# Orphan well methane: Targeting unlocks abatement yet climate gains limited

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**Abstract**

We conduct a novel climate benefit-cost analysis of a $25 million orphan well plugging effort funded by the 2021 U.S. Infrastructure Investment and Jobs Act. Our dataset represents the largest new dataset of measured methane emissions from orphaned wells to date: 842 wells in northern Louisiana. We find that 23 percent of wells leak detectable amounts of methane, with average emission rates nearly three times higher than EPA emission factors. Most emissions come from a handful of wells. In simulations of hypothetical plugging programs, we demonstrate a general principle: when emissions are highly variable and budgets are limited, prioritizing mitigation based on quantified emissions improves the cost-effectiveness of abatement efforts. Nevertheless, even under assumptions that increase benefit-cost ratios—no measurement costs, operational efficiencies from plugging clusters of wells, perfect targeting, and half-century leak durations—climate benefits alone justify plugging relatively few wells compared to Louisiana's remaining 4,900 orphans.

Around 60 percent of methane ($CH_4$) emissions over the 2008–2017 period came from anthropogenic sources, with fossil fuel extraction and use being the second-largest source after agriculture (Saunois et al., 2020). One

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source of anthropogenic $CH_4$ from the fossil fuel sector is leaks from unplugged abandoned oil and gas wells. When oil and gas production from a well ceases, U.S. federal and state regulations generally require that a well be decommissioned. Before being permanently decommissioned, wells may be temporarily abandoned. Temporary abandonment involves closing valves on the wellhead but leaving surface equipment in place. Temporarily abandoned wells are later permanently plugged by removing the wellhead and setting cement plugs in the wellbore. The cement isolates subsurface oil and gas from groundwater sources and the surface. However, sometimes years (or decades) pass before these wells are permanently plugged. We call these wells "unplugged abandoned wells" (UAWs). There are an estimated 3.7 million abandoned wells in the U.S., about 2.2 million of which are UAWs (unplugged), and the remainder of which have been plugged (DOI, 2023).

Here, we gather new measurements of methane emissions from 842 wells and plugging costs from 535. These data come from plugging activities undertaken by the State of Louisiana's Oilfield Site Restoration Program funded by a \$25 million grant under the 2021 Infrastructure Investment and Jobs Act (IIJA). Using these data, we estimate the distribution of unmeasured emissions from orphan wells in the northern part of the state, conduct a novel benefit-cost analysis of the climate impacts of plugging, and present lessons learned that can broadly be applied.

Consistent with prior studies, we find a right-skewed distribution in which a small number of wells contribute the majority of the $CH_4$ emitted into the atmosphere. We find that average emissions from northern Louisiana's orphaned UAWs are $27\,\mathrm{g_{CH_4}\,h^{-1}}$. Based on our measurements, we estimate that expected total emissions from the unmeasured 2994 orphaned UAWs are $675\,\mathrm{t_{CH_4}\,yr^{-1}}$ with 90% CI 471–946 $\mathrm{t_{CH_4}\,yr^{-1}}$. In contrast, the relevant EPA emissions factor is 2.7x lower ($10.02\,\mathrm{g_{CH_4}\,h^{-1}}$ for non-Appalachian wells) and implies annual emissions of $263\,\mathrm{t_{CH_4}\,yr^{-1}}$ (U.S. EPA, 2022).

Extrapolating our estimates to the unmeasured wells, we simulate hypothetical plugging programs to estimate the climate benefits of using information about emissions and plugging costs to prioritize plugging, and to understand the climate benefits relative to program costs. We find that quantifying emissions and plugging large leakers first leads to greater climate benefits compared to programs that only prioritize plugging based on information about costs, or no information at all. Specifically, in the context of the Louisiana program, we calculate that with a \$10 million budget for plugging activities and the remaining 2994 unmeasured orphaned UAWs, using quantification would in expectation allow for $674\,\mathrm{t_{CH_4}\,yr^{-1}}$ of abated emissions [557–799, 90% CI] versus only 55 $t_{CH_4}$ $yr^{-1}$ [26–96, 90% CI] without using any emissions information—a difference of 618 $t_{CH_4}$ $yr^{-1}$ [505–737 90% CI]. For this size of a program and a 20-year leak duration, the climate benefits of increased emissions reductions possible because of quantification far outweigh the added cost of measurement.

Our empirical analysis also demonstrates a general principle: when emissions are highly variable, prioritizing mitigation based on quantified emissions improves the cost-effectiveness of abatement efforts if measurement costs are low and the order in which wells are plugged does not affect abatement costs. This is not surprising, as the majority of emissions come from just a few wells: given a limited budget, finding and plugging these large leakers yields larger abatement relative to plugging wells based on a lowest-cost or other criteria. We perform sensitivities considering how long leaks last, and demonstrate how longevity of leaks might impact a benefit-cost analysis.

Our estimates of climate benefits relative to program costs are an upper bound for two reasons. First, we assume zero measurement costs. Second, our plugging cost data come from clusters of wells in close proximity to each other (see Figure 1). Plugging clusters of wells can create operational efficiencies through reduced travel times, shared equipment and materials, and shared learnings specific to wells in the cluster. Our simulations assume plugging wells in a different order—not as clusters of nearby, similar wells—will not increase plugging costs. If a program were to measure all wells before plugging and then plug them in strict order of emission rate divided by plugging cost, the total cost per well might be significantly higher. Thus, there is a further economic tradeoff between measurement costs, realizing operational efficiencies, and the number of wells that can be plugged. Clustering plugging jobs for operational efficiencies is a complex operations-research problem that is the subject of other ongoing, applied work (Jaffe et al., 2024).

We find that even when we assume that operational efficiencies from plugging clusters are all realized, that measurement costs are zero, and that leaks last a half-century to increase climate benefits, climate benefits alone justify plugging few wells relative to Louisiana's remaining approximately 4900 orphaned wells under the current federal social cost of methane (SCM). Further research might investigate whether large UAW plugging programs could be justified on an economic benefit-cost basis by also factoring in other benefits, such as groundwater, local air pollutants, and other safety benefits.

# 1 Background

We reviewed a growing body of research over the past decade that has attempted to estimate emissions from UAWs. Using Google Scholar, we searched for combinations of the keywords “methane,” “leak,” “well,” and “abandoned.” We excluded papers that did not include North American data or were focused on active wells rather than UAWs. In addition, we used “chain-referral” and included studies that were cited by other papers in our review or that cited papers in our review. In total, we estimate that 979 of the 2.2 million UAWs have been measured (Table A1). Average emission rates from the studies range over more than two orders of magnitude (from $1.7\,\mathrm{g\,h^{-1}}$ to $520\,\mathrm{g\,h^{-1}}$), but there are few consistent predictors of whether wells leak. The paucity of data and large variation in measured emission rates leave uncertainty to what degree UAWs are a contributor to U.S. and global $CH_4$ emissions.

One consistent finding in the literature is the important role of the largest emitters in driving total emissions. In most studies to date, a small proportion of leaking wells were responsible for a large proportion of total $CH_4$ emissions. This is perhaps most notable in a recent Colorado sample in which a single well leaked $76\,\mathrm{kg\,h^{-1}}$ (Riddick et al., 2024). Other outliers include wells in Alberta ($5.2\,\mathrm{kg\,h^{-1}}$, Bowman, El Hachem, and Kang, 2023) and Pennsylvania ($3.4\,\mathrm{kg\,h^{-1}}$, DiGiulio et al., 2023). Of the studies we reviewed, leaks were only detected at a small share of wells (Table A1), though we note that the ability to detect small leaks depends on the sensitivity of the instruments used.

In addition to uncertainty over the size and distribution of $CH_4$ emissions from UAWs, there is also uncertainty over abatement costs. Some UAWs are orphaned, meaning that—oftentimes due to bankruptcy—there is no financially viable owner of the well. In this case, plugging falls to state or federal governments. Uncertainty over plugging costs further complicates the question of how society should expend scarce economic resources to plug UAWs.

Society has limited resources for GHG emissions reductions. Maximizing these requires prioritizing some abatement opportunities over others. Plugging UAWs is one abatement option, but other abatement options could be more cost effective (e.g., plugging leaks from active infrastructure). Moreover, plugging some UAWs may be more cost-effective than plugging others. Economic theory prescribes prioritizing abatement opportunities to maximize the ratio of abated emissions to abatement costs since this leads to the greatest emissions reductions given a limited budget. A useful concept is the idea of *marginal abatement cost* (MAC): the cost to abate one additional unit of pollution given a current level of abatement. MAC curves order abatement opportunities from lowest to highest cost so that it is least expensive to abate the $(n+1)^{th}$ unit of pollution relative to $n^{th}$ unit of pollution.

The concept of MAC is important for two reasons. First, in a climate policy with a limited budget, an MAC curve identifies which abatement opportunities should be pursued first to maximize emission abatement given a limited budget. MAC curves depend on both the joint distribution of costs and emissions, as well as the information policymakers have about them. For well-plugging programs, as with many methane abatement efforts, perfect information is not available. This challenge is particularly acute when emissions follow highly skewed distributions with 'super-emitters,' as is common in oil and gas infrastructure. Using imperfect information (like binary leak detection or average emission rates) means more cost-effective abatement opportunities may be overlooked in favor of less cost-effective ones. We empirically demonstrate the extent to which quantifying emissions and using this to prioritize plugging can improve cost-effectiveness under the assumption that measurement costs are low and that there are no cost efficiencies from plugging wells close together.

Second, a MAC curve for emissions abatement can be paired with the SCM to understand which abatement opportunities make sense to pursue at all. The SCM is a measure of the economic damages to society caused by emitting an additional tonne of methane into the atmosphere. Economics prescribes that society should pursue methane reductions when the MAC is less than the SCM. Beyond this point, the benefits of abatement to society are exceeded by the costs, and (on the margin) pursuing them would make society worse off.

A growing literature calculates the SCM by using integrated assessment models (IAMs). IAMs estimate the economic damages caused by emission of an additional tonne of greenhouse gas through climate change. While imperfect, IAMs are nonetheless widely used in policymaking and reflect the current framework to estimate the SCM. Since U.S. EPA's social cost numbers are a key input to regulatory impact analyses in government climate policy, we adopt the EPA's SCM $1874\,\mathrm{USD}_{2020}\,\mathrm{t}_{\mathrm{CH}_4}^{-1}$ for emissions in 2023 (EPA, 2023a). We note, however, that estimates of the SCM in the literature do vary (Azar et al., 2023; Errickson et al., 2021; Prest et al., 2022; Stoerk et al., 2024).

A number of MAC curves have been constructed for $CH_4$ emissions from the oil and gas industry. In general, they fall into two groups: most take an engineering approach and base the MAC on the cost to abate emissions from specific sources along with information about the frequency of these. A few, however, take an econometric approach. These use natural experiments that vary economic incentives to capture $CH_4$ along with data on $CH_4$ emissions and a model of economic behavior to statistically estimate an MAC curve.

