Examining the Impacts of Methane Leakage on Life-Cycle Greenhouse Gas Emissions of Shale and Conventional Natural Gas

by Andrew Burnham and Corrie Clark

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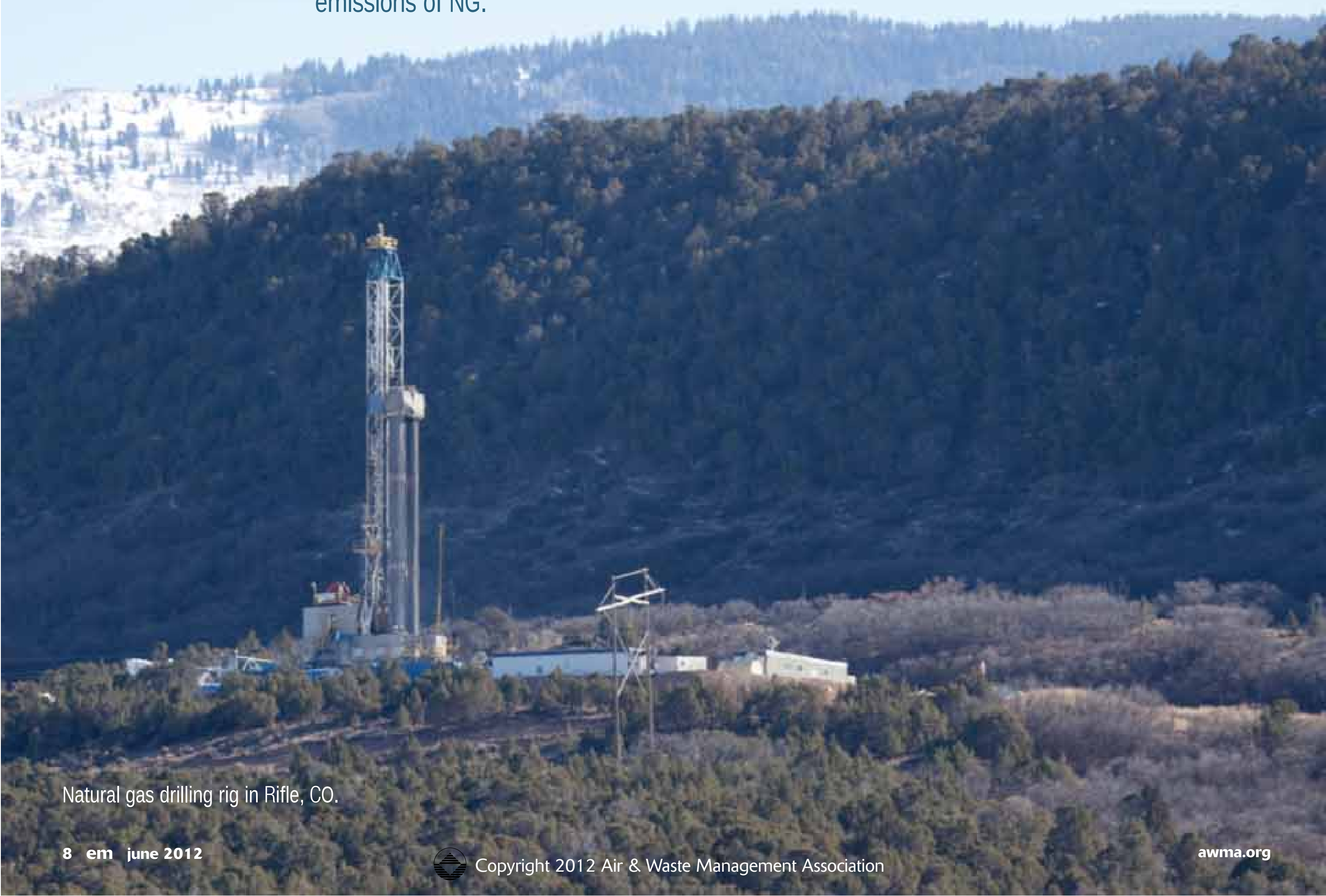
The development of large-scale shale gas production has been described as a game-changer for the U.S. energy market and has generated interest in expanding the usage of natural gas (NG) in sectors such as electricity generation and transportation. This development has been made possible by improvements in drilling technologies, specifically utilizing hydraulic fracturing in conjunction with horizontal drilling. However, the environmental implications of NG production and its use have been called into question.[1-4] One of the major concerns is the amount methane (CH_4) leakage from production activities and its impact on the life-cycle greenhouse gas (GHG) emissions of NG.



