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Policy Analysis

Repair Failures Call for New Policies to Tackle Leaky Natural Gas Distribution Systems

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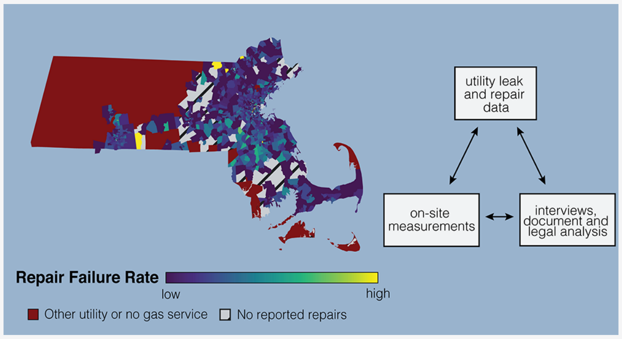
ABSTRACT: Methane leaks in natural gas systems are low-hanging fruit for near-term, locally driven climate policy. Recent work suggests this emissions source is larger than previously believed and that repairing a small number of high emitters can cost-effectively reduce system-wide leakage. How successful are these repairs on the ground? Here, we assess the effectiveness of repair policies in the Massachusetts distribution system. Our analysis leverages state-wide utility data, on-site empirical measurements, stakeholder interviews, and document and legal analysis. We use these mixed methods to investigate the rate of *repair failure*, where a gas utility identifies and fixes a leak, but on-site emissions are not eliminated. We find that repair failures are relatively common, yet they are repeatedly neglected in policy. By not accounting for repair failures, policy may overestimate the effectiveness of distribution system repairs in meeting local greenhouse gas reduction targets. These results also underscore the importance of data transparency for monitoring and verifying subnational climate policies.



INTRODUCTION

The urgency of the climate crisis[1] and a shortfall in national policies[2] have inspired subnational actors to seek out opportunities to reduce greenhouse gas emissions.[3] One promising near-term strategy is to reduce methane (CH_4) emissions throughout the natural gas supply chain. Natural gas use continues to expand in the U.S. and globally due to a combination of technology, policy, and market forces,[4] including the deployment of directional drilling and high-volume hydraulic fracturing technologies[5,6] and pressures to retire coal-fired power plants.[7] While natural gas emits less carbon dioxide (CO_2) than coal during combustion, it is composed primarily of CH_4, a shorter-lived but potent greenhouse gas.[8] Reducing natural gas CH_4 emissions is a low-hanging fruit for climate change mitigation that is accessible to many actors, including utilities and state and local governments. Recent subnational efforts to reduce natural gas emissions in the U.S. range from state legislation on upstream emissions to enhanced measurement and reporting, pipeline repair and replacement, and, more recently, bans on new natural gas hookups.[9−11,87]

Scientific understanding of CH_4 emissions from natural gas systems has coevolved with policy over the past decade.[12] Emissions were traditionally estimated indirectly, rather than through direct measurements, most commonly using outdated emissions factors derived from a limited sample of sources.[13,14] Early efforts to update these estimates focused on unconventional natural gas production in the U.S.[15] and later expanded to investigate other sources and stages of the supply chain.[16−18] Maps of mobile concentration measurements called attention to the surprisingly large number of leaks along distribution systems,[19−21] and bottom-up[22,23] and top-down[24,25] studies found that CH_4 emissions across the system were higher than previously believed.[26,27] Research suggests that a small number of "super-emitting" elements produce the bulk of total emissions,[28−30] partially explaining the difficulties in estimating system-wide emissions.[31] Repairing and replacing the highest emitters, if they can be accurately identified and eliminated, may cost-effectively reduce overall emissions.[32] However, the effectiveness of this strategy is largely unverified.

Data limitations, particularly at subnational scales, present an ongoing challenge for climate policy.[33,34] Despite significant local interest in leaks in the natural gas distribution system, to our knowledge no study has assessed repair performance at this stage of the supply chain. Evidence from upstream efforts

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suggests that leak detection and repair (LDAR) programs are partially effective. A measurement study in Alberta, Canada, found that new leaks offset roughly half the emissions reductions achieved by LDAR in unconventional natural gas facilities.[35] Modeling studies suggest that policy effectiveness can vary dramatically with baseline emissions, leak size distribution, and measurement approaches.[9] While the distribution system represents a small fraction (~8%[36]) of natural gas emissions, local emissions depend strongly on the material and age of pipelines. For cities along the East Coast with leak-prone infrastructure, leaks can make up a significant fraction of local emissions, and addressing them may be critical for meeting state-level climate targets.

Here, we develop a novel, mixed methods process to assess policies to repair gas leaks and apply it to the Massachusetts distribution system. Massachusetts is an ideal state for exploring this issue, given its first-mover status, along with Pennsylvania, in linking lost gas from distribution systems to climate change.[37,38] First, we build a large geospatial data set of gas leak reporting and repair activity and use it to calculate the rate of *repair failure*, where a repair occurs and subsequently a new leak is reported or repaired at the same location. Second, we perform on-site measurements before and after repair for a sample of potentially high-emitting leaks to assess repair performance. Third, we use stakeholder interviews and document and legal analysis to explore how technical, organizational, and policy factors created enabling conditions for the repair failures we observe. By combining these methods, we assess the extent of the repair failure problem in Massachusetts from multiple perspectives and identify potential strategies for reducing CH_4 emissions from natural gas distribution.