Within the bottom-up engineering studies, Warner et al. (2015) constructed an MAC curve for $CH_4$ emissions from oil and gas infrastructure by identifying emissions sources, estimating the costs to change equipment or detect and plug fugitive emissions, and accounting for the revenue gained by the sale of the captured gas. The study found significant opportunities for negative net abatement costs and low overall abatement costs, with the vast majority of emissions abated for under $20\,\mathrm{USD}_{2013}\,\mathrm{t}_{\mathrm{CO_2e}}^{-1}$. Using similar methods, ICF International (2016) estimated $CH_4$ emissions sources within the oil and gas industry in the U.S. and found that fugitive emissions from compressors along with venting from pneumatic devices, engine exhaust, and centrifugal compressors accounted for nearly 40 percent of the total emission from natural gas systems. They, too, found significant emissions reduction with negative net abatement costs; the highest abatement costs were slightly under $20\,\mathrm{USD}\,\mathrm{t}_{\mathrm{CO_2e}}^{-1}$. IEA (2023) constructed an MAC curve for the oil and gas industry. The study estimated that about $30\,\mathrm{Mt/yr}$ ($CH_4$) could have been abated at negative net cost, and essentially all of the methane emissions from the oil and gas sector could have been abated at prices below $15 per mmbtu. A plurality of the prospective low-cost abatement potential came from leak detection and repair in the upstream sector. Harmsen et al. (2019) used a suite of IAMs to calculate how $CH_4$ emissions changed with a carbon price. They found that as carbon prices rose, $CH_4$ emissions decreased with a roughly 60 percent decrease at carbon prices of about $500\,\mathrm{USD}\,\mathrm{t}_{\mathrm{CO_2e}}^{-1}$. While Harmsen et al. (2019) did not derive MAC curves, their work used MAC curves developed by Criqui (2002), EPA (2013), and Lucas et al. (2007).

Marks (2022) and Dunkle Werner and Qiu (2024) both took an econometric approach to estimating an MAC curve by relating variation in firms' incentives to capture gas to emissions. Marks (2022) used inventory-based emissions estimates from EPA's Greenhouse Gas Reporting Program. The study found that abatement costs were relatively low, with about 60 percent of fugitive emissions abated with a carbon price of $5\,\mathrm{USD}\,\mathrm{t}_{\mathrm{CO_2e}}^{-1}$. Dunkle Werner and Qiu (2024) used aerial emissions surveys to measure emissions and also found that a large share of emissions could be abated at relatively low costs.

This literature, taken together, suggests that a large share of potential

$CH_4$ reductions could be realized at a low cost relative to the climate benefit (e.g., the SCM); however, these studies were on active infrastructure rather than UAWs.

The most obvious option to abate $CH_4$ emissions from UAWs is to permanently plug them, though there are other options (Kang et al., 2019). In our study, we only consider plugging, so that the MAC is the cost to plug each well divided by its emissions. A few studies have examined plugging costs for this population of wells. IOGCC (2019, 2020) estimate a plugging cost of 24,000–48,000 USD per well. Raimi et al. (2021) obtained data on plugging costs for onshore state-designated orphaned wells from state regulators in Kansas, Texas, Montana, New Mexico and Pennsylvania. The study found that median plugging costs were 20,000 USD, increasing to 76,000 USD when surface reclamation was included. However, the study also found that costs varied widely between states and between wells. Some wells cost just a few thousand dollars to plug, but some cost more than one million. Kang et al. (2019) estimate that plugging costs average 36,535 USD/well for all wells and 57,774 USD/well for gas wells in Pennsylvania.

Table 1 links MACs and SCM together in the context of plugging UAWs and shows how the two concepts can be helpful in guiding policy. It also illustrates the key importance of $CH_4$ leak duration in determining the climate benefits of plugging UAWs. The second two columns calculate the social cost (in present-value USD (2020) terms) of $1\,\mathrm{t_{CH_4}\,yr^{-1}}$ and $1\,\mathrm{g_{CH_4}\,h^{-1}}$ leaks that last different lengths of time, from 1 to 50 years starting in 2024. The climate costs vary over two orders of magnitude depending on the length of a leak. The right three columns assume plugging costs of $40{,}000\,\mathrm{USD_{2020}}$ to $60{,}000\,\mathrm{USD_{2020}}$ and show breakeven leak rates. These represent how much a well must leak and for how long for the climate benefit of plugging it to exceed the cost. These breakeven leak rates also vary over two orders of magnitude. Under a $50{,}000\,\mathrm{USD_{2020}}$ plugging cost, plugging an UAW leaking $50\,\mathrm{g_{CH_4}\,h^{-1}}$ is only a net climate benefit to society if the leak will last for 50 years. If a well leaks $3\,\mathrm{kg_{CH_4}\,h^{-1}}$, however, plugging is justified by a 1-year leak duration.

There is significant uncertainty about how leaks from UAWs vary over time. Riddick et al. (2020) repeatedly measured leaks at 18 wells in the U.S. and the UK and found that they varied by an average factor of 8 over a period of 24 hours. While this suggests a high degree of variability, what matters for justifying plugging activities on a climate basis is how leaks evolve over the span of years.

Of course, plugging UAWs creates other benefits for society beyond climate mitigation. Plugging UAWs can increase labor demand (“create jobs"), which is a political and social consideration, and can also have other environmental benefits such as preventing groundwater contamination or other releases of fluids (El Hachem and Kang, 2023; Harleman, Weber, and Berkowitz, 2022; Kang et al., 2021).

Table 1: SCM and breakeven leak rates under leak duration and P&A cost assumptions. This table shows how leak duration affects the social cost of methane and minimum leak rates needed to justify plugging costs.

| | Duration (yrs) | Social cost of leak ($USD_{2020}$) $1\,t\,yr^{-1}$ | $1\,g\,h^{-1}$ | Breakeven leak ($g_{CH_4}\,h^{-1}$) given cost \$40,000 | \$50,000 | \$60,000 |
|---|---|---|---|---|---|---|
| 2023–23 | 1 | \$1,874 | \$16 | 2,435 | 3,044 | 3,652 |
| 2023–27 | 5 | \$9,722 | \$85 | 469 | 587 | 704 |
| 2023–32 | 10 | \$20,203 | \$177 | 226 | 282 | 339 |
| 2023–42 | 20 | \$43,117 | \$378 | 106 | 132 | 159 |
| 2023–52 | 30 | \$67,635 | \$593 | 67 | 84 | 101 |
| 2023–62 | 40 | \$92,318 | \$809 | 49 | 62 | 74 |
| 2023–72 | 50 | \$116,024 | \$1,017 | 39 | 49 | 59 |

Calculations assume that a leak persists at a constant rate. We take the social cost of methane (SCM) from EPA (2023b, Table A.5.1, p. 154). All costs are measured in $USD_{2020}$. Office of Management and Budget (2023, Appendix D) mandates that benefit-cost analyses use a 2% discount rate, so we take the SCM under the 2% discount rate and use 2% to compute the present value of a leak of a given duration. To convert $t_{CH_4}\,yr^{-1}$ to $g_{CH_4}\,h^{-1}$, we assume that there are 365.25 days per year. The last 3 columns show the minimum leak rate ($g_{CH_4}\,h^{-1}$) for the social benefits of abated methane to equal various P&A costs.

## 2 Methods

Under §40601 of the U.S. Infrastructure Investment and Jobs Act of 2021 (IIJA), the U.S. federal government allocated up to \$4.275 billion to states to plug orphan UAWs. These are a convenient target for state natural resource managers because they have the legal authority to plug orphans but lack such authority for non-orphaned UAWs. The first tranche of IIJA orphan well funds provided eligible states (including Louisiana) with \$25 million each for measurement and plugging, with states receiving additional funds at future dates. Our data on emissions and plugging costs come from efforts funded with this initial grant.

Louisiana's Oilfield Site Restoration (OSR) Program manages the state's orphan wells and directs plugging for both IIJA-funded efforts, as well as normal plugging efforts funded by a fee on oil and gas production. Normally, the OSR program scores wells based on a variety of characteristics, with actively leaking wells receiving higher score and, therefore, higher priority. That said, the program has not historically viewed $CH_4$ abatement for climate impacts as part of its prioritization, or sought to quantify $CH_4$ leaks.

To utilize the IIJA funds, the program selected two contractors and provided each with a list of orphaned wells. The contractors then selected which wells to plug from these lists, prioritizing them primarily on the basis of cost and convenience.

### 2.1 Well characteristics

Orphan wells are identified in the Louisiana Department of Energy and Natural Resources (DENR) Strategic Online Natural Resources Information System (SONRIS) database. The SONRIS database also provides the corresponding well locations and characteristics for these identified orphan wells, which are referenced by their unique well serial numbers. We obtained this data from SONRIS, as well as data on historical well production from commercial data provider Enverus that we merged. We also spatially merged in data on road segments (United States Census Bureau, 2022) and landcover (Davidson and McKerrow, 2016). Coal-bearing areas were defined based on digitized maps of lignite deposits from EIA (1994, p. 49). These deposits, located primarily in northwestern Louisiana, consist of relatively thin lignite beds.

### 2.2 Cost modeling

In 2023, two contractors plugged 535 orphan UAWs in Louisiana. We obtained accounting data on plugging costs. The wells were located in the Monroe and Shreveport districts, which encompass the North and Central part of the Louisiana (Figure 1). No wells have been plugged yet in the Lafayette district with federal funds, which is the third district and encompasses the southern part of the state. One contractor plugged wells in the Shreveport District while the other contractor plugged wells in the Monroe District, so we cannot separate geographic cost differences from cost differences associated with the contractors. Some costs were already allocated by the contractors to individual wells in our data, but other costs (e.g. general conditions, overhead, bonding and insurance) were not.

