Technology and Policy Solutions to Reduce Harmful Natural Gas Flaring

Columbia University School of International and Public Affairs

graduate capstone report in consultation with

Environmental Defense Fund

Authors:
Ludwig van Bedolla
Weiduo (Victoria) Cai
Zoë Martin
Fan Yu

Columbia University Faculty Advisor:
Robert Kleinberg

Environmental Defense Fund Contacts:
Dan Grossman
Colin Leyden

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Abstract

Technology and Policy Solutions to Reduce Harmful Natural Gas Flaring
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Gas flaring is the intentional burning of natural gas that is produced as a byproduct of oil production. The harmful emissions associated with gas flaring around the world are staggering - an estimated 145 bcm of gas is flared each year. The capstone team conducted a comprehensive research analysis of the regulatory, economic, and technological factors involved in natural gas flaring. The team found that gas flaring is inefficiently and/or ineffectively regulated, leading to significant under reporting and inaccurate monitoring. New data streams, such as satellite observations, provide a more comprehensive overview of the problem, but many gaps in knowledge remain.

The team recommends a combination of technology and policy solutions, with measurement and reporting accuracy as a high priority. Gas is a valuable commodity that can be used at or near its source to power oilfield equipment or computing centers. Flaring can be made more efficient to reduce methane emissions, which are even more harmful than flaring. Government regulations should combine the best practices that have been devised by individual states. Operating companies can be incentivized to be more efficient through the use of environment, social, and governance (ESG) ratings, on which the financial community is increasingly relying to grade its investments. Nonprofits and independent researchers should continue working to bridge the gap between satellite and reported data, working with both industry and governments to understand the full extent of the problem.

Executive Summary

Overview

This report contains a comprehensive research analysis of the regulatory, economic, and technological factors involved in the harmful flaring of associated gas and related emissions, followed by a discussion of technology and policy solutions. The primary purpose of this report is to support the advocacy goals of the Environmental Defense Fund (EDF) in their fight to reduce wasted energy and pollution through stronger flaring regulations and better industry practices for the long term protection of the environment. The research and analysis was conducted by Masters students at Columbia University's School of International and Public Affairs (SIPA) as a semester-long graduate capstone consultancy, under the guidance of a faculty advisor from the Center for Global Energy Policy (CGEP) at Columbia. Although the focus of this report is the oil and gas industry and regulation in the United States, EDF and CGEP aim to collaborate to apply policy and technology solutions to gas flaring around the world.

Background and Context

Gas flaring is the intentional burning of associated gas, which is the natural gas that is produced as a byproduct of oil production. Associated gas can also be captured and used for energy production or released into the atmosphere directly through venting or lost through leaking (called "fugitive emissions"), but a significant amount is burned through routine gas flaring practices. Routine flaring is essentially a waste disposal system for associated gas, akin to a chemical manufacturer using a nearby body of water to dispose of chemical waste. However instead of chemicals in a lake, the waste from oil and gas production consists of potent greenhouse gases that are deposited into the atmosphere - contributing to global climate change.

The harmful emissions associated with gas flaring around the world are staggering. According to the World Bank, approximately 145 bcm of gas is flared each year, which is equivalent to about 400 million tons of CO_2 in emissions.[1] In order to offset this amount of carbon in the atmosphere, we would have to plant 6.6 trillion trees[2] - more than *double* the number of trees currently on Earth.[3] These emissions are estimates of flaring amounts based on available satellite data, and do not account for the methane gas released directly into the atmosphere through venting and fugitive emissions. This is an important distinction, as the global warming effect of methane is over 25 times more powerful than carbon dioxide.[4]

Gas flaring is practiced worldwide and is increasing overall - up 3% in 2018 from the previous year, largely due to a 48% increase in flaring in the United States (US).[5] In the US, the increase in flaring is driven by booming oil production in three states - Texas, North Dakota, and New

1 https://www.worldbank.org/en/programs/zero-routine-flaring-by-2030#7
2 Epa emissions comparison calculator tool
3 Nature tree density
4 https://www.epa.gov/ghgemissions/overview-greenhouse-gases#CH4-reference
5 Increased Shale Oil Production and Political Conflict Contribute to Increase in Global Gas Flaring

Mexico. These three states are home to the largest oil plays in the US, the Permian (Texas and New Mexico) and the Bakken (North Dakota) basins. The US oil boom, particularly in the Permian basin, is one of the main drivers that help maintain the status quo of flaring regulation and technology. The introduction of fracking has allowed production to far outpace infrastructure development, and many producers cite increased flaring due to lack of access to natural gas pipelines and processing capacity. Even where gas capture technology and infrastructure is available, it often costs oil producers more capital to capture, process, and transport associated gas than they would make from selling it.[6]

Other important factors that limit the success of flaring interventions include economically motivated policies and political maneuvering. A booming oil industry boosts local economies and provides significant tax revenue for states such as New Mexico, where oil and gas revenue accounts for over one-fourth of the state's yearly revenue.[7] As a result, many lawmakers are hesitant to enforce flaring and venting regulations that may reduce production and lower revenue. For example, the Chairman of the Texas Railroad commission has argued that increased flaring is "just what happens in a boom." She asserted that flaring may be a shame and a waste of natural resources, but it's not an urgent enough reason for a regulatory crackdown.[8] There are also some driving factors, such as political conflict, that are far outside the influence of local policy or technology solutions to gas flaring.[9] This means the areas we can address - such as accurate reporting, regulations, and technology innovation - are vital to long-term success.

Comprehensive Assessment of the Extent of the Problem

For this report, EDF also asked us to conduct a comprehensive assessment of the extent of the problem of gas flaring - including analyzing local and federal legislation, the accuracy of data from independent reporting and new data streams, and the influence of infrastructure, operational, and safety factors. Our most important finding is that while gas flaring is widely discussed and debated, there is limited agreement on either the extent or urgency of the problem across the industry, government, and nonprofit sectors. As a result, we shifted our focus to include an analysis of the many factors preventing an accurate and comprehensive assessment of the extent of the problem. With an understanding of these factors and how they interact, we can better provide policy and technology options to lay the foundation for a successful solution.

These factors include:

- *Inaccurate Measurement:* Regulations require that all flared and vented gas be either measured or estimated, but provide few guidelines for methodology, accuracy, or enforcement. Each measurement tool has strengths and limitations, and they are not all used systematically. Operators and regulators rely on on-site metering or estimations, but it is currently impossible to determine from the reported data which measurement methods operators use. Researchers and reporters frequently cite satellite data, which cannot currently differentiate between individual operators. The current challenge for policy and technology is

6 https://www.rrc.texas.gov/media/53466/01-0308609-pfd-exco.pdf
7 State of New Mexico FY20 Budget in Brief
8 Report: Permian Basin oil producers flaring more natural gas than they told the state
9 Increased Shale Oil Production and Political Conflict Contribute to Increase in Global Gas Flaring

to bridge the gap between what is measured in real time and then self-reported by operators and what is measured on large scales by satellites.

