.71	196	No Inv.	City of Mesa Municipal Sys	Municipal

[3] The Cities of San Francisco and Oakland calculated the annual emisisons and emissions factor. These estimations were created using the assumption that the average liters per minute measured in this study are consistent throughout the duration of the year. This assumption and resulting calculation does not represent the view of EDF or Google.

[4] Inventory includes fugitive emissions for entire New York Area. For the City of New York, 318,000 MTCO2e was estimated from natural gas distribution line leaks. Staten Island consists of only 19% of the land mass of New York City, yet the Google & EDF study found 33% of the estimated fugitive emissions to be there. It is possible that the inventory is underestimated.

An example of the information found on the EDF Methane Maps Web page is seen in **Figure B-6.** More information can be found on their site: **https://www.edf.org/climate/methanemaps**.

Figure B-6: Pasadena Methane Leak Map

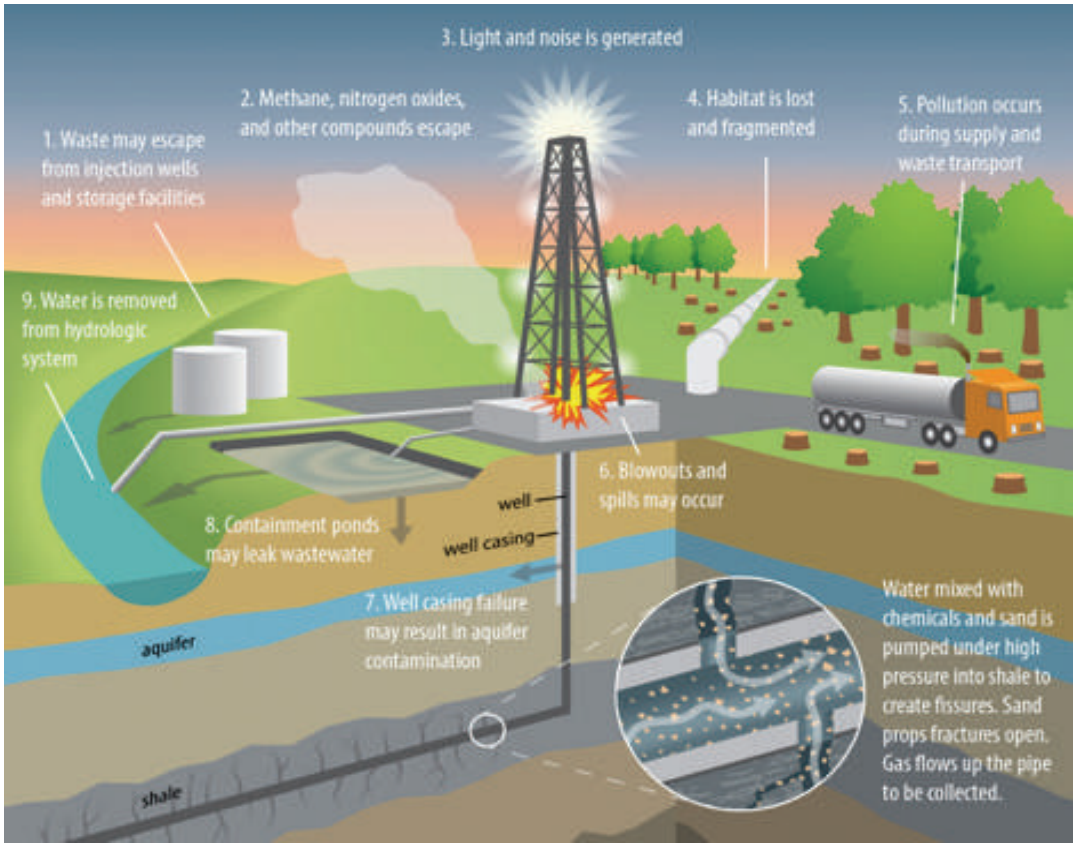


Source: EDF

Appendix C: Public Health Impacts

Emissions from the natural gas system, from extraction to distribution and end-use combustion, impact our health. Populations most at risk include: those who live close to extraction wells, production facilities, and storage centers; young and active populations that spend more time outdoors; and populations of seniors, children, and pregnant women who can be more affected by contaminants.[48] Sources of harmful health effects include both the diminished air quality due to emissions of methane and other chemicals found in natural gas and the contamination of groundwater from well-casing leakage or evaporative pond leakage. **Figure C-1** shows areas of air and water contamination at a production zone.

Figure C-1: Diagram of Possible Contamination due to Hydraulic Fracturing[49]



Source: Princeton

Air Quality Impacts from Natural Gas Distribution

Impacts from Enclosed Methane Leaks

Aside from the health impact from increased ground-level ozone, pipeline leaks can pose dangers to health as well. Small leaks within enclosed spaces can accumulate over a period of time and cause serious, sometimes fatal, health hazards as they add a significant amount of pollutants, which stress the immune system and other bodily functions.

Table 6: Health Impacts of Exposure to Enclosed Leaks[50]	
Low Concentrations	• Pneumonia • Nausea • Vomiting • Irregular breathing • Memory loss • Fatigue • Sinus pain • Headache
High Concentrations	Methane can cause: • Dizziness • Headache • Fatigue • Nausea • Irregular breathing Ethanol the odorant in natural gas can cause: • Dizziness • Headache • Vomiting • Shivering • Fever • Unconsciousness
Very High Doses	• Asphyxiation (can lead to loss of consciousness, brain damage, and death - people with high chemical sensitivity are more susceptible to this)

Impacts from the Combustion of Natural Gas

When natural gas is burned, it produces nitrogen oxides, carbon dioxide, and methane and also releases water vapor, ashes, and VOCs. Households that use natural gas have much higher nitrogen dioxide (NO_2) levels than homes with other fuel uses. Exposure to high levels of NO_2 and other nitric oxides is very dangerous as it interferes with the blood's ability to carry oxygen through the body. Health effects are described in the following table.

Table 7: Health Impacts of Exposure to Combusted Natural Gas[51]

Low Exposure - Combination of Releases	• Contributes to asthma • Intestinal problems • Harm to reproductive organs • Depression • Pain in hands and legs
Exposure to Nitrogen Oxides [52]	• Headache • Fatigue • Dizziness • Blue color of skin and lips • Collapse • Rapid burning • Swelling of tissues in throat and upper respiratory tract • Difficulty breathing • Throat spasms • Fluid buildup in the lungs • Death
Exposure to Nitrogen Dioxide	Contributes to: • Reduced lung function • Increased susceptibility of asthma • Worsening symptoms of asthma • Increased likelihood of developing allergies • Irritation to eyes, nose, throat, and lungs At high concentrations: • Extensive lung damage

Air Quality Impacts from Natural Gas Production

Impacts from Leaks at Production Zones

Methane and black carbon are the only two agents that are known to cause both warming and diminishing air quality. While methane is a dangerous chemical to breathe in high quantities, it can also diminish regional air quality because of its ability to create ground-level ozone. Methane combines with either the nitrous oxides or the volatile organic compounds (VOCs), both of which are emitted at production zones, and react with sunlight to create ground-level ozone, or smog.[53]

Table 8: Health Impacts of Smog[54]

Short-Term Exposure	• Coughing • Difficulty breathing • Fatigue • Nausea • Lung damage • Irritation to eyes, nose, and throat • Increased susceptibility to lung infection • Lung disease aggravation • Increased frequency of asthma attacks • Increased risk of early death from heart or lung disease
Long-Term Exposure	• Lung tissue damage • Reduction in lung function
Other	• Crop yield loss

Studies by the National Oceanic and Atmospheric Administration (NOAA) found that in the remote natural gas reserve called the Uintah Basin, ground-level ozone surpassed federal health standards even during the winter while gas is in production. In the summer, ozone levels usually increase as more intense sunlight is necessary to spark the chemical reactions that create ozone. It is also more typical to see ozone pollution in more urban areas, where transportation modes emit more nitrous oxides and VOCs. In the Uintah Basin, it was found that the levels of VOCs were so high they triggered ozone-forming reactions themselves. In 2013, ozone around this basin exceeded national air quality standards 49 times during the winter. To compare, the dense urban area of Riverside exceeded national air quality standards for ozone about half that many times during the summer.[55]

Impacts from Exposure to Chemicals Used at Production Zones

The process of recovering natural gas depends on the use of products containing over 1,000[56] chemicals, including at least 100 known or suspected endocrine-disrupting chemicals.[57] More than 75 percent of the chemicals identified could affect the skin, eyes, and other sensory organs, as well as the respiratory and gastrointestinal systems. Approximately 40–50 percent could affect the brain and nervous system, immune and cardiovascular systems, and the kidneys. Thirty-seven percent could affect the endocrine system, and 25 percent could cause cancer and mutations.[58]

At the production site, leaks of natural gas and the chemicals used in fracturing fluid, can cause compounding air quality issues. Natural gas contains contaminants such as polychlorinated biphenyl, benzene, toluene, radon, hydrocarbons, particulate matter, nitrous oxides, and volatile organic compounds. The inhalation of these chemicals can pose serious health threats, including reproductive harm and cancer.

Table 9: Health Impacts of Chemical Exposure [59]

Radon	• Known to the State of California to cause cancer
Benzene	• Known to the State of California to cause cancer • Various forms of leukemia, anemia and other blood disorders • Immunological effects • Maternal exposure to ambient levels associated with birth defects
Toluene	• Known to the State of California to cause reproductive harm
Xylene	• Irritation to the eyes, nose, throat • Difficulty breathing • Impaired lung function • Affect the nervous system
Volatile Organic Compounds *Can vary greatly from being highly toxic to having no known health effects, depending on the compound*	Generally, short-term exposure can cause: • Eye and respiratory tract irritation • Headaches • Dizziness • Visual disorders • Fatigue • Loss of coordination • Allergic skin reactions • Nausea • Memory impairment
	Long-term exposure can cause: • Damage to the liver, kidneys, and central nervous system

A person's residential proximity to a production site has been shown to determine the risk of cancer. Benzene, xylene, and hydrocarbons are known as major contributors to the 40 percent increase in the risk of cancer for residents living within a half mile of a Colorado production site versus the residents who live farther away.[60]

Water Quality Impacts

Generally, natural gas production is linked to groundwater contamination with benzene, toluene, ethyl benzene, and xylene (BTEX), as described earlier, and heavy metals. In Pennsylvania, during the natural gas production boom, 250 instances of impacted water supplies were confirmed by the Department of Environmental Protection to have resulted from oil and gas operations.[61] Groundwater near natural gas productions wells can become contaminated with production chemicals; the unsafe release of fracturing fluid can contaminate downstream water supplies; and surface spills can contaminate groundwater. The following Case Studies provide more insight into the risks:

Piceance Basin

A 2013 study in Colorado compared water samples in areas with high natural gas activity versus those with limited development. Endocrine-disrupting chemicals were found in high-development areas compared to areas with limited development. The Colorado River, a drainage basin for the region, exhibited moderate levels of endocrine-disrupting chemicals, or chemicals that have the ability to disrupt normal hormone activity, indicating that natural gas-related spills surrounding the river could be contributing to endocrine-disrupting chemical activities.[62]

Marcellus Shale Region

Several studies indicate degradation of ground and surface waters in the dense drilling regions of Pennsylvania. Higher elevations of thermogenic (heat-producing) methane were found in private well waters within 1 kilometer of one or more gas wells; elevated levels of chloride and bromide in downstream waters consistent with the production waters used with Marcellus extraction; and Radium 226 concentrations in near-source sediments were found to be approximately 200 times greater than upstream and background sources. The data suggests that contamination most likely resulted from poor well casting.

Texas Barnett Region

High levels of the heavy metals strontium, selenium, and arsenic were found in private wells located within 2 kilometers of active gas wells relative to baseline data (before natural gas extraction started), and relative to private wells located farther from the drilling site. Shallower water wells near the drilling area showed the highest level of contamination.

Kentucky (Appalachian Region)

The release of hydraulic fracturing fluid into a Knox County stream resulted in fish stress and mortality. Water analysis showed elevated conductivity, lowered pH and alkalinity, and toxic levels of heavy metals.

Colorado

Seventy-seven surface spills impacting groundwater were reported in a one-year period. Of these, 62 included the BTEX chemicals, most of them in excess of federal standards.[63]

Soil and Street Tree Health Impacts

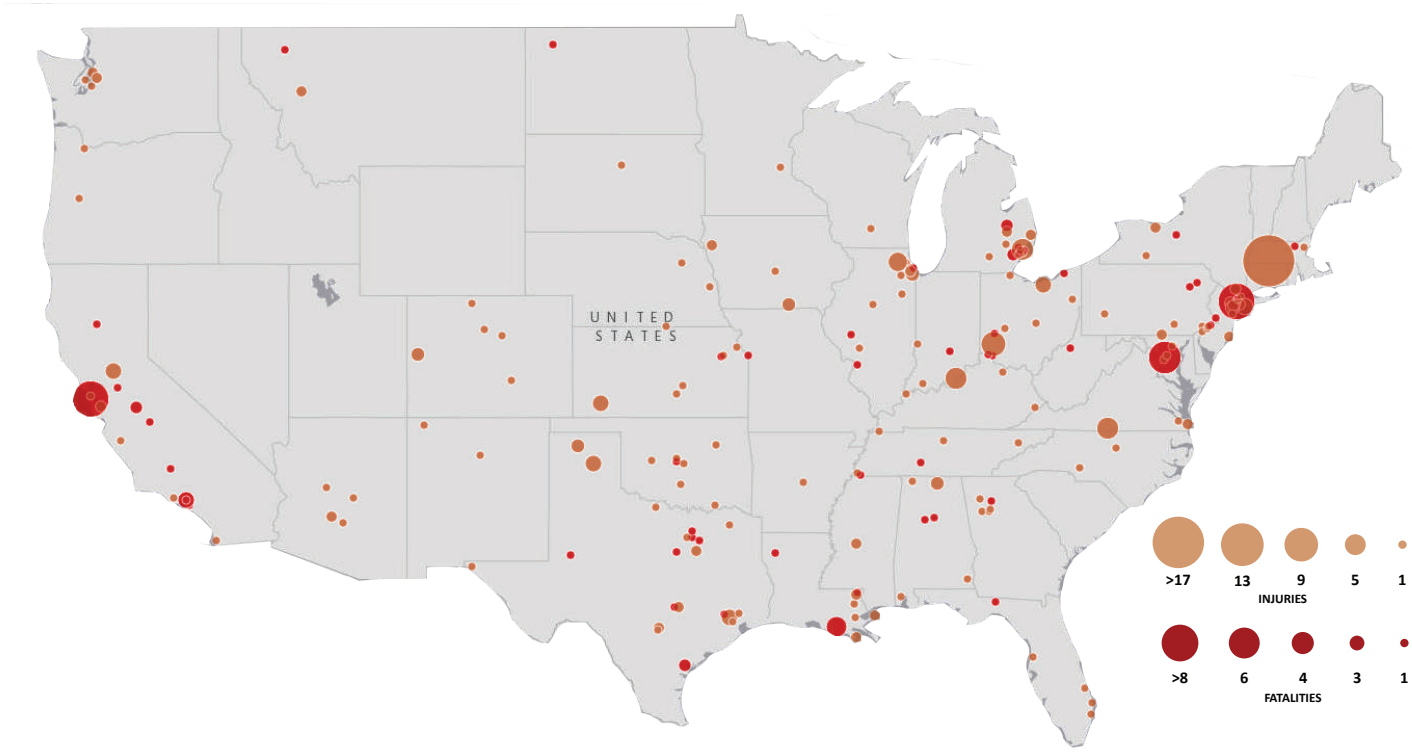
Leaks of natural gas have been proven to deplete the oxygen levels in soil, causing the death of trees and foliage. J. Hoeks first proved this in 1972. The microbial analysis of these studies demonstrates that when natural gas is present, methane-consuming bacteria multiply in the contaminated soil, using up the oxygen and giving off carbon dioxide.[64] It is common practice for utilities to find gas leaks through plant and tree death. Municipalities have sued gas companies for the cost of tree deaths as this is a large cost incurred by municipalities.

Appendix D: Public Safety Impact

Incidents Along the Natural Gas Distribution Lines

Public safety issues arise when highly flammable gas is transported across the United States through aging infrastructure. On average, 236 incidents, 14 fatalities, 66 injuries, and $198 million in damages have occurred every year since 2010 along the natural gas pipeline system. **Figure D-1** shows the injuries and fatalities that have occurred from natural gas pipeline incidents.[65]

Figure D-1: Pipeline Incidents Since 2010 that Have Resulted in Hospitalization or Fatalities [66]



This map excludes incidents from the remainder of the natural gas system; however, it is worth noting that fatalities over the last decade within the oil and gas extraction, well-drilling, support activities, and pipeline construction industries have averaged 133 fatalities per year.[67]

Table 10 shows the year-by-year breakdown of reported incidents from the natural gas pipeline system.

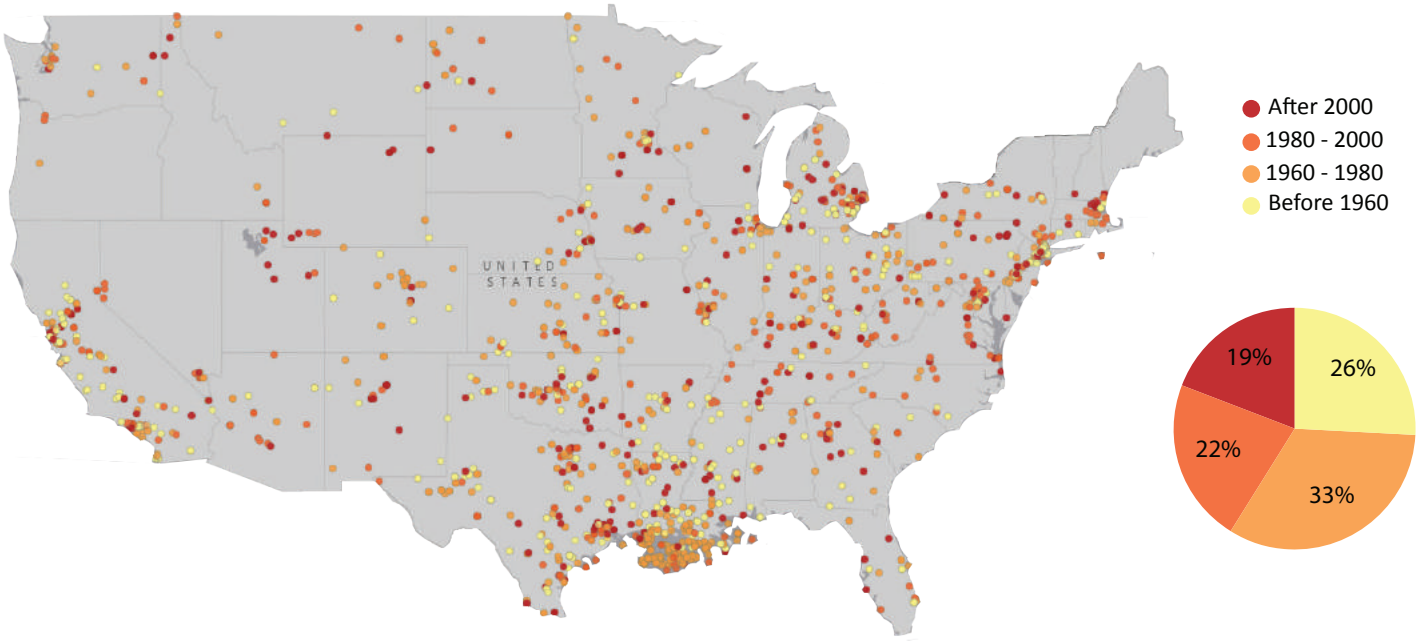
Table 10: Pipeline Incidents - 20 Year Trends[68]				
Year	Number	Fatalities	Injuries	Total Cost As Reported
1997	175	10	72	$24,571,280
1998	236	19	75	$63,542,428
1999	172	18	88	$43,754,779
2000	234	37	77	$41,267,095
2001	211	7	51	$37,745,711
2002	184	11	49	$50,519,071
2003	238	12	66	$71,640,969
2004	294	18	44	$101,815,498
2005	350	15	45	$939,008,498
2006	285	21	34	$76,863,443
2007	279	11	39	$93,460,094
2008	284	6	54	$417,242,011
2009	285	9	60	$104,900,306
2010	236	21	105	$617,306,887
2011	247	13	54	$153,025,323
2012	206	9	53	$84,355,911
2013	217	8	38	$71,434,907
2014	250	19	94	$131,882,457
2015	251	11	49	$87,000,876
2016	216	14	77	$109,758,317
Grand Total	4,850	289	1,224	$3,321,095,861
20 Year Average 1997 - 2016	243	14	61	$166,054,793
Average 2012 - 2016	228	12	62	$96,886,494

The years 2005 and 2010 also proved to be very costly years. In 2005, the local gas distribution company in New Orleans, Entergy New Orleans, Inc., reported a total cost to repair the natural gas system of $470 million,[69] as multiple leaks were reported throughout the entire city that needed repairs as a result of Hurricane Katrina.[70] In 2010, a 30-inch carbon-coated transmission pipe ruptured in San Bruno, California, resulting in eight fatalities, 51 injuries, and $560 million in reported total costs.[71]

The maps on the following pages use data from the Pipeline and Hazardous Material Safety Administration (PHMSA) to better understand pipeline incidents that occurred from 2010-2015. The leaks shown on the maps contain data about pipeline incidents reported to the PHMSA - including incidents by pipe age and pipe material, the size of the gas leak, and the cost incurred.