We constructed well-level plugging costs from the accounting data in

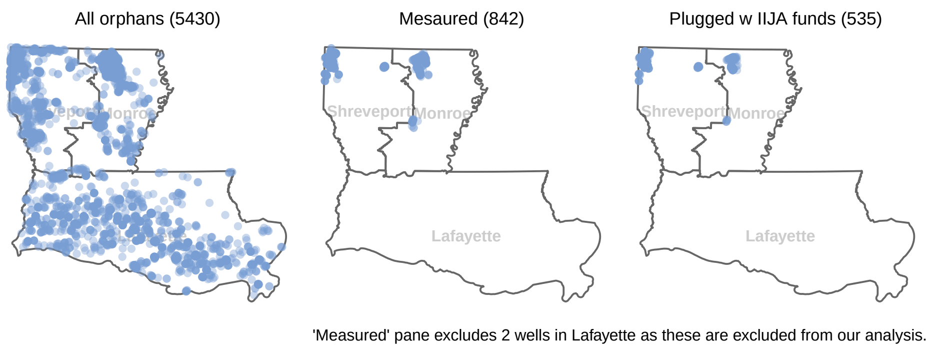


Figure 1: Locations of all orphan UAWs in Louisiana, as well as measured and plugged orphan UAWs in our dataset

several steps. First, we separated out pre-plug $CH_4$ measurement costs (\$650/measurement) since methane measurement is a separate process. Plugging costs include permitting and inspections, NORM surveys, supervision, and contingency costs. We then allocated the bonding, insurance, and other overhead costs to each well in proportion to the well's plugging cost and added construction management fees. Finally, there were a number of wells for which plugging jobs were started but not completed. We summed these costs and allocated them as "waste" to the completed and incomplete plugging jobs in proportion to their shares of total costs. We speculate that these unfinished plugging jobs could have been more expensive to complete than the completed jobs in our sample, so our final cost estimates likely understate the cost to plug all wells. Finally, we deflated costs from 2023 dollars to 2020 dollars so that plugging costs are comparable to the SCM.

We index wells by $i$ and model well-specific plugging costs $c_i$ (including allocated costs) as a linear function of a vector $X_i^c$ of well characteristics and an unpredictable cost-shock $u_i$:

$$c_i = X_i^c \cdot \beta_c + u_i. \tag{1}$$

We estimated parameters from (1) using ordinary least squares. Results are discussed in Section 3.1, and Table A5 reports parameter estimates.

### 2.3 Methane measurement

Contractors working for the Louisiana Department of Energy and Natural Resources measured $CH_4$ emissions before plugging operations from 842 wells in 5 parishes of the Monroe and Shreveport districts of Louisiana using a two-step procedure. An initial survey was done using a cooled-core optical gas imaging (OGI) camera (Teledyne FLIR GFx320) to identify leaks at each well site. $CH_4$ emission rates were then measured at the detected leak points using a high flow sampler (Semtech Hi-flow sampler).

There is not a single minimum detection threshold for OGI cameras. Instead, the ability to detect leaks depends on ambient temperature, wind-speed and direction, the experience of the operator, and the number of leaks from a wellhead (Ravikumar, Wang, and Brandt, 2017). As a result, rather than a minimum detection threshold, it is more useful to identify the probability that a leak of a given size is detected. In controlled studies of OGI systems in field conditions in Colorado, inspectors with relatively little experience using OGI systems were able to detect about 50% of leaks under about $250\,\mathrm{g\,h^{-1}}$, but those with greater experience were able to detect 50% of leaks under about $17\,\mathrm{g\,h^{-1}}$ (Zimmerle et al., 2020, Figure 2a). Ravikumar et al. (2018) found similar results and noted that the detection probability increases significantly when operators are closer to leaks. When the OGI camera is 1.5 m from the leak, the 50% detection threshold drops to about $3\,\mathrm{g\,h^{-1}}$. Given these detection limits, it is likely that our method missed some leaks, and it is difficult to estimate the number or size of these unknown leaks. However, the contractors in this study were within 2 m of the wellhead, so we expect that they detected most leaks larger than about 5–$10\,\mathrm{g\,h^{-1}}$. Missing small $10\,\mathrm{g\,h^{-1}}$ or even $20\,\mathrm{g\,h^{-1}}$ leaks will not change overall emissions totals or averages much, particularly given that the standard deviation of overall emission rates is an order of magnitude larger (see Table 2). For reference, a $10\,\mathrm{g\,h^{-1}}$ leak represents only $87.66\,\mathrm{kg\,yr^{-1}}$. The climate cost of a one-year $CH_4$ leak of this size in 2023 is $164\,\mathrm{USD_{2020}}$. From a policy perspective and given plugging costs (see Table A2), plugging such small leaks is unlikely to be justifiable under a climate-only benefit-cost test, even with a 50-year leak length (see Table 1). Thus, the effect of small, missed emissions on our results and their policy implications is minimal.

The high flow sampler is widely used for direct measurement of individual $CH_4$ leaks, and the overall uncertainty of the method is estimated to be approximately ±5% for an individual leak rate measurement (Townsend-Small et al., 2016a). The Semtech Hi-Flow sampler uses a high flow rate of air and a modified enclosure to completely capture the gas leaking from an individual component. Tunable Diode Laser Absorption Spectroscopy based $CH_4$ measurements are used to record the exit concentration in the air stream of the system. Emissions from well $i$ are calculated as:

$$Q_{\mathrm{CH}_4,i} = flow \times (conc_{sample,i} - conc_{bkgrnd,i}) \tag{2}$$

where $Q_{CH_4}$ is the $\mathrm{CH}_4$ leak rate (standard $\mathrm{ft}^3$/min); $flow$ is the sample flow rate (standard $\mathrm{ft}^3$/min); $conc_{sample,i}$ is the concentration of methane in the sample (%); and $conc_{bkgrnd,i}$ is the concentration of methane in the background near the leak (%).

### 2.4 Methane emissions model

A key goal of our study was to understand the distribution of emissions from orphaned wells in Louisiana's Monroe and Shreveport districts, and then predict emissions at unmeasured wells in these two districts. We modeled emissions $e_i$ from well $i$ as the product of whether the well is leaking or not ($L_i \in \{0,1\}$) and the leak size ($\bar{e}_i \in (0,\infty)$) so that $e_i = L_i \times \bar{e}_i$. We allow for well characteristics to be correlated with $L_i$. Given a vector of well characteristics $X_i^L$ and unknown parameter vector $\beta_L$, we assume that the probability well $i$ leaks is

$$\Pr(i \text{ is leaking}) = E\left[L_i \middle| X_i^L\right] = \Phi\left(X_i^L \cdot \beta_L\right) \tag{3}$$

where $\Phi$ is the standard normal CDF. The distribution of positive contractor measurements $\bar{e}_i$ was not well-approximated by common parametric distributions (see Table A6 and discussion in Section 3.3).

### 2.5 Distribution of emissions from unmeasured wells

We collect our parameters for (3) along with the vector of leak-sizes and their probabilities into vector $\theta$. Given our estimates $\hat{\theta}$, we proceeded to estimate the distribution of emissions from unmeasured wells in the Monroe and Shreveport districts. We denote the sum of unmeasured emissions from orphan wells $i = 1, \ldots, n$ as $E = \sum_{i=1}^{n} L_i \bar{e}_i$. Because $E$ does not have a closed form, we simulate its distribution using Monte Carlo integration with 20,000 draws. We compute several statistics of this distribution, including mean, standard deviation, the CDF, and various quantiles. Our estimates of $\theta$ are subject to sampling uncertainty, so to obtain confidence intervals, we bootstrap statistics with 1,000 bootstrap replications.

### 2.6 Plugging policy modeling

In 2024, there were 4791 UAWs designated as orphans in the Louisiana (including the 535 which were plugged in our study), and the state has around 9700 additional UAWs which have not produced in five years. The state has a system for prioritization of plugging activities, but potential climate impacts of methane has not historically been one of the factors included.

Because IIJA funds to plug orphaned wells are framed as $CH_4$ abatement efforts, our policy simulations focus solely on maximizing $CH_4$ abatement given a limited budget. Assuming that the order in which wells are plugged does not impact cost (e.g., no operational efficiencies from plugging clusters of wells), this can be done by prioritizing wells based on the expected ratio of emissions to costs given an information set $\mathcal{I}$. Formally, a plugging policy is a permutation $\varphi(\cdot;\mathcal{I})$ that maps well indices $i = 1, \ldots, n$ into a plugging priority order where the expected ratio of emissions to plugging cost (benefit–cost ratio) is non-increasing:

$$E\left[e_{\varphi(i;\mathcal{I})}/c_{\varphi(i;\mathcal{I})}\middle|\mathcal{I}\right] \geq E\left[e_{\varphi(j;\mathcal{I})}/c_{\varphi(j;\mathcal{I})}\middle|\mathcal{I}\right] \qquad \forall\varphi(i;\mathcal{I}) \leq \varphi(j;\mathcal{I}). \tag{4}$$

There is not a unique permutation $\phi(\cdot;\mathcal{I})$ that satisfies (4) because the regulator may be indifferent between plugging two wells (for example, non-leakers). In this case, we assume the ordering is random.

We simulated cumulative $CH_4$ abatement and plugging costs under seven different information sets $\mathcal{I}^s$ that include different amounts of information about $CH_4$ emissions and plugging costs. In terms of emissions, we assumed that the regulator has access to:

1. Quantification of emissions from all wells ($e_i$);
2. Leak detection for all wells (leak or no leak, $L_i$); or
3. No information about emissions from any wells.

For plugging costs, we also assume three levels of information:

(a) Perfect information about *ex-post* well plugging costs ($c_i$);
(b) Expected costs given observable well characteristics ($\mathbb{E}[c_i|X_i^c]$); or
(c) No cost information ($\mathbb{E}[c_i]$).

Different combinations of information about $CH_4$ emissions and plugging costs gave us seven scenarios for the regulator's information set:

- 1a: "Perfect information" (Quantification with perfect information about costs);
- 1b: Quantification with expected costs;
- 1c: Quantification only;
- 2b: Leak detection with expected costs.

- 2c: Leak detection only;
- 3b: Expected costs only (baseline);
- 3c: No information.

We consider 3b to be the baseline case as contractors chose which wells to plug primarily on the basis of cost (to maximize the number of wells plugged given their budget), and 2b and 1b to be plausible alternative policies. It is unlikely that regulators would either have perfect information about *ex-post* plugging costs, nor would they have zero information about costs (for example, deeper wells tend to be more costly to plug). However, these extremes provide useful points of comparison.