Massachusetts is a valuable case study for evaluating subnational climate policies in general and natural gas distribution systems in particular. As in many states in the Eastern U.S., natural gas infrastructure in Massachusetts is particularly leak-prone, due to the age and material of the pipelines (e.g., bare steel, cast iron, wrought iron).[28] Gas leaks have captured local public attention for over a decade—in fact, state representatives introduced a bill in 2011 to give operators responding to leaks a duty to “limit the amount of greenhouse gas emitted to the atmosphere.”[39] Massachusetts has taken a variety of actions to address gas leaks over the intervening years. Public concern focused first on safety risks,[40] costs to consumers from lost and unaccounted for gas,[41] and transparency around leak reporting and repair.[87] More recent actions frame gas leaks as a climate issue.[19,42,43] They emerged from an interplay of collaborative research and organizing between civil society, academia, and utilities, allowing us to draw insights from a large network of stakeholders.

■ MATERIALS AND METHODS

Data Analytics. We first investigate the effectiveness of repair policies using data from the three largest utilities in Massachusetts. Utility leak and repair data are sourced from the Massachusetts Department of Public Utilities File Room.[44] Utilities were required by law to report these data publicly in 2014.[87] Our data set includes the address of each leak detection or repair, the date, and the leak grade. While exact definitions differ across utilities, a grade 1 leak poses an existing or probable hazard to life or property, a grade 2 presents a probable future hazard, and a grade 3 is reasonably expected to remain nonhazardous. We calculate latitude and longitude for leak and repair addresses using the Google Maps API and screen to identify entries whose mapped address does not correspond to the original address provided in utility records. Where possible, records are manually corrected (e.g., for spelling errors). For less than 5% of repairs, correct addresses are ambiguous. For example, some addresses list a street in a particular town where it does not exist, but that street does exist in multiple nearby towns. Ambiguous entries were excluded from the analysis, a conservative choice that may slightly underestimate the rate of repair failure. Duplicate records were also removed.

We use this data set to analyze the rate of repair failure in Massachusetts. A repair failure is defined broadly as any unsuccessful or impermanent attempt to eliminate CH_4 emissions at a particular location. Approximately 50 000 repairs were reported from 2014 to 2018, while the count of unrepaired leaks that remained on the books at the end of a calendar year ranged from approximately 18 000 leaks in 2014 to 16 000 leaks in 2018 (see SI Figure 7). For each repair, we search for leak detections or repairs that occurred at the same location after the initial repair. This approach enables us to investigate the effectiveness of a large number of repairs over several years. Repair failures may be observed if the original repair is unsuccessful, if not all leaks at the site are repaired, or if a new leak emerges. Maps of results were created using leaflet, Mapbox, and GeoPandas, with additional geospatial data from publicly available sources.[45,46] Other code used in the analysis was written in Python and R and is available upon request. Cleaned leak and repair data are continuously updated and are available at https://heet.org/library.

Empirical Measurements. The next part of our analysis uses empirical measurements to analyze the failure rate for a sample of 61 repairs performed on potentially high-emitting grade 3 leaks from 2019 to 2020. Candidate leaks were identified by utilities using the *leak extent method*, a two-step process where (1) a leak is identified by elevated CH_4 concentrations using a combustible gas indicator (CGI) with a minimum resolution of 0.05% CH_4 (by volume) or 500 ppm and (2) the leak edges are defined by the perimeter where measured CH_4 elevations equal zero. The gas saturated surface area (length times width) is used as an indicator of emissions rate. This method correlates well with standard flux chamber measurements (r^2 = 0.86) and is considerably less labor-intensive.[47] It was also recognized by DPU as an acceptable method for utilities in Massachusetts to identify and prioritize grade 3 leaks for repair. It is now the standard method used by all three major utilities, replacing an earlier method that was shown to be uncorrelated with flux measurements.[47] A cutoff of 2000 ft^2 is currently the threshold to indicate a leak with significant environmental impact (SEI). For each leak, we measured the leak extent before and within a year after repair, leaving at least 30 days for residual gas to dissipate.

We classified repair outcomes into three groups. Outcomes were classified as (a) *SEI*, if a leak was present after repair with a footprint above the cutoff for significant environmental impact (2000 ft^2), (b) *non-SEI*, if a leak was present after repair with a footprint less than 2000 ft^2, or (c) *eliminated*, if no CH_4 emissions were detected at the site. Data on pre- and postrepair measurements are provided in SI Section D. Since surface CH_4 concentrations are influenced by leak migration patterns and other factors,[48,49] and because the CGI resolution is 0.05%, the leak footprint is subject to uncertainty, and some leaks we classify as eliminated may have small, nonzero