- *Inconsistent and Unenforced Reporting:* There is no systematic reporting of flared or vented gas. All data are self-monitored and self-reported by operators to various state agencies. Each state has different regulations for how associated gas must be measured, plus different methods for reporting. State-level data is then provided to federal agencies, which then analyze it and publish it online after a nine-month delay. The current forms of reported data make it impossible to differentiate between flaring, venting, and fugitive emissions, or between what is necessary for safety or waste disposal.

- *Infrastructure, Operation, and Safety:* The extent of gas flaring is also influenced by infrastructure, such as pipeline and storage access and capacity, all of which are costly to build and maintain. Ideally, new wells should be built to have direct access to pipelines, while new pipeline infrastructure is built to keep up with demand. However, pipeline availability is not a sufficient condition to reduce flaring or venting and many factors influence where they can be built. On the operational side, fugitive emissions from leaks in equipment and pipes are an unreported and often unmeasured component of vented associated gas. These can be addressed through enhanced leak detection technologies and equipment maintenance. Gas flaring is sometimes necessary to ensure the safety of operating personnel and surrounding communities, such as during drilling, testing, well completion, maintenance, and to release pressure in an emergency such as equipment failure or a power outage. Flaring may also be necessary if the associated gas contains significant amounts of hydrogen sulfide (sour gas), which is extremely toxic to humans and animals and is prevalent in the Permian basin.

- *International Initiatives:* In addition to state and federal regulations, there are a number of international and non-profit efforts to measure and reduce methane emissions and gas flaring. Many oil and gas companies are members of these initiatives and pledge to reduce their routine flaring practices, but actual compliance is voluntary and difficult to assess. Policy solutions and voluntary initiatives need to include requirements for transparency in both reporting and practices, as well as secondary verification and enforcement mechanisms.

Economics

The flaring of associated gas is a byproduct of increased oil and gas production, and as such is partially driven by market dynamics and prices. Oil prices influenced by supply and demand worldwide play a prominent role globally, whereas the economics of natural gas has a more regional focus. These dynamics will not only impact the current status of gas flaring, but also provide implications for future trends of flaring emissions. Additionally, the price and demand for natural gas play a large role in flaring amounts, as low prices can make gas capture and processing uneconomical for many companies. Regulations and incentives are required where the costs of solutions create an unnecessary burden. One interesting incentive has been through increased incorporation of Environmental and Social Governance (ESG) ratings by financial investors.

It is important to note that this project began and was researched during the very early stages of the COVID-19 epidemic, which has caused an unprecedented drop in crude oil demand, slowing both production and flaring. The long term effects of the epidemic are as impossible to predict as the virus itself, as we still do not know how long the economic shutdown will last or what will happen to the highly volatile oil market when or if normal activity resumes.

Technologies

The technology solutions we researched to monitor and reduce gas flaring fall into five main categories:

- *Accurate and direct volume measurement:* Increase the use of flow meters on each flare to accurately measure the volume of gas being flared at each well. This will help gain a more detailed picture of how much gas is flared and how much is released through venting and fugitive emissions.
- *Improved combustion efficiency of flares:* These technologies increase the amount of gas successfully burned to reduce the percentage methane vented from a flare. This is an important environmental concern to reduce the greenhouse effect of the gases released into the atmosphere.
- *Gas utilization:* Conversion of associated gas to liquid natural gas enables companies to more easily transport the gas in the absence of pipelines. Associated gas can also be burned on-site for power generation or transfered to power nearby facilities, such as newly built block chain and data mining centers.
- *Keeping the gas at the reservoir:* Associated gas can be stored underground at the reservoir using gas reinjection technologies.
- *Timely infrastructure development:* Prioritize the development of pipeline capacity and gas processing facilities to keep pace with the boom in production.

Regulations

Under the US Federal system, each state has the jurisdiction and authority to implement its own regulation, or to set specific goals, milestones, and objectives to reduce natural gas flaring. Legislation has approached the problem in two ways: First, the air quality regulation which aims to control air pollution, including greenhouse gases, and to protect human health in the short and long terms. Second, the permits and operation framework which establishes the administrative procedures that the oil and gas industry must follow to operate. Through analysis of how regulations differ in each state, we identified several best practices in place and pieces of legislation that could improve reduction of gas flaring and venting in the local environment. The following six characteristics are what we consider would be the Ideal Regulation to measure, monitor, and reduce natural gas flaring and venting in the US:

1. *Mandatory Measurement and Reporting:* The local regulation must explicitly ask for the owners/operators to measure the volume of associated gas produced, separated, vented

and flared throughout the production chain. In the best case the report should be submitted to the authority on a monthly or quarterly basis.

2. *Flaring and Venting Differentiation*: The regulation must mandate a clear distinction between these two processes. This is crucial for environmental and air quality control since each one has different global warming potentials and impact on the environment.
3. *Clear Definition of Safety and Unnecessary Flaring*: The regulation must distinguish between unnecessary and necessary (for safety or maintenance purposes) flaring and venting. The distinction is important because it gives the operators the necessary margin to operate a well. However, the regulation must establish a maximum period after which flaring or venting cannot be considered for safety.
4. *Flaring Threshold:* The regulation must set a specific volume threshold to distinguish what constitutes safety or acceptable flaring from unnecessary waste.
5. *Waste Definition:* The regulation must contain a cohesive and concise definition of what constitutes waste in the oil and gas industry. This is imperative to avoid owners or operators using this classification to dispose of natural gas that would otherwise be consumed or commercialized. Today each state legislation has its own legal definition creating an intricate system independent from other regulations, which makes it very difficult to coordinate or integrate them in a way that will properly address the problem.
6. *Third Party Monitoring:* The local laws should incorporate the use of new technologies to measure natural gas flaring and venting from above to validate the operator's and owner's data.

Recommendation

There is no quick fix for the problem of gas flaring due to its global prevalence, unknown extent, and widespread implications. Based on our analysis we believe the best path forward is a combination of technology and policy solutions, with measurement and reporting accuracy as the first priority. Governments should increase and enforce their requirements for complete, accurate reporting that is differentiated by flaring, venting, fugitive leaks, and safety. Industry should invest in on-site technology solutions to make measurement easier and more accurate. Nonprofits and independent researchers should continue working to bridge the gap between satellite and reported data, working with both industry and governments to understand the full extent of the problem.

1. Introduction and Context

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Environmental Defense Fund (EDF) and Center for Global Energy Policy (CGEP) at Columbia University seek to collaborate on furthering policy and technology solutions leading to the reduction of overall gas flaring volumes and better operational performance when gas flaring is necessary. While many companies are flaring excessive amounts of natural gas, some companies have demonstrated that routine flaring is unnecessary and that the copious amounts of wasted energy and pollution from flaring can be significantly reduced with better planning and improved oilfield operations. There is growing agreement from multiple stakeholders – environmental advocates, investors, and some oil and gas companies – of the benefit and need for policies to reduce flaring, such as gas capture requirements that would set firm limits on the percentage of gas that companies are allowed to flare, extending the gas production tax to include flared gas, displaying up-to-date flaring data online, and ensuring that innovation and new data streams, such as satellite data, are utilized to identify problems and hold operators accountable. The ultimate goal of such efforts is to align policies with a growing industry and investor consensus that operators must move quickly toward a near-zero upstream emission profile.