From the incidents reported to PHMSA, the breakdown of installation year (or pipe manufacture year in which the installation year is not available) is characterized in **Figure D-2** below. Prior to 1940, the primary pipeline material used was cast or wrought iron. In the 1940-50's, a transition to steel pipeline only was made, and after 1970, plastic piping began to be used for smaller diameter pipelines.[72]

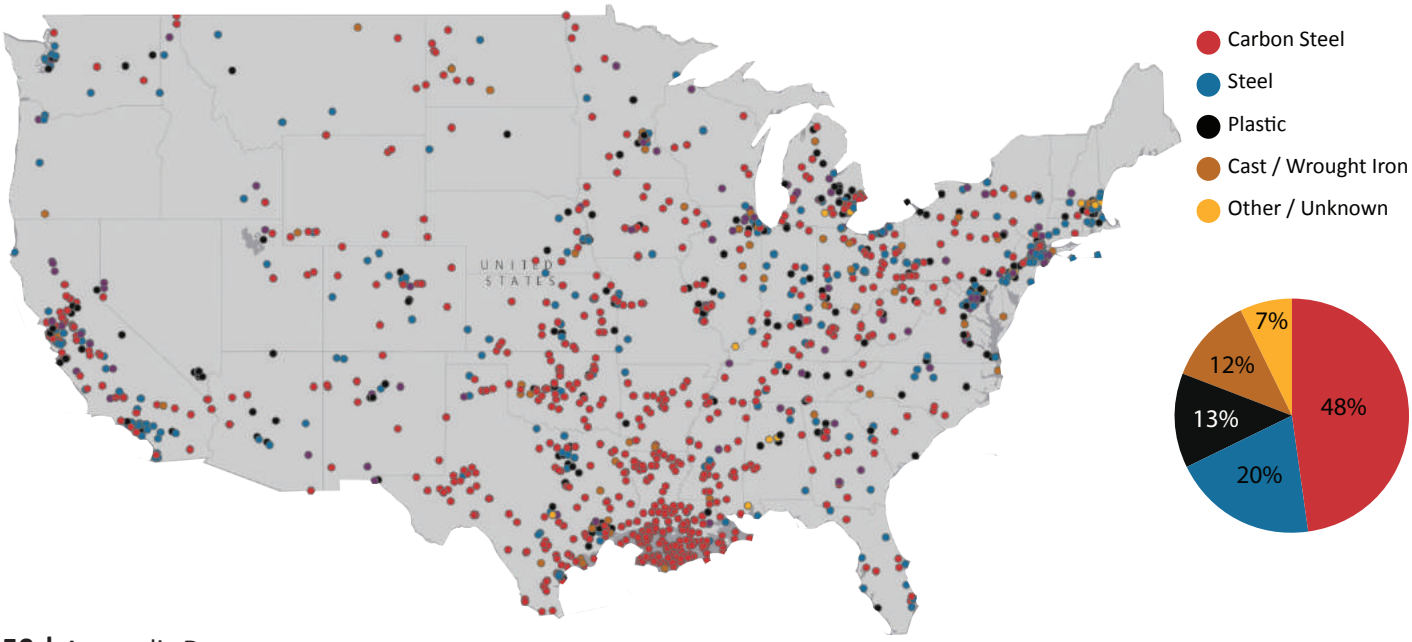
Figure D-2: Pipeline Incidents Since 2010 by Installation Year [73]



Each material has distinct failure mechanisms as they age. Cast iron's brittle properties make it subject to cracking and breaking. Ground movement and large temperature fluctuations are a particular threat. Steel pipe runs the risk of corrosion. Federal pipeline safety rules mandated cathodic protection of all steel pipe installed after 1970. Some classifications of plastic pipeline have shown to be subject to premature failure as well. Regardless, pipeline incidents are distributed fairly evenly across installation years.

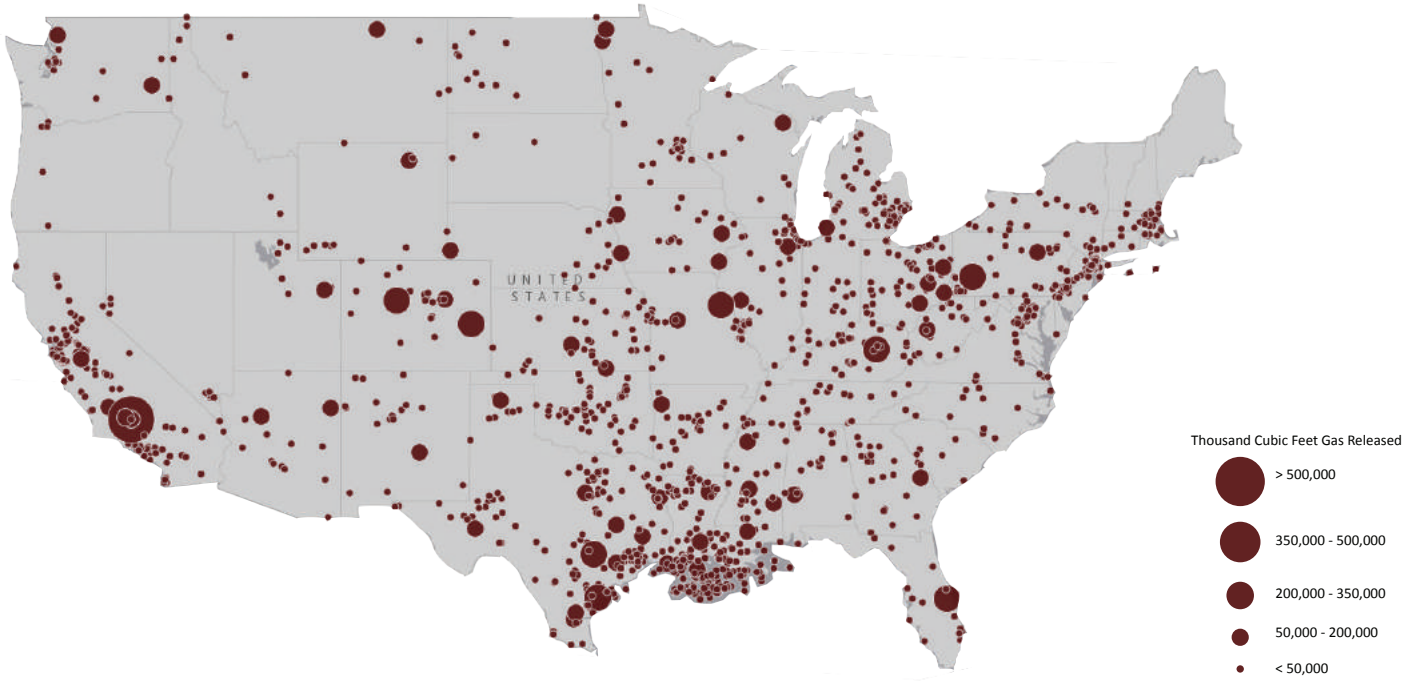
Of those incidents reported to PHMSA, the breakdown of pipe material is characterized within **Figure D-3** below. In both maps, it is important to note the prevalence of failures of pipeline installed post-2000 (19 percent of the incidents since 2010) as well with plastic piping (13 percent of the incidents since 2010).

Figure D-3: Pipeline Incidents Since 2010 by Pipeline Material [74]



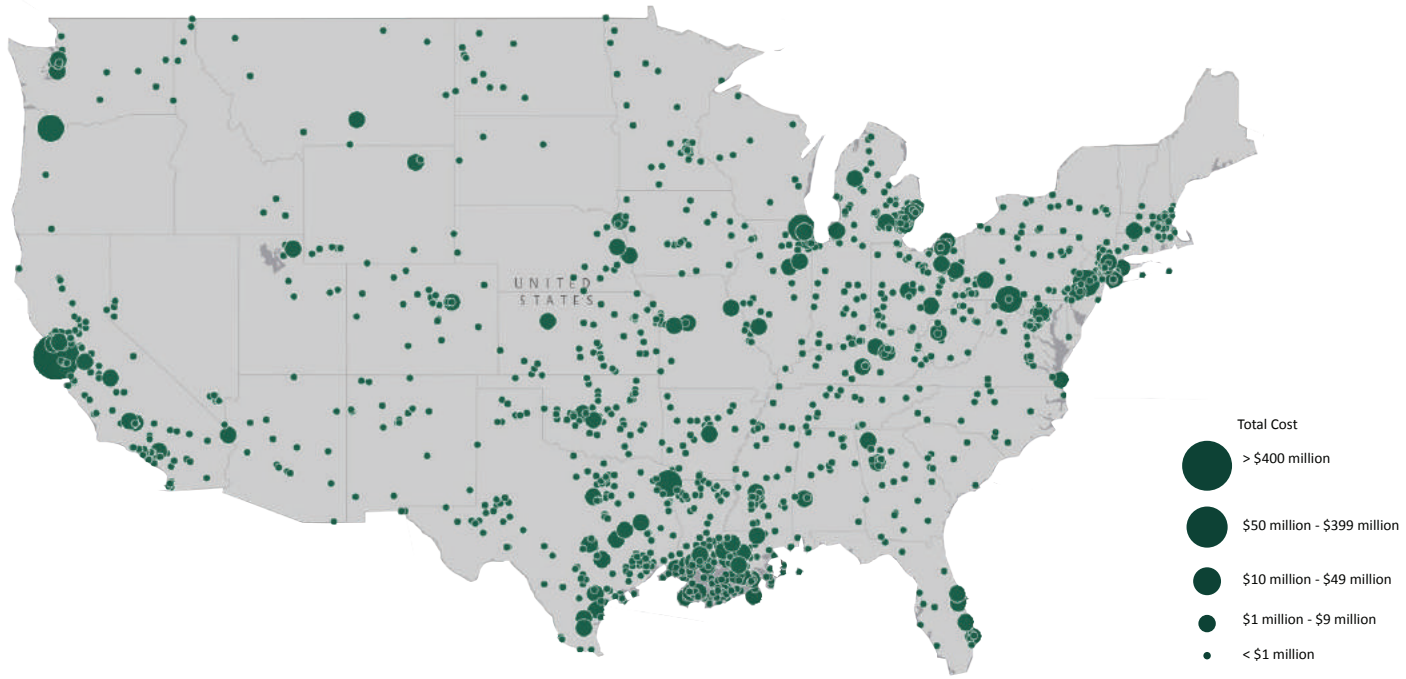
Gas releases due to pipeline incidents are shown in **Figure D-4**. Of the incidents and quantities reported, approximately 11 percent of the methane emissions from pipelines, as estimated in the USGHGI, are accounted for.

Figure D-4 Thousand Cubic Feet of Gas Released in Pipeline Incidents Since 2010 [75]



These can be very costly incidents, and in most cases, the costs are passed on to the ratepayer. For the cost of only the lost natural gas commodity, $37.9 million was lost due to incidents from 2010 to 2015. Total costs for damage and emergency responders totaled $1.2 billion in that time frame. Additionally, the Inspector General of the EPA estimates that more than $192 million is passed on to customers for non-incident distribution line leaks annually.[76] Total cost, as reported in **Figure D-5**, is the sum of the cost of gas released, emergency services, property damage, and other costs the operator had to pay.

Figure D-5: Cost of Pipeline Incidents Since 2010 [77]



Leak Safety Rating System

The only regulatory enforcements on pipeline leaks are for safety reasons. The Department of Transportation (DOT) is the regulating authority for pipeline transportation of flammable, toxic, or corrosive gasses - including natural gas. They provide the minimal federal regulations and enforce safety through the DOT's Pipeline and Hazardous Material Safety Administration (PHMSA). The PHMSA requires that leaks must be surveyed every five years and for leaks to be fixed "as soon as feasible" unless the leak creates a pipeline integrity issue. If the leak does create an integrity issue, repair dates vary between these variables: immediately, a one-year timeline, or to be monitored.[78] State authorities and utilities are tasked with monitoring leaks for safety reasons. There are currently no standards to which a leak needs to be fixed due to environmental reasons, and the EPA has no regulatory authority over pipeline leaks.[79]

States and utilities are tasked with determining best practices for managing leak repairs. The following rating system is used by the California Public Utilities Commission (CPUC) for the prioritization of leak repairs.[80]

Grade 1

Definition: A leak that represents an existing or probable hazard to persons or property.
Timeline: Immediate and continuous action until conditions are no longer hazardous
Action:

a. Implement a company emergency plan
b. Evacuate premises
c. Block off an area
d. Reroute traffic
e. Eliminate sources of ignition
f. Vent the area
g. Stop the flow of gas by closing valves or other means
h. Notify police and fire departments

Grade 2

Definition: A leak that is recognized as being non-hazardous at the time of detection, but justifies scheduled repair based on its probability as a future hazard.
Timeline: Should be cleared or repaired within one calendar year, no later than 15 months from report date. Should be reevaluated every six months until cleared.
Note: As Grade 2 leaks vary greatly in hazard potential, some may justify repairs within five working days versus 30 days. Other Grade 2 leaks, based on location and magnitude, can be scheduled for repair on a normal routine basis with periodic re-inspection necessary.
Action:

a. Determine the repair priority, considering criteria such as the following:
    i. Amount and migration of gas.
    ii. Proximity of gas to buildings and subsurface structures.
    iii. Extent of pavement.
    iv. Soil type and soil conditions (such as frost cap, moisture and natural venting).
b. Bring the leak to the attention of the individual responsible for scheduling leak repair.

Grade 3

Definition: A leak that is non-hazardous at the time of detection and can be reasonably expected to remain non-hazardous.
Timeline: None specified.
Action: These leaks should be reevaluated during the next scheduled survey, or within 15 months of the date reported, whichever occurs first, until the leak is regraded or no longer results in a reading.

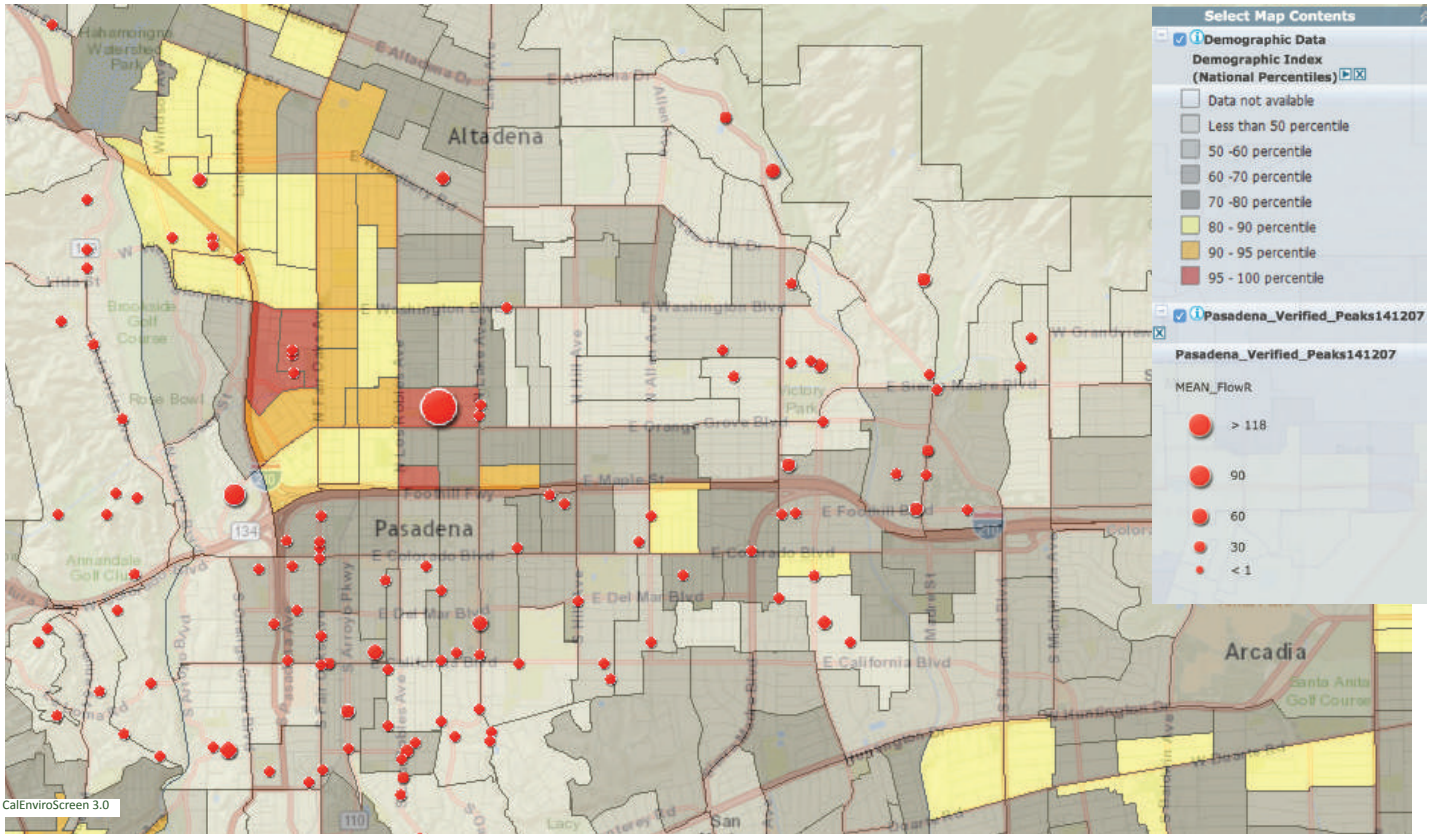
Pacific Gas and Electric, a regional utility within California, has incorporated the addition of a "Grade 2+" leak within their own rating system. This is a leak that would fall under the "Grade 2" category but requires prioritization and is flagged to be fixed within 90 days.