In our simulations, we include the 2994 unmeasured orphan wells in the Monroe and Shreveport districts of Louisiana. For each simulation $m = 1, \dots, M$ we generated simulated emissions and costs for each well $i = 1, \dots, n$. We set $M = 20,000$. We take cost parameters for (1) from Table A5, leak probability parameters for (3) from Table A3, and draw randomly from the set of 191 observed leaks. We use a truncated normal distribution to simulate costs, truncating from below at the lowest P&A cost we observe in our sample, $8574\,\mathrm{USD}_{2020}$, in order to avoid negative costs. For each simulation $m$ and information set $\mathcal{I}^s_m$, we construct a new well prioritization $\varphi(\cdot; \mathcal{I}^s_m)$. We then calculate cumulative $CH_4$ abatement and plugging costs under that policy by adding up emissions and abatement for wells with priority index $1, \dots, k$:

$$E^s_{km} = \sum_{\varphi(i;\mathcal{I}^s_m)=1}^{k} e_{\varphi(i;\mathcal{I}^s_m),m} \qquad C^s_{km} = \sum_{\varphi(i;\mathcal{I}^s_m)=1}^{k} c_{\varphi(i;\mathcal{I}^s_m),m}.$$

Cumulative abatement ($E_k$) and plugging cost ($C_k$) are two separate random variables, and we collapse them into a single variable in two ways in order to generate the distribution of MAC curves. First, for each simulation, we ask how many wells would have to be plugged to achieve abatement of at least $\underline{E}$ under each information scenario $\mathcal{I}^s$. Given a particular realization of emissions, this is

$$\underline{k}^s_m\left(\underline{E}\right) = \min\{k : E^s_{km} \geq \underline{E}\}.$$

The minimum cost to achieve this level of abatement is then simply $C_{\underline{k}^s_m,m}$. By calculating $\underline{k}^s_m$ for a common grid of abatement targets for each draw of emissions, we generate a distribution of costs required to achieve a given level of abatement. Similarly, we define the maximum number of wells that can be plugged given a budget cap as

$$\overline{k}^s_m\left(\overline{C}\right) = \max\{k : C^s_{km} \leq \overline{C}\},$$

and calculate the corresponding maximum $CH_4$ abatement that can be achieved under this cap: $E_{\overline{k}^s_m, m}$. Again, for each simulation $m$ and information scenario $\mathcal{I}^s_m$, we compute $\overline{k}^s_m\left(\overline{C}\right)$ for a grid of budget caps and generate distributions of realized abatement under each budget cap. In addition to calculating a distribution of costs for each abatement target and a distribution of abatement for each budget cap, we also calculated a distribution of marginal abatement costs ($c/e$) from the last well plugged (marginal well) under a given abatement target or budget cap. This is a well-behaved distribution for the initial wells under a perfect information policy, but when wells may have zero emissions so that the denominator is zero, the mean does not exist. Because of this, we also calculate a cost-effectiveness measure of abatement per dollar $e/c$, which is well-defined for all wells and simulations since costs are strictly positive.

### 2.7 Data availability

Well characteristics data used in this study are publicly available from the Louisiana Department of Energy and Natural Resources SONRIS database (https://sonris.dnr.louisiana.gov/). Methane measurement data and plugging cost data generated during this study will be deposited in Harvard Dataverse (link to be provided) upon publication. Historical production data were obtained from Enverus and are available with a commercial license from Enverus (https://www.enverus.com).

### 2.8 Code availability

The custom computer code used for analyzing methane emissions distributions, simulating plugging policies, and generating figures will be deposited in Harvard Dataverse (link to be provided) upon publication. Prior to publication, the code is available from the corresponding author upon reasonable request.

## 3 Results

### 3.1 Results: Plugging cost estimates

We collected cost data on 535 wells that were successfully plugged in the Shreveport and Monroe districts in 2023 and use the GDP Implicit Price

Deflator from the U.S. Bureau of Economic Analysis (BEA) to deflate costs to 2020 levels. Table A2 displays summary statistics. The average cost was 42,100 $\mathrm{USD}_{2020}$ with higher costs average in Monroe (54,800 $\mathrm{USD}_{2020}$) relative to Shreveport (35,800 $\mathrm{USD}_{2020}$). We regressed well costs on well characteristics and found that deeper wells, wells that had an unknown target (vs oil or gas-designated wells), wells farther from roads, and wells with higher cumulative production were more expensive to plug than other wells. Missing production data and coal-bearing geology were correlated with reduced costs. However, the most important determinant of cost was the district. We are unable to empirically differentiate the extent to which the difference in costs across districts was associated with the difference in contractor, district, or some other well characteristic correlated with district. Overall, about 68% of the variance in cost could be explained in the final model (Table A5). If we partial out the district constants and examine only within-district variation in wells, this falls to around 52%.

### 3.2 Results: Methane measurement

Contractors detected leaks at 23% of wells (Table 2). Leaking wells emitted 119 $\mathrm{g_{CH_4}\,h^{-1}}$ on average. Including both leaking and non-leaking wells, the average emission rate was 27 $\mathrm{g_{CH_4}\,h^{-1}}$. For comparison, the U.S. EPA Greenhouse Gas Inventory assumes average emission rates of 10.02 $\mathrm{g_{CH_4}\,h^{-1}}$ in non-Appalachian wells; our estimate of leak rate exceeds the EPA's emissions of 2.7 (U.S. EPA, 2022). Figure 2 illustrates how the majority of emissions came from just a small share of leaks.

We tried fitting a lognormal distribution to leak rates $\bar{e}_i$ (see Q-Q plot in Figure A1), but the implied lognormal distribution over-predicts large emissions relative to measurements. While our sample of methane measurements is skewed right and exhibits excess kurtosis, consistent with the literature on methane emissions, the distribution is not as heavy-tailed as the lognormal or as found elsewhere in active production sites (Brandt, Heath, and Cooley, 2016). In fact, the kurtosis (and, hence, the largest emissions) implied by the lognormal parameter estimates are unreasonable relative to our sample (see Table A6).

### 3.3 Well characteristics

We used data from Louisiana's SONRIS database to characterize wells. Tables A7 and A8 display summary statistics for orphaned wells in our sample, differentiating them by district, whether the wells were plugged, and

Table 2: Contractor methane emissions measurements in Monroe and Shreveport districts

| | Contractor | | |
|---|---|---|---|
| | Not leaking | Leaking | **Overall** |
| Wells measured | 651 | 191 | **842** |
| Percent | 77% | 23% | **100%** |
| Implied total emissions from measured wells (t/yr) | 0.0 | 199.9 | **199.9** |
| Max emission observed (g/hr) | 0.0 | 2,888.7 | **2,888.7** |
| Median emission observed (g/hr) | 0.0 | 13.9 | **0.0** |
| Min emission observed (g/hr) | 0 | .12 | **0** |
| Mean emission rate (g/hr) | 0.0 | 119.4 | **27.1** |
| SD emission rate (g/hr) | (0.0) | (318.5) | **(159.5)** |
| Kurtosis | . | 40.23 | **169.18** |

Table only includes contractor measurements of wells in the Monroe or Shreveport districts. Calculation of total emissions assumes that emissions rates are constant for the entire year. U.S. EPA (2018) emissions factors for unplugged orphaned wells are 30.57 g/hr for wells in Appalachia based on Kang et al. (2016b) and 10.02 g/hr for wells elsewhere in the U.S. based on Townsend-Small et al. (2016b).

whether they were measured. Then we estimated the binary probit leak model, equation (3), using this data. We found that older wells, wells with lower cumulative production, wells with missing production data (which might indicate a dry well), and wells in coal-bearing areas were less likely to leak, but well depth, years idle, district, and product type did not have an effect (Table A3). None of the variables predicted leak-size (Table A4). The lower likelihood of leaking in coal-bearing areas was unexpected as in other states coal seams are associated with $CH_4$ emissions. However, Louisiana's relatively thin lignite deposits may have different characteristics than the thicker bituminous or anthracite seams found in other states, so any $CH_4$ release from coal seams could be overwhelmed by other factors.

### 3.4 Results: Methane emissions from unmeasured wells

Figure 3 displays the distribution (CDF and mean) of total emissions, the number of leaks, the share of leakers, size of leaks, and average emission for the 2994 and unplugged orphan wells in the Monroe and Shreveport districts. We estimate that the P10, P50, and P90 of total $CH_4$ emissions from Louisiana's unplugged orphan wells are 581, 672 and 773 $t_{CH_4}\,yr^{-1}$ with 90% confidence intervals of [412–819], [470–942], and [542–1076] $t_{CH_4}\,yr^{-1}$. For comparison EPA's emissions factors estimates predict that Louisiana's

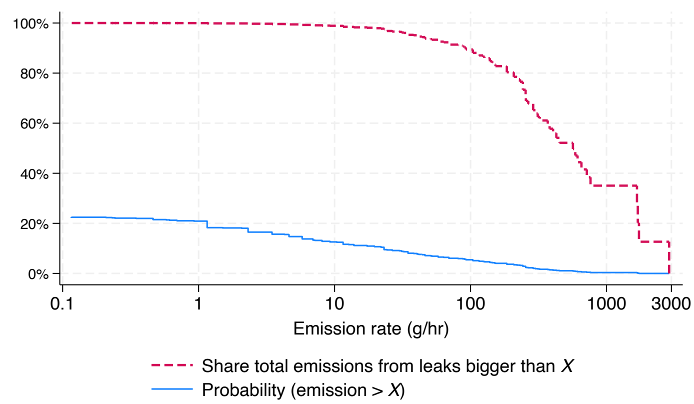


Figure 2: CDF and share of total positive emissions using logarithmic scale

orphan wells should emit 263 $t_{CH_4}\,yr^{-1}$ under the general U.S. orphan well emission factor, or 802 $t_{CH_4}\,yr^{-1}$ under the Applachia factor. Table A9 provides more complete results for the unmeasured orphan and 9842 idle wells in the two districts.

Our estimates for unmeasured orphans are essentially out-of-sample extrapolations of in-sample measurements. Because large emissions are important determinants of overall emissions, researchers have found in practice that extrapolating out of sample methane emissions based on smaller measurement samples may lead to under-estimates of total emissions (Schissel, Allen, and Dieter, 2024). This is possible in our case, even though sample averages are known to be unbiased estimators of the mean, and total emissions are simply the product of the number of wells and the mean of emissions.

### 3.5 Results: Plugging policy simulations

We compared the cost-effectiveness of alternative policies with and without quantification of emissions and with and without cost information. In a first step, we analyzed the distribution of emissions and costs for the first 100 wells plugged under a perfect-information benchmark (1a).

Figure 4 depicts the results for the perfect information policy 1a. The variation in emissions is larger than the variation in plugging costs, so emission rates drive prioritization. The largest leakers are plugged first (see top left), and emission rates—as well as uncertainty over leak sizes (see bottom left panel)—decline. Relative to emission rates, costs per well (top right panel) remain relatively constant but do increase mildly in expectation. The bump at the beginning is an artefact of our sampling from a discrete distribution (the set of leaks we observed), not a continuous distribution. It reflects the fact that the large leakers all have the same leak size and are then ordered with respect to cost until we get to the second-highest leak size. With a continuous distribution like the lognormal, the curve rises monotonically (see Figure A2). Turning to MACs in the bottom right, the combination of decreasing leak sizes and increasing costs raises MACs, as expected.

We note that estimates for the very first wells plugged depend on order statistics (e.g., very top leak rates). Because of this, our estimates for these top wells are likely of lower accuracy given that we have a finite sample and do not assume a parametric distribution. For example, our largest observed leak is $2889\,\mathrm{g_{CH_4}}\,\mathrm{h}^{-1}$, but it is entirely possible for unmeasured wells to be leaking much more—especially since most wells have yet to be measured. Without these (possibly) larger leaks in our sample, we will understate the emissions and cost-effectiveness statistics for top leakers. However, estimates will become more accurate as we move beyond the very top leakers into the body of the emissions distribution.