For this report, graduate students at Columbia University's School of International and Public Affairs were asked to research technology and policy solutions to inform the advocacy goals of EDF and CGEP. Additionally, EDF asked us to conduct a comprehensive assessment of the extent of the problem of gas flaring - including analyzing local and federal legislation, the economic effect of oil and gas markets, and the accuracy of data from independent reporting and new data streams.

1.1. Associated Gas - Flaring, Venting, Capturing

Associated gas is natural gas that is produced as a byproduct of oil production. Its primary component is methane, but other gases (hydrocarbons) and pollutants are often present in varying amounts.[10] In a long term low-gas price scenario, natural gas that is produced during upstream oil production is all too often considered waste - a resource that is much less valuable, harder to get to market, and depending on the regulatory context, cheaper and easier to dispose of through flaring. Although associated natural gas can be - and often is - captured to be used and sold, there are many economic and operational obstacles that limit this from happening. Associated gas that is not captured is often referred to as "lost gas,"[11] and is either released into the atmosphere through venting, burned in gas flaring, or lost through leaking.

10 Greenhouse Gas Footprint of Oilfield Flares Accounting for Realistic Flare Gas Composition and Distribution of Flare Efficiencies

11 "Lost oil or lost gas means produced oil or gas that escapes containment, either intentionally or unintentionally, or is flared before being removed from the lease, unit, or communitized area, and cannot be recovered." Bureau of Land Management definition https://www.regulations.gov/document?D=BLM-2018-0001-223600

Gas flaring is the intentional burning of associated gas. Occasionally gas flaring is required for safety purposes or operational upsets, but the majority of associated gas flaring occurs through routine flaring. Routine flaring is a method of disposing of associated natural gas that operators fail to capture and place in gathering infrastructure to be transported, processed and sold. Routine flaring is an operational method that is an alternative to other management options such as insertion into gathering pipelines, on-site electrification or other beneficial use. Routine flaring can be thought of as a waste disposal system for associated gas, akin to a chemical manufacturer using a nearby body of water to dispose of chemical waste. However instead of chemicals in a lake, the waste from oil and gas production consists of potent greenhouse gases and other air pollutants that are deposited into the atmosphere - contributing to global climate change and local air pollution.

1.2. Effects of Gas Flaring - Climate Change to Public Health

From an environmental standpoint, there are important differences between associated gas that is directly released (vented) into the atmosphere and gas that is flared. Associated gas is mostly made up of methane, or CH_4, which is an extremely powerful greenhouse gas. When it is burned in a flare, most of the methane combusts with oxygen to form carbon dioxide (CO_2). When vented or leaked directly into the atmosphere, methane becomes a powerful climate pollutant. Over a 100-year timeframe, the global warming potential (GWP) of methane is 25 times more powerful than that of carbon dioxide.[12] But methane is an even more powerful heat-trapping agent over the short term. Using a 20-year timeframe, methane is 84 to 86 times more powerful than CO2. So while both methane and carbon dioxide are harmful, CO_2 is the "lesser of the two evils" which means that efficient gas flaring is preferable to venting or leaking.

Despite these differences, gas flaring and venting are often reported together as one amount, which may or may not include data from leaks. Even where regulations require operators to differentiate between the flaring and venting, compliance is often loosely followed or enforced. For example, at the end of 2015 the Oil Conservation Division of New Mexico updated their reporting guidelines to require operators specify all lost gas as either vented or flared. Over a year later, only 51 out of 603 active operators were reporting their vented and flared volumes correctly.[13] Without the ability to determine the ratio of flared to vented gas, the actual greenhouse gas effect of reported data is nearly impossible to estimate.

Even taking reporting inconsistencies into account, the harmful emissions associated with gas flaring are staggering. According to the World Bank, approximately 145 bcm of gas is flared each year, which is about 400 million tons of CO_2 equivalent in emissions.[14] For comparison, this is approximately equal to the gas consumption of all of Central and South America, or the carbon emissions from 926 million barrels of oil.[15] In order to offset this amount of carbon, we would have to plant 6.6 trillion trees - more than *double* the number of trees currently on Earth.[16]

12 https://www.epa.gov/ghgemissions/overview-greenhouse-gases#CH4-reference
13 March 8 notice to operators
14 https://www.worldbank.org/en/programs/zero-routine-flaring-by-2030#7
15 Epa emissions comparison calculator tool
16 Nature tree density

Gas flaring and venting is also a public health concern for both surrounding communities and global populations. Studies have shown that areas with more pollution have significantly higher fatality rates from COVID-19[17] and other respiratory outbreaks.[18] Hydrogen sulfide is a naturally occuring gas that is much rarer than methane but is extremely toxic to humans and animals. In areas where there are high concentrations of hydrogen sulfide or "sour gas," the associated gas absolutely must be burned through flaring or incineration - it is far too toxic to vent or store.[19] Flaring of sour gas results in sulfur dioxide emissions, which is a less toxic gas but it is a known cause of acid rain. Acid rain is devastating to natural environments and ecosystems, and can occur thousands of miles from where the gas was emitted.[20] Finally, carbon emissions are the direct cause of global climate change and the devastating effects it already has around the world.

1.3. Geography and History

Routine gas flaring practices are seen world wide, almost anywhere there is significant oil production. As stated above, the World Bank estimate of gas flaring is approximately 145 bcm (5,118.5 bcf) worldwide in 2018. This was an increase of 3% from the previous year, largely due to the 48% increase in flaring in the United States.[21] Analysis of satellite data for gas flares indicates that Russia flares more gas than any other country, but the United States has a much higher number of individual flare sites (2,399 compared to Russia's 1,053 and Canada's 302 as of 2012 data).[22]

In the United States, the increase in flaring is driven by oil production in three states - Texas, North Dakota, and New Mexico. These three states are home to the largest oil plays in the US, the Permian (Texas and New Mexico) and the Bakken (North Dakota) basins, which have been experiencing significant booms in production the last few years. Texas alone flared enough associated gas in 2018 to power every household in the state that year.[23]

The flaring and venting of associated gas is not a new phenomenon, and neither is its regulation. In the 1930s, an estimated one billion cubic feet of associated gas was flared daily - more than the amount flared in Texas in 2018. The flares reportedly illuminated surrounding areas of the state so much that cars could drive at night without their headlights, and people could read newspapers by the light of the flares even from miles away.[24] This led to a lively, 15-year battle between regulators and producers over the excessive waste of one of the state's natural

17 Air pollution linked to far higher Covid-19 death rates, study finds

18 Air pollution and case fatality of SARS in the People's Republic of China: an ecologic study

19 https://www.capp.ca/explore/flaring-and-venting/

20 https://www.epa.gov/acidrain/what-acid-rain

21 Increased Shale Oil Production and Political Conflict Contribute to Increase in Global Gas Flaring

22 Elvidge 2016

23 Permian Basin Is Flaring More Gas Than Texas Residents Use Daily

24 Prindle, David F. "The Texas Railroad Commission and the Elimination of the Flaring of Natural Gas, 1930-1949." The Southwestern Historical Quarterly 84, no. 3 (1981): 293-308. Accessed April 20, 2020. www.jstor.org/stable/30238689.

resources. Although natural gas use was still in its early stages and had significantly less value than oil, the Texas Railroad Commission eventually succeeded in shutting down production in 17 oil fields for excessive flaring.[25] These regulations were upheld by the Texas Supreme court in 1949, notably ruling that “the preservation and conservation of natural resources of the state are public rights and duties,” and “private enterprise would not need the compulsion of law to conserve these resources if the practice were financially profitable.”[26] Conservation of natural gas is a public right, regardless of how unprofitable it may be. This ruling seems largely overlooked by Texas producers and regulators today, but still serves as an important precedent and reminder for future policy makers and industry.