Appendix E: Environmental Justice Issues and Distribution Line Leaks

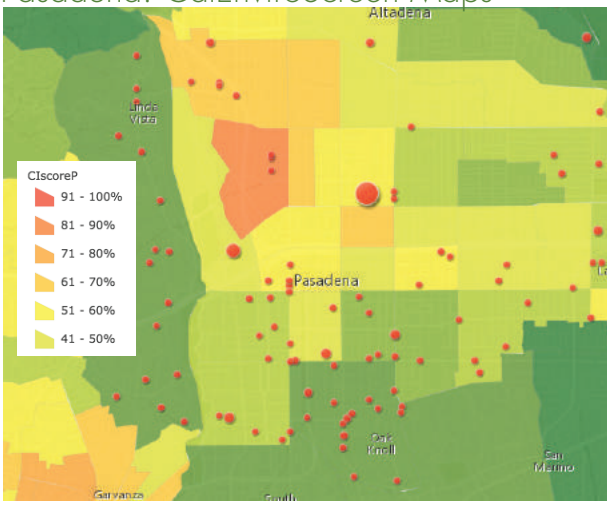
For the purposes of this report, the question of a disproportionate amount of leaks within low-income and minority areas was studied. Through the visual inspection of EPA Environmental Justice Screen maps,[81] a map overlay indicating census blocks of low-income and minority populations and the leak locations from the EDF/Google Methane Maps, it was found that no distinct correlation exists between the census statistics and leak locations in the areas studied. The EPA Environmental Justice Screen tool however, may not take into account all that a community deals with in terms of environmental justice. It is recommended to locate and quantify leaks within the jurisdiction in question and use community-oriented data to assess environmental justice issues. The following are examples of map overlays.

Western United States

Pasadena: EPA Environmental Justice Screen Maps



Pasadena: CalEnviroScreen Maps



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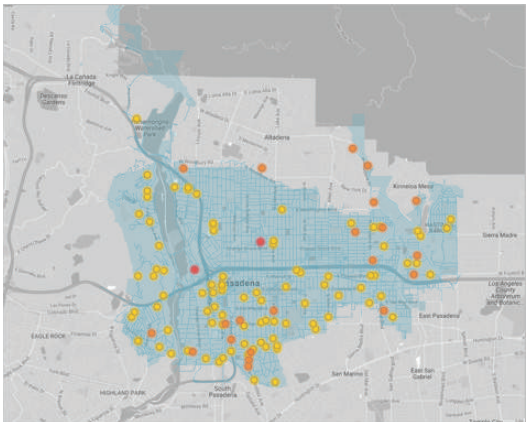
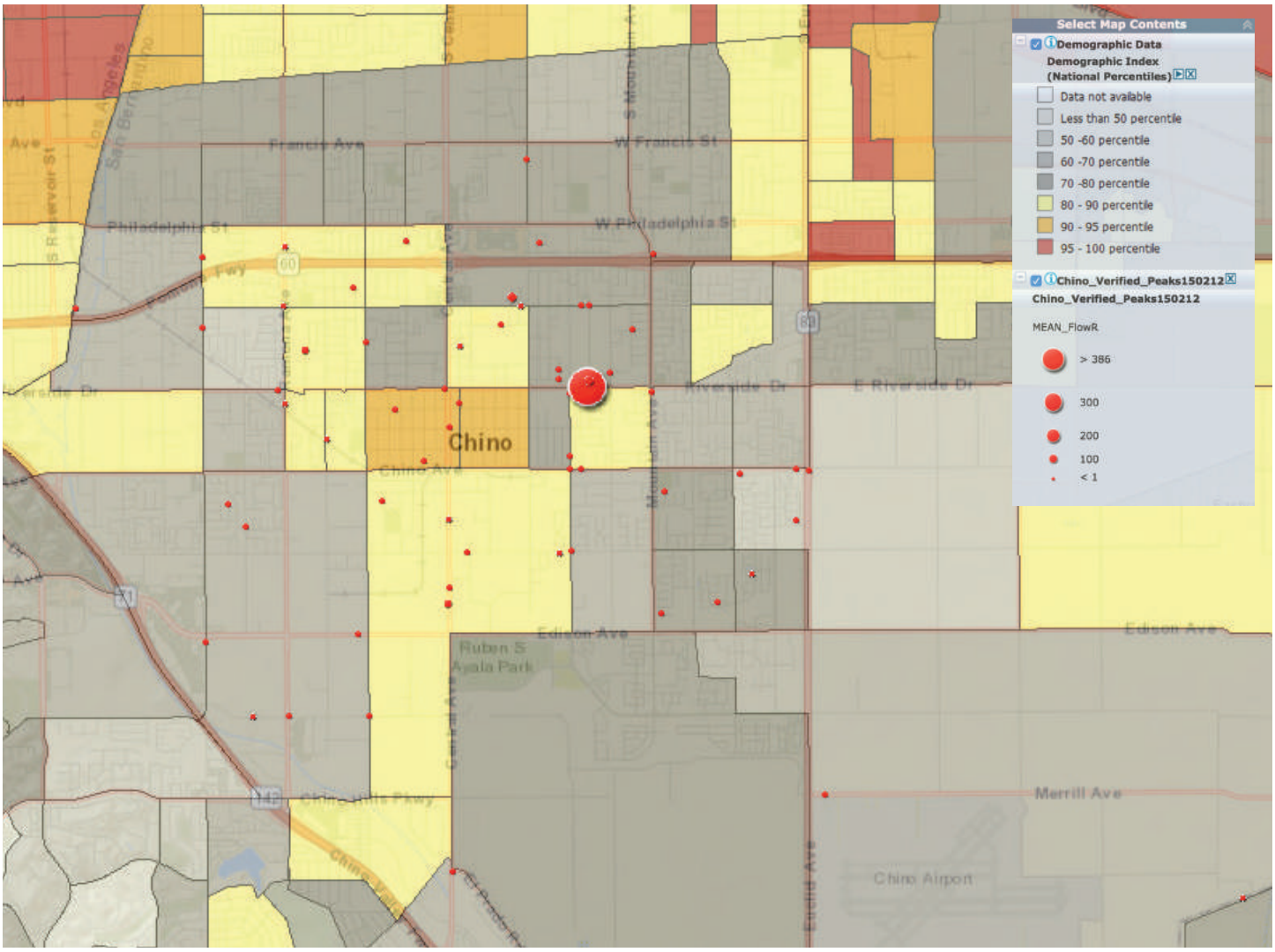
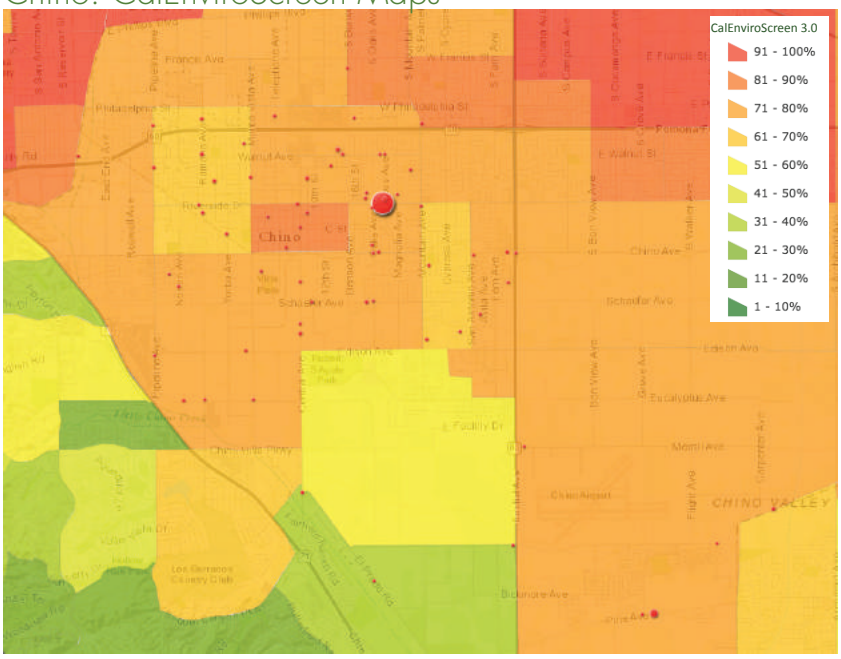


Chino: EPA Environmental Justice Screen Maps



Chino: CalEnviroScreen Maps



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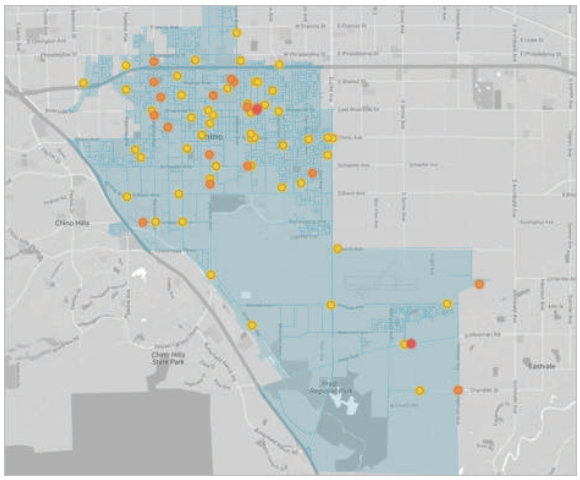
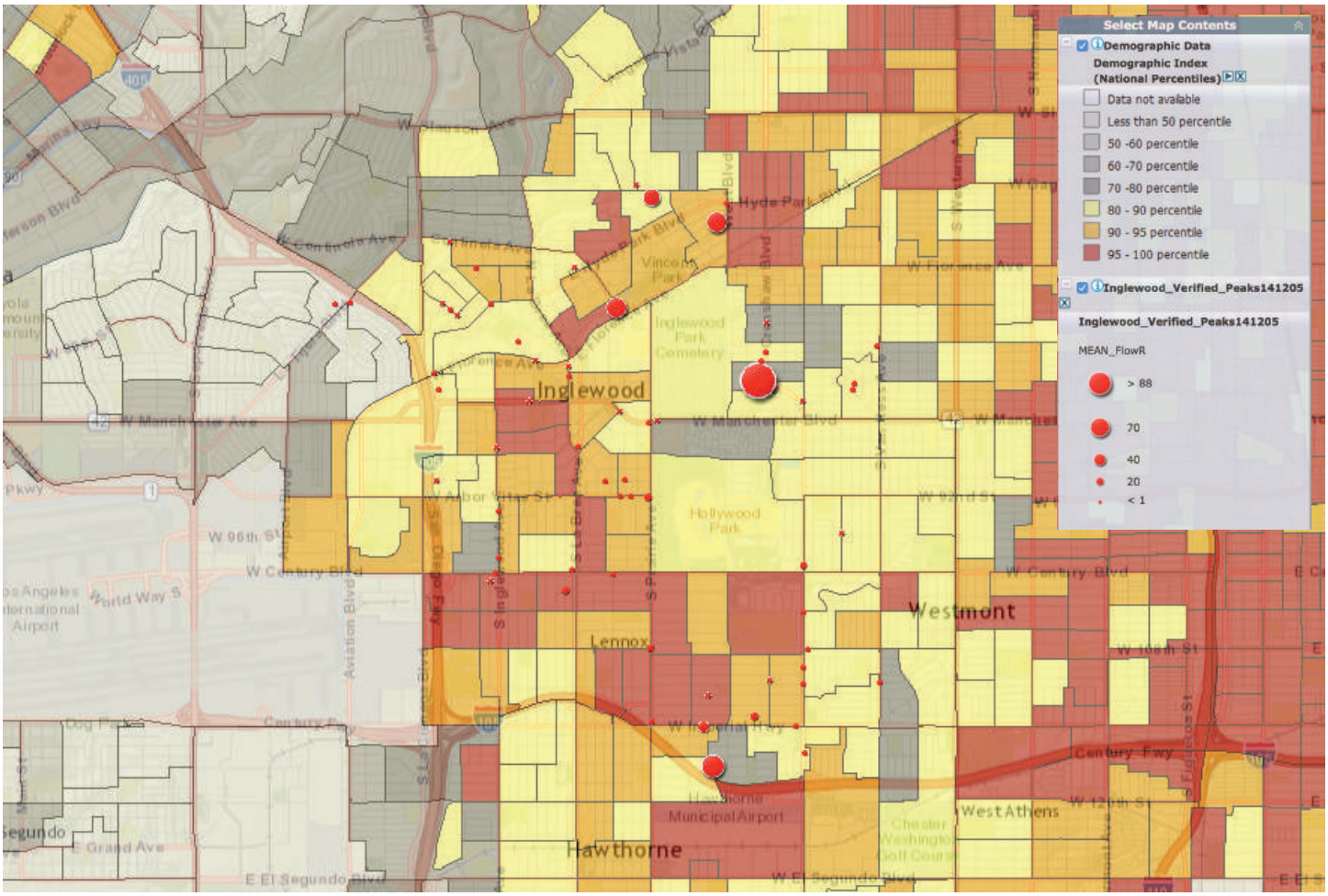
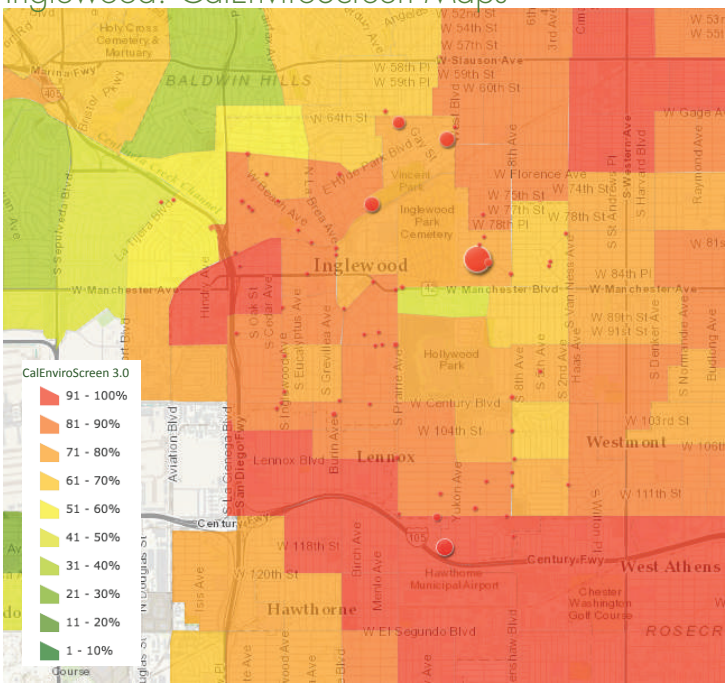


Inglewood: EPA Environmental Justice Screen Maps



Inglewood: CalEnviroScreen Maps



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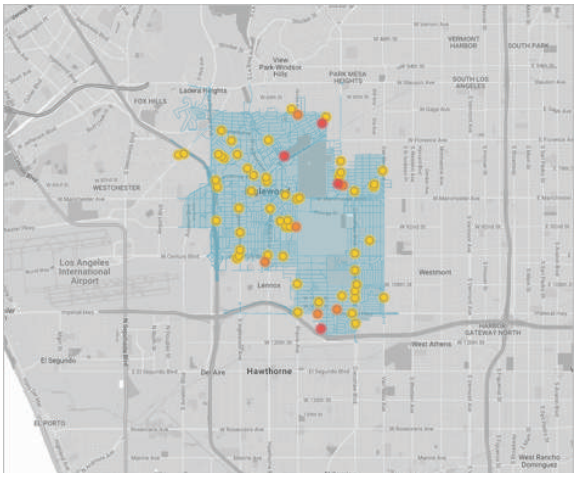
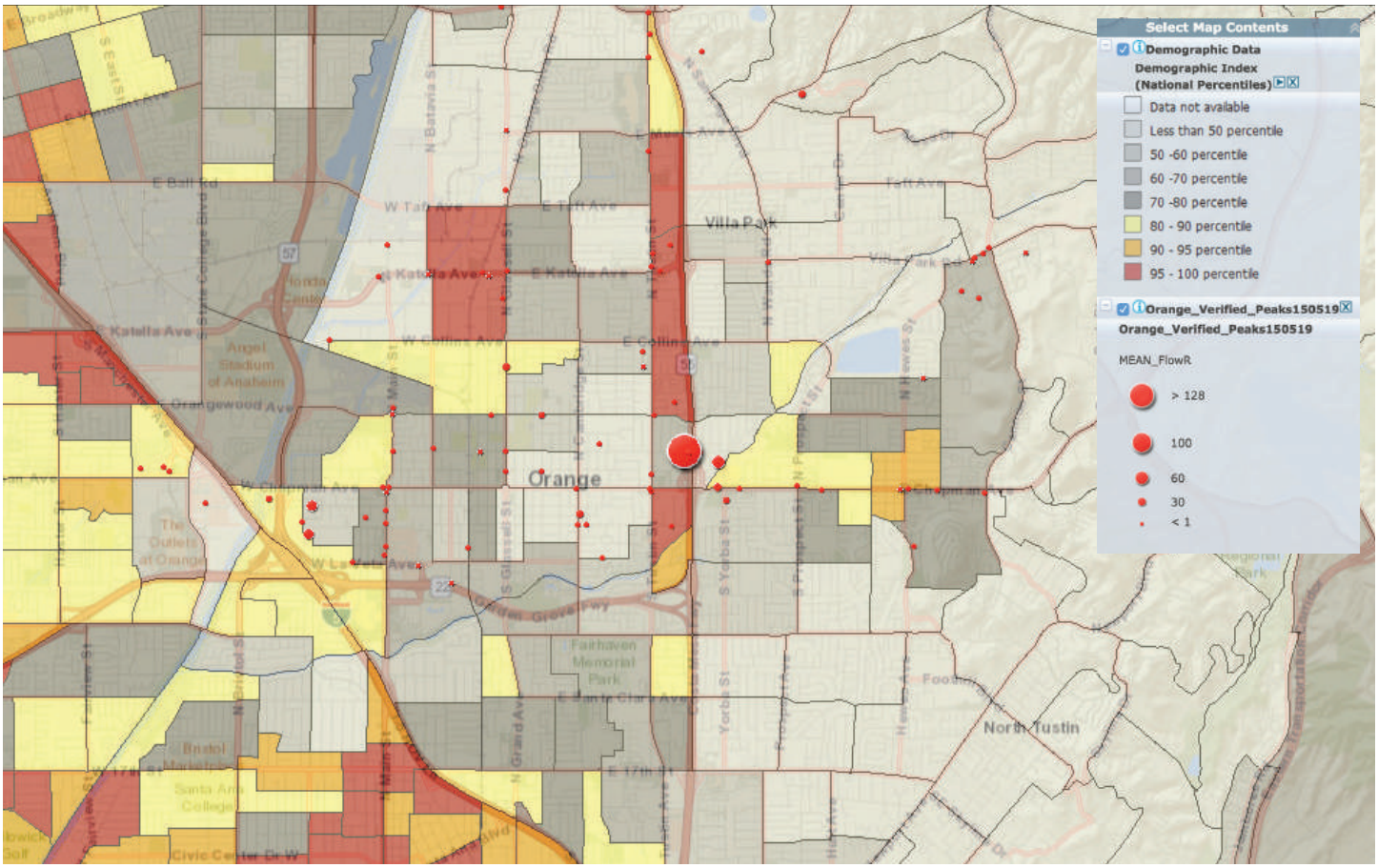
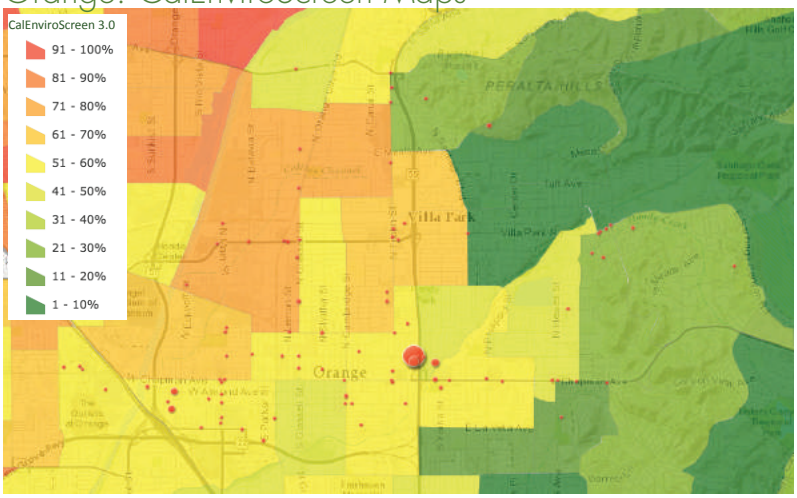