Natural gas drilling rig in Rifle, CO.

Natural gas has been referred to as a low-carbon fuel as its combustion produces significantly less carbon dioxide (CO_2) than from gasoline, diesel, or coal combustion on an energy-equivalent basis. However, to understand the implications on climate change, one must look at not only the GHG emissions during combustion, but also those from upstream production activities. In 2011, the U.S. Environmental Protection Agency (EPA) made major changes to its methodology for calculating CH_4 emissions from the U.S. natural gas system in its annual GHG inventory, which more than doubled the total estimate from the previous year.[5]

EPA's revised methodology suggests that considerably more CH_4 leakage occurs during production than previously thought. Our goal was to examine the implications of the most recent estimates of CH_4 leakage on the life-cycle GHG emissions of NG use. We utilized the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model developed at Argonne National Laboratory to estimate up-to-date GHG emissions and also to understand the uncertainties involved in calculating their life-cycle GHG impacts.[6] In this article, we will discuss the methodology used to complete our life-cycle analysis (LCA), several key parameters that greatly affect our findings, and finally the results of our study.

Methods

After determining the purpose of an LCA, the scope of the study needs to be defined. This involves considering issues such as system boundaries and functional units. In our LCA of shale and conventional NG, we examined the GHG emissions, specifically CO_2, CH_4, and nitrous oxide (N_2O), from NG recovery, processing, transmission, distribution, and end use. In addition, we expanded the system boundary typically used in the GREET model to include the establishment of infrastructure, as we were especially interested in the impacts of well drilling and completion, see Figure 1.

As we wanted to study the impacts of expanded NG use in electricity generation and transportation, we chose to examine the following functional units: per-kilowatt-hour (kWh) of electricity produced and per-vehicle-mile-traveled for transportation services. These functional units take into account the efficiency (e.g., power plant efficiency and vehicle fuel economy) of converting energy into energy services, which can significantly impact LCA results when comparing different fuel and technology combinations. Other researchers have focused on per-megajoule results, which represent the amount of energy produced from direct combustion.[4] However, coal is predominantly used for electricity generation, while petroleum-based fuels are mainly used for transportation. Therefore, comparing direct combustion of NG to that of coal or diesel may lead to faulty conclusions, as the other fuels are not typically used in this fashion.

Data Sources and Key Parameters

Large amounts of GHG data are made available using the methodologies EPA has developed for its annual U.S. GHG inventory to estimate emissions for different sectors, including the oil, coal, and NG industries. Previous estimates were based on an examination of the U.S. NG industry's emissions in 1992, prior to large-scale shale gas production.[7] As such, the recent increase in the estimate of CH_4 leakage was due to a few major updates, including (1) adding the emissions from shale gas well completions, which involves preparing a well to produce gas after it is drilled and includes the process of hydraulic fracturing; and (2) revising the emissions resulting from conventional NG liquid unloadings, which involves removing the accumulation of fluids in wet gas wells. In this article, we will focus on the emission estimates from these well infrastructure