1.4. Drivers that maintain the status quo

Despite the numerous harmful effects of gas flaring, the practice continues to increase year after year. While there are many initiatives and regulations aimed at reducing flaring and venting, the various forces maintaining the status quo are currently more powerful. These range from technology and infrastructure challenges, to economically motivated policies and political maneuvering - all of which we will discuss in more detail in this report.

The increase in flaring in the United States in recent years is directly correlated to increased oil production in the Permian and Bakken basins. The introduction of fracking to these regions has caused a dramatic oil production boom, with which gas take-away infrastructure has been unable to keep up. Many producers cite increased flaring due to lack of access to natural gas pipelines or lack of processing and storage capacity. As was true in Texas in the 1930s, the market value of natural gas is significantly less than oil. Even where gas capture technology and infrastructure exists, it often costs oil producers more to capture, process, and transport associated gas than they would make from selling it. Companies also have limited incentive to build more infrastructure for the same reasons.

The low price of gas is contrasted by the high price of oil, the sale of which creates significant revenue for states and boosts local economies. New Mexico receives approximately $2.3 billion from the oil and gas industry each year,[27] making up over one fourth of the state’s total revenue.[28] This revenue is vital to education and social programs in New Mexico, which are consistently ranked last in the nation.[29] Similarly, Texas is the biggest oil and gas producer in the country and its economy is closely tied to oil prices.[30] These factors imply that lawmakers are hesitant to enforce flaring and venting regulations that may reduce production and lower revenue.

25 *Ibid.*
26 Railroad Commission v. Flour Bluff Oil Co., 219 S.W.2d 506 (Tex. Civ. App. 1949) error ref'd p. 508.
27 NM Finance fast facts FINANCE
28 State of New Mexico FY20 Budget in Brief
29 NM the worst place in America to be a kid, again
30 Texas economy still rises and falls with oil

For example, New Mexico has received praise for their ambitious carbon-neutral energy plans, but the emissions targets do not directly affect oil and gas exports and associated emissions.[31] In Texas, the former Chairman of the Texas Railroad Commission, Christi Craddick argued that increased flaring is "just what happens in a boom." She said flaring may be a shame and a waste of natural resources, but it's not an urgent enough reason for a regulatory crackdown.[32] Another Railroad Commissioner recently authored a report stating that any flaring regulations that slow oil production in Texas will result in *increased* flaring worldwide as other countries ramp up production and flaring to cover demand.[33] This may be a compelling argument, but it is impossible to verify based on the currently available data.

Additionally, inconsistent and unenforced reporting requirements also help maintain the status quo. Operators and oil companies can get away with wasting more gas, whether by intentionally under reporting or carelessly measuring amounts, and governments have either no or limited resources to verify data. Additionally, regulations surrounding amounts that companies are allowed to flare vary widely with apparently limited compliance.

Outside of the United States, research shows that severe political conflict is associated with an increase in gas flaring. In Venezuela over the last two years gas flaring has increased sharply while oil production has declined. This trend was also observed amidst previous conflicts in Syria and Yemen.[34] There are some driving factors that are far outside the influence of local policy and technology solutions to gas flaring, which means the areas we can address - such as accurate reporting, regulations, and technology innovation - are vital to long-term success.

31 New Mexico Aims To Be Fossil-Fuel Free By 2045, Despite Oil Boom
32 Report: Permian Basin oil producers flaring more natural gas than they told the state
33 Sitton Q1 Executive Summary
34 Increased Shale Oil Production and Political Conflict Contribute to Increase in Global Gas Flaring

2. Comprehensive Assessment of the Extent of the Problem

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The most important step to finding a successful, long-term solution to any problem is to develop a comprehensive understanding of it. We used several avenues of research to analyze the extent of gas flaring around the world, focusing primarily on the United States. Our most important finding is that while gas flaring is widely discussed and debated, there is limited agreement on either the extent or urgency of the problem across the industry, government, and nonprofit sectors.

Despite the many important research and policy initiatives, in many instances the information needed to design a solution is simply not there. For example, most reporting combines venting and flaring emissions as the amount of gas lost overall, although there are important environmental distinctions. Many technology and policy solutions focus on interventions for either venting or flaring practices, so the actual policy effect is difficult to predict. Further, the close relationship and interchangeability of flaring and venting practices implies that interventions to reduce one may effectively increase the other. For example, all gas flaring could be outlawed tomorrow, but all associated gas would simply be vented instead. A more likely scenario is the implementation of a technology to prevent fugitive emissions through leaks means that more gas must be processed, and may result in increased flaring. This would be an improvement for the environment, but would also result in a significant increase in reported flaring amounts.

For these reasons, we include an analysis of the many factors preventing an accurate and comprehensive assessment of the extent of the problem. With an understanding of these factors and how they interact, we can better provide policy and technology options to lay the foundation for a successful solution.

Note on Data Availability

One of the difficulties in determining the extent of the problem is the limited public availability of research and data. In most areas of research and consulting, raw data is often proprietary or confidential. To the extent that raw data is available, it often requires specific resources and skills to process and analyze, such as with the Visible Infrared Imaging Radiometer Suite (VIIRS) satellite data. For this project, we chose not to employ raw data analysis and focused instead on published reporting. However, there are several independent researchers and institutions that are working to collect data and estimate many important aspects of the flaring and venting problem, and new information is published often.

Finally, it is important to remember that all the data are wrong. At this point in time, there is no definitive information for the extent of gas flaring, either in the United States or worldwide. Every measurement tool and reporting method available has varying degrees of limitations and margins of error, many of which are not fully understood.

2.1. Measurement Tools and Practices

One of the major obstacles to determining the extent of flaring is that there are no systematic or timely measurement tools and practices. Gas flaring and venting amounts can be measured in many ways, all with varying degrees of accuracy. Each measurement tool has strengths and limitations, and specific types of measurement data collection are used by different stakeholders. Operators and regulations use on on-site metering or estimations, which is then relied on by government regulators. Nonprofit and academic researchers more often employ satellite data analysis and air quality monitoring to measure overall emissions on larger scales.

Operator Measurement Requirements

Most regulations require that all flared and vented gas be either measured or estimated, but provide few guidelines for methodology, accuracy, or enforcement. Additionally, company and operator level data are self-reported to various agencies, enabling the likelihood of human error and under-reporting. Outside of regulatory requirements or voluntary climate initiatives, operators have little incentive to accurately and consistently measure how much gas they are flaring or venting.