Orange: EPA Environmental Justice Screen Maps



Orange: CalEnviroScreen Maps



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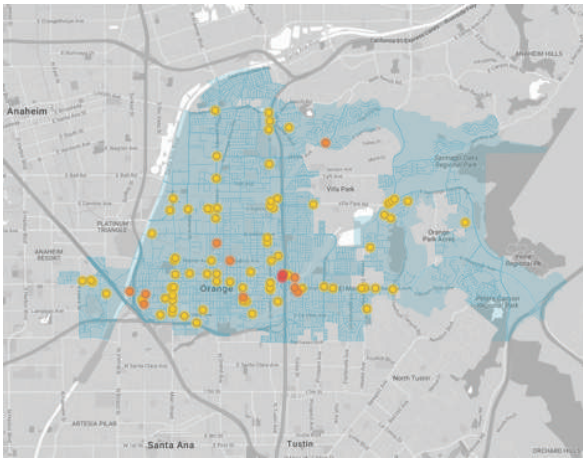
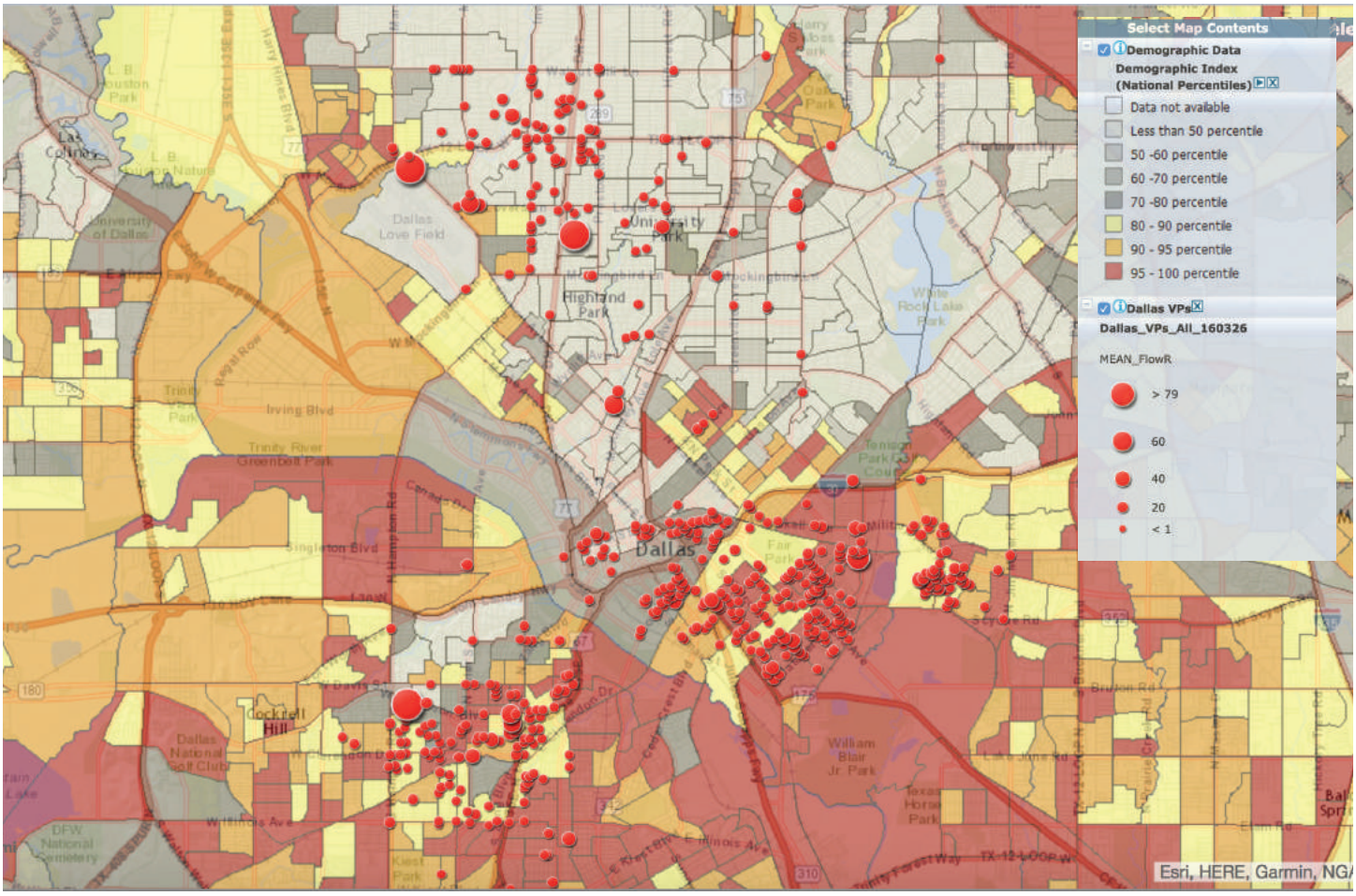


South-Western United States
Dallas



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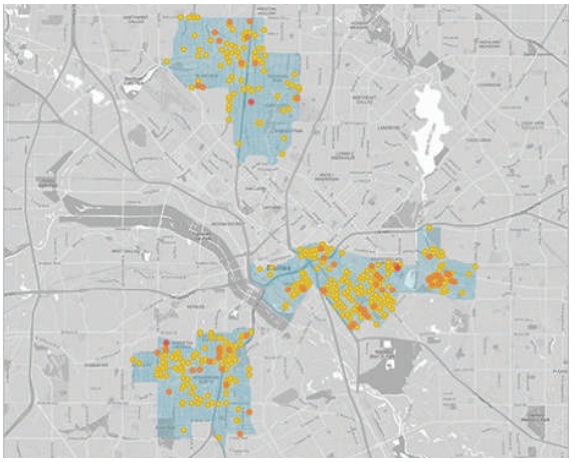
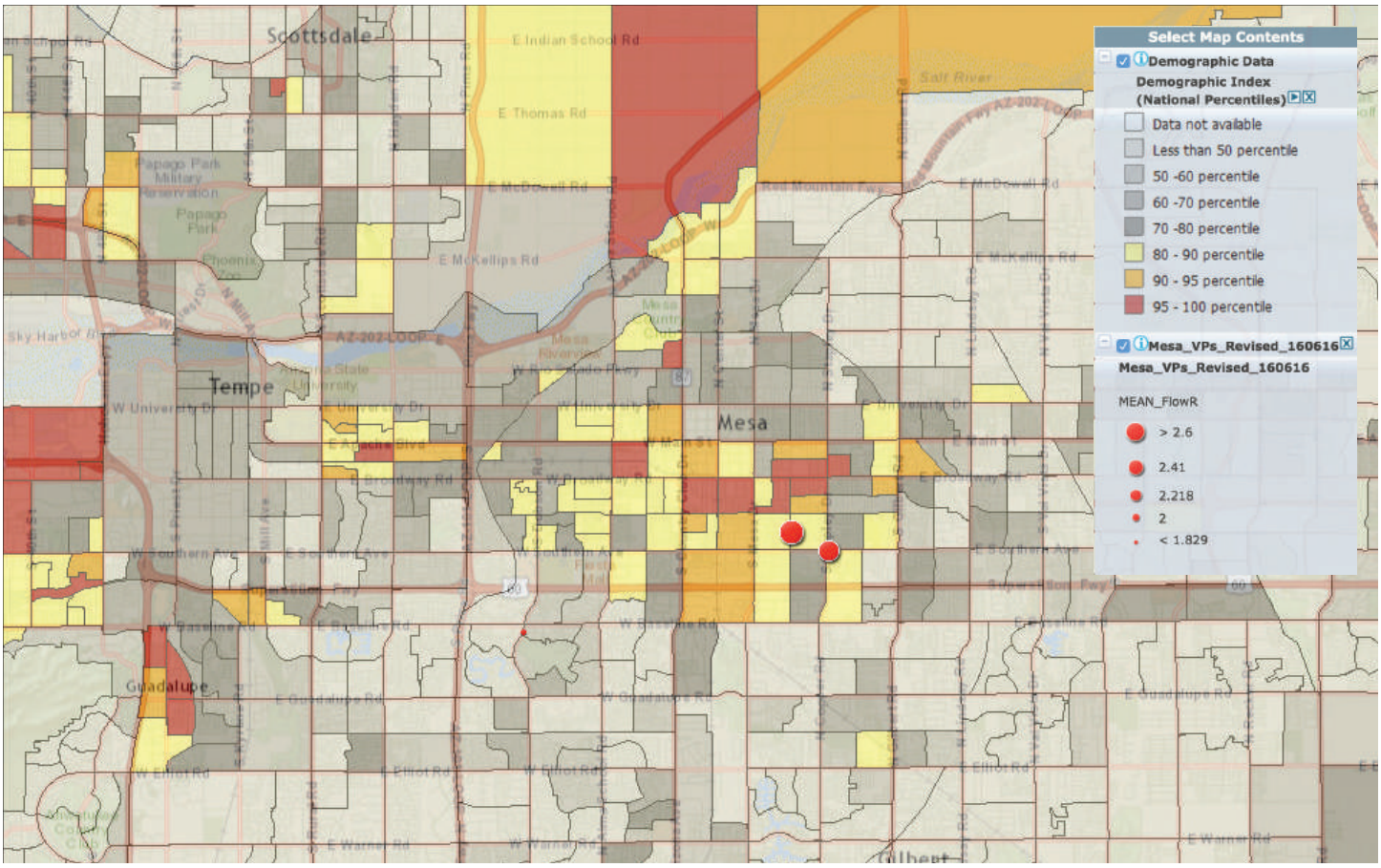


Mesa



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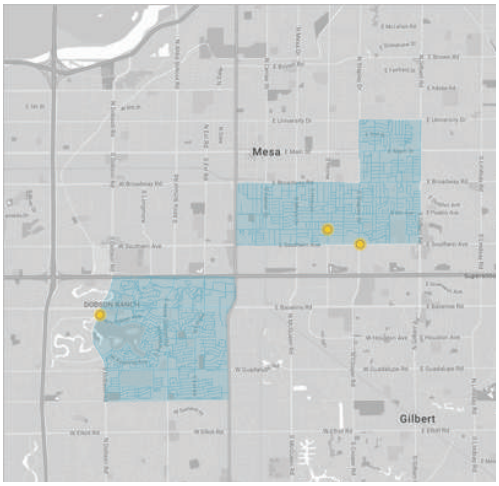
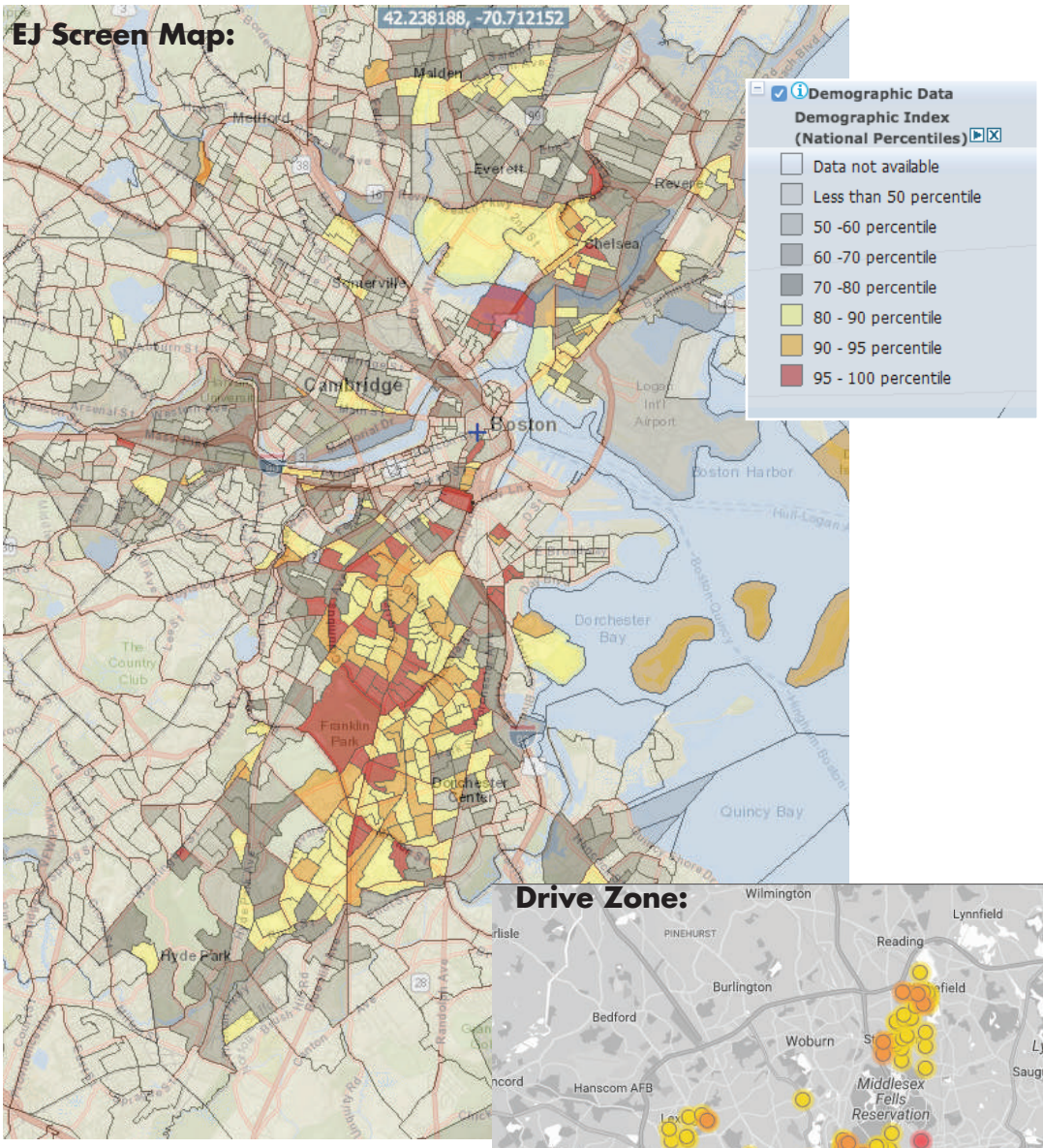


North-Eastern United States

Boston

EJ Screen Map:



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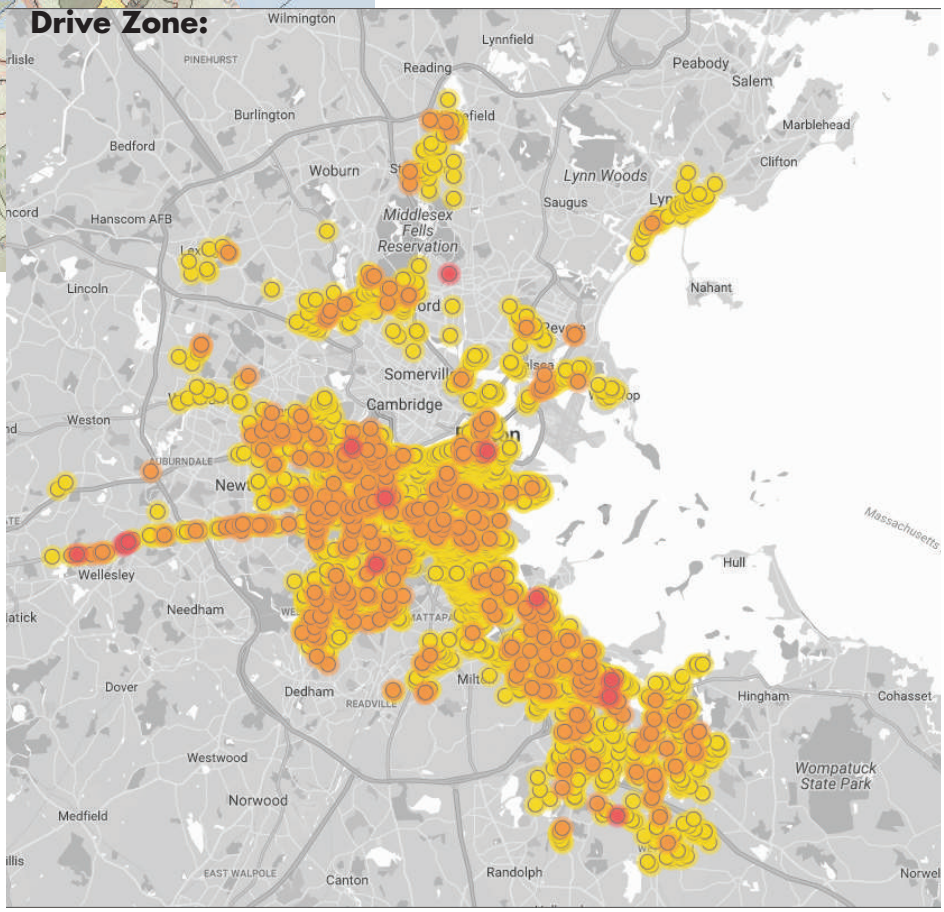
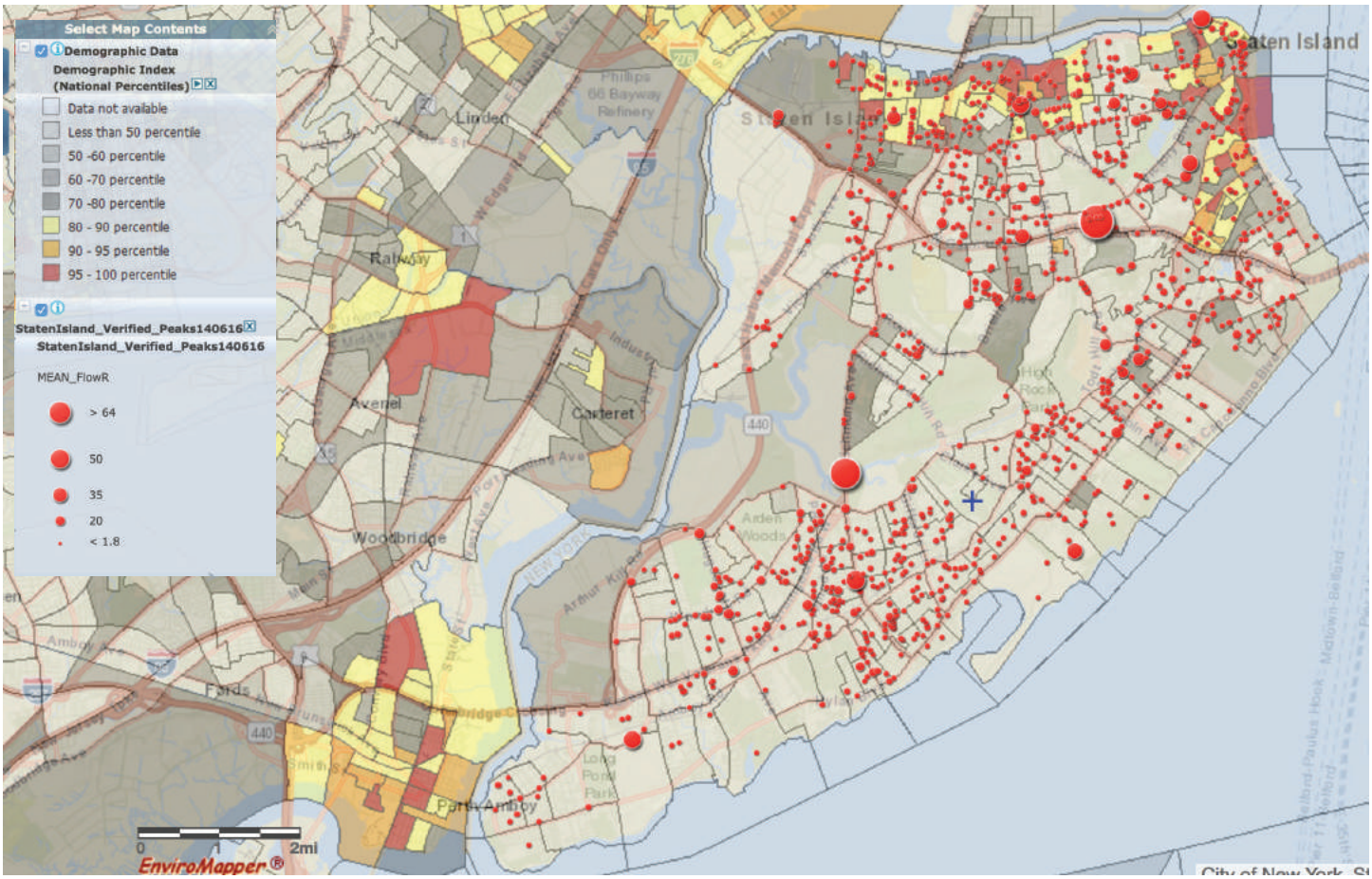