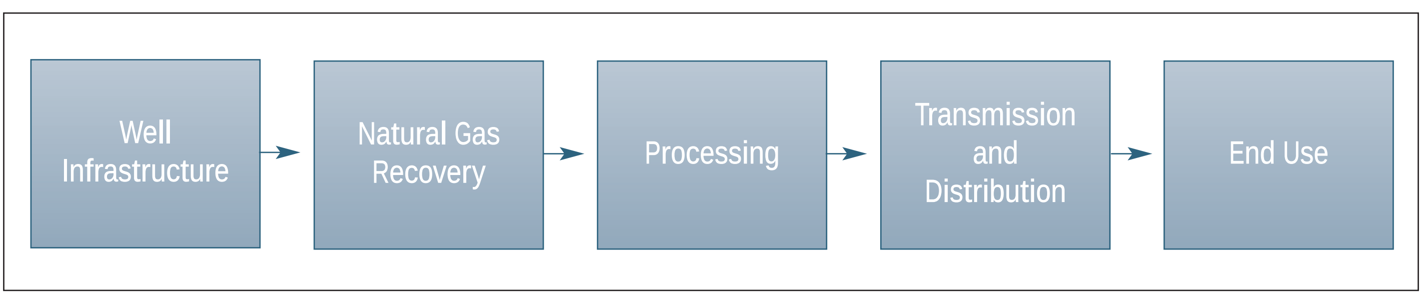


Figure 1. System boundary for shale and conventional NG pathways.

Significant CH_4 emissions from shale gas well completions can occur after hydraulic fracturing as flowback water is removed from the well prior to the beginning of gas production.

and recovery activities. However, CH_4 emissions can come from other well equipment and downstream from the recovery stage during NG processing, transmission, and distribution. For these stages, it is assumed that shale and conventional NG are treated in a similar manner and therefore the CH_4 emissions would be equivalent.[8]

Estimated Ultimate Recovery

Given that the EPA emissions for well completions and liquid unloadings are estimated on a per-well basis, it was necessary to determine the estimated ultimate recovery (EUR) of gas from a well to amortize these periodic emissions over the total amount of NG produced. This is done so that all emissions can be estimated on an equivalent-energy basis, which is calculated by multiplying the volume of gas produced by its heating value. The implication of EUR is that the lower the amount of NG produced, the higher the life-cycle GHG impact is for these periodic emissions.

For shale gas wells, an EUR range of 1.6 to 5.3 billion cubic feet (Bcf) was produced using estimates for several important plays (i.e., shale formations containing NG): Marcellus, Barnett, Haynesville, and Fayetteville. The low estimates, which were generated for the U.S. Energy Information Administration (EIA), capture the variable productivity of a play by evaluating the EUR for the best, average, and below-average areas.[9] That study also suggested that areas being actively developed would typically have a larger EUR than those that are not yet developed. The high estimates, which represent industry average values, correlate well with the EIA data for developed wells.[10] This range points to a large uncertainty in estimating life-cycle GHG emissions from shale gas, as we have to rely on estimates of lifetime productivity, while the industry is in its infancy and many of the plays have only recently been drilled.

On the other hand, conventional NG production is quite mature and well productivity has been declining over the past few decades.[11] We found that the average conventional NG well has a relatively low EUR, ~1.0 Bcf. The implication of this is that, on average, periodic CH_4 emissions from conventional wells will have a larger impact on life-cycle GHG emissions as compared to shale gas, due to the smaller amount of gas produced over its lifetime.

Well Completions

Significant CH_4 emissions from shale gas well completions can occur after hydraulic fracturing as flowback water, which includes frac fluids, sand, and natural gas, is removed from the well prior to the beginning of gas production. EPA calculated uncontrolled completion emissions ranging from 700 to 20,000 thousand cubic feet (Mcf) of NG per shale gas completion (conventional wells are not hydraulically fractured).[12] These emissions assume no control technologies, such as flaring or reduced emission completions (RECs), which use equipment to capture the gas. Periodically, a shale gas well may need a workover to improve gas flow, which can involve hydraulically fracturing the well again. EPA assumes a well requires a workover every 10 years, so for a well with an assumed 30-year lifetime, hydraulic fracturing would be required three times and could release substantial amounts of CH_4 to the atmosphere.

However, there is considerable uncertainty with these estimates as they were developed using engineering calculations with very limited data and not based on direct measurements of CH_4 leakage. For example, EPA might be overestimating emissions, as they based their values on operators involved with the Natural Gas STAR program, an industry and government partnership to reduce CH_4 emissions, which employed RECs. The REC equipment allows operators to flow back fluids for a longer time prior to production as they will not lose the gas, which is desirable as this process removes debris and improves well productivity. Wells without REC equipment flow back for a shorter time and thus will potentially have much less vented emissions.