Operators may use a variety of on-site metering or estimation tools, but it is currently impossible to determine from the reported data which measurement methods operators use. For example, Texas regulation requires that oil and gas be measured by any "device or technology that conforms to standards established, as of the time of installation...for measuring oil or gas."[35] There are no specifications for accuracy or efficiency, and the likelihood of outdated technology is high considering wells can produce for decades and equipment is often reused. Common devices used on-site to measure gas are various types of flow meters, including coriolis, turbine, thermal, and volumetric flow meters. Overall, the accuracy of flow meters for reporting flared and vented amounts depends on their type and location in processing equipment. For example, a flow meter on a pipe leading to a flare stack will measure how much gas is flared, but not fugitive emissions or gas intentionally vented at another stage of processing. The accuracy and efficiency of different types of flow meters will be discussed further in Section 4.

[35] Texas Administrative Code 3.27

The Bureau of Land Management (BLM) requires vented and flared gas measurement through either Gas-to-Oil Ratio (GOR) estimations, measuring the volume of the flared gas (BLM wording does not include venting), *or* through a state regulation.[36] A GOR estimation is based on tests that determine the ratio of oil to gas, which is then compared to the volume of oil production and gas sales from a well to deduce the amount of gas unaccounted for. This method does not differentiate between flaring, venting, or fugitive emissions, and accuracy can vary.[37]

Environmental Protection Agency (EPA) regulations recommend the use of optical gas imaging (OGI) for leak detection, which has limitations. Controlled research experiments show that successful leak detection rates are lower than expected, and vary with multiple factors - including leak size, wind, the training level of the person measuring, and different field protocols.[38] These lower detection rates, combined with the fact that inspections are only required every six months (plus *no* BLM leak detection or reporting requirements), means there are significant emissions from leaks that are undetected and unreported.

Research and Satellite Measurement

The conclusion that methane emissions are underreported by operators is supported by recent publications studying methane leaks in Pennsylvania gas fields and the Permian Basin. Researchers analyzed hundreds of thousands of operator reports in Pennsylvania and found that including unreported fugitive emissions increases overall methane emissions by 15%.[39] Further, researchers from EDF and Harvard recently published an analysis of satellite data that shows methane leak emissions in the Permian basin from 2018-19 were 60% higher than the national average, significantly more than previous estimates.[40] In fact, for years studies comparing satellite data to reported data have overwhelmingly found that the satellite data suggests far greater amounts of flaring and venting than what is reported.[41]

It is important to note that satellite data also has limitations. Many satellite studiesflaring use data collected by the Visible Infrared Imaging Radiometer Suite (VIIRS) on a US National Oceanic and Air Administration satellite (NOAA). VIIRS collects global flare data every night, only sampling each flare site for a fraction of a second. This results in undersampling of small flares and any flares that are intermittent or unlit, which decreases the accuracy of flared gas estimations.[42] Additionally, VIIRS infrared imaging detects heat and light sources, which must be analyzed to separate flares from other fires and hot sources, and does not include measurements of methane gas that is not burned. These methane emissions can be analyzed using data from different satellites, such as GHGSat[43] or the Tropospheric Monitoring

36 https://www.regulations.gov/document?D=BLM-2018-0001-223600
37 Proposal - CGA p14
38 https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=346342
39 Explore Pennsylvania's oil and gas pollution
40 https://advances.sciencemag.org/content/6/17/eaaz5120/tab-pdf
41 Satellite data confirms Permian gas flaring is double what companies report and https://platform.mi.spglobal.com/web/client?auth=inherit&sf200858251=1#news/article?id=47199929&cdid=A-47199929-12062
42 Elvidge 2015
43 https://www.ghgsat.com/

Instrument (TROPOMI) used in the recent Permian methane study.[44] TROPOMI calculates methane concentrations through monthly atmospheric column measurements in specific areas with high spatial resolution. These tools are useful for determining overall venting and leaking emissions in a region over time, but do not measure flared amounts. Despite these limitations and the fact that one tool measures flaring while the others measure venting, each source of satellite data separately shows far greater emissions than the *combined* vented and flared self-reported amounts.

The challenge for policy makers is to bridge the gap between what is measured in real time and self-reported by operators and what is measured on large scales by satellites. No form of satellite measurement can definitively calculate individual operator-level data, although new technologies are constantly being researched and developed. For example, researchers from Los Alamos National Laboratory, Aeris Technologies, and Rice University are developing a technology called ALFa LDS - Autonomous, Low cost, Fast Leak Detection system.[45] ALFa LDS can be deployed on a drone and used to detect, locate, and quantify methane leaks across entire networks of gas production and consumption. It is significantly more sensitive, accurate, and cost-effective than current leak detection technologies, and could likely be implemented quickly at large scales.

2.2. US Federal and State Reporting

In addition to inconsistencies in measurement practices, there is no systematic reporting framework for flared gas. Unfortunately, regulations and requirements are often highly politicized for economic and environmental reasons and are subject to change between different administrations.[46] The following analysis pertains to regulations in effect as of the writing of this report. Additionally, this regulatory analysis is focused on reporting requirements and issues in the available data, a more thorough analysis of policies and regulations surrounding gas flaring is provided in Section 5.

Based on our analysis of reporting and measurement requirements, combined with independent data and anecdotal evidence, operator under-reporting - whether willful or not - is not a question of *if* it's happening, but by *how much*. Determining the amount of flaring and venting that goes unreported involves investigation into several key factors, including on-site measurement and estimation practices, intentional venting versus fugitive leaks, regulation loopholes and exceptions, intentional data manipulation, and possible prevailing practices from beliefs that associated gas is only waste. Further, many aspects of regulation leave room for interpretation, which leads to wide ranges of data reported from different operators for the same practices. For example, a recent analysis of self-reported production efficiency in New Mexico found rates of

44 https://advances.sciencemag.org/content/6/17/eaaz5120/tab-pdf
45 https://www.lanl.gov/discover/news-stories-archive/2019/July/0710-alfa-lds-technology.php
46 https://www.sciencedirect.com/science/article/abs/pii/S0301421519300461
and
The Texas Railroad Commission and the Elimination of the Flaring of Natural Gas, 1930-1949

methane waste range from *zero* waste to *100%* methane waste.[47] While different operators and wells undoubtedly have some varying degrees of waste, the most logical explanations for this range are vague regulations and inconsistent reporting.

US Federal Reporting and Regulations

On the federal level in the United States, the Department of the Interior's Bureau of Land Management (BLM) oversees gas flaring and venting on federal land through its methane waste rule entitled "Waste Prevention, Production Subject to Royalties, and Resource Conservation".[48] This rule provides guidelines for when gas may be flared or vented, including the provision that gas must be flared instead of vented where possible. The allowed exceptions for venting result in significant emissions that are likely avoidable. As of the 2018 revision of the rule, the BLM has no requirements for methane leak reporting, detection, or repair. As a result, aside from the EPA requirements discussed below, there is no direct limitation on gas that is emitted through leaks. In terms of Federal reporting of the amounts of gas vented or flared, the BLM requires that all volumes of "lost oil and gas, whether avoidably or unavoidably," be estimated or measured and reported to the Office of Natural Resources Revenue (ONRR).[49] As described above, the methods the rule allows for the estimation and measurement of lost gas leave the potential for holes in accuracy and efficiency.