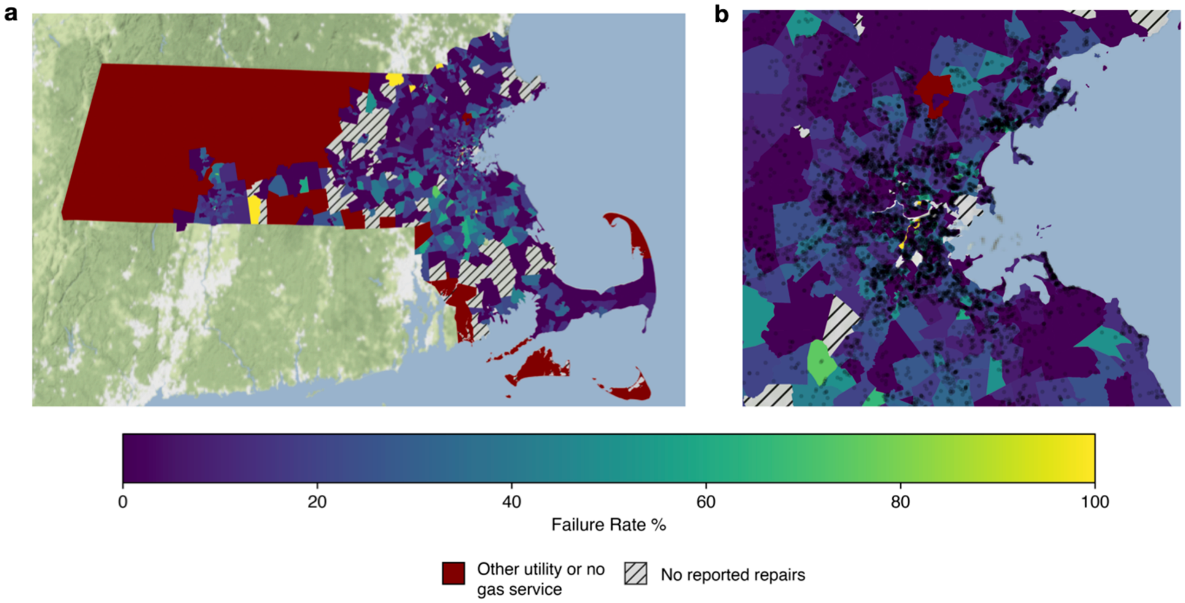

Figure 1. Gas leak repair failure rates in Massachusetts by census tract, where a repair occurs and a leak is subsequently repaired or reported in the same location. Here, we show repairs (black dots, in b only) and failure rates for the three largest gas utilities in Massachusetts for the year 2017 for (a) the entire state and (b) a portion of the state that includes Boston and other dense parts of the natural gas network. (Map tiles by Stamen Design, under CC BY 3.0. Data by OpenStreetMap, under ODbL. © OpenStreetMap contributors.)

emissions. It is also possible that residual gas persists beyond the minimum 30-day interval after repair, which may result in a false positive leak detection. Candidate repairs were identified through a combination of direct utility communications with the authors and quarterly and annual public utility reports. For the latter case, the window between repair activity and postrepair measurement was sometimes longer (though not exceeding one year), leaving more time for a new leak to emerge. This would lead to a higher repair failure count.

Qualitative Analysis. We investigated potential factors that contribute to repair failures by (a) analyzing a variety of legal and policy documents and (b) conducting semistructured interviews with 31 subject matter experts with knowledge of CH_4 emissions from the natural gas distribution system and potential technical, organizational, and policy responses to these emissions. Our document analysis and interview topics addressed the period from 2005 to the present. Archival data included media accounts, documents prepared by organizations, legislative history, peer-reviewed studies, and state, federal, and local agency reports and records, including proceedings before the Massachusetts Department of Public Utilities (DPU). Semistructured interviews were carried out in person and via telephone with subject matter experts. Interviewees were identified via document analysis and recommendations from other interviewees via a snowball sampling method. They included leaders of coalition member organizations, agency leaders and analysts, commissioners, utility executives and workers, environmental scientists, and participants in publicly reported proceedings, meetings, and disputes.

Each interview included questions concerning several topics: (1) organizational objectives and practices during the study period; (2) work on CH_4 leakage from natural gas distribution networks; (3) definitional and measurement concerns for downstream natural gas leaks; (4) the evolution of climate policy generally and specifically with regard to natural gas leaks; (5) major disputes and agreements between stakeholders over the classification of natural gas leaks, identification of environmentally significant leaks, and leak management; (6) data gaps in measurement, reporting, and verification of gas leaks and CH_4 emissions; (7) organizational contributions to or use of various data sets; and (8) the availability of a range of regulatory design tools to address these issues. Interviews were completed on a voluntary basis with informed consent. They were recorded and transcribed using Otter with manual verification.

Qualitative research began with analysis of the work of the Gas Leaks Allies, a coalition selected for their role in elevating the issue of gas leaks in Massachusetts in general and in gathering, analysis, and use of data on gas leaks specifically. Narrative construction followed the standard case study protocol developed by Yin.[50] Data reduction in the form of analytic coding was used to extract evidence of the development, evolution, and application of natural gas leak measures, indicators, and tools by stakeholder organizations and collaboratives. Analytic coding involves assigning labels to segments of text that represent similar phenomena, such as acts, meanings, relationships, and settings.[51] Triangulation (between primary organizational or governmental data and secondary sources containing similar data) was used where possible to ensure data accuracy. Additional details on our qualitative methods and findings are presented in SI section A.