Using our Monte Carlo simulations, we calculate mean cost effectiveness (e.g., $e_k/c_k$) of the 1$^{\text{st}}$ to 100$^{\text{th}}$ well plugged under different policies. This is shown in Figure 5. The net climate benefits of an orphan well plugging program (the social value of abated methane less plugging costs) are maximized when wells are plugged up until the cost-effectiveness measure ($e_k/c_k$) falls below the inverse SCM. Using information about the actual plugging costs ($c_i$) or conditional expectations ($\mathbb{E}[c_i|X_i^c]$) makes little difference to the cost-effectiveness of the policy because the range of costs is relatively limited. Conversely, knowledge of emissions at individual wells significantly increases the cost-effectiveness of policies. Perfect knowledge (1a), quantification with expected cost information (1b), and quantification without cost information (1c) all yield virtually identical cost-effectiveness. Compared to the SCM, the benefits of plugging under a quantification-based policy exceed the costs for roughly the first 100 wells in expectation (assuming a 20-year leak duration) but plugging wells randomly (3c) or with only cost information (3b) does not. Leak detection (2b and 2c) are a middle-case, and both policies appear to meet a climate benefit-cost test under a 20-year leak duration.

Figure 6 displays results of our Monte Carlo study under the perfect information policy. While the perfect information policy is infeasible because costs are not certain, it is instructive. The top two panes show the relationship between cumulative plugging costs and cumulative $CH_4$ abatement under a budget cap (top left) or given an abatement target (top right), while the bottom panes show how marginal abatement costs rise with spending and achieved reductions. On each of these panes, we also include the total SCM (top panes) and marginal SCM (bottom) under the assumptions that leaks last for 1, 5, 10, 20, or 50 years (see Table 1). In the top panes, the social benefits of abatement are equal to program costs where the red lines cross the total abatement and cost curves. In the bottom panes, the intersection of the red lines and MAC curves shows where net benefits (social value of abatement less plugging costs) are maximized. To the left of this point, plugging an additional well meets a benefit-cost test, but to the right, it does not. The bottom left pane most clearly shows that even under perfect information, net benefits are maximized when relatively few wells are plugged.

The top left pane of Figure 6 shows that there is uncertainty in the amount of abatement that is achievable given a budget cap. Our use of a discrete distribution limits the degree of uncertainty—performing the same exercise with a lognormal distribution that has an infinite support and larger kurtosis significantly increases the amount of uncertainty (see Figure A2). The largest driver of uncertainty over abated emissions given a budget cap is the emissions of the largest leakers. As the highest leaking wells are plugged first, emissions from subsequent wells fall within a narrower range, and as a result, the confidence intervals stop increasing as wells are plugged (see bottom left pane of Figure 5).

The larger uncertainty in MAC with respect to abatement target versus budget cap (bottom right vs left panes of Figure 6) illustrates that policymakers should be able to set budget caps with more confidence about MACs than abatement targets. The effect grows as large leaks become more important and is particularly pronounced with a heavy-tailed distribution. Comparing the two bottom plots of Figure 6, the bottom left plot shows that given a specific budget, policymakers can be fairly confident about the MAC and thus ensure that the MAC falls below some threshold (like the SCM). In contrast, the graph on the bottom right shows that if policymakers were to set a $CH_4$ emissions target of, for example $550\,\mathrm{t_{CH_4}\,yr^{-1}}$, the MAC could be expected to be between $1,000/t and infinity.

Finally, turning back to our seven policy scenarios, Figure 7 shows the expected (mean) total abatement achieved under a range of budget caps for each scenario. The gray shaded regions illustrate where the different programs meet a climate benefit–cost test. Under a 1-year leak duration, only programs that use quantification and plug a very few wells meet a benefit–

cost test. Under 20-year assumed leak duration, programs with leak detection can meet a benefit–cost test. The quantification and leak detection lines join around a \$30 million expenditure cap, which is where all leaking wells have been plugged in the Monroe and Shreveport districts. Plugging based on expected cost alone (the status quo, 3b) or randomly (3c) never meets a benefit–cost test. Figure 8 displays cumulative abatement given the feasible policy 1b (quantification with expected costs), business-as-usual policy 3b (expected costs only), and the difference in abatement between the two. At a budget cap of \$10 million $\mathrm{USD}_{2020}$, policy 1b achieves $674\,\mathrm{t}_{\mathrm{CH}_4}\,\mathrm{yr}^{-1}$ of abated emissions in expectation [557–799, 90% CI] versus only $55\,\mathrm{t}_{\mathrm{CH}_4}\,\mathrm{yr}^{-1}$ [26–96, 90% CI] under 3b. Thus, in expectation, quantified emissions instead of zero emission information leads to an additional expected $618\,\mathrm{t}_{\mathrm{CH}_4}\,\mathrm{yr}^{-1}$ [505–737 90% CI] of abatement under a \$10 million budget cap. At a cost of \$650/measurement, the total cost of measuring all 2994 unmeasured wells in Monroe and Shreveport is 1.9 million USD. Under the assumption that leaks last 20 years, the climate benefits of the additional emissions reductions possible because of the information are 26.6 million USD in expectation. We note that the value of information depends on the size of the plugging budget. For example, if the budget is very large so that all wells will be plugged regardless of their emissions, knowing which wells leak allows for no extra climate benefits since they will be plugged with or without the information.

# 4 Discussion

Our findings highlight the value of quantifying $CH_4$ emissions and using this information to enhance the climate benefits of orphan well plugging programs—as well broader $CH_4$ mitigation efforts. Quantifying emissions is particularly valuable when emissions vary significantly more than abatement costs. Policymakers aiming to maximize $CH_4$ emissions reductions within a constrained budget should consider prioritizing the measurement of large numbers of wells and targeting plugging efforts on the largest leakers. Such a targeted approach is likely to achieve the highest climate benefits per dollar spent. However, this strategy is not without tradeoffs. Specifically, foregoing operational efficiencies from clustering plugging jobs together and incurring $CH_4$ measurement costs may mean that fewer wells are ultimately plugged under a given budget. This may diminish other potential benefits of well plugging, such as reduced risks to groundwater quality or reduced local air pollution, which extend beyond $CH_4$ abatement (El Hachem and Kang, 2023; Harleman, Weber, and Berkowitz, 2022; Kang et al., 2021).

Our results underscore that climate benefits alone are unlikely to justify a orphan well plugging program in a benefit-cost analysis. Even under the most optimistic scenarios—zero $CH_4$ measurement costs, optimal targeting of large emitters, operational efficiencies from clustering plugging jobs, and leaks that persist for half a century—the climate benefits alone justify plugging relatively few of Louisiana's remaining approximately 4,900 orphan wells under the current federal social cost of methane (SCM).

## 5 Author contributions

M.A. conceived the study, performed economic analyses, and wrote the paper. S.N. processed data and assisted with analysis. B.S. designed the methane measurement protocol and wrote the paper. As PI, G.U. conceived the study, oversaw the project, and wrote the paper. All authors discussed the results and implications and edited the manuscript.

## 6 Materials and Correspondence

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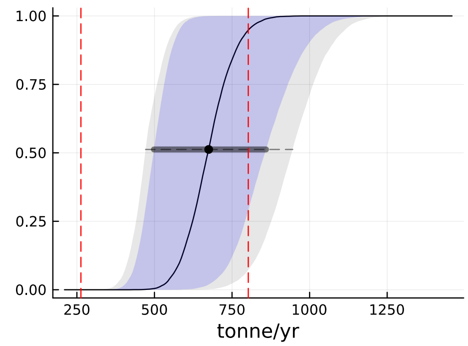
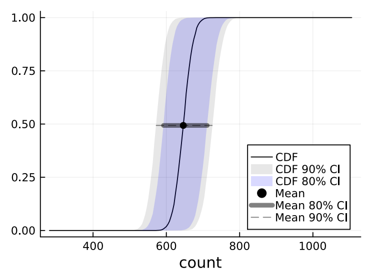
## 7 Competing interests

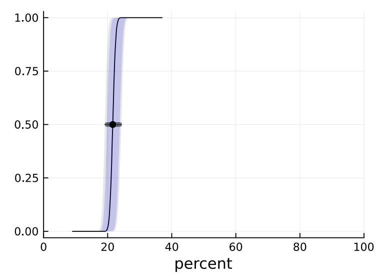
The authors declare no competing interests.



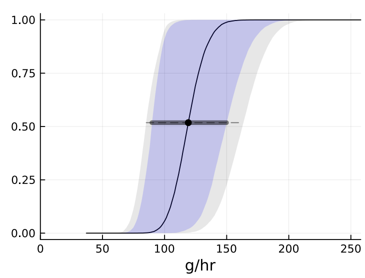

(a) Total emissions



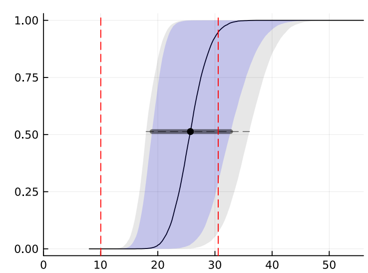

(b) Number of leaks




(c) Share leaking




(d) Size of leaks




(e) Emissions/well

Figure 3: Distribution of 2994 unmeasured orphan wells. We use contractor Hi-Flow measurements from 842 wells to estimate equation (3) characterizing the probability a well is leaking. We calculate each of the figures above characterizing out-of-sample unmeasured orphan wells using 10,000 realizations of $L_i$ and $\bar{e}_i$ from each well where $\bar{e}_i$ is drawn from the sample of observed leaks. Confidence intervals account for sampling uncertainty and are calculated using 1,000 bootstrap draws. Confidence intervals for the CDFs are vertical, and confidence intervals for the mean are horizontal. Red dashed lines represent EPA emission factors for USA and Appalachian orphan wells (10.02 and 30.57 $\mathrm{g_{CH_4}\,h^{-1}}$), or emissions factors scaled by the number of wells.