The United States Energy Information Administration (EIA) publishes the total amounts of venting and flaring by year and state.[50] These data are supplied to the EIA by each state's own reporting agency, which summarizes it from the amounts reported by operators within the state. Therefore accuracy and completeness of the EIA data relies entirely on the self-reported amounts by operators, who are subject to varying regulations and limited enforcement. This multi-tiered system also allows for a high possibility of data analysis and transmission errors, and creates a significant delay from when flaring and venting occur and when data becomes available. Nonetheless, the data reported by the EIA is widely used as a baseline for researchers, policy makers, and journalists.

On the air quality protection side, flaring and venting emissions are federally monitored by the Environmental Protection Agency as part of the Greenhouse Gas Reporting Program.[51] All gas emissions from venting and flaring must be self-reported each year to the EPA, which then processes it and uploads it the following October, another significant delay.[52] In contrast to the BLM, the EPA does require that operators monitor for leaks and fugitive emissions twice a year, and that any identified leaks be fixed within 30 days.[53] Oil wells operate year-round, leaving ample time for leaks to go undetected between inspections.

47 NM methane draft report 2019, p 112
48 Methane and Waste Prevention Rule
49 https://www.regulations.gov/document?D=BLM-2018-0001-223600
50 https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_VGV_mmcf_a.htm
51 https://www.epa.gov/ghgreporting
52 https://ghgdata.epa.gov/ghgp/main.do?site_preference=normal#
53 40 CFR 60 Subpart OOOOa

It is also important to note that industry stakeholders used the existence of the EPA leak detection requirements to argue that the BLM rule was redundant and caused unnecessary burden. However, from the policy and research perspective there are important bureaucratic separations that make reliance on only rule insufficient. For example, the measurement units used are different between agencies - EPA data are measured in metric tons of CO_2 equivalent, while the BLM and EIA data are in cubic feet of gas. Converting data from volume-based units to mass-based units requires assumptions about gas composition and density, which varies between well location and time. Even if consistently accurate assumptions and conversions are made, EIA does not cite EPA emissions data as a source and we could not find evidence that EIA converts and incorporates the EPA leak emissions data into their reports on flaring and venting amounts.[54]

State Reporting

Each state in the US sets their own requirements for the reporting of flaring and venting practices.[55] Differences in regulations and reporting requirements between states result in varying data availability, compatibility, and wide margins of error from the almost unlimited potential for compounding factors. An important example of regulatory differences between states is the reporting requirements between Texas and New Mexico. These two neighboring states share the Permian basin, one of the biggest oil plays in the country, and many operators and pipelines cross state lines.

Texas

Texas reports the highest amount of flared gas (and oil production) compared to any state in the US, with over 238 bcf in 2018.[56] Oil and gas production in Texas, including flaring, is regulated by the Railroad Commission of Texas (RRC), which is made up of three elected commissioners serving staggered six year terms.[57] The fact that these regulators are elected state-wide, and that the Texas economy is very closely tied to oil is cause for concern. A study published by an independent non-profit found that 60% of campaign funding for RRC elections was supplied by the oil and gas industry.[58] The RRC regulations on venting and flaring are vague at best.

Rule §3.32 of the Texas Administrative Code requires operators to flare associated gas instead of venting it, but with several exceptions.[59] Gas may be vented if the release lasts less than 24 hours and is within ten days of the completion of the well. It may also be vented if a well must be “unloaded or cleaned up” as long as the release is not longer than 24 hours continusously or more than 72 hours in one month, but there are notably no volume restrictions. All of the released gas is required to be measured and reported, but fugitive emissions are always exempt

54 Table Definitions, Sources, and Explanatory Notes
55 DOE report
56 https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_VGV_mmcf_a.htm
57 https://www.rrc.state.tx.us/about-us/commissioners/
58 RIGGED: How the Texas Oil and Gas Industry Bankrolls its Own Regulators
59 Texas Administrative Code

from both. However, operators do not have to specify whether lost gas is vented or flared when they report it, so it is unclear how these provisions are enforced.

Assuming these regulations are monitored and enforced, the rule also allows operators to apply for “administrative exceptions” to continue venting or flaring. All exception requests cost $375,[60] and last for 180 days, unless the release is less than 50 mcf per day for each well. Requests for longer than six months and higher volumes must be through a final order signed by the commission. The RRC received 27,000 flaring exception requests between 2012 and July 2019, of which they approved *every single one*.[61] If every permit that the commission receives still gets approved, there is effectively no regulation on flaring or venting in Texas. It appears unlikely that the RRC will strengthen regulations or approve fewer permits - the Chairman has said that “this is just what happens in a boom.”[62]

New Mexico

The oil and gas industry is not as well established in New Mexico, but the introduction of tight oil extraction has led to a dramatic increase in production in recent years. Industry activity is regulated by the Oil Conservation Division (OCD) of the Energy, Minerals, and Natural Resource Department.[63] In contrast to the Texas RRC, which has regulated gas flaring since the 1930s, New Mexico has only started to address flaring and venting in recent years. In 2019 the governor issued an executive order for the state to develop a regulatory framework to reduce methane emissions from oil and gas production,[64] and OCD issued a public Request for Proposals to draft flaring and venting regulations that is still active as of April 2020.[65] Currently, New Mexico regulation allows operators unlimited venting and flaring within the first 60 days of well completion. Exceptions for flaring beyond 60 days are granted when a district supervisor determines flaring is “reasonably necessary to protect correlative rights, prevent waste or prevent undue hardships on the applicant.”[66]

In 2015, OCD began studying venting and flaring in New Mexico in order to reduce methane emissions and develop a gas capture plan. They issued a Notice to Operators to update required reporting to include separate codes for actual flaring and venting volumes, but no guidelines or methodology for measurement or reporting were provided to operators.[67]This led to a severe lack of compliance (only 8%) as highlighted in a subsequent Notice,[68] and it is still impossible to tell from the published data if this is being followed. The lack of guidelines leaves room for operators to interpret rules in different ways, such as including fugitive emissions and leak data

60 https://www.rrc.state.tx.us/media/8015/swr32datasht.pdf

61 Texas Showdown Flares Up Over Natural-Gas Waste

62 Report: Permian Basin oil producers flaring more natural gas than they told the state

63 http://www.emnrd.state.nm.us/OCD/

64 https://www.governor.state.nm.us/wp-content/uploads/2019/01/EO_2019-003.pdf

65 http://www.emnrd.state.nm.us/OCD/documents/RFPreNaturalGasVentingandFlaring.pdf

66 19.15.18 NMAC

67 10-19-15 Notice to operators http://www.emnrd.state.nm.us/OCD/documents/201510-19NoticetoOperators-Flaring_000.pdf

68 03-08-17 Notice to Operators

or only reporting intentionally vented amounts. There is also a high likelihood of operator error as OCD has a limited capacity to independently verify reporting data. Without a regulatory framework with checks and balances, there is little incentive for operators to ensure complete and accurate reporting. For these reasons, in a state-commissioned report on methane emissions, representatives from the oil and gas industry expressed their support for the development of a reporting system to include detailed guidance and establish consistency across New Mexico.[69]

Texas has detailed regulations which are vague and unenforced, while New Mexico has only limited regulations but is working hard to research and develop them. Operators are required to submit their data separately for each state, on specific forms that differ in format and requirements. Additionally, neither state regulates oil and gas industry emissions outside of the EPA requirements. It's unsurprising that data is under-reported in these states - it's almost a wonder that anything is reported at all.