■ RESULTS AND DISCUSSION

Data Analytics. We identify 9861 repair failures from 2014 through 2017 in our state-wide data set. This represents a failure rate of 20%. Repair failures can be detected (through a new leak report or repair) several years after a repair occurs, but the likelihood decreases as the time after repair increases. For repairs performed in 2014, 1650 resulted in a new leak or repair reported within one year. A further 544, 444, 333, and 125 failures were detected in the second, third, fourth, and fifth

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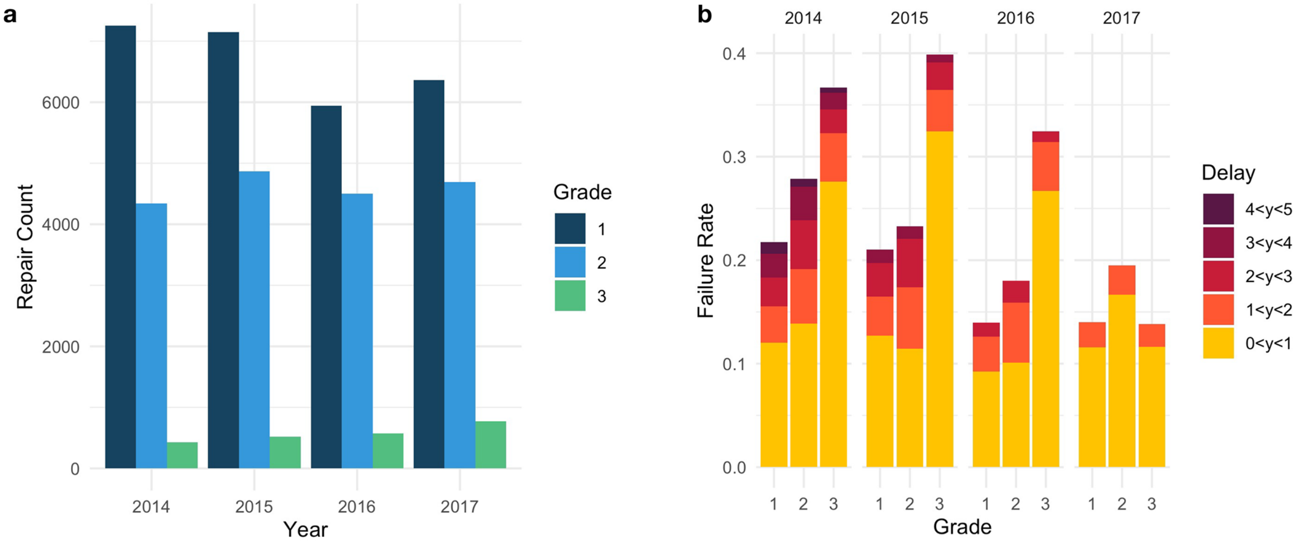

Figure 2. Total repairs and failure rates analyzed using a large data set of gas leaks and repairs. (a) Repairs by grade, where grade is a measure of safety hazard (1 = existing or probable hazard; 2 = potential future hazard; 3 = nonhazardous). (b) Repair failure rates by year and grade, with colored bars indicating the time delay for repair failure detection (in years). Because our data set continues through 2018, the time window for detecting repair failures is shorter for later years (i.e., less than two years for 2017, three years for 2016, and four years for 2015 repairs).

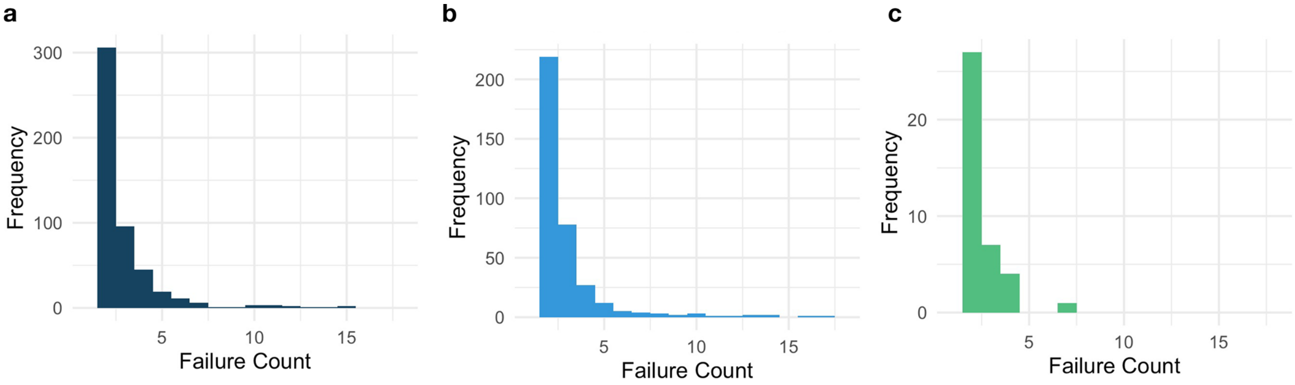

Figure 3. Distribution of repeat repair failures analyzed using a large data set of gas leaks and repairs. Repair failures by location (with initial repair occurring in 2014) for locations where at least two failures are detected for grade (a) 1, (b) 2, and (c) 3 leaks. Leak grade is a measure of safety hazard (1 = existing or probable hazard; 2 = probable future hazard; 3 = nonhazardous).

year after repair, respectively, resulting in a failure rate of 25% for 2014. Figure 1 maps the distribution of repair failure rates for the year 2017 by census tract, and maps of failure rates for 2014, 2015, and 2016 are presented in SI sections B and C. The rate of failure detected within the first year is similar across repair years and ranges from 11 to 14%. However, because our data set runs through 2018, there are fewer years in which to detect failures for more recent repairs. As a result, the overall rate of repair failure is lower for more recent repair years. When comparing repair failures detected within the same period of time (for example, one year), there is no clear trend in rates of repair failure over time. Across all years where the relevant observations are fully available, there is an average failure rate of 12.6% within the first year and 4.5%, 3.6%, and 2.6% within the second, third, and fourth years.