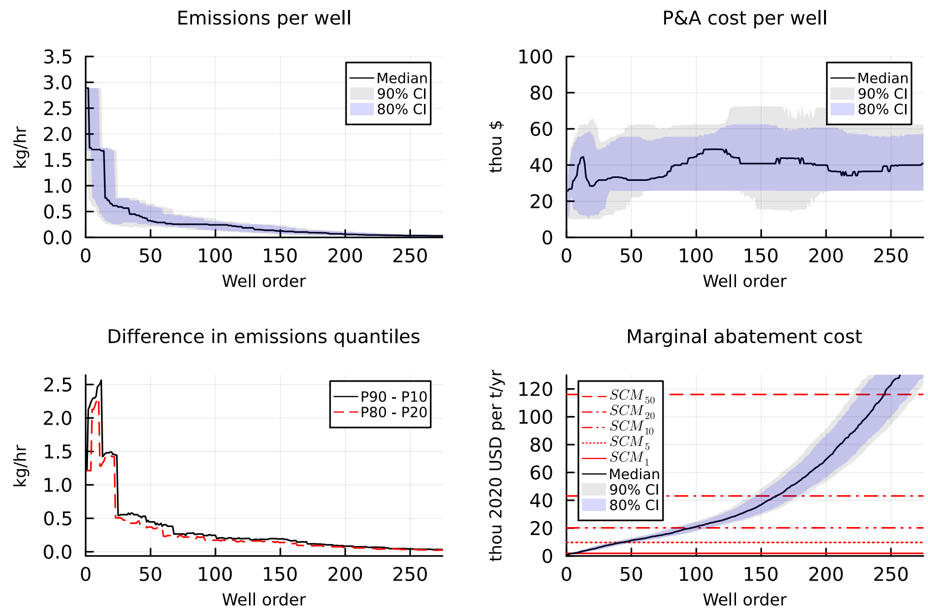



Figure 4: Marginal emissions, costs, abatement costs by well under perfect targeting optimistic costs

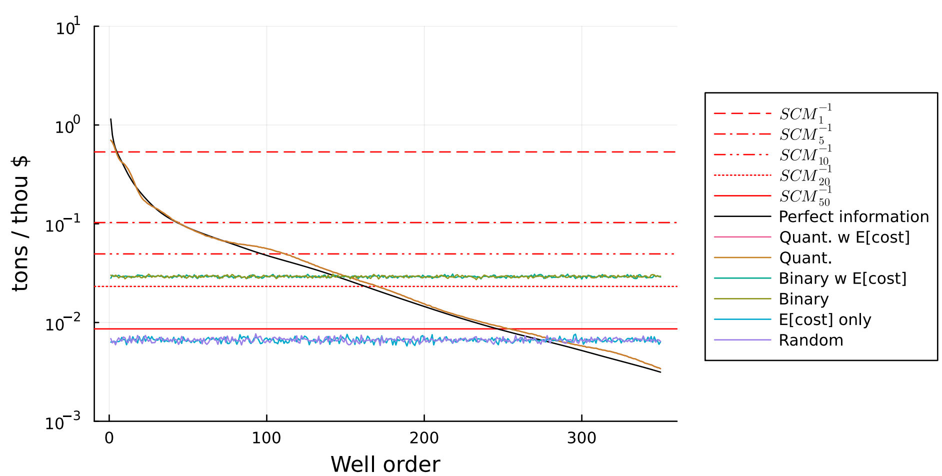



Figure 5: Mean marginal cost-effectiveness over well order under different policies

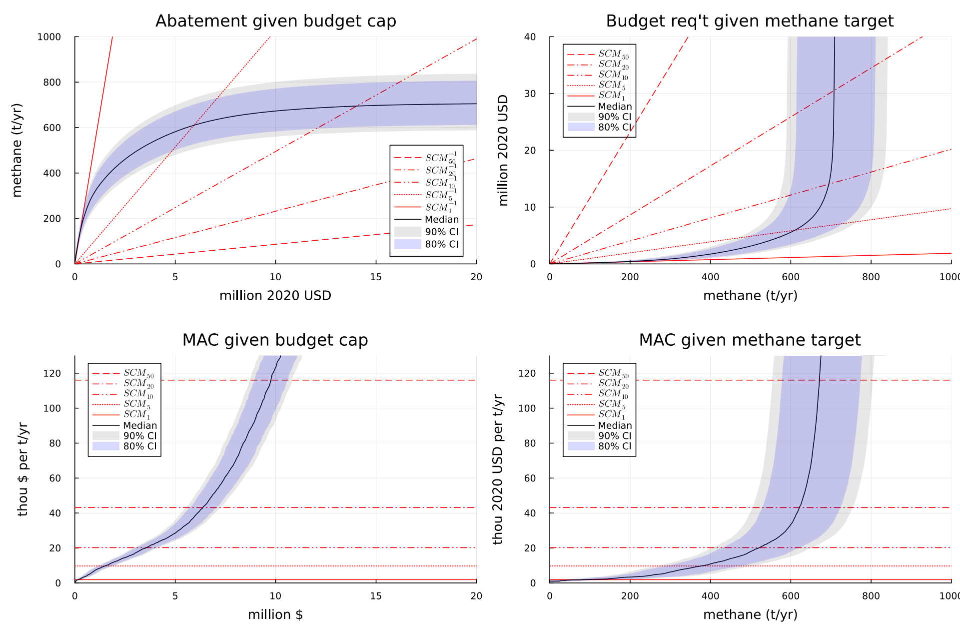



Figure 6: Monte Carlo simulation of "Perfect information" benchmark policy. Confidence intervals are all vertical.

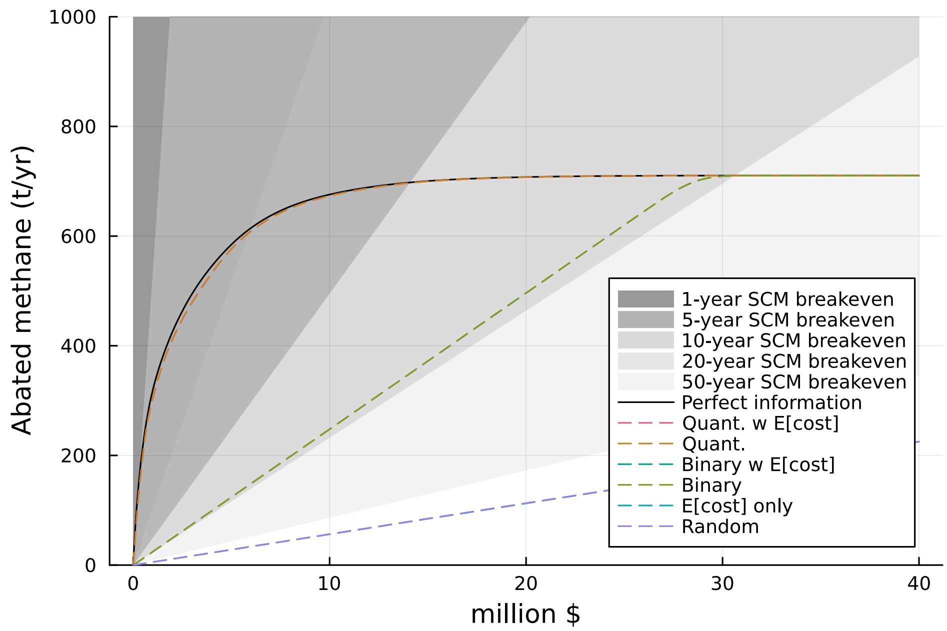



Figure 7: Mean abatement given budget cap

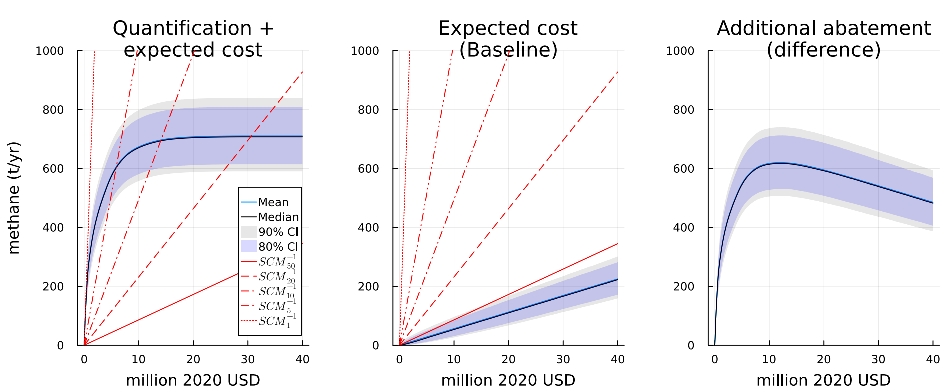



Figure 8: Abatement under feasible policies and additional abatement achieved because of quantification

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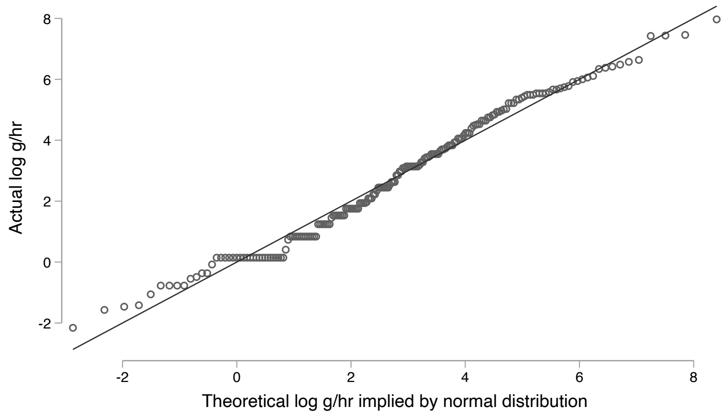


Y-axis log of observed leak (log g/hr). X-axis is the corresponding value drawn from the same quantile of the normal distribution, that is, $\mu + \sigma\Phi(p_i)$ where $p_i$ is the quantile of emissions.
842 orphan wells have been measured with 191 leaks found in Monroe and Shreveport districts.
Plot generated on 15 Aug 2024.

Figure A1: Q-Q plot of log emissions

# A Supplementary information

Table A1: Studies that have evaluated leak rates of UAWs

| Study region | Sample size (UAWs only) | Coal region | Leaking (%) | Max leak ($g\,h^{-1}$) | Mean leak ($g\,h^{-1}$) | Median leak ($g\,h^{-1}$) | Citation |
|---|---|---|---|---|---|---|---|
| California | 17 | N | 64 | 246 | 35 | 0.4 | Lebel et al. (2020) |
| Texas Permian | 37 | N | 51 | 132 | 6.2 | – | Townsend-Small and Hoschouer (2021) |
| Pennsylvania | 88 | Y | – | 350 | – | – | Kang et al. (2016a) |
| Pennsylvania | 19 | Y | – | – | 11.25 | – | Kang et al. (2014) |
| Oklahoma | 159 | N | 26 | – | 2.7 | – | Saint-Vincent et al. (2020) |
| Eastern US | 6 | – | – | – | 10.2 | – | Townsend-Small et al. (2016a) |
| Western US | 13 | – | – | – | 1.7 | – | Townsend-Small et al. (2016a) |
| Pennsylvania | 22[a] | Y | 100 | 174 | 29 | 10 | Pekney et al. (2018) |
| Pennsylvania | 48 | – | 31 | 3,458 | 91 | 2.9 | DiGiulio et al. (2023) |
| Alberta | 111 | N | – | 5,200 | 89 | – | Bowman, El Hachem, and Kang (2023) |
| Saskatchewan | 106 | N | – | – | 8.1 | – | Bowman, El Hachem, and Kang (2023) |
| West Virginia | 147 | Y | 28 | – | 3.2 | – | Riddick et al. (2019) |
| Ontario | – | – | – | – | 16.6 | – | El Hachem and Kang (2022) |
| Colorado | 206 | N | 61 | 76,000 | 586 | – | Riddick et al. (2024) |

Note: "–" indicates data not available. Studies excluded because measurements included wells outside of North America or wells that had already been plugged: Boothroyd et al. (2016); Schout et al. (2019); Vielstädte et al. (2015); Moghadam, Peters, and Nelskamp (2023); Jordan et al. (2024). Study excluded as meta-analysis: Williams, Regehr, and Kang (2020). Study excluded because it focused on change in emissions over time: Riddick et al. (2020).