2.3. Infrastructure, Operational, and Safety Factors

The extent of gas flaring is also influenced by infrastructure access, capacity, and operational standards. Many policies and interventions to reduce gas flaring are dependent on infrastructure, which is costly to build and maintain. It is important for policy makers to understand these limitations and where there is room for growth.

Infrastructure

An effective alternative to the venting and flaring of associated gas is to capture it for use or sale as a source of energy. There is a growing market for natural gas in the United States (described in Section 2), but transportation and processing require infrastructure.

Pipelines

Natural gas is costly to transport relative to liquid fuels. Associated natural gas that is not flared is primarily transported through gas pipelines, although new transportation technologies will be discussed in Section 4. The US has over 2.6 million miles of pipelines through which flows trillions of cubic feet of natural gas every year.[70] Ideally, new wells should be built to have direct access to pipelines, while new pipeline infrastructure is built to keep up with demand.

However, pipeline availability is not a sufficient condition to reduce flaring or venting. Pipeline infrastructure stretches over millions of miles and is buried deep underground, requiring complicated maintenance plans and leaving it vulnerable to gas leaks. Processing plants on the receiving end of a pipeline also vent and leak gas. Further, although Texas has a vast network of natural gas pipelines, the RRC has approved every one of the flaring permit applications it received in recent years. In at least one case, an operator was permitted to flare even though a

69 (p 156 of NM methane report)
70 https://www.phmsa.dot.gov/faqs/general-pipeline-faqs#QA_6

nearby pipeline was accessible and had available capacity.[71] In North Dakota, pipelines built during the Bakken production boom in the early 2010s did result in decreased reported flaring amounts, but production has overtaken pipeline capacity in the last few years.[72]

It is also important to note that pipeline construction is often opposed and prevented for many other environmental, social, and even religious reasons. In areas where construction is banned or too costly, flaring and venting will likely continue.

On-site Processing and Power Generation

Natural gas is a valuable resource for power generation and well sites require a lot of energy to drill and produce oil, so a logical solution to flaring associated gas is to capture and use it for on-site power generation. However the pumps, trucks, drilling rigs, and compressors used run on motors powered by diesel fuel and are incompatible with natural gas.[73] There are efforts to introduce electric and natural gas powered equipment, and the costs for a new well are estimated to be similar for new diesel equipment.[74] Unfortunately, for existing wells these upgrades can be prohibitively costly,[75] and there is little incentive when diesel equipment is properly functioning and there is no gas capture or processing method currently on-site. Aside from reduced flaring, there are secondary benefits to upgrading from diesel to natural gas equipment that should be taken into account. Diesel fuel is more expensive than natural gas, and it must be transported to well sites from refineries. By using locally produced natural gas, operators can eliminate both the costs and emissions associated with the transportation of diesel fuel.

Ideally natural gas power generation would allow operators to directly transfer gas from wells to a generator, but there are technical challenges that must be addressed.[76] The quality and composition of associated gas from tight oil wells varies across different locations and times. There is a higher composition of natural gas liquids in addition to methane, which are usually processed and sold separately. Associated gas must either be processed on site, or technologies must be developed or interchanged to adapt to varying gas compositions.

Operation

As described above, fugitive emissions from leaks in equipment and pipes are an unreported and often unmeasured component of vented associated gas. Although the term *leak* often implies an insignificant amount, Chevron estimates that fugitive emissions account for as much as one-third of their total methane emissions.[77] The EPA found that fugitive emissions are more closely

71 https://www.wsj.com/articles/texas-showdown-flares-up-over-natural-gas-waste-11563361201
72 https://www.eia.gov/todayinenergy/detail.php?id=42195
73 Fuel - Permian Drilling Activity Drives Diesel Demand and Projects to Supply More of It
74 https://rbnenergy.com/shes-electric-are-e-fracs-a-fix-for-permian-gas-constraints-and-giveaway-prices
75 https://rbnenergy.com/you-re-as-cold-as-ice-the-economics-of-switching-from-diesel-to-lng
76 Improving utilization of associated gas in US tight oil fields
77 https://www.chevron.com/sustainability/environment/greenhouse-gas-management

correlated with the amount of equipment rather than with production, so it is likely that these emissions amounts are consistent among small producers and low-production wells.[78]

The EPA requires operators to check for leaks semi-annually, which means that leaks may remain undetected for months at a time. There are a number of on-site solutions that operators can adopt to detect leaks more quickly and accurately, such as using real-time electrochemical sensors. The Department of Energy's ARPA-E has created the MONITOR program (Methane Observation Networks with Innovative Technology to Obtain Reductions) to support innovative research into comprehensive and timely leak detection systems.[79] In addition to safety and environmental benefits, real-time leak detection can have a significant return on investment by increasing the amount of gas that can be captured and sold downstream.

Another important operational factor that contributes to high methane emissions is flare efficiency, including flares that are unlit or go out. A recent EDF survey of over 300 well sites in the Permian basin found that 1 in 10 flares were unlit or malfunctioning, causing the gas to be directly released into the atmosphere.[80] The combustion efficiency of a flare is the percentage of methane successfully converted to carbon dioxide, and is an important indicator for accurate emissions measurement. Efficiency is generally assumed to be high in the industry (98%), but research shows that a significant portion of flares are actually very inefficient.[81] Both of these issues contribute to the underestimation and under-reporting of emissions from flaring. Ensuring that flares remain lit and highly efficient can be addressed through maintenance and monitoring requirements, as well as with improved efficiency technologies (discussed further in Section 4).

Safety

In certain circumstances, gas flaring is necessary to ensure the safety of operating personnel and surrounding communities. For example, gas must be safely diverted and disposed of during drilling, testing, and well completion, which occurs before pipelines or processing infrastructure are connected. Although most regulations currently allow unlimited flaring from drilling and completion, there are efforts to reduce these emissions through reduced emission completions or "green completions" using portable processing equipment at the well site.[82] Gas must also be released to relieve pressure during maintenance and in an emergency, such as equipment failure or a power outage.[83]The current form of reported data makes it impossible to differentiate how much flaring is for safety or waste disposal. Improving specialized reporting requirements is necessary to understand the extent of flaring for safety, as well as for research into enhanced safety practices.