Staten Island



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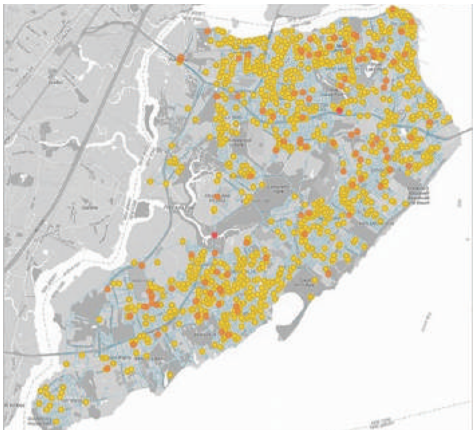
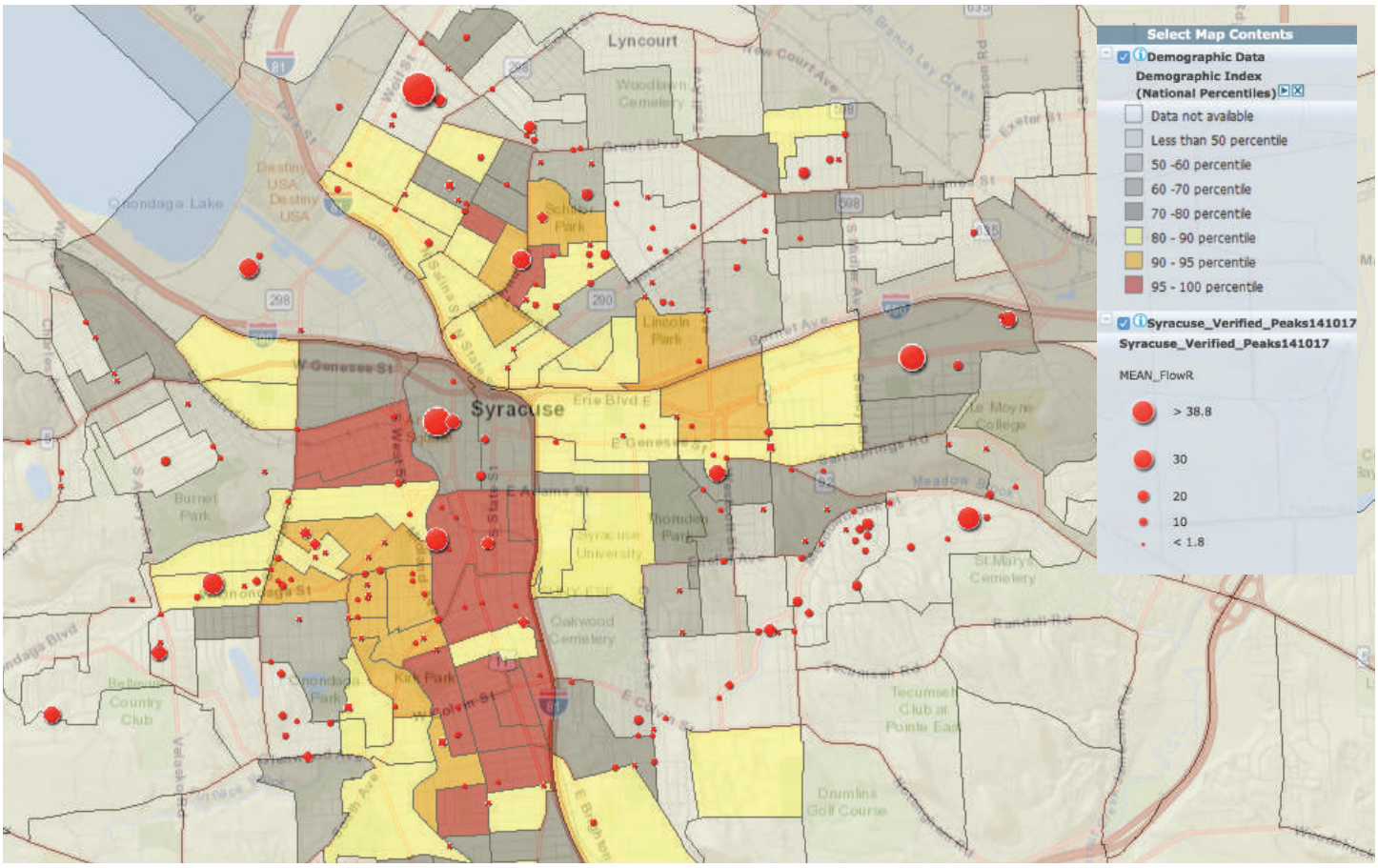


Syracuse



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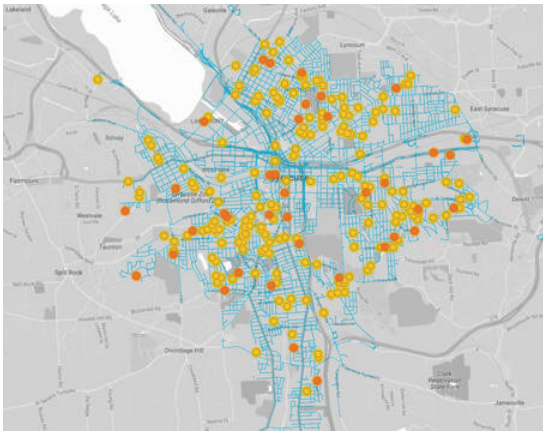
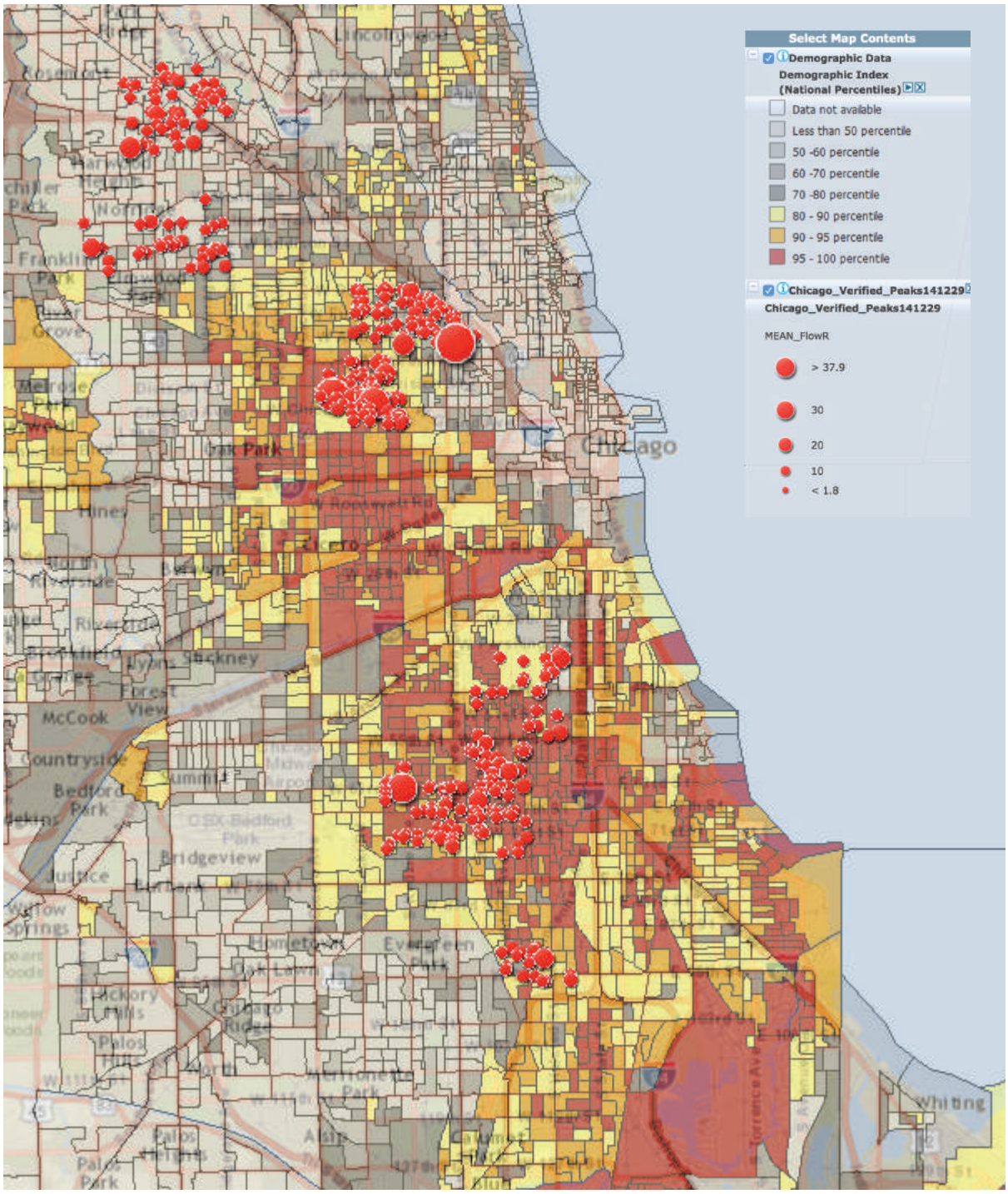


Chicago



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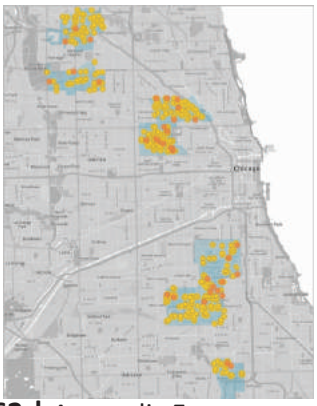
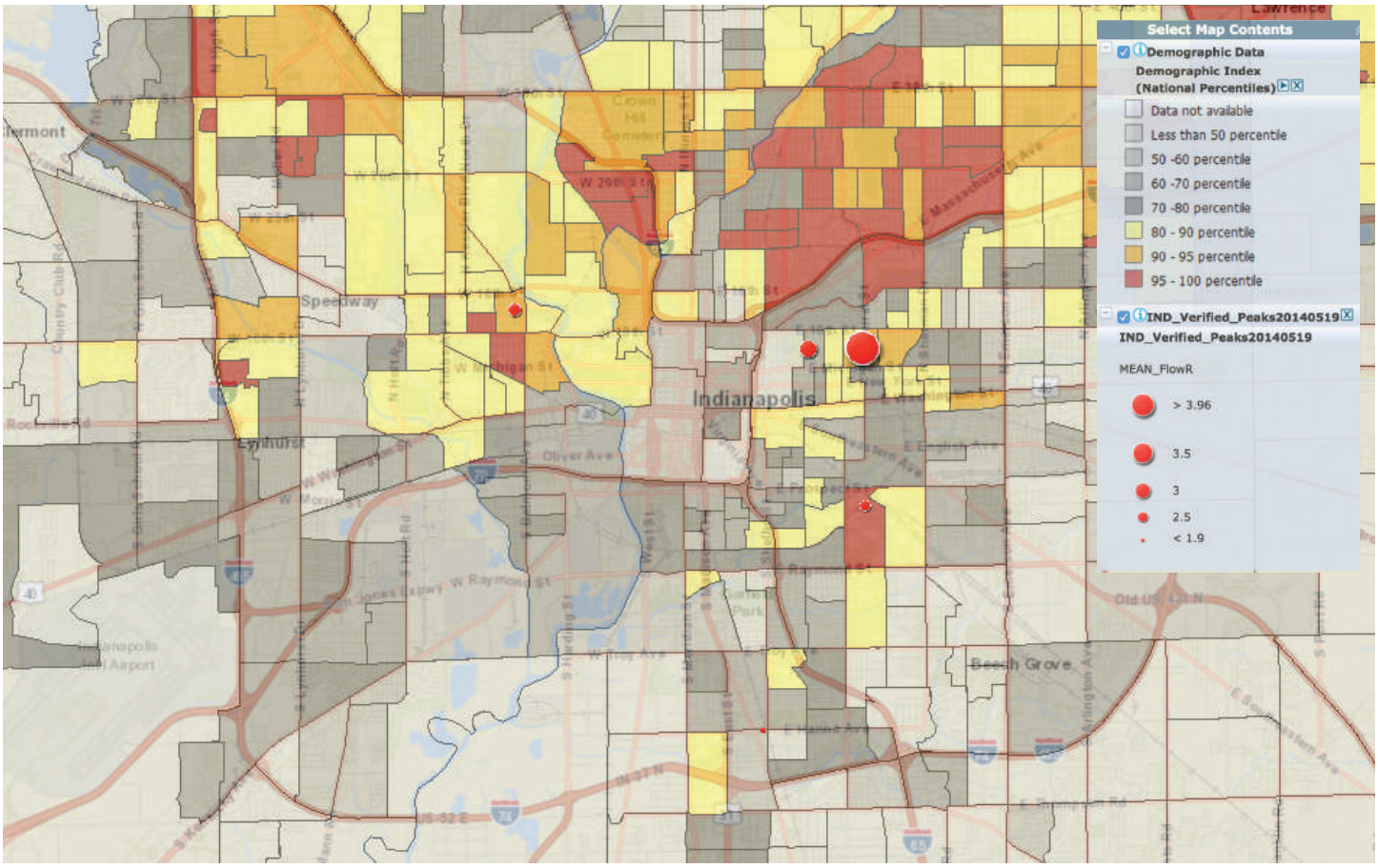


Indianapolis



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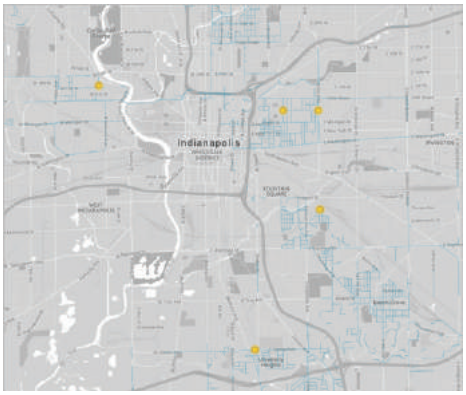
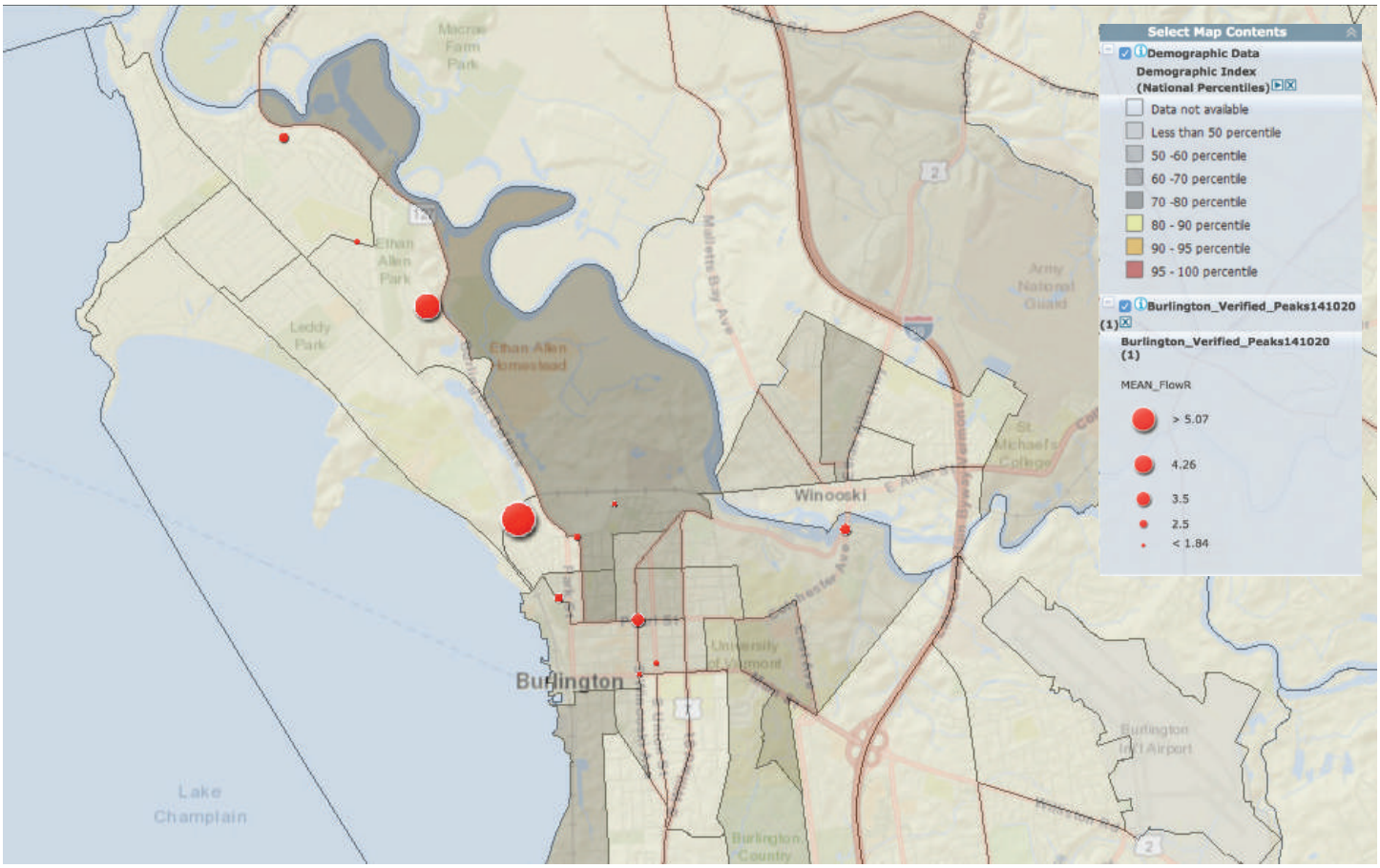