Our analysis suggests that repair failures are a widespread phenomenon in Massachusetts and are not limited to a particular year, utility, or geographic area. Repair counts vary across census tracts, with the largest number of repairs concentrated in the Boston Metropolitan Area and other large cities such as Worchester, Springfield, and Lowell. While there is variation across locations and over time, repair failures roughly track with the count of overall repairs at the census tract level (see SI Figures 1−3 for repair failure rates by census tract for repairs performed in 2014, 2015, and 2016). The median failure rate across census tracts ranges from 12 to 21% across the study years (see SI Table 1 and Figure 5). The extreme high and low repair failure rates observed for some census tracts are likely due to random chance, since census tracts with these extreme values are not constant from year to year and have a small number of total repairs (see SI Figure 6). We present additional maps of leaks, repairs, and repair failures in sections B and C of the SI.

Repair failures present not only a climate issue but also a safety hazard. Gas leaks are graded according to their existing or probable hazard to persons or property, taking into account factors such as operating pressure, leak migration, and proximity to buildings and other structures. Figure 2 presents repair counts and failures by grade. Because existing and potential hazards are determined by a variety of factors, the

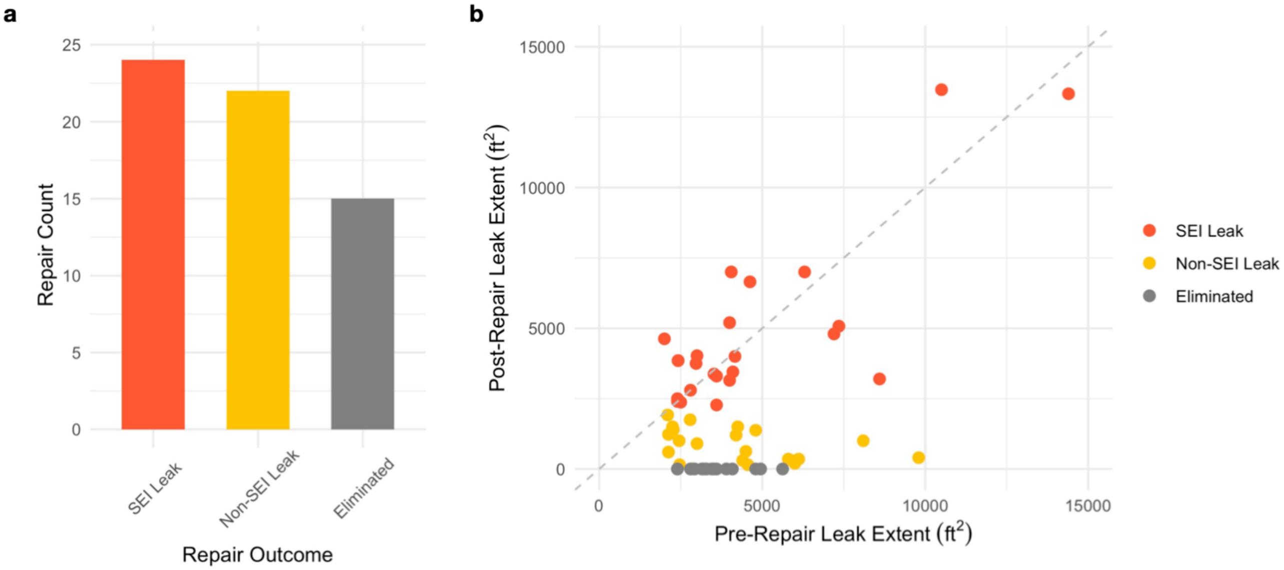

Figure 4. Empirical measurements of repair failure rates for a sample of 61 potentially high-emitting leaks. (a) Repairs in the sample that result in an SEI leak (footprint 2000 ft^2 or greater), a non-SEI leak, and an eliminated leak. (b) Scatterplot of leak extents before and after repair.

grading system is not an indicator of CH_4 flux. Some of the highest-emitting leaks are grade 3. These leaks are believed not to pose a safety hazard (and are regularly re-evaluated for safety at intervals set by state regulation) but can be a significant concern for climate change. As repairs are largely driven by safety concerns, there are fewer grade 3 repairs in our data set. However, we expect to see a greater number of these repairs in the future—Massachusetts DPU completed rule-making to redefine high-emitting grade 3 leaks as "environmentally significant" and accelerate their repair in 2019.[43] Among grade 3 leaks that were repaired, the overall failure rate is approximately 60% higher than for grade 1 repairs and 30% higher than for grade 2 repairs.