Liquid Unloadings

EPA significantly increased their emission factor for liquid unloading, which is the process of removing liquids that can slow and even block gas flow in wet gas wells. EPA assumes that liquid unloading only occurs in conventional wells as shale gas is typically dry; however, as production expands to other formations (e.g., Antrim and New Albany are considered wet) this might not be the case. The uncontrolled emission factor is based upon fluid equilibrium calculations to calculate the amount of gas needed to blow down a column of fluids blocking a well and Natural Gas STAR partner data on the amount of additional venting after a blowdown.[12]

Similar to the issues with well completion emissions, considerable uncertainty for liquid unloading emissions arises from the limited data sources used and the applicability of Natural Gas STAR program activities to calculate industry baseline emissions. This is especially important as liquid unloadings account for 33% of the uncontrolled CH_4 emissions from the NG industry in the latest GHG inventory.[5] Therefore, the lack of reliable data creates a large degree of uncertainty for conventional NG emissions.

Best Practices to Reduce Methane Emissions

We have been discussing the uncontrolled emissions from completions and unloadings; however, in reality, the industry uses various technologies to reduce these emissions by either flaring or capturing the gas. Therefore, the uncontrolled emission factors for completions and unloadings needed to be adjusted to represent real-world conditions. However, there is a lack of transparency with the data as reported savings by activity are highly aggregated by EPA (to protect confidential business information).

Using background information provided by EPA, we separated most of the Natural Gas STAR reductions for completions and liquid unloadings.[13] For shale completions, we estimated that uncontrolled emissions were reduced by between 38% and 70%, while liquid unloading emissions were reduced by between 8% and 15%. While there is significant uncertainty with these estimates, the data show that large amounts of shale gas are being captured through the use of RECs and that industry should examine what technologies and practices could be implemented to further reduce conventional liquid unloading emissions.

End Use Efficiency

To examine our functional units of per-kWh and per-vehicle-mile-traveled, we needed to examine the efficiencies to convert an energy product (in this case, NG) into these energy services.[8] Natural gas can be utilized in a steam boiler to produce electricity at roughly 33% efficiency (lower heating value); however, the United States has numerous natural gas combined cycle (NGCC) power plants

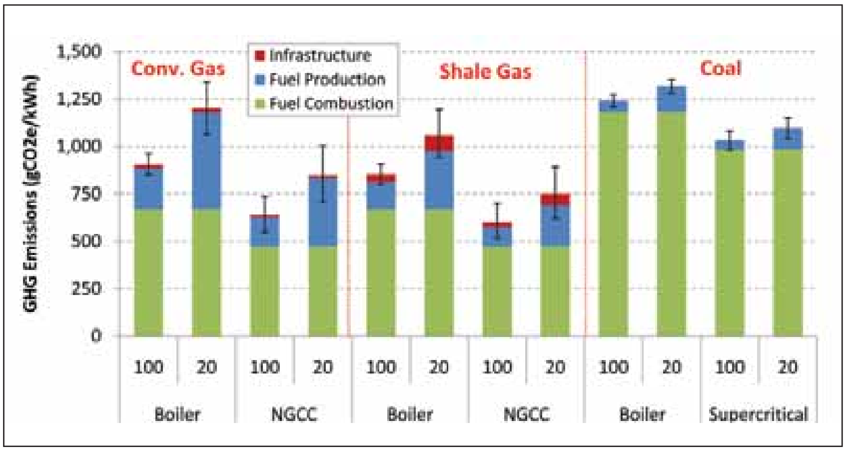


Figure 2. Life-cycle GHG emissions per kWh of electricity produced (100-year and 20-year timeframes).