Burlington



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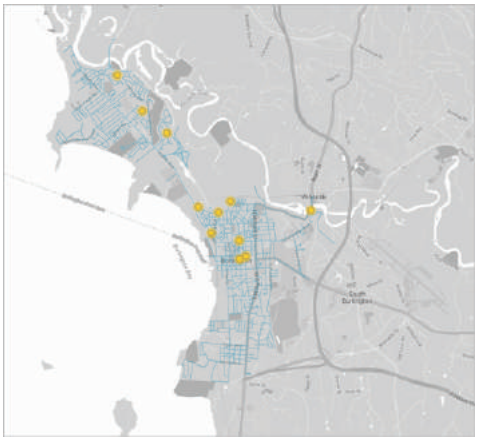
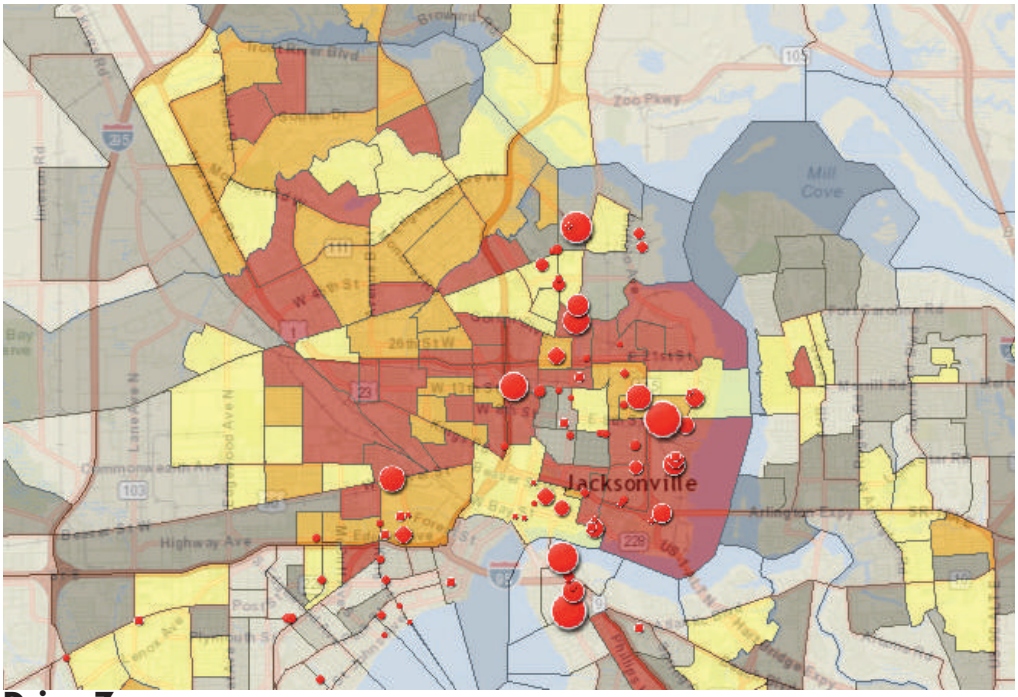
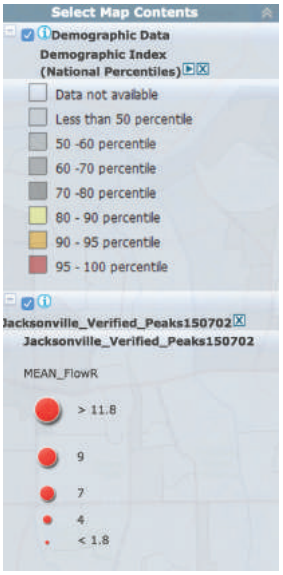


South-Eastern United States

Jacksonville





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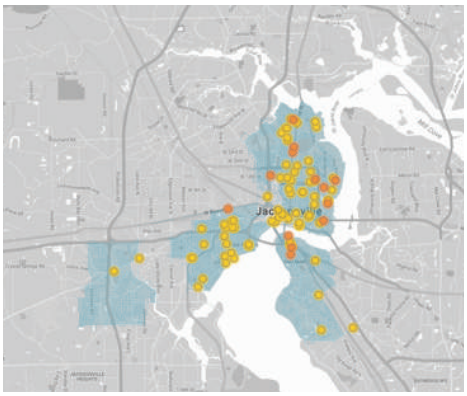

While distribution line leaks did not necessarily correlate with national standards for environmental justice communities, cases of environmental justice along the natural gas supply chain have been reported. For example, while the large storage tank leak at Aliso Canyon California garnered national attention and a response from local, state, and federal entities, including relocation, investigation, and lawsuits, a similar leak in Alabama occurred in 2008 after a storage tank was hit by lightning. This leak failed to garner national attention because Mobile Gas, the local utility, did not report the severity of the leak to state authorities. Residents complained of odor and adverse health effects for years, though state authorities did not begin to respond until late 2011 and the EPA not until mid-2012.[82]

The extraction and production of natural gas, however, has shown to spur a variety of environmental justice issues. While this evaluation is out of the scope of this report, additional readings are listed below.

Environmental Justice Issues with Hydraulic Fracturing

- Just Fracking: A Distributive Environmental Justice Analysis of Unconventional Gas Development in Pennsylvania, USA. Emily Clough and Derek Bell. Environmental Research Letters - IOP Publishing
- Environmental Justice and Hydraulic Fracturing: The Ascendancy of Grassroots Populism in Policy Determination. Nancy C. Carre, Walden University. Journal of Social Change
- The New Politics of Environmental Degradation: Unexpected Landscapes of Disempowerment and Vulnerability. Anna J. Willow. Ohio State University, USA.

Appendix F: Current and Planned Policy Solutions

State and local action is necessary to curb greenhouse gas emissions and the public health effects from the contamination of air and water, because major loopholes exist in federal regulations for natural gas and hydraulic fracturing practices. Many of the exemptions for the acts described in the following section stem from the Energy Policy Act of 2005, known to some as the "Halliburton Loophole."[83] These exemptions will be described later in this Appendix.

Local Action

Boston, MA

Leak Repair Ordinance (Takes Effect July 1, 2017)

Repair Coordination
The ordinance mandates that when the City plans to open up a street for any purpose, the City will notify the gas company and give it the opportunity to survey nearby areas for leaks to repair while the street is open. If the utility chooses not to survey, and repairs cause leaks when the street is open, the City may deny future non-emergency permit applications from the gas company to reopen streets.

Reporting
Each year, the gas companies must provide the City a five-year gas leak repair plan, an Annual Service Quality Report, a schedule of planned infrastructure repair activities within the City, and any leak data normally provided to the Department of Public Utilities regarding environmentally significant leaks or volume of greenhouse gas emissions of any leaks.

Tree Damage
The City will develop, publish, and implement procedures for pursuing compensation for trees damaged by gas leaks and mitigate any further damage to trees caused by gas leaks.[85]

Brookline, MA

Tree Death Lawsuits
The town of Brookline filed a lawsuit against National Grid in 2010 for $1 million in damages due to so many tree deaths, deeming the damages as negligence by the utility company. At the time of this writing, this suit was still in litigation.[86]

Palo Alto, CA

Electrification Study and Task Force
Palo Alto created an Electrification Task Force to determine the feasibility of switching its primary fuel source from a natural gas infrastructure to electric. The City, which currently owns and operates the distribution of electricity and provides 100 percent emission-free electricity, is looking at the feasibility of instilling a heat pump space heating and water heating mandate. In 2016, the City of Palo Alto completed a feasibility analysis for electrification of new and existing buildings within the City. The study looked at code feasibility and cost effectiveness of electrifying buildings. Conclusions are summarized in the "Recommendations" section.[87]

Deep Dive: Heat Pump Water Heater

In a 2016 study* that analyzed the greenhouse gas and cost-saving potential of switching out water heating technology to heat pump water heaters, it was found that all efficiency natural gas water heaters emit more greenhouse gasses than a heat pump, even when the heat pump is powered with coal electricity. As 68 percent of the households in the U.S. heat water using natural gas heaters, and 24 percent use electric-resistance water heaters, if all water heaters were switched out to heat pumps, the nation could see a **75 percent savings in greenhouse gas emissions** (235 MMTCO2e) from these devices, or a reduction of 2.7 percent of total national GHG emissions.

This translates into a **59 percent reduction in ratepayer costs** - saving $17 billion a year or $120/year for households that replace a natural gas water heater and $214/year for households that replace an electric resistance water heater[88]. *The study used 2009 consumption and appliance data.

In Palo Alto's Electrification Study, it was found that heat pump packages could be more cost effective for new construction when packaged with a heat pump space heater. Even more consumer savings can be realized when a natural gas connection to the building is avoided altogether, and additional packaging of electric infrastructure is installed.[89]

Other

Local Hydraulic Fracturing Bans

Hydraulic fracturing bans have been issued in more than 45 municipalities using different methods, including rights-based ordinances, zoning laws, or land use changes, direct bans, and perpetual or temporary moratoriums.[90]

Rights-Based Ordinance Examples
- Community Rights and Protection from Natural Gas Exploitation Ordinance ((Forest Hill, PA)
- Community Water Rights and Local Self-Governance Ordinance (Las Vegas, NM)
- Community Protection of Natural Resources (Town of Wales, NY)
- Community Bill of Rights and Protection from Shale Gas Drilling and Fracking (Mansfield, OH)

Zoning Law / Land Use Change Examples
- Specific Use Regulations (Albany, NY)
- Prohibition on Heavy Industry - zoning law updated to include natural gas in the definition of "heavy industry" (Plainfield, NY)

Direct Bans
- Resolutions to Ban Fracking (Clinton Town NJ)
- Resolution to Ban Shale Drilling (Hinckley Township, OH)
- Resolution to Ban Extraction, Storage, Transfer, Treatement, or Disposal of Natural Gas Exploration and Production Wastes (Niagara Falls, NY)

Perpetual Moratorium
- Ban Until Potential Impacts are Identified and Addressed (Onondaga County, NY)
- Ban Until Deemed Safe (Cross Village Township, MI)

Temporary Moratorium
- Moratorium on Acceptance or Processing of Land Use Applications for Oil and Gas Exploration (Colorado Springs, CO)
- Moratorium to Effect a Ban on Natural Gas Exploration, Storage, and Disposal (Binghamton, NY)

State Actions

California

Senate Bill 605 & 1383 - Short-Lived Climate Pollutants Reduction Strategy

SB605, which passed September 2014, required the California Air Resources Board (CARB) to do the following: complete an inventory of sources and emissions of short-lived climate pollutants (methane, black carbon, and hydrofluorocarbons) using available data; identify research needs to address data gaps; identify existing and potential control measures to reduce emissions; prioritize the development of new measures for reducing short-lived climate pollutants that offer co-benefits, such as improving air and water quality and community health; and to coordinate with other state agencies and districts to develop a comprehensive strategy to reduce short-lived climate pollutants.[91]

SB 1383, which passed in September 2016, then built upon the insights that resulted from SB605 to set short-lived climate pollutant-reduction goals. It requires CARB to develop and implement strategies to reduce methane by 40 percent and hydrofluorocarbons (HFCs) and black carbon by 50 percent by 2030. Though focused primarily on livestock and dairy production and landfill methane reduction, the bill requires state agencies to consider the use of sustainable production and the use of renewable gas, or biomethane. The bill requires five pilot projects to be implemented to interconnect dairy biomethane to gas corporations throughout the pipeline system by January 1, 2018.[92] If followed worldwide, the restrictions would cut the current projections of global warming in half by 2050.[93]

Senate Bill 1371 - Natural Gas Leak Abatement

SB 1371 required the California Public Utilities Commission (CPUC) to adopt rules governing the operation, maintenance, repair, and replacement of commission-regulated gas transmission and distribution pipelines to minimize hazardous leaks, while giving due consideration to the California Global Warming Solutions Act of 2006, which requires California to reduce GHG emissions to 15 percent below its 1990 levels by 2020.

This bill required gas corporations to file a report summarizing utility leak management practices, a list of new methane leaks in 2015 by grade, a list of open leaks that are being monitored or are scheduled to be repaired, and a best estimate of gas loss due to leaks. The rules adopted were required to provide the following: the maximum technologically feasible avoidance, reduction, and repair of leaking components; leak repair as soon as possible after discovery; evaluate operations, maintenance, and repair practices to determine effectiveness; establish best practices for leak surveys, patrols, and prevention; and require owners of CPUC-regulated pipelines to report system-wide leak rates.[94] An analysis of the success of this bill is analyzed in the "Deep Dive: SB 1371" section on the following pages.

Senate Bill 1441 - Proposed Ratepayer Protection Bill

SB 1441 would prohibit gas corporations from recovering the cost of natural gas lost to the atmosphere from any point along the natural gas life cycle from extraction to delivery from ratepayers. While this bill is opposed by utilities such as PG&E for the inability of utilities to receive cost recovery from ratepayers for fugitive emissions outside of their jurisdiction, it enjoys support from environmental advocacy groups for its ability to provide economic incentive for utilities to fix leaks, something that has been lacking.

Proposed Greenhouse Gas Emissions Standards for Crude Oil and Natural Gas Facilities - CA Code of Regulations Title 17 Div 3 Ch 1 Subchapter 10 Climate Change Article 4

The proposed standards aim to cut methane emissions from oil and gas facilities 40-45 percent by 2025. This would reduce 1.5 million MTCO2e (GWP_{20}) of methane emissions per year, 3,600 tons of VOCs per year, and 100 tons per year of benzene, toluene, ethyl-benzene, and xylene. Greenhouse gas emission standards for crude oil and natural gas facilities would apply to facilities in natural gas production, underground storage, gathering and boosting, processing plants, and transmissions compressor stations.[95]The proposal will be brought to vote in spring of 2017 and, if adopted, will phase in from January 1, 2018 to January 1, 2020.[96]

Massachusetts

EO569 - Establishing an Integrated Climate Change Strategy for the Commonwealth

Within the executive order, the Department of Environmental Protection is tasked with considering emission limits from leaks in the natural gas system as a strategy of meeting greenhouse gas reduction goals of 25 percent below 1990 levels by 2020, and 80 percent below 1990 levels by 2050.[97]

Leak Fixes during Construction - Proposed
Bill H.2871 - An Act Relative to Gas Leak Repairs During Road Projects

The proposed bill mandates that utilities monitor and fix leaks when streets are open for repaving unless it is an explosive leak, in which case, the leak shall be fixed immediately.[98]

Ratepayer Protection Bill - Proposed, No Further Action (Dead)
Bill H 2870 - An act to protect gas consumers from paying for the leaked and unaccounted-for natural gas

Unaccounted-for natural gas (the difference between total gas available from all sources and the total gas accounted for as sales) must be measured and reported by system type. The cost of unaccounted-for natural gas will be disallowed for ratemaking purposes, according to **Table 21**.[99]

Table 21: Massachusetts Maximum Allowable Unaccounted-For Gas for Ratemaking Purposes

Year	Distribution	Transmission	Storage	Public Utility	Other
1	1.0%	0.5%	0.25%	0.25%	0.25%
2	0.75%	0.25%	0.10%	0.10%	0.10%
3	0.5%	0.1%	0.05%	0.05%	0.05%
4	0.25%	0.05%	to	to	to
5	0.10%	to	to	to	to
6	0.0%	0.0%	0.0%	0.0%	0.0%

Pennsylvania

Oil and Gas Act

The Pennsylvania Department of Environmental Protection (DEP) requires all oil and gas wells to acquire a permit before drilling, which may be denied if the issuance of the permit violates the Pennsylvania Oil and Gas Act. Other actions include having a permanent well casing that runs through the freshwater strata, requiring fracking fluid control and a disposal plan, and creating a water plan that governs water withdrawal and disposal.[100]

Air Quality Permit Exemptions

Issued guidance that exempts oil and gas facilities from certain air-quality permitting requirements if they implement changes to reduce gas loss, such as developing a leak detection and repair program using an infrared camera with methane concentrations in air of 0-5 percent, reducing VOC emissions from storage vessels to fewer than 2.7 tons per year, and limiting flaring activity.[101][102]

Pennsylvania Code Chapter 78 Section 78.51
Any landowner who experiences a reduction in water quality may request an investigation by the DEP and receive a determination within 10–45 days. If the DEP finds the oil or gas operator to be the cause of water-quality reduction, the well operator must restore or replace the affected supply with an alternative source of water with adequate quality and quantity. If the pollution occurs within six months of drilling, the DEP may presume the well operator is responsible for water contamination, unless an affirmative defense is given.[103]

Pennsylvania Code Chapter 78 Section 78.51
Each natural gas distribution company and city natural gas distribution operation shall reduce distribution system loss performance in accordance with the metrics shown in Table 22. The metric starts with 5 percent in the first year and decreases by 0.5 percent every year in the subsequent years until it reaches 3 percent. Adjustments must be individually categorized, reported, and supported by metered data and sound engineering practices.[104]

Table 22: Pennsylvania Maximum Allowable Unaccounted-For Gas for Ratemaking Purposes

Year	Percent Unaccounted-for Gas
1	5.00%
2	4.50%
3	4.00%
4	3.50%
5	3.00%

Texas

Admin code Rule 7.5525 - Ratepayer Protection Bill
Adopted in 2002, all expenses for lost gas in excess of the maximum allowable shall be disallowed for ratemaking purposes. The maximum allowable loss for the distribution system is 5 percent of the amount metered in, and the maximum amount allowable for the transmission system is 3 percent of the amount metered in.[105]

Colorado

Air Quality Control Commission Regulations, Regulation 7, 5 CCR 1001-9
Adopted comprehensive statewide regulations to: limit VOC emissions from venting and leaks, require operators to implement leak detection and repair programs, replace high-bleed pneumatic controllers with low-bleed, and control emissions from storage vessels.[106]

Oil and Gas Conservation Act
The Act gives the Colorado Oil and Gas Conservation Commission (COGCC) the authority to regulate oil and gas operations to mitigate environmental impacts to air, water, soil, and biological resources. Under regulation, an operator must apply for a permit-to-drill that indicates the proposed well location, the location of water wells, and the location of water sources within 400 feet of the wellhead. Actions include additional well-casing requirements, disclosure of injection chemicals, permitting, and waste-disposal requirements. The Director of COGCC may withhold approval based on reasonable cause of threat to public health, safety, and welfare.[107]

Wyoming

Non-attainment Area Regulations Chapter 8 - Regulate Volatile Organic Compound Emissions
Adopted VOC limiting regulations similar to Colorado's in the Upper Green River Basin, a "non-attainment area," where air quality does not meet national ozone standards adopted by the EPA under the Clean Air Act.[140] Actions include operating pneumatic pumps to 98 percent VOC destruction efficiency, routing pump discharge streams into a closed loop system, or replacing pump with solar-, electric-, or air-driven pumps, and creating a Leak Detection and Repair protocol for fugitive emissions.[108]

Wyoming Admin Code Oil and Gas Conservation Commission General Agency Chapter 3 Section 8
Permits are required for the drilling and deepening of wells and the on-site storage of waste materials from state oil and gas supervisors. Pits are required to be lined when adjacent to surface, groundwater, a river drainage basin, or when they endanger human health or wildlife. Drilling fluids may not be discharged into live water or drainages that lead to live waters of the state.[109]

New York

State Environmental Quality Review Act - 6 NYCRR Part 617
Hydraulic fracturing was initially not allowed in New York's portion of the Marcellus Shale formation as of a 2010 Executive Order banning the practice until the Department of Environmental Conservation (DEC) completed a review to certify the practice was safe.[119] After seven years of study, the DEC concluded "high-volume hydraulic fracturing poses significant impacts to land, air, water, natural resources, and potential significant public health impacts that cannot be adequately mitigated" and banned the practice in 2015.[110]

Vermont

Assembly Bill H.464 - Ban Hydraulic Fracturing
The practice of hydraulic fracturing was banned in the state of Vermont to ensure the state's drinking water remains uncontaminated.[111]

Maryland

House Bill 1325 - Ban Hydraulic Fracturing
The practice of hydraulic fracturing was banned in the state of Maryland for the exploration or production of oil or natural gas. .[112]

Louisiana

Title 43 Part IX Natural Gas Policy Act - Permit Requirements for Well Drilling
Work permits must be obtained, including a simulation of the well before construction. Well casings must be regulated to a certain depth, and hydraulic fracturing flowback must be stored in a tank or lined pit above the 100-year floodplain, though they are exempt from the Louisiana Hazardous Waste Program. Operators must disclose the amount and composition of fracking fluids used after completing the well.[113]

Industrial Commission Order 24665 - Phase Down Flaring

Adopted innovative program to phase down flaring by operators statewide, requiring a 91 percent gas capture rate by 2020. Actions include requiring Gas Capture Plans for all permit applications, reports of gas capture, and to conduct an annual review of progress and goals with the Department of Mineral Resources.[114]

Federal Action

Exemptions to Federal Regulations

Safe Drinking Water Act

The EPA typically regulates any underground injection of fluids for disposal or enhanced oil recovery. However, under the Energy Policy Act of 2005, the EPA revised the term "underground injection" to explicitly exclude the injection of fluids for hydraulic fracturing unless diesel fuels are used; therefore, it exempts the practice from any regulation under the Safe Drinking Water Act (SDWA) Underground Injection Control (UIC) program.[115] Since the 2005 Energy Policy Act, two bills have been proposed in Congress. The first, in 2008, was introduced in the House of Representatives to protect drinking water from oil and gas development.[116] In the second bill, in 2015, the Senate introduced the Fracking Responsibility and Awareness of Chemicals Act (FRAC Act), though neither bill made it through Congress.[117]

States can assume the primary enforcement authority for the Underground Injection Control (UIC) as long as the state program meets EPA requirements. The following states and areas have state programs regulating underground oil and gas injection:

Alabama, Alaska, Arkansas, California, Illinois, Indiana, Kansas, Louisiana, Mississippi, Missouri, Montana, Nebraska, New Mexico, North Dakota, Ohio, Oklahoma, Oregon, South Dakota, Texas, Utah, West Virginia, Wyoming, the Navajo Nation, and the Assiniboine and Sioux Tribes of the Fort Peck Indian Reservation.