While the majority of leaks along the distribution system see at most one repair failure, there is a long tail of "super failures," or locations where repair failures occur repeatedly. Figure 3 shows the frequency of repeat repair failures, where a repair failure occurs more than once at the same location, for grade 1, 2, and 3 leaks. For locations where repairs occurred in 2014, 944 experienced a second repair failure, representing 8% of repairs for that year. While less common, a small number of locations experienced multiple repair failures—93 locations experienced five or more. There are several potential causes for these repeat repair failures. Utility workers may apply temporary fixes without eliminating the underlying leak. Leaks may also re-emerge along leak-prone segments of the network, or repairs may only address one of many leaks in the same vicinity. We suggest that locations with repeat repair failures be targeted for more in-depth study. These locations may be good candidates for early transitions to electrified heating.

Our results underscore the potential for using existing public data sets, reported by law, to evaluate the effectiveness of climate policies. This approach is relatively low cost and potentially accessible to many local actors. However, these data sources have limitations. Utilities vary in their procedures for surveying, grading, and repairing leaks. Leak and repair locations are also reported as addresses, which are both imprecise and subject to error. Leak counts reported by utilities are lower than those identified through more comprehesive surveys,[19,36,49] with one study suggesting that utilities find only one-third of leaks.[22] Studies of upstream leaks suggest that detection rates can vary according to worker experience and survey protocols.[52] Distribution system leaks are also identified via community reports, which may depend on leak detectability (e.g., size and location) and the level of community awareness. Under-reporting biases estimates of repair failures downward, whereas imprecise locations bias estimates upward (for example, if multiple leaks exist at the same address). More comprehensive leak surveys, sensitive instruments, and precise location tagging in utility reports would reduce these sources of bias. These limitations suggest that there are benefits to combining secondary data analysis and empirical measurements.

Empirical Measurements. Out of the 61 repairs for which we conducted on-site measurements, 15 effectively eliminated the leak, 22 reduced the leak extent below the cutoff for significant environmental impact (2000 ft^2) but did not eliminate it, and 24 did not reduce the leak below the cutoff (see Figure 4). While the sample of leaks is small compared to the state-wide data analysis, it also focuses on leaks that were screened by utilities as potential high emitters. These leaks are particularly significant for climate policy. Since the natural gas system is characterized by superemitter behavior, success in repairing the largest leaks is essential for reducing greenhouse gas emissions. Particularly concerning are the 24 sites where SEI leaks were identified after repair. As in our state-wide analysis, these sites may be the result of an unsuccessful repair or a leak that emerges between utility repairs and our postrepair measurements. More rapid postrepair measurement and repeated measurements of the same leak could reduce uncertainty in the causes of repair failures and characterize measurement errors in identifying SEI and non-SEI leaks.

Using the same definition of repair failure as in our state-wide analysis (i.e., any unsuccessful or impermanent attempt to eliminate CH_4 emissions), the effective failure rate for our empirical measurements is 75%. This rate is considerably higher than found in our state-wide analysis. Four potential explanations may contribute, individually or in combination, to this difference. First, leaks can go undetected by utilities, which would underestimate repair failures in our state-wide data analysis. This is particularly likely for repairs that reduce but do not eliminate leaks, since smaller emissions sources are less likely to be detected.[52] Second, utilities replace some leak-prone pipelines each year through the Gas System Enhancement Program (GSEP), and the probability of repair failure is lower if a line is replaced after repair (see SI section F). Third, our measurement sample focuses on high-emitting leaks, which may be more difficult than average to repair or receive less attention in repair and verification (because they do not pose a safety hazard). Finally, some differences may be attributable to sampling bias or random chance. Despite these differences, both analyses point to substantial repair failures and suggest there is room to improve the effectiveness of leak repairs as a climate policy lever.

Qualitative Analysis. Experts in our semistructured interviews noted technical, organizational, and policy challenges to leak repair. Insights from these interviews and document analysis are presented in full in the SI, and here we highlight key emergent themes. Leaks frequently appear in clusters along leak-prone segments of the natural gas distribution network, and repairs may not fix all leaks in these clusters. New leaks can appear after repair due to corrosion, construction damage, earth movement, breakdown of joints, cracking, and other factors. (Leaks that emerge or are detected at the location of a previous repair would be coded as repair failures in our analysis.) Utilities have historically focused on repairing hazardous leaks, leading to a backlog of grade 3 leaks. Since utilities recover the cost of lost gas from ratepayers, there are few financial incentives to repair grade 3 leaks as they are identified. Concerns over repair costs may lead utilities to apply temporary fixes (e.g., venting CH_4 through drill holes) to avoid the higher costs of more permanent repairs. Other cost-cutting measures, including using contract rather than full-time workers, may also elevate the risk of repair failures.

Beyond these technical challenges, several policy factors contribute to the ongoing repair failures we observe. National attention to CH_4 emissions has focused primarily on other parts of the natural gas system. While federal and state laws and regulations[53−55] call for actions such as leakage surveys, pressure testing, and corrosion inspection at prescribed intervals based on material or equipment type,[56] standards for distribution networks[56] are less comprehensive than for other elements of the natural gas system, including transmission lines, compressor stations, and lines that operate at higher pressure.[53−56] At the state level in Massachusetts, while the Global Warming Solutions Act imposes annual declining CH_4 emissions limits, distribution lines were only added as a source category after considerable litigation.[42] Compliance is determined using emissions and activity factors rather than direct emissions measurements[57] and thus does not account for repair effectiveness. Repair failures were not seen as a problem historically; in fact, in an investigation required under the Green Communities Act, which was designed to significantly reduce state barriers to energy efficiency and renewable energy, DPU concluded that additional inspection, maintenance, and repair protocols were unnecessary.[37]