Notes: Colored bars represent base-case results; error lines represent 90% confidence interval reflecting the uncertainty due to distribution functions developed for each key parameter in the study.

that have far greater thermal efficiencies. Our base case for NGCC is 47%, though depending on its operation this can vary significantly. To compare with coal, we examined the efficiency of an average subcritical coal boiler, 34%, and a more advanced design, a supercritical boiler, which has recently been made commercially available, 42%.

We investigated both a passenger car and transit bus using compressed natural gas (CNG) as both vehicle types are in use today. CNG cars have a fuel economy penalty of ~5% as compared to a gasoline car, primarily due to the weight penalty of the CNG tanks. Meanwhile, a CNG transit bus has a greater fuel economy penalty of ~15% as compared to a diesel bus, as CNG buses use spark-ignited engines, which are much less efficient than diesel compression-ignition engines during the low speeds and loads typical of a bus' duty cycle.

Global Warming Potential

Global warming potential (GWP) provides a simple measure to compare the relative radiative effects of various GHG emissions. When comparing the impacts of different fuels, researchers must choose a timeframe for comparison. We follow the Intergovernmental Panel on Climate Change's recommendation to use the 100-year timeframe when evaluating various climate change mitigation policies; however, some researchers have suggested that the 20-year timeframe should be examined to understand near-term implications of expanded NG use.[8] When using a 20-year timeframe, the effects of CH_4 are amplified as it has a relatively short (~12 year) perturbation lifetime, whereas CO_2 contributes to climate change for a longer time period.

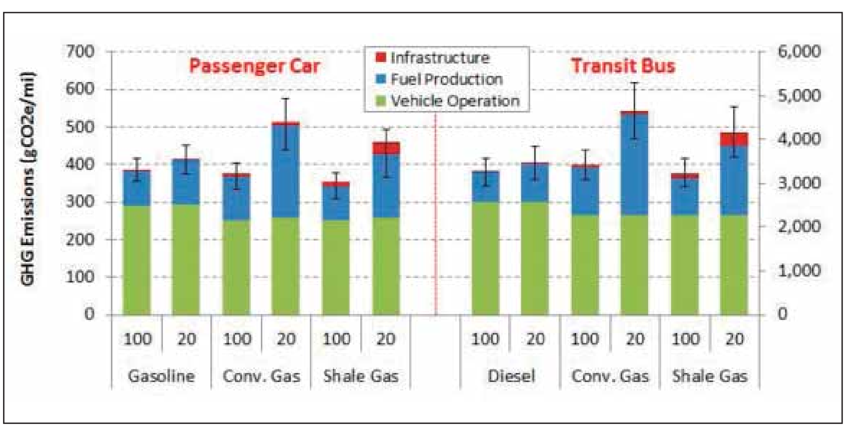
Results

Our assessment using the GREET model found that NG power plants show considerable life-cycle GHG benefits for the 100-year timeframe, as shown in Figure 2. For example, a NGCC plant reduces GHG emissions by ~50% as compared to an average subcritical coal boiler and by ~40% as compared to a supercritical boiler. We also present the results using GWPs for the 20-year timeframe for comparison sake and see the emission benefits for the NG pathways are diminished, but only for the worst case of an NG boiler do the emissions approach the advanced supercritical coal boiler.

In Figure 3, we see that there is no statistical difference between the petroleum-fueled and CNG vehicles for the 100-year timeframe, while the emissions are ~25% higher for CNG vehicles for the 20-year timeframe. For CNG vehicles to improve their GHG emissions, they must increase their fuel economy. European CNG cars using technologies such as direct injection and turbocharging have shown promise in enhancing fuel economy and performance. These technologies are growing in popularity in gasoline vehicles in the United States and as such provide an opportunity for CNG vehicle development.

An interesting result from our analysis is that the base-case shale gas GHG emissions are slightly lower than conventional NG; the reason being is that the estimates of conventional liquid unloading CH_4 emissions are slightly higher than those from shale gas well completions. However, as there is great uncertainty in those estimates, our results show that there is statistical uncertainty whether shale gas emissions are indeed lower.

Figure 3. Life-cycle GHG emissions per vehicle mile traveled (100-year and 20-year timeframes).