The EPA has lead implementation authority in the following states (in the remaining states, authority is shared):

Kentucky, Michigan, New York, Pennsylvania, and Virginia.[118]

Clean Water Act

The Clean Water Act (CWA) sets water quality standards for storm water discharge. In 1987, Congress amended the CWA to require the EPA to develop a permitting plan for storm water runoff. However, this amendment exempted oil and gas exploration, production, processing, treatment operations, and transmission facilities from the permitting requirement unless the facilities were under construction. Through the 2005 Energy Bill, Congress re-defined the term "oil and gas exploration, production, process, or treatment operations and transmission facilities" to include construction activities, therefore, exempting it from the requirement.[119]

While the regulation prohibits discharges of wastewater pollutants from onshore unconventional gas extraction facilities, currently under the CWA, all phases of oil and gas systems, including associated construction activities, are not required to obtain a National Pollutant Discharge Elimination System permit for storm water discharges unless there is a reportable quantity spill, or the discharge contributes to a water quality violation.[120]

Comprehensive Environmental Response, Compensation, and Liability Act

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) holds most industries responsible for cleaning up abandoned hazardous waste sites. CERCLA included a petroleum exclusion that defines the term "hazardous substance" to exclude petroleum, natural gas, natural gas liquids, liquefied natural gas, synthetic natural gas, or mixtures of natural and synthetic gas. This excludes oil and gas wastes and abandoned sites from regulation or cleanup under CERCLA.[121] This exemption was allowed for because these wastes should be covered under the Oil Pollution Act of 1990, though the act does not specifically account for natural gas wastes in any way.[122]

Emergency Planning and Community Right to Know Act

The Emergency Planning and Community Right to Know Act requires companies to report the release of significant levels of toxic substances to the EPA's Toxic Release Inventory (TRI). The natural gas industry typically guards the chemicals used for extraction as trade secrets, and the EPA historically has not required the oil and gas industry to comply with full reporting standards. Currently, only the facilities that recover sulfur from natural gas are required to report.[123]

Clean Air Act [10]

The Clean Air Act limits the emissions of nearly 190 toxic air pollutants, including many emitted from oil and gas operations. A source must produce a certain threshold of toxins to be covered by the Act and includes an aggregation requirement, which requires smaller sources of emissions that together produce pollution above a certain threshold, to be covered under the Act. This aggregation requirement is intended to protect the public from smaller emissions sources that may be relatively harmless in solidarity, but which collectively release large amounts of toxic substances, though the act exempts oil and gas operations.

A Natural Resource Defense Council study that found the 460 well sites in Garfield County, Colorado released more than 30 tons of benzene in a given year, or nearly 20 times the amount released by a large oil facility in Denver. Due to the exemption from the aggregation requirement, none of the 460 oil and gas wells were subject to major source emission standards. While the EPA is still able to set standards from small oil and gas facilities if they occur within a metropolitan area with a population greater than 1 million people, much of the drilling occurs outside urban areas and is therefore exempt from these regulations.[124]

National Environmental Policy Act

The National Environmental Policy Act exempts certain oil and gas drilling activities, obviating a need to conduct environmental impact statements. The exemption, enacted by Congress in 2005, shifts the burden of proof to the public to prove that such activities would be unsafe.[125]

Resource Conservation and Recovery Act

The Resource Conservation and Recovery Act sets forth standards for disclosure and safety in handling hazardous waste in an effort to reduce hazardous waste and develop non-toxic alternatives. The Resource Conservation and Recovery Act (RCRA) required the EPA to determine the criteria for listing hazardous wastes subject to regulation under Subtitle C – a statue that regulates the generation, transportation, treatment, storage, and disposal of hazardous waste. Drilling fluids, produced waters, and other wastes associated with oil and gas development were explicitly exempted from being listed as hazardous wastes, until the EPA conducted a Regulatory Determination as to whether such wastes warranted regulation. This determination was required in 1982, though in 1980, Congress enacted the Solid Waste Disposal Act that exempted the wastes from Subtitle C, unless the EPA could prove the wastes posed hazards to human health and the environment. In 1988, the EPA completed their regulatory determination and determined that regulation under Subtitle C was not necessary since existing state and federal regulations were adequate, and the economic impact to the petroleum industry would be substantial.

This ruling resulted in solid wastes from the oil and gas industry to only be subject to regulations under Subtitle D – ensuring that wastes are stored in a manner that does not constitute a fire, health, or safety hazard and will not result in spillage. If regulated under Subtitle C, the surface pits in which wastes from hydraulic fracturing are typically stored would be required to have a liner designed to prevent any migration of wastes to the adjacent soil or groundwater.[126]

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[5] During the Obama era, the EPA finalized a rule to amend the new source performance standards (NSPS) under the Clean Air Act to regulate methane and VOCs from certain processes and activities in the oil and natural gas category. The rule covered unregulated processes under NSPS, including hydraulically fractured oil well completions, pneumatic pumps, and fugitive emissions from well sites and compressor stations. It also covered sources that are regulated for VOCs, but not methane, including equipment leaks at processing plants, pneumatic controllers, centrifugal compressors, and reciprocating compressors.[127] Additional administrative actions, such as enhancing leak detection and emissions reporting, proposing natural gas pipeline safety standards that focused on safety with the co-benefit of reducing methane emissions, and modernizing transmission and distribution infrastructure, were also included. This rule was a part of the Methane Pollution Standard under the Obama Administration's Climate Action Plan, the goal of which was to reduce methane emissions from the oil and gas sector by 40-45 percent below 2012 levels by 2025. The regulations apply to equipment and activities of onshore oil and natural gas. The standards were expected to reduce 39 million tonnes of carbon pollution (GWP20) and up to 290,000 tons of VOCs per year, the equivalent of 5 Aliso Canyon Disasters per year.[128]

Other Obama-era EPA proposals included requiring natural gas processing facilities to report chemicals used to the EPA's Toxic Release Inventory under the Emergency Planning and Community Right to Know Act, and reducing natural gas loss through equipment leaks, venting, and flaring on Native American and Bureau of Land Management Lands through the prohibition of venting natural gas unless it is an emergency, and, alternatively, capturing the gas for transport, process, and sale as an average of 120MMTCO2e was emitted annually from 2009-2014 on public lands from natural gas operations.

Appendix References:

Appendix A: Background on the U.S. Natural Gas System

1 "Natural Gas Consumption by End Use - Area." *Natural Gas,* U.S. Energy Information Administration Independent Statistics and Analysis, 2016. http://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm

2 "Natural Gas Explained: Use of Natural Gas." U.S. Energy Information Administration Independent Statistics & Analysis. http://www.eia.gov/energyexplained/index.cfm?page=natural_gas_use

3 "Natural Gas Consumption by End Use - Date Series." Natural Gas, *U.S. Energy Information Administration Independent Statistics and Analysis*, 2016. http://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm

4 "Use of Natural Gas" Energy Explained, *U.S. Energy Information Administration.* http://www.eia.gov/energyexplained/index.cfm?page=natural_gas_use

5 "Table: Total Energy Supply, Disposition, and Price Summary." *Annual Energy Outlook*, U.S. Energy Information Administration Independent Statistics and Analysis, 2016. http://www.eia.gov/outlooks/aeo/data/browser/#/?id=1-AEO2016&region=0-0&cases=ref2016&start=2014&end=2040&f=A&linechart=~ref2016-d032416a.31-1-AEO2016&ctype=linechart&sourcekey=0

6 "Ample natural gas supply is adequate to meet growth in both export and domestic markets." Market Trends: Natural Gas, *Annual Energy Outlook 2016*, 15 Sep 2016. https://www.eia.gov/outlooks/archive/aeo16/MT_naturalgas.cfm#natgasprod_exp

7 "How much natural gas does the United States have, and how long will it last?" Frequently Asked Questions, *U.S. Energy Information Administration.* 22 Dec 2016 https://www.eia.gov/tools/faqs/faq.cfm?id=58&t=8

8 "U.S. Natural Gas Gross Withdrawls." *U.S. Energy Information Administration Independent Statistics and Analysis,* 30 Dec 2016 http://www.eia.gov/dnav/ng/hist/n9010us2a.htm

9 "U.S. Natural Gas Total Consumption" Natural Gas, *U.S. Energy Information Administration Independent Statistics and Analysis.* https://www.eia.gov/dnav/ng/hist/n9140us2A.htm

10 "Natural gas production from shale gas and tight oil plays leads growth in U.S. natural gas supply." Market Trends, *Natural Gas Annual Energy Outlook 2016,* 15 Sep 2016. https://www.eia.gov/outlooks/archive/aeo16/MT_naturalgas.cfm#natgasprod_exp

11 "Understanding Drilling Technology" Paleontological Research Institution Marcellus Shale: The Science Beneath the Surface Issue 6 Jan 2012. http://www.museumoftheearth.org/files/marcellus/Marcellus_issue6.pdf

12 Tiemann, Mary and Adam Vann. "Hydraulic Fracturing and Safe Drinking Water Act Regulatory Issues." *Congressional Research Service* 13 Jul 2015. https://fas.org/sgp/crs/misc/R41760.pdf

13 "Natural gas production from shale gas and tight oil plays leads growth in U.S. natural gas supply." Market Trends: *Natural Gas Annual Energy Outlook 2016*, 15 Sep 2016. https://www.eia.gov/outlooks/archive/aeo16/MT_naturalgas.cfm#natgasprod_exp

14 "Draft SGEIS on the Oil, Gas and Solution Mining Regulatory Program." *Department of Environmental Conservation,* Sep 2011.

15 Osborn, Stephen G., et al. "Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing." *Proceedings of the National Academy of Sciences of the United States of America.* Vol 108 No 20 14 Apr 2011. http://www.pnas.org/content/108/20/8172.full

16 Vidic, R.D., et al. "Impact of Shale Gas Development on Regional Water Quality" *Science Magazine,* Vol. 340, Issue 6134, 17 May 2013.

17 Bame, Dorthe and Michael Fehler. "Observations of long period earthquakes accompanying hydraulic fracturing" *Geophysical Research Letters.* Vol. 13 Issue 2, Feb 1986. http://onlinelibrary.wiley.com/doi/10.1029/GL013i002p00149/full

18 Colborn, Theo, et al. "An Exploratory Study of Air Quality Near Natural Gas Operations Human and Ecological Risk Assessment" *An International Journal* Volume 20, 2014 - Issue 1, Taylor & Francis Online, 26 Nov 2012. http://www.tandfonline.com/doi/abs/10.1080/10807039.2012.749447

19 Howarth, Robert W., Anthony Ingraffea, and Terry Engelder. "Natural gas: Should fracking stop?" *Nature.* 477, 271-275. 15 Sept 2011. http://www.nature.com/nature/journal/v477/n7364/fig_tab/477271a_F1.html

20 "Natural Gas Explained: Natural Gas Pipelines." *U.S. Energy Information Administration Independent Statistics and Analysis.* http://www.eia.gov/energyexplained/index.cfm?page=natural_gas_pipelines

21 "U.S. Natural Gas Pipeline Network," About U.S. Natural Gas Pipelines, *U.S. Energy Information Administration*, 2009. https://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/ngpipelines_map.html

22 "Improvements Needed in EPA Efforts to Address Methane Emissions From Natural Gas Distribution Pipelines." *U.S. Environmental Protection Agency,* Office of Inspector General, Report No. 14-P-0324, 25 Jul 2014. https://www.epa.gov/sites/production/files/2015-09/documents/20140725-14-p-0324_0.pdf

23 Howard, Touche. "University of Texas study underestimates national methane emissions at natural gas production sites due to instrument sensor failure." *Energy Science & Engineering,* Wiley Online Library. Vol 3, Issue 5. 4 Aug 2015 http://onlinelibrary.wiley.com/doi/10.1002/ese3.81/full

24 Howards, Touche "Sensor transition failure in the high flow sampler: Implications for methane emission inventories of natural gas infrastrucutre." *Journal of the Air & Waste Management Association.* Research Gate. DOI: 10.1080/10962247.2015.1025925 Mar 2015 https://www.researchgate.net/publication/277573257_Sensor_transition_failure_in_the_high_flow_sampler_Implications_for_methane_emission_inventories_of_natural_gas_infrastructure

25 "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 2014." U.S. Environmental Protection Agency. 15 Apr 2016. https://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2016-Main-Text.pdf

26 Allen, David T. et al. "Measurements of methane emissions at natural gas production sites in the United States." *Proceedings of the National Academy of Sciences of the United States of America.* PNAS Vol 110: 17601. 29 Oct 2013. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3816463/

27 Miller, Scot M., et al. "Anthropogenic emissions from methane in the United States." P*roceedings of the National Academy of Sciences of the United States of America.* PNAS 2013 110 (50) 20018-20022, http://www.pnas.org/content/110/50/20018.abstract

28 Petron, Gabrielle, et al. "Estimation of Emissions from Oil and Natural Gas Operations in Northeastern Colorado." *National Oceanic and Atmospheric Administration.* https://www3.epa.gov/ttnchie1/conference/ei20/session6/gpetron.pdf

29 Karion, Anna et al. "Methane emissions estimate from airborne measurements over a western United States natural gas field." *Geophysical Research Letters.* Vol 40. 12 Jun 2013 http://www.achd.net/shale/pubs/Karion_et-al_2013_Methane.pdf

30 Schneising, Oliver, et al. "Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations." *Earth's Future.* Volume 2, Issue 10, 2014. http://onlinelibrary.wiley.com/doi/10.1002/2014EF000265/full

31 Caulton, Dana et al. "Toward a better understanding and quantification of methane emissions from shale gas development." *Environmental Sciences Proceedings of the National Academy of Sciences.* Vol 111 No. 17 PNAS

32 Schneising, Oliver, et al. "Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations." *Earth's Future.* Volume 2, Issue 10, 2014. http://onlinelibrary.wiley.com/doi/10.1002/2014EF000265/full

33 Kort, Eric et al. "Four corners: The largest US methane anomaly viewed from space" *Geophysical Research Letters.* 10.1002/2014GL061503 AGU Publications

34 Peischel, J et al. "Quantifying sources of methane using light alkanes in the Los Angeles basin, California." *Journal of Geophysical Research: Atmospheres* Vol 118, 4974-4990

35 Frankenburg, Christian, et al. "Airborne methane remote measurements reveal heavy-tail flux distribution in Four Corners region." *Proceedings of the National Academy of Sciences.* Vol 113 No. 35 9734-9739. 30 Aug 2016.

36 "Natural Gas Explained: Natural Gas Pipelines." *U.S. Energy Information Administration Independent Statistics and Analysis,* http://www.eia.gov/energyexplained/index.cfm?page=natural_gas_pipelines

37 "Oil and Natural Gas Sector Leaks." *U.S. EPA Office of Air Quality Planning Standards.* Apr 2014. http://www.ourenergypolicy.org/wp-content/uploads/2014/04/epa-leaks.pdf

38 "Improvements Needed in EPA Efforts to Address Methane Emissions From Natural Gas Distribution Pipelines." *U.S. Environmental Protection Agency,* Office of Inspector General, Report No. 14-P-0324, 25 Jul 2014. https://www.epa.gov/sites/production/files/2015-09/documents/20140725-14-p-0324_0.pdf

39 "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 2014." *U.S. Environmental Protection Agency.* 15 Apr 2016 https://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2016-Main-Text.pdf

40 "Methodological Descriptions for Additional Source or Sink Categories." *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 2013,* Annex 3, 2016 https://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2016-Annex-3-Additional-Source-or-Sink-Categories.pdf

41 "Inquiry into Philadephia Gas Works' Pipeline Replacement Program." *Pennsylvania Public Utility Commission Staff Report,* 21 Apr 2015. http://www.puc.state.pa.us/NaturalGas/pdf/PGW_Staff_Report_042115.pdf

42 "Improvements Needed in EPA Efforts to Address Methane Emissions From Natural Gas Distribution Pipelines." *U.S. Environmental Protection Agency, Office of Inspector General*, Report No. 14-P-0324, 25 Jul 2014. https://www.epa.gov/sites/production/files/2015-09/documents/20140725-14-p-0324_0.pdf

43 "Natural Gas Infrastructure," *Appendix B: Nautral Gas Department Natural Gas Outlook*. https://energy.gov/sites/prod/files/2015/06/f22/Appendix%20B-%20Natural%20Gas_1.pdf

Appendix B: Background on the U.S. Natural Gas System

44 Phillips, Nathan G. "Mapping upban pipeline leaks: Methane leaks across Boston." *Environmental Pollution.* Vol. 173 Pg. 1-4 Science Direct Feb 2013 http://www.sciencedirect.com/science/article/pii/S0269749112004800

45 McKain, Katheryn, et al. "Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts." *Proceedings of the National Academy of Sciences of the United States of America.* 2015.

46 Jackson, Robert B. et al. "Natural Gas Pipeline Leaks Across Washington DC." *Environmental Science and Technology.* ACS Publications. 16 Jan 2014.