While Massachusetts has been the site of considerable action on gas leaks, legislation and rulemaking has largely focused on issues other than repair effectiveness. These include repair and replacement timelines, transparency and public reporting, and standardized calculations for lost and unaccounted for gas. Our analysis suggests that high-emitting grade 3 leaks may be particularly difficult to repair. Interviewees described grade 3 leaks as inherently complex. They can appear in clusters along leak-prone pipes, which one interviewee described as a "sieve." They have unique risk profiles, more commonly due to corrosion or mechanical failure, that may warrant distinct repair and surveillance. Nevertheless, a recent focus on these leaks under the Energy Diversity Act did not adjust repair standards for leaks "identified as having a significant environmental impact."[58,87] In fact, while new rules promise to accelerate the repair of grade 3 SEI leaks, DPU has rejected calls from the New England Gas Workers Alliance (NEGWA) and other intervenors to adopt best practices for leak repair, arguing that utilities should fine-tune their own standards[58] to account for differences in service territory, geography, historical performance, and other factors.[59]

Longstanding failure to address grade 3 leaks in particular contributes to maintenance traps where cost-cutting is paramount. For example, NEGWA claimed in comments before DPU that utilities "avoid identifying gas leaks" or "apply temporary fixes to avoid the costs associated with more permanent repairs."[60] Proposed legislation dating back 20 years may have better prepared utilities to mitigate these dynamics. They required immediate scheduled repair of "nuisance grade 3" leaks;[61] additional training, experience, and permanent job status for workers grading leaks;[61] more extensive leak monitoring and resurveying;[62,63] a general duty for operators to "limit the amount of greenhouse gas expelled to the atmosphere;"[63] random leak inspections by DPU employees;[62] penalties for each leak not surveyed as required;[64] and rate adjustments to address CH_4 emissions.[65] Legislation proposed in the aftermath of the 2018 Merrimack Valley disaster also addresses many of these issues, with provisions for postrepair surveillance, reports by certified inspectors that repairs are free from defects, additional criteria for leaks to be eliminated rather than repaired, and more precise location tagging using GPS.[43]

Our analysis of repair failures also points to the conditions necessary for data disclosure to enable effective policy-making (referred to as "governance by disclosure").[66−69] Data were first disclosed under state law for leak and repair activity in 2014. However, as climate policy embraced CH_4 emissions as a source category, lawmaking shifted from disclosure to identifying environmentally significant leaks, with less attention to how repairs are verified or linked to climate targets under the Global Warming Solutions Act. Emissions are calculated using protocols provided by the Environmental Protection Agency, which multiply pipeline length by average emissions rates for different materials. Whereas accelerated replacement of cast iron or bare steel pipelines (for example, under GSEP) is reflected in inventories, emissions reductions from targeted repair are not. The effectiveness of either leak repair or pipeline replacement as climate policy levers, as well as opportunity costs due to fossil fuel infrastructure lock-in, could be better informed through analysis of public data, yet this link was largely missing prior to our analysis.[70]

■ CONCLUSIONS

As climate policy moves from national and subnational commitments to implementation and measurement, reporting, and verification of emissions on the ground, understanding the effectiveness of actions to reduce greenhouse gas emissions is increasingly important. Quantifying emissions from different sources is an ongoing challenge in natural gas and other infrastructure systems, particularly when emissions vary significantly across locations and system components.[71,72] Engineering evaluations of climate policies frequently assume perfect implementation, yet evidence points to technical, organizational, and policy barriers to realizing theoretical reduction potentials.[73] Challenges in tracking policy impacts are amplified by the increasingly broad and diverse coalition of actors that work to reduce emissions, including local, state, and national governments as well as utilities, facility owners and operators, nonprofit organizations, and communities. We develop a mixed methods approach for triangulating policy effectiveness by combining multiple lines of scientific evidence and apply it to the Massachusetts natural gas distribution system.

Fixing gas leaks has emerged as an important policy lever in Massachusetts and other states with aging infrastructure. However, the effectiveness of leak repair was largely unknown. Our analysis leverages data analytics to understand the scale of the repair failure problem, empirical measurements to calculate failure rates for a sample of high-emitting leaks, and stakeholder interviews and document and legal analysis to gain insights into the drivers of repair failures and potential policy solutions. Our results suggest that a substantial fraction of repairs fail to eliminate emissions. Analyzing a large utility-reported data set, we identify nearly 10 000 repair failures, representing 20% of repairs conducted from 2014 to 2017. Because failures continue to appear years after a repair occurs, we expect future years of data to reveal additional repair failures. On-site measurement of a sample of high-emitting leaks suggests that over half of the repairs did not fully eliminate leaks. Through stakeholder interviews and document and legal analysis, we identify factors that limit the effectiveness of current repair policies. As each method in our analysis carries its own strengths and limitations, convergence across multiple methods provides greater confidence in our findings.