[a] Excluding 9 buried wells.

Table A2: Summary of actual P&A costs to date

| | Monroe | Shreveport | **Total** |
|---|---|---|---|
| Number of wells | | | |
| P&A Completed | 179 | 356 | **535** |
| P&A In Progress | 24 | 2 | **26** |
| Not P&Aed | 1,666 | 1,609 | **3,275** |
| **Total** | **1,869** | **1,967** | **3,836** |
| Total cost (million $) | | | |
| P&A Completed | $9.8 | $12.7 | **$22.5** |
| P&A In Progress | $0.1 | $0.0 | **$0.1** |
| **Total** | **$9.9** | **$12.7** | **$22.7** |
| Average cost (thou USD) | | | |
| P&A Completed | $54.8 | $35.8 | **$42.1** |
| | ($8.9) | ($13) | **($15)** |
| P&A In Progress | $5.1 | $0.0 | **$4.7** |
| | ($3.2) | ($0) | **($3.4)** |
| Minimum (thou USD) | | | |
| P&A Completed | $23.1 | $8.6 | **$8.6** |
| P&A In Progress | $2.5 | $0.0 | **$0.0** |
| Maximum (thou USD) | | | |
| P&A Completed | $107.8 | $76.9 | **$107.8** |
| P&A In Progress | $17.5 | $0.0 | **$17.5** |

Standard deviations in parentheses.

Table A3: Binary leak model parameter estimates

| | (1) | (2) |
|---|---|---|
| Is leaking? | | |
| Constant | -2.345 | -1.820** |
| | (-1.90) | (-2.65) |
| Log well age (0 = Dec 2023) | 0.466* | 0.506** |
| | (2.24) | (3.08) |
| Log measured depth | 0.0487 | |
| | (0.33) | |
| Log cum. production (BOE) | -0.100* | -0.0920* |
| | (-2.33) | (-2.49) |
| Log years idle (0=Jan 2024) | -0.00727 | |
| | (-0.09) | |
| Missing production data? | -0.361* | -0.474** |
| | (-2.13) | (-3.20) |
| In coal area? | -0.374* | -0.368* |
| | (-2.28) | (-2.38) |
| *District* | | |
| Monroe | -0.0317 | |
| | (-0.19) | |
| *Product type* | | |
| Oil | 0.423 | |
| | (1.70) | |
| Gas | 0.427 | |
| | (1.60) | |
| Observations | 842 | 842 |
| $\chi^2$ | 3.291 | |
| $\chi^2$ dof | 5 | |
| $\Pr(\chi^2)$ | 0.655 | |

$t$ statistics in parentheses
Observations are dropped in the model because outcomes are perfectly predicted by included covariates (e.g., 'Missing production?'). Omitted categories are District: Shreveport and Product type: Missing. The log of cumulative production (BOE) and the log of the time the well has been idle (years) are interpolated for missing variables (Missing production data == 1) using a 4th-degree Chebyshev polynomial of the well's longitude and latitude, as well as the log of the well's age, the measured depth, whether the well is in coal-country, whether the well is in a coastal area, whether the well is orphaned versus idle, the well's DENR district, and the well's product type (oil vs gas). The $\chi^2$ statistic tests the joint hypothesis that omitted coefficients are all zero.
$^{*}$ $p < 0.05$, $^{**}$ $p < 0.01$, $^{***}$ $p < 0.001$

Table A4: Leak size model (Contractor measurements)

| | (1) | (2) |
|---|---|---|
| Constant | 2.705 | 2.767*** |
| | (0.44) | (17.38) |
| Log well age (0 = Dec 2023) | -0.655 | |
| | (-0.78) | |
| Log measured depth | 0.0400 | |
| | (0.07) | |
| Log cum. production (BOE) | 0.118 | |
| | (0.85) | |
| Log years idle (0=Jan 2024) | 0.291 | |
| | (1.05) | |
| Missing production data? | 0.454 | |
| | (0.77) | |
| In coal area? | -0.203 | |
| | (-0.34) | |
| *District* | | |
| Monroe | -0.0245 | |
| | (-0.04) | |
| *Product type* | | |
| Oil | 0.709 | |
| | (0.73) | |
| Gas | 0.599 | |
| | (0.55) | |
| Observations | 191 | 191 |
| $\hat{\sigma}$ | 2.235 | 2.200 |
| $R^2$ | 0.0165 | 0 |
| adj $R^2$ | -0.0324 | 0 |
| $\chi^2$ | . | |
| $\chi^2$ dof | 9 | |
| $\Pr(\chi^2)$ | 0.961 | |

$t$ statistics in parentheses
Dependent variable is the natural logarithm of positive leaks.
Omitted categories are District: Shreveport and Product type: Missing.
The log of cumulative production (BOE) and the log of the time the well has been idle (years) are interpolated for missing variables (Missing production data == 1) using a 4th-degree Chebyshev polynomial of the well's longitude and latitude, as well as the log of the well's age, the measured depth, whether the well is in coal-country, whether the well is in a coastal area, whether the well is orphaned versus idle, the well's DNR district, and the well's product type (oil vs gas).
The $\chi^2$ statistic tests the joint hypothesis that all coefficients are zero except the constant.
$^{*}$ $p < 0.05$, $^{**}$ $p < 0.01$, $^{***}$ $p < 0.001$

## Table A5: Linear cost model estimates

| | (1) Monroe | (2) Shreveport | (3) Combined | (4) Final |
|---|---|---|---|---|
| Dist to road (km) | 0.161 | 8.931** | 6.780** | 5.407* |
| | (4.931) | (3.064) | (2.599) | (2.390) |
| MD (thou ft) | -5.459 | 8.542*** | 8.047*** | 7.900*** |
| | (11.98) | (0.529) | (0.502) | (0.457) |
| Log cum. production (BOE) | 2.027* | 0.0309 | 0.617 | 0.557 |
| | (0.874) | (0.394) | (0.359) | (0.327) |
| Missing production data? | -1.804 | -5.399*** | -5.803*** | -6.546*** |
| | (5.797) | (1.319) | (1.266) | (1.218) |
| In coal area? | 0 | -2.666** | -3.237** | -2.959** |
| | (.) | (1.020) | (1.028) | (1.039) |
| Years idle | 0.0772 | -0.0803 | -0.0184 | |
| | (0.0944) | (0.0491) | (0.0412) | |
| Well age (years) | 0.116 | 0.00384 | 0.0167 | |
| | (0.0977) | (0.0354) | (0.0324) | |
| *Product type* | | | | |
| Oil | -6.413 | -2.844 | -2.062 | |
| | (11.90) | (1.812) | (1.738) | |
| Gas | 1.131 | -3.595 | -2.925 | |
| | (5.764) | (1.981) | (1.865) | |
| Oil or Gas | | | | -3.159 |
| | | | | (1.642) |
| *District* | | | | |
| Monroe | 38.47 | | 30.25*** | 34.47*** |
| | (30.87) | | (3.745) | (2.989) |
| Shreveport | | 22.73*** | 17.56*** | 21.43*** |
| | | (3.625) | (3.382) | (2.779) |
| Leaking | -1.027 | 2.109 | 0.702 | |
| | (1.551) | (1.168) | (0.933) | |
| *Land use* | | | | |
| Developed & Other Human Use | 1.494 | 1.690 | 1.130 | |
| | (4.314) | (1.755) | (1.615) | |
| Forest & Woodland | 3.609 | 2.578 | 2.004 | |
| | (3.736) | (1.442) | (1.312) | |
| Recently Disturbed or Modified | 7.653 | 1.378 | 3.210* | |
| | (4.007) | (1.737) | (1.526) | |
| Shrub & Herb Vegetation | 8.651 | 0.523 | 4.501 | |
| | (4.570) | (4.441) | (2.622) | |
| Open Water | | -9.376 | -10.40* | |
| | | (5.047) | (5.139) | |
| Observations | 179 | 354 | 533 | 535 |
| $\hat{\sigma}$ | 8.584 | 8.260 | 8.480 | 8.812 |
| $R^2$ | 0.132 | 0.640 | 0.692 | 0.663 |
| adj $R^2$ | 0.0632 | 0.624 | 0.683 | 0.659 |
| Joint $F$ | 1.946 | 1.861 | 1.729 | |
| $F$ dof | 7 | 8 | 8 | |
| Pr($F$) | 0.0654 | 0.0652 | 0.0891 | |
| $F$ | 0.497 | 0.299 | 0.483 | |
| Pr($F$) | 0.482 | 0.585 | 0.487 | |

Standard errors in parentheses
Omitted land use class is 'Agricultural & Developed Vegetation.'
Omitted product type is 'No product specified.'
Dependent variable is P&A cost, including allocated overheads and wastage (thou 2020 USD).
All wells in Monroe district plugged by Dynamic, and all wells in Shreveport, by Lemoine.
Joint $F$ is for $H\_0$ that years Years Idle, Well Age, and Land Use coefficients are all zero.
The within-district $R^2$ for the final model (4) is 0.479 after partialling out district indicator variables.
$^{*}$ $p < 0.05$, $^{**}$ $p < 0.01$, $^{***}$ $p < 0.001$

Table A6: Moments of empirical vs fitted distributions

| | Mean | $\sqrt[4]{\kappa}$ | p50 | p90 | p95 | p99 | log lik. |
|---|---|---|---|---|---|---|---|
| Empirical | 119.4 | 2.5 | 13.9 | 289 | 566 | 1,733 | . |
| LogNormal | 178.8 | 126.8 | 15.9 | 267 | 593 | 2,655 | -949.572 |
| Weibull | 105.2 | 3.2 | 22.2 | 276 | 479 | 1,181 | -961.4614 |
| Gamma | 119.4 | 2.1 | 34.6 | 347 | 526 | 987 | -978.6247 |

Table displays empirical moments versus those distributions fit with maximum likelihood. $\sqrt[4]{\kappa}$ is the quartic root of the distribution's kurtosis. *log lik.* is the log likelihood of the fitted parameters.