Notes: Colored bars represent base-case results; error lines represent 90% confidence interval reflecting the uncertainty due to distribution functions developed for each key parameter in the study.

In Figure 4, we present a sensitivity analysis of several key parameters to investigate this uncertainty. We see that for conventional NG, liquid unloadings cause the greatest amount of uncertainty as there is a wide range in the estimates of how much CH_4 is vented. For shale gas, CH_4 emissions from well completions and workovers are the greatest source of uncertainty, while EUR is also very important, especially if wells have a lower productivity than industry projections.

Discussion

Our LCA of shale and conventional NG found that CH_4 leakage from production activities is the key contributor to upstream NG GHG emissions and can reduce the life-cycle GHG benefit of NG as compared to coal and petroleum. However, data with substantial uncertainties have been used to update EPA's GHG inventory and therefore could potentially support erroneous conclusions. Reliable data for parameters such as EURs, well completions, and liquid unloadings will help spur a healthy debate of the role of NG in the U.S. energy supply.

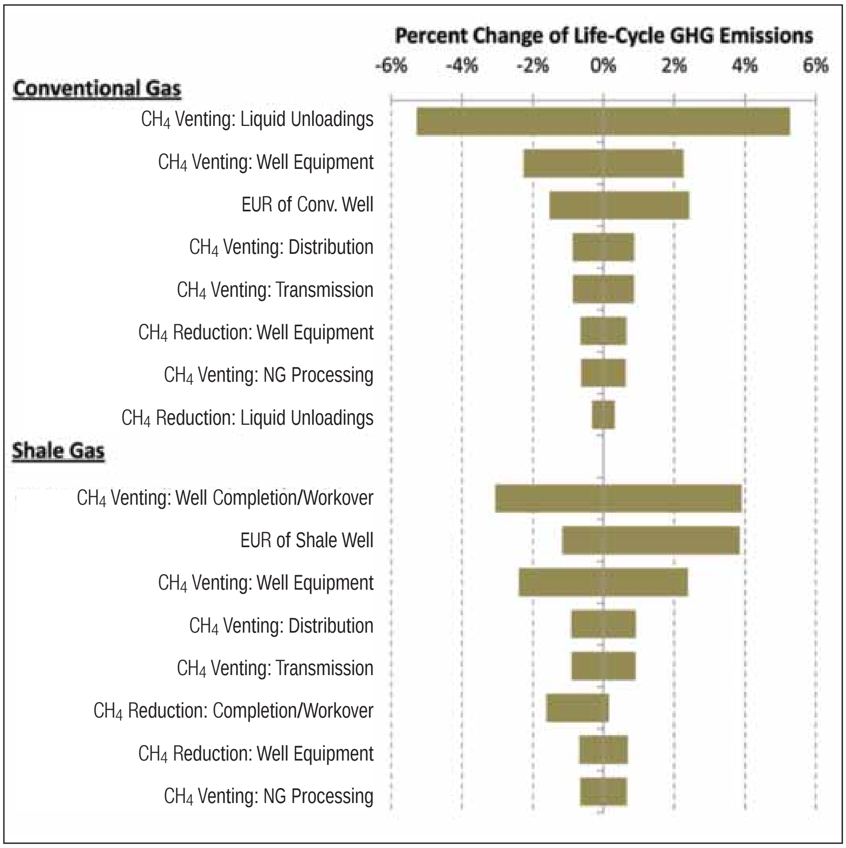


Figure 4. Sensitivity analysis of selected key parameters (100-year timeframe).

Environmental management and GHG emissions reduction strategies need to be exercised for shale and conventional NG to reduce the environmental and energy burdens associated with producing these fuels. The voluntary partnership of the NG industry and EPA under the Natural Gas STAR program has helped reduce CH_4 emissions, and EPA's recently finalized New Source Performance Standards for the oil and gas industry will require reductions from shale gas well completions. However, further efforts could be undertaken to extend the application of emissions reduction projects across the industry, develop new mitigation measures, and address the remaining environmental issues associated with NG production and transmission. **em**

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