Repair failures—that is, any unsuccessful or impermanent attempt to eliminate natural gas emissions at a particular site—reflect both discrete and broader sociotechnical systems failures. A repair failure may be due to a specific engineering error such as failing to fix a leak or disturbing nearby pipelines and creating a new leak. However, a failure also occurs if a repair eliminates one leak but fails to fix others that cluster nearby, or if a new leak emerges at the site of a previous repair. Quantifying the overall frequency of repair failures is critical for assessing policies to reduce CH_4 emissions across thousands of miles of distribution pipelines. However, attributing failures to different causes is challenging. Utilities do not report the size or exact location of leaks, and both are difficult to determine precisely due to leak migration and variation in measurement conditions over time (e.g., soil heterogeneity, moisture content, temperature, and wind patterns).[48,49] Uncertainties in the causes of repair failures can be reduced with (a) more precise measurement and reporting and (b) more frequent and comprehensive leak surveys, which can be used to calculate baseline rates of emergence for new leaks. Improved attribution would enable more targeted and effective policy responses to repair failures.

By analyzing factors that contribute to repair failures, we identify opportunities to improve maintenance and repair along the distribution network. Each utility or contractor in Massachusetts is largely responsible for developing and implementing its own standards to assess repair work. Policymakers can create incentives to successfully repair leaks (especially those that are high emitting but nonhazardous) and develop clear protocols to verify and monitor repairs. Enhanced oversight by DPU, including random spot surveys to verify repair work and greater transparency in utility decision-making, could support future analysis of repair failures and policy responses. Given that repair rates are limited by the availability of trucks and crew, targets to fix all leaks within a certain leak-prone segment of the network, rather than addressing a single point source, could also reduce overall costs. A new wave of policy proposals could address many of these issues, including improved provisions for postrepair surveillance, certification by gas inspectors, additional criteria for defining leaks as eliminated, and more precise location tagging for repairs. However, some repair failures may be difficult to eliminate on inherently leak-prone infrastructure.

Broader policy responses are also available to mitigate the climate impacts of repair failures. Utilities could perform a larger number of repairs, factoring in a realistic failure rate, to target the reductions that would be achieved if repairs were 100% effective. Additional repairs could be achieved at an average cost of approximately $3380 per repair (see SI section E). Accelerated replacement of leak-prone pipelines is also a strategy deployed through Gas System Enhancement Plans, at a higher cost of over $1 million per mile of replaced pipeline. However, pipeline replacement locks communities into carbon-intensive energy choices, and as with other types of fossil fuel infrastructure,[7,74] these assets may later be stranded. This added risk, compounded by high CH_4 emissions from natural gas systems and failure to mitigate these emissions through leak repair, suggests that there are benefits to accelerating the transition from natural gas to low-carbon heating sources. Careful planning will be essential to ensure a just transition and prevent the costs of legacy systems from falling disproportionately on those who are least able to pay.[75−79]

Going forward, repair failures could be addressed in performance-based ratemaking.[80] For example, recent petitions have proposed accelerated repair timelines for SEI leaks.[81] These targets could be revised in future proceedings to account for repair failures, potentially addressing disputes by some parties about whether they will result in emissions reductions. Discussion of repair failures is otherwise absent from previous cost-of-service rate cases. However, this may change, as DPU opened an investigation into the role of gas companies in achieving state-level climate targets.[82] As part of this process, DPU could revisit proposals for enforcement mechanisms that account for repair failures (e.g., using annual leak inventories, rather than repair rates). A reduction in leaks could also be linked to adjustments to allowed rates of return or rate change requests under accelerated replacement and transition programs.[83] As utilities commit themselves to achieving carbon neutrality by midcentury (or earlier), new performance metrics could be used to assess the effects of repair failures on emissions reductions.[84]

A complementary path forward is through asset integrity metrics. Pipeline safety regulations require that operators develop integrity management programs to ensure that pipelines are safe and running properly throughout their life cycle. Current federal rules require reporting on the number of hazardous leaks eliminated or repaired by cause and material.[85]

Utilities must also develop procedures to identify threats to their systems, improve leak management, and consider available data sources to evaluate the effectiveness of their programs.[86,86] At the state level in Massachusetts, accelerated pipeline replacement under GSEP is linked to integrity management,[87] with criteria for prioritizing segments of the network for replacement.[88] Interviewees suggested the next stage of policy-relevant research should focus on trend detection as well as system-wide prioritization of leaks and segments for repair, replacement, and transition (for example, to electrified heating). Integrity management procedures could be revised to require analysis and reporting on performance measures for grade 3 leaks, especially those with significant environmental impact.

The groundswell of local climate policies presents new demands for measuring policy effectiveness.[33,34,89] The approach we present here, bringing together multiple sources of evidence, suggests a pathway to monitoring and verifying emissions reductions under decentralized, locally driven policies. Similar challenges are playing out in other areas, including energy efficiency, conservation, and fuel switching in buildings, industry, and transportation.[90−94] Emerging data sets and disclosure requirements present new opportunities for policy evaluation. However, for these opportunities to be seized, data must have a lifecycle beyond reporting. It should be used to assess the performance of climate actions and revisit and adapt when they are ineffective. As subnational actors set increasingly ambitious climate targets, and those with aging infrastructure consider gas leaks in their portfolio of mitigation options, they can make better use of new and existing data sources to ensure that policies lead to real emissions reductions.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c07531.

A, supplementary interview and document and legal analysis; B, spatial analysis of repair failures by census tract; C, supplementary results figures and maps; D, pre- and postrepair leak extent measurements; E, leak repair and replacement cost estimates (PDF)

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Notes

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