Table A7: Summary statistics by well status and district

| | Plugged orphans | | Unplugged orphans | | All orphans | |
|---|---|---|---|---|---|---|
| | Monroe | Shreveport | Monroe | Shreveport | Monroe | Shreveport |
| Well count | 179 | 356 | 1,690 | 1,611 | 1,869 | 1,967 |
| Dist to road (km) | .14 | .16 | .36 | .2 | .34 | .19 |
| | (.14) | (.17) | (.41) | (.28) | (.4) | (.26) |
| MD (thou ft) | 2.3 | 1.8 | 2.8 | 2.7 | 2.7 | 2.6 |
| | (.15) | (1.2) | (1.9) | (2.1) | (1.8) | (2) |
| Years idle | 11 | 18 | 14 | 24 | 14 | 23 |
| | (10) | (12) | (14) | (12) | (13) | (12) |
| Well age (years) | 47 | 48 | 49 | 53 | 49 | 53 |
| | (7.7) | (18) | (12) | (19) | (12) | (19) |
| Log cum. production (BOE) | 8.7 | 8 | 8.9 | 8.8 | 8.8 | 8.6 |
| | (.92) | (1.5) | (1.4) | (1.6) | (1.4) | (1.6) |
| Cum. oil production (bbl) | 170 | 9,085 | 8,255 | 18,165 | 7,411 | 16,212 |
| | (1,584) | (63,883) | (58,506) | (57,047) | (55,422) | (58,677) |
| Cum. gas production (mcf) | 45,201 | 17,247 | 81,715 | 89,061 | 77,901 | 73,616 |
| | (30,720) | (109,961) | (276,049) | (471,891) | (261,652) | (422,153) |
| Missing production data? | | | | | | |
| 1 | 1.7% | 24% | 11% | 39% | 9.8% | 36% |
| In coal area? | | | | | | |
| Yes | 0% | 31% | 0% | 20% | 0% | 22% |
| Product type for the well | | | | | | |
| Not specified | 1.7% | 11% | 11% | 24% | 9.7% | 22% |
| Oil | 3.4% | 62% | 10% | 58% | 9.4% | 59% |
| Gas | 95% | 27% | 79% | 18% | 81% | 19% |

Top variables have mean and standard deviation below in parentheses. Bottom variables are percentages. Not all wells have oil or gas production, so these are conditional means.

Table A8: Summary statistics by contract measurement and district

| | Measured | | Not measured | | All orphans | |
|---|---|---|---|---|---|---|
| | Monroe | Shreveport | Monroe | Shreveport | Monroe | Shreveport |
| Wellcount | 383 | 459 | 1,486 | 1,508 | 1,869 | 1,967 |
| Dist to road (km) | .17 | .16 | .38 | .2 | .34 | .19 |
| | (.18) | (.18) | (.42) | (.28) | (.4) | (.26) |
| MD (thou ft) | 2.3 | 1.9 | 2.8 | 2.8 | 2.7 | 2.6 |
| | (.38) | (1.3) | (2) | (2.1) | (1.8) | (2) |
| Years idle | 12 | 19 | 14 | 24 | 14 | 23 |
| | (11) | (12) | (14) | (12) | (13) | (12) |
| Well age (years) | 47 | 51 | 50 | 53 | 49 | 53 |
| | (9.2) | (19) | (12) | (19) | (12) | (19) |
| Log cum. production (BOE) | 8.7 | 8.1 | 8.9 | 8.8 | 8.8 | 8.6 |
| | (1.1) | (1.4) | (1.4) | (1.7) | (1.4) | (1.6) |
| Cum. oil production (bbl) | 269 | 9,609 | 9,427 | 18,526 | 7,411 | 16,212 |
| | (2,612) | (59,033) | (62,602) | (58,407) | (55,422) | (58,677) |
| Cum. gas production (mcf) | 53,969 | 16,891 | 84,658 | 93,496 | 77,901 | 73,616 |
| | (47,278) | (101,073) | (294,905) | (485,431) | (261,652) | (422,153) |
| Factor-variable percent | | | | | | |
| Missing production data?=1 | 3.1% | 29% | 12% | 38% | 9.8% | 36% |
| In coal area?=Yes | 0% | 27% | 0% | 21% | 0% | 22% |
| Product type for the well=Not specified | 2.9% | 14% | 11% | 24% | 9.7% | 22% |
| Product type for the well=Oil | 3.9% | 62% | 11% | 58% | 9.4% | 59% |
| Product type for the well=Gas | 93% | 24% | 78% | 18% | 81% | 19% |

Top row is well count. Middle rows are mean and standard deviation in parentheses. Bottom variables are percentages. Not all wells have oil or gas production, so these are conditional means.

Table A9: Distribution of emissions from unmeasured wells

| | Total emissions (t/yr) | | Number leaking | | Percent leaking | | Avg leak (g/hr) | | Avg emission (g/hr) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Est | [90% CI] | Est | [90% CI] | Est | [90% CI] | Est | [90% CI] | Est | [90% CI] |
| Orphan | | | | | | | | | | |
| Num wells | 2994 | | | | | | | | | |
| Mean | 675 | [471, 946] | 646 | [572, 726] | 22% | [19%, 24%] | 119 | [85, 163] | 26 | [18, 36] |
| SD | (75) | [44, 101] | (22) | [21, 23] | (0.7%) | [1%, 1%] | (12.6) | [7.4, 17.0] | (2.9) | [1.7, 3.8] |
| P1 | 516 | [366, 722] | 594 | [524, 673] | 20% | [17%, 22%] | 92 | [67, 126] | 20 | [14, 28] |
| P5 | 555 | [397, 784] | 610 | [538, 688] | 20% | [18%, 23%] | 99 | [72, 136] | 21 | [15, 30] |
| P10 | 581 | [412, 819] | 618 | [546, 697] | 21% | [18%, 23%] | 103 | [74, 142] | 22 | [16, 31] |
| P50 | 672 | [470, 942] | 646 | [572, 726] | 22% | [19%, 24%] | 119 | [85, 163] | 26 | [18, 36] |
| P90 | 773 | [542, 1076] | 675 | [600, 755] | 23% | [20%, 25%] | 136 | [97, 185] | 29 | [21, 41] |
| P95 | 803 | [563, 1115] | 683 | [607, 763] | 23% | [20%, 25%] | 141 | [100, 192] | 31 | [21, 42] |
| P99 | 862 | [603, 1188] | 698 | [622, 779] | 23% | [21%, 26%] | 150 | [105, 204] | 33 | [23, 45] |
| Idle | | | | | | | | | | |
| Num wells | 9835 | | | | | | | | | |
| Mean | 1778 | [1222, 2556] | 1698 | [1494, 1964] | 17% | [15%, 20%] | 119 | [88, 160] | 21 | [14, 30] |
| SD | (121) | [77, 160] | (36) | [34, 39] | (0.4%) | [0%, 0%] | (7.7) | [4.7, 10.3] | (1.4) | [0.9, 1.9] |
| P1 | 1506 | [1069, 2182] | 1611 | [1414, 1876] | 16% | [14%, 19%] | 102 | [75, 138] | 17 | [12, 25] |
| P5 | 1582 | [1111, 2282] | 1639 | [1437, 1901] | 17% | [15%, 19%] | 107 | [79, 144] | 18 | [13, 26] |
| P10 | 1626 | [1133, 2343] | 1651 | [1450, 1915] | 17% | [15%, 19%] | 110 | [81, 147] | 19 | [13, 27] |
| P50 | 1774 | [1221, 2552] | 1698 | [1493, 1964] | 17% | [15%, 20%] | 119 | [88, 160] | 21 | [14, 30] |
| P90 | 1936 | [1311, 2772] | 1745 | [1538, 2013] | 18% | [16%, 20%] | 130 | [94, 174] | 22 | [15, 32] |
| P95 | 1984 | [1338, 2829] | 1758 | [1551, 2027] | 18% | [16%, 21%] | 133 | [96, 178] | 23 | [16, 33] |
| P99 | 2076 | [1393, 2923] | 1784 | [1573, 2052] | 18% | [16%, 21%] | 138 | [99, 185] | 24 | [16, 34] |

Table shows moments of emissions, etc from unmeasured wells Orphan and Idle wells. Moments are based on our sample of data from 842 wells measured by contractors using a Hi-Flow instrument. 10000 Monte Carlo simulations were used to generate each distribution, and confidence intervals (5th and 95th percentiles) were obtained using 100 bootstrap draws. For reference, US and Appalachia EPA emissions factors for orphan wells are 10.02 and 30.57 $g_{CH_4}\ h^{-1}$.

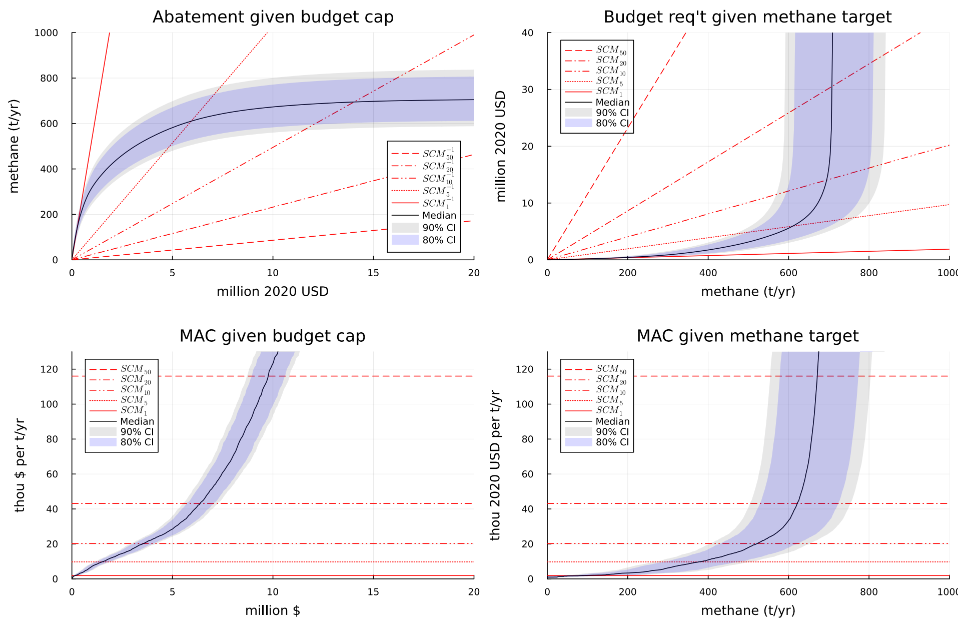


Figure A2: Monte Carlo simulation of "Perfect information" benchmark policy with log normal leaks instead of discrete distribution. Confidence intervals are all vertical.