47 "Natural gas: Local leaks impact global climate." *Environmental Defense Fund.* Google Earth Outreach. https://www.edf.org/climate/methanemaps

Appendix C: Public Health Impacts

48 "The potential impacts of shale gas and oil development on children as a vulnerable population." *Science Summary,* PSE Healthy Energy. Feb 2015 http://psehealthyenergy.org/data/SS_Vulnerable_Pop_3.7_.pdf

49 "Fracking in the Dark: Biological Fallout of Shale-Gas Porduction Still Largely Unknown." *Woodrow Wilson School.* http://wws.princeton.edu/news-and-events/news/item/fracking-dark-biological-fallout-shale-gas-production-still-largely

50 "Chemicals in Oil and Gas Operations - Health" *TEDX The Endocrine Disruption Exchange.* http://endocrinedisruption.org/chemicals-in-natural-gas-operations/health

51 "Chemicals in Oil and Gas Operations - Health" *TEDX The Endocrine Disruption Exchange.* http://endocrinedisruption.org/chemicals-in-natural-gas-operations/health

52 "Nitrogen Oxides." *Tox Town,* U.S. National Library of Medicine. https://toxtown.nlm.nih.gov/text_version/chemicals.php?id=19

53 "Chemistry in the Sunlight," *NASA,* Earth Observatory, http://earthobservatory.nasa.gov/Features/ChemistrySunlight/chemistry_sunlight3.php%60

54 McAllister, Karen, M.E.S. and Helen Lofgren, M.A. "Medical-Environmental Report," Mar 1997. http://web.archive.org/web/20090829053731/http://geocities.com/rainforest/6847/report1.html#6.0

55 "New study explains wintertime ozone pollution in Utah oil and gas fields" *National Oceanic and Atmospheric Administration.* 1 Oct 2014. http://www.noaanews.noaa.gov/stories2014/20141001_utahwinterozonestudy.html

56 Elliott, Elise G., et al. "A systematic evaluation of chemicals in hydraulic-fracturing fluids and wastewater for reproductive and developmental toxicity" *Journal of Exposure Science and Environmental Epidemiology.* 27, 90-99 Nature America Inc. 16 Jan 2016

57 Kassotis, Christopher D., et al. "Estrogen and Androgen Receptor Activities of Hydraulic Fracturing Chemicals and Surface and Ground Water in a Drilling-Dense Region." *Endrocrinology: Molecular and Physiological Basis of Endocrine Health and Disease.* Vol 155, Issue 3, Endocrine Society, 16 Dec 2013. http://press.endocrine.org/doi/full/10.1210/en.2013-1697

58 "Chemicals in Oil and Gas Operations - Health" *TEDX The Endocrine Disruption Exchange.* http://endocrinedisruption.org/chemicals-in-natural-gas-operations/health

59 "Chemicals in Oil and Gas Operations - Health" *TEDX The Endocrine Disruption Exchange.* http://endocrinedisruption.org/chemicals-in-natural-gas-operations/health

60 McKensie, LM., et al. "Human health risk assessment of air emissions from development of unconventional natural gas resources." *Science of the Total Environment* Vol 424, pg 79-87 ScienceDirect, 1 May 2012. http://www.sciencedirect.com/science/article/pii/S0048969712001933

61 "Surface and groundwater contamination association with modern natural gas development." *Science Summary.* PSE Healthy Energy Oct 2014. http://www.psehealthyenergy.org/data/Water_Studies_Science_Summary_Oct20141.pdf

62 Kassotis, Christopher D., et al. "Estrogen and Androgen Receptor Activities of Hydraulic Fracturing Chemicals and Surface and Ground Water in a Drilling-Dense Region." *Endrocrinology: Molecular and Physiological Basis of Endocrine Health and Disease.* Vol 155, Issue 3, Endocrine Society, 16 Dec 2013. http://press.endocrine.org/doi/full/10.1210/en.2013-1697

63 "Surface and groundwater contamination association with modern natural gas development." *Science Summary.* PSE Healthy Energy. Oct 2014. http://www.psehealthyenergy.org/data/Water_Studies_Science_Summary_Oct20141.pdf

64 Davis Jr, Spencer H. "The Effect of Natural Gas on Trees and Other Vegetiation." *Journal of Arborculture.* Aug 1977

Appendix D: Public Safety Impacts

65 "All Reported Incident 20 Year Trend." *Pipeline Incident 20 Year Trend*, Pipeline and Hazardous Materials Safety Administration. 11 Feb 2017. http://www.phmsa.dot.gov/pipeline/library/data-stats/pipelineincidenttrends

66 "Distribution, Transmisssion & Gathering, LGN, and Liquid Accident and Incident Data." *Pipeline and Hazardouse Materials Safety Administration. U.S. Department of Transportation.* http://www.phmsa.dot.gov/pipeline/library/data-stats/distribution-transmission-and-gathering-lng-and-liquid-accident-and-incident-data

67 Bureau of Labor Statistics. "Census of Fatal Occupational Injuries Charts, 1992-2015 (final data)." United States Department of Labor, https://www.bls.gov/iif/oshcfoi1.htm#charts

68 "All Reported Incident 20 Year Trend." *Pipeline Incident 20 Year Trend,* Pipeline and Hazardous Materials Safety Administration. 11 Feb 2017. http://www.phmsa.dot.gov/pipeline/library/data-stats/pipelineincidenttrends

69 Daly, Erin Marie. "Entergy Rises Out of Bankruptcy." *Law 360.* 9 May 2007. https://www.law360.com/articles/24337/entergy-rises-out-of-bankruptcy

70 Larino, Jennifer. "Entergy learns Katrina lessons, but damage prevention is still in question." *Nola.com,* The Times-Picayune. 25 Aug 2015. http://www.nola.com/katrina/index.ssf/2015/08/entergy_katrina_10_power_outag.html

71 "Distribution, Transmisssion & Gathering, LGN, and Liquid Accident and Incident Data." *Pipeline and Hazardouse Materials Safety Administration.* U.S. Department of Transportation. http://www.phmsa.dot.gov/pipeline/library/data-stats/distribution-transmission-and-gathering-lng-and-liquid-accident-and-incident-data

72 Yardley Associations. "Gas Distribution Infrastructure: Pipeline Replacement and Upgrades." *The American Gas Foundation.* July 2012 https://opsweb.phmsa.dot.gov/Pipelineforum/docs/07-2012%20Gas%20Distribution%20Infrastructure%20-%20Pipeline%20Replacement%20and%20Upgrades.pdf

73 "Distribution, Transmisssion & Gathering, LGN, and Liquid Accident and Incident Data." *Pipeline and Hazardouse Materials Safety Administration. U.S. Department of Transportation.* http://www.phmsa.dot.gov/pipeline/library/data-stats/distribution-transmission-and-gathering-lng-and-liquid-accident-and-incident-data

74 "Distribution, Transmisssion & Gathering, LGN, and Liquid Accident and Incident Data." *Pipeline and Hazardouse Materials Safety Administration. U.S. Department of Transportation.* http://www.phmsa.dot.gov/pipeline/library/data-stats/distribution-transmission-and-gathering-lng-and-liquid-accident-and-incident-data

75 "Distribution, Transmisssion & Gathering, LGN, and Liquid Accident and Incident Data." *Pipeline and Hazardouse Materials Safety Administration. U.S. Department of Transportation.* http://www.phmsa.dot.gov/pipeline/library/data-stats/distribution-transmission-and-gathering-lng-and-liquid-accident-and-incident-data

76 "Improvements Needed in EPA Efforts to Address Methane Emissions From Natural Gas Distribution Pipelines." *U.S. Environmental Protection Agency,* Office of Inspector General, Report No. 14-P-0324, 25 Jul 2014. https://www.epa.gov/sites/production/files/2015-09/documents/20140725-14-p-0324_0.pdf

77 "Distribution, Transmisssion & Gathering, LGN, and Liquid Accident and Incident Data." *Pipeline and Hazardouse Materials Safety Administration.* U.S. Department of Transportation. http://www.phmsa.dot.gov/pipeline/library/data-stats/distribution-transmission-and-gathering-lng-and-liquid-accident-and-incident-data

78 U.S. Government Publishing Office Title 49 Subtitle B Chapter I Subchapter D Part 192. *Electronic Code of Federal Regulations.* http://www.ecfr.gov/cgi-bin/text-idx?SID=5fbb53cbfd91e4487022c8392b7a8132&mc=true&tpl=/ecfrbrowse/Title49/49cfr192_main_02.tpl

79 "Improvements Needed in EPA Efforts to Address Methane Emissions From Natural Gas Distribution Pipelines." *U.S. Environmental Protection Agency,* Office of Inspector General, Report No. 14-P-0324, 25 Jul 2014. https://www.epa.gov/sites/production/files/2015-09/documents/20140725-14-p-0324_0.pdf

80 "Leak Survey Results." *California Public Utilities Commission.* 16 Mar 2016. http://www.cpuc.ca.gov/General.aspx?id=10456

Appendix E: Environmental Justice Issues

81 "EJ Screen: Environmental Justice Screening and Mapping Tool." *U.S. Environmental Protection Agency.* https://www.epa.gov/ejscreen

82 Banerjee, Neela. "A tale of two leaks: Fixed in California, ignored in Alabama." *Inside Climate News* ,Alabama.Com. http://www.al.com/news/index.ssf/2016/03/a_tale_of_two_leaks_fixed_in_c.html

Appendix F: Current and Planned Policy Solutions

83 Brady, William J. "Hydraulic Fracturing Regulation in the United States: The Laissez-Faire Approach of the Federal Government and Varying State Regulation." *University of Denver, Grimshaw & Harring, P.C.* http://www.law.du.edu/documents/faculty-highlights/Intersol-2012-HydroFracking.pdf

84 U.S. Energy Information Administration. "Use of Natural Gas" *Energy Explained.* http://www.eia.gov/energyexplained/index.cfm?page=natural_gas_use

85 City of Boston. "An Ordinance Regarding Management and Elimination of Natural Gas Leaks" *The Boston City Code,* Ordinances, Chapter XIII. https://d3n8a8pro7vhmx.cloudfront.net/mothersoutfront/pages/935/attachments/original/1481813389/BostonGasLeaksOrdinance_20161212.pdf?1481813389

86 "New report looks at numbers and reporting of natural gas leaks in Brookline." *Wicked Local Brookline.* 22 Aug 2016. http://brookline.wickedlocal.com/news/20160822/new-report-looks-at-number-and-reporting-of-natural-gas-leaks-in-brookline

87 City of Palo Alto. "Agenda: Electrification Task Force," 26 Jul 2016. http://www.cityofpaloalto.org/civicax/filebank/documents/53262

88 Hong, Bongghi and Robert Howarth. "Greenhouse gas emissions from domestic hot water: heat pumps compared to most commonly used systems." *Energy Science & Engineering.* DOI 10.1002/ese3.112 15 Dec 2015.

89 "Palo Alto Electrification Final Report" *TRC Solutions,* City of Palo Alto. 16 Nov 2016.

90 "Municipality fracking bans" Baldwin Hills Oil Watch. 2017. http://baldwinhillsoilwatch.org/action-center/municipality-fracking-bans/

91 "SB-605 Short-lived climate pollutants." *Califronia Legislative Information.* http://leginfo.legislature.ca.gov/faces/billCompareClient.xhtml?bill_id=201320140SB605

92 "SB-1383 Short-lived climate pollutants: methane emissions: dairy and livestock: organic waste: landfills." *California Legislative Information.* Senate Bill No. 1383. Chapter 395 19 Sept 2016. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB1383

93 Nemec, Richard. "California Governor Signs Nation's Toughest Methane Emissions Law." *Natural Gas Intellegence.* 22 Sept 2016. http://www.naturalgasintel.com/articles/107832-california-governor-signs-nations-toughest-methane-emissions-law

94 "SB-1371 Natural gas: leakage abatement." *Califronia Legislative Information.* http://leginfo.legislature.ca.gov/faces/billCompareClient.xhtml?bill_id=201320140SB1371

95 "Appendix A: Proposed Regulation Order." *California Code of Regulations*, Title 17, Division 3, Chapter 1, Subchapter 10 Climate Change, Article 4. California Air Reseources Board. https://www.arb.ca.gov/regact/2016/oilandgas2016/oilgasappa.pdf

96 Whetzel, Carolyn. "California Moves Forward with Oil, Gas Methane Rules." *Energy and Climate Report.* Bloomberg BNA 21 Jul 2016 https://www.bna.com/california-moves-forward-n73014445151/

97 Commonwealth of Massachusetts "Executive Order No. 569." *Constitution,* Part 2, Section 1, Art 1. http://www.mass.gov/courts/docs/lawlib/eo500-599/eo569.pdf

98 "An act relative to gas leak repairs during road projects." Bill H.2871. https://malegislature.gov/Bills/189/House/H2871

99 "An act relative to protecting consumers of gas and electicity from paying for leaked and unaccounted for gas" Bill H.2870. https://malegislature.gov/Bills/189/H2870/BillHistory

100 Brady, William J. "Hydraulic Fracturing Regulation in the United States: The Laissez-Faire Approach of the Federal Government and Varying State Regulation." *University of Denver, Grimshaw & Harring, P.C.*, http://www.law.du.edu/documents/faculty-highlights/Intersol-2012-HydroFracking.pdf

101 Jones, Enesta. "EPA Releases First-Ever Standards to Cut Methane Emissions from the Oil and Gas Sector." *News Releases,* Environmental Protection Agency. 12 May 2016. https://www.epa.gov/newsreleases/epa-releases-first-ever-standards-cut-methane-emissions-oil-and-gas-sector

102 "Air Quality Perment Exemptions." *Department of Environmental Protection.* 26 Jul 2003. http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-96215/275-2101-003.pdf

103 Brady, William J. "Hydraulic Fracturing Regulation in the United States: The Laissez-Faire Approach of the Federal Government and Varying State Regulation." *University of Denver, Grimshaw & Harring, P.C.* http://www.law.du.edu/documents/faculty-highlights/Intersol-2012-HydroFracking.pdf

104 "Unaccounted-For-Gas." *The Pennsylvania Code.* Section 59.111. 9 Aug 2013. http://www.pacode.com/secure/data/052/chapter59/s59.111.html

105 "Rule 7.5525 Lost and Unaccounted for Gas." *Texas Administrative Code.* Title 16 Part 1 Chapter 7 Subchapter E. 29 Jul 2002. https://texreg.sos.state.tx.us/public/readtac$ext.TacPage?sl=R&app=9&p_dir=&p_rloc=&p_tloc=&p_ploc=&pg=1&p_tac=&ti=16&pt=1&ch=7&rl=5525

106 "Regulation Number 7 Control of Ozone Via Ozone Precursors and Control of Hydrocarbons via Oil and Gas Emissions." *Code of Colorado Regulations,* Colorado Secretary of State. 5 CCR 1001-9. 14 Jan 2017. https://www.sos.state.co.us/CCR/DisplayRule.do?action=ruleinfo&ruleId=2341&deptID=16&agencyID=7&deptName=Department%20of%20Public%20Health%20and%20Environment&agencyName=Air%20Quality%20Control%20Commission&seriesNum=5%20CCR%201001-9

107 Brady, William J. "Hydraulic Fracturing Regulation in the United States: The Laissez-Faire Approach of the Federal Government and Varying State Regulation." *University of Denver, Grimshaw & Harring, P.C.* http://www.law.du.edu/documents/faculty-highlights/Intersol-2012-HydroFracking.pdf

108 "Chapter 8: Nonattainment Area Regulations." *Department of Environmental Quality*. Air Quality. State of Wyoming. 020.0002.812202016. 20 Dec 2016. https://rules.wyo.gov/Search.aspx?mode=1

109 Brady, William J. "Hydraulic Fracturing Regulation in the United States: The Laissez-Faire Approach of the Federal Government and Varying State Regulation." *University of Denver, Grimshaw & Harring, P.C.* http://www.law.du.edu/documents/faculty-highlights/Intersol-2012-HydroFracking.pdf

110 Coin, Glenn. "New York State Officially Bans Fracking." *Syracuse.com.* 29 June 2015. http://www.syracuse.com/news/index.ssf/2015/06/new_york_officially_bans_hydrofracking.html

111 "An act relating to hydraulic fracturing wells for natural gas and oil production." *General Assembly of the State of Vermont.* H.464. http://legislature.vermont.gov/assets/Documents/2012/Docs/ACTS/ACT152/ACT152%20As%20Enacted.pdf

112 "Oil and Natural Gas - Hydraulic Fracturing - Prohibition." *General Assembly of Maryland.* HB1325 (CH0013). 5 Apr 2017. http://mgaleg.maryland.gov/webmga/frmMain.aspx?id=hb1325&stab=01&pid=billpage&tab=subject3&ys=2017RS

113 Brady, William J. "Hydraulic Fracturing Regulation in the United States: The Laissez-Faire Approach of the Federal Government and Varying State Regulation." *University of Denver, Grimshaw & Harring, P.C.* http://www.law.du.edu/documents/faculty-highlights/Intersol-2012-HydroFracking.pdf

114 "North Dakota Industrial Commission Order 24665 Policy/Guidance Version 102215." https://www.dmr.nd.gov/oilgas/GuidancePolicyNorthDakotaIndustrialCommissionorder24665.pdf

115 "Stormwater Discharges from Oil and Gas Operations or Transmission Facilities." *Natural Gas Extraction - Hydraulic Fracturing.* Environmental Protection Agency. https://www.epa.gov/hydraulicfracturing#stormwater

116 "To repeal the exemption for hydraulic fracturing in the Safe Drinking Water Act, and for other purposes." *Congress.Gov.* H.R. 7231 110th Congress 2007 - 2008 https://www.congress.gov/bill/110th-congress/house-bill/7231

117 "FRAC Act." *Congress.Gov.* S. 785 - F 114th. Congress. 2015 - 2016. https://www.congress.gov/bill/114th-congress/senate-bill/785/text

118 Tiemann, Mary and Adam Vann. "Hydraulic Fracturing and Safe Drinking Water Act Regulatory Issues." *Congressional Research Service.* 13 Jul 2015 https://fas.org/sgp/crs/misc/R41760.pdf

119 Brady, William J. "Hydraulic Fracturing Regulation in the United States: The Laissez-Faire Approach of the Federal Government and Varying State Regulation." *University of Denver, Grimshaw & Harring, P.C.* http://www.law.du.edu/documents/faculty-highlights/Intersol-2012-HydroFracking.pdf

120 "Stormwater Discharges from Oil and Gas Operations or Transmission Facilities." *Natural Gas Extraction - Hydraulic Fracturing.* Environmental Protection Agency. https://www.epa.gov/hydraulicfracturing#stormwater

121 "33 U.S. Code Section 2701" *Legal Information Insitute*. Cornell University Law School. Title 33 Ch. 40, Subchapter I. https://www.law.cornell.edu/uscode/text/33/2701

122 U.S. Environmental Protection Agency. "Is My Facility's Six-Digit NAICS Code a TRI-Covered Industry?" *Toxics Release Inventory (TRI) Program.* https://www.epa.gov/toxics-release-inventory-tri-program/my-facilitys-six-digit-naics-code-tri-covered-industry

123 "Free Pass for Oil and Gas: Oil and Gas Industry Exemptions." *Environmental Working Group*, Oct 2015. http://www.ewg.org/research/free-pass-oil-and-gas/oil-and-gas-industry-exemptions

124 Ibid.

125 Brady, William J. "Hydraulic Fracturing Regulation in the United States: The Laissez-Faire Approach of the Federal Government and Varying State Regulation." *University of Denver, Grimshaw & Harring, P.C.* http://www.law.du.edu/documents/faculty-highlights/Intersol-2012-HydroFracking.pdf

126 U.S. Environmental Protection Agency. "Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources" *Federal Register.* EPA-HQ-OAR-2010-0505 2 Aug 2016 https://www.federalregister.gov/documents/2016/06/03/2016-11971/oil-and-natural-gas-sector-emission-standards-for-new-reconstructed-and-modified-sources

127 Jones, Enesta. "EPA Releases First-Ever Standards to Cut Methane Emissions from the Oil and Gas Sector." *News Releases,* Environmental Protection Agency. 12 May 2016. https://www.epa.gov/newsreleases/epa-releases-first-ever-standards-cut-methane-emissions-oil-and-gas-sector