78 Federal Register/Vol. 81, No. 107/Friday, June 3, 2016/Rules and Regulations

79 https://arpa-e.energy.gov/sites/default/files/documents/files/MONITOR_ProgramOverview.pdf

80 When the flames go out, the Permian's methane problem worsens

81 Greenhouse Gas Footprint of Oilfield Flares Accounting for Realistic Flare Gas Composition and Distribution of Flare Efficiencies

82 Reduced Emissions Completions for Hydraulically Fractured Natural Gas Wells

83 Natural Gas Flaring and Venting: State and Federal Regulatory Overview, Trends, and Impacts

Flaring may also be necessary if the associated gas contains significant amounts of hydrogen sulfide (H_2S), which is extremely toxic and can be corrosive to oil field equipment and pipes. Researchers have found high amounts of H_2S in the associated gas in the Permian basin that appear to be increasing.[84] Due to its toxicity, associated gas with high H_2S often cannot be safely transported, and on-site processing requires specialized equipment. This increases the cost of any gas capture solutions, and many operators are motivated to flare the gas as the safest and most economic option. Further, the discovery of high H_2S concentrations in areas where drilling infrastructure was not properly developed to handle it safely may require costly equipment upgrades and retrofitting. Flaring the gas allows operators to avoid excessive capital costs and perceived value destruction resulting from their lack of appropriate preparation.[85]

These factors strongly imply that high H_2S concentration is an unattributed reason for increased flaring in the Permian basin. In addition to the toxicity concerns from sour gas, the burning of H_2S produces sulfur dioxide (SO_2). The Clean Air Act strongly regulates SO_2 emissions, due to significant environmental effects that are not traditionally associated with methane flaring, such as acid rain. Considering the high number of unlit Permian flares and efficiency concerns mentioned above, there is an urgent need for further investigation and specialized policy and technology solutions.

2.4. Independent, Non-profit, and International Efforts

In addition to state and federal regulations, there are a number of international and non-profit efforts to measure and reduce methane emissions and gas flaring. Many oil and gas companies are members of these initiatives and pledge to reduce their routine flaring practices, but actual compliance is voluntary and difficult to assess.

European Union

The European Commission has been making strides towards establishing an independent institution to monitor and improve emissions, as discussed in their March 2020 methane stakeholder workshop.[86] The goal of the institution is to develop a holistic approach to control methane emissions throughout the oil and gas supply chain, including venting and flaring initiatives. The image below represents how the institution will focus on many areas including monitoring and detection, accurate reporting, verification, and transparency - all or many of which are lacking from current regulations around the world.

84 Hydrogen Sulfide (H2S) in the Permian Basin, #10950 (2017).
85 Personal communication with expert, May 4, 2020.
86 Workshop: Strategic plan to reduce methane emissions in the energy sector

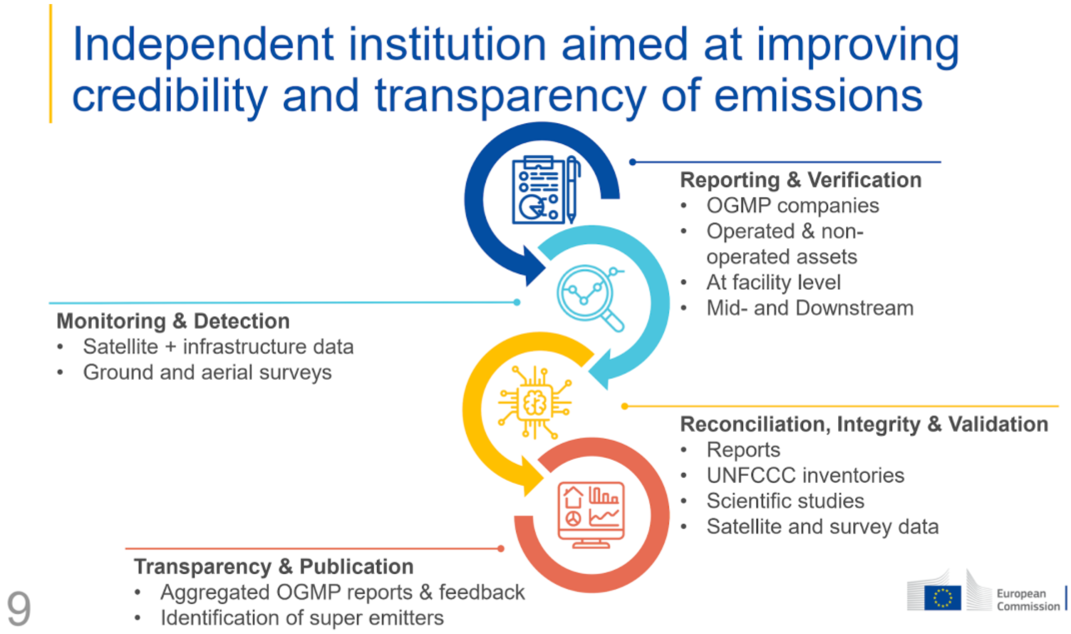

Table 2.1 EMAS from European Commission

EMAS
The European Commission has a voluntary environmental management instrument called the Eco-Management and Audit Scheme (EMAS).[87] EMAS helps companies and organizations improve their environmental performance by providing support for measurement, reporting, and best practices. It is used by many different types of organizations and not focused on flaring or the oil and gas industry, but it is an important example of how an independent agency can help align environmental regulation with private industry practices.[88]

Initiatives and Partnerships

World Bank Initiatives
The World bank has two initiatives that are aimed at reducing gas flaring around the world, the Global Gas Flaring Reduction Partnership (GGFR)[89] and Zero Routine Flaring by 2030.[90] The latter initiative has been endorsed by many governments and companies around the world, including the US, but it is not legally binding nor does it include an enforcement mechanism beyond establishing a public commitment. It is only focused on self-reporting of routine flaring, which is not clearly defined, and it does not require reduction of fugitive emissions or flaring and venting for safety and maintenance. The GGFR is a public-private initiative that works to reduce

87 https://ec.europa.eu/environment/emas/index_en.htm
88 GOOD REASONS FOR EMAS
89 https://www.worldbank.org/en/programs/gasflaringreduction
90 https://www.worldbank.org/en/programs/zero-routine-flaring-by-2030#1

flaring by researching best practices and developing technology and country-specific regulatory solutions. The US is not a member of the GGFR partnership.

Methane Guiding Principles
The Methane Guiding Principles are five principles developed by an international partnership of industry and non-industry stakeholders that are focused on reducing methane emissions throughout the natural gas supply chain.[91] The five principles also advocate for reporting transparency, measurement data accuracy, and sound policy. They are focused on the entire natural gas supply chain, including flaring, and adoption and participation is voluntary.

Oil & Gas Methane Partnership
The Oil and Gas Methane Partnership is an initiative created in 2015 by the Climate and Clean Air Coalition in order to help oil and gas companies reduce methane emissions.[92] The partnership comprises ten oil and gas companies, the Environmental Defense Fund, the United Nations Environment Programme, and the European Commission. This initiative includes a reporting framework that enables participating companies to show improvements in methane emissions, through transparency and progress towards set targets. The initiative's framework has been the primary input into proposed European Union regulations.

IPIECA
Originally the International Petroleum Industry Environmental Conservation Association, IPIECA is a global association of oil and gas companies that is focused on improving environmental and social performance within the industry.[93] It provides the industry's main channel of communication with the United Nations. IPIECA work includes promoting transparency in reporting and emissions management, as well as supporting the Methane Guiding Principles and the Zero Routine Flaring by 2030 initiative.

The Environmental Partnership
This is a US-based partnership of oil and gas companies led by the American Petroleum Institute (API) with the goal of producing energy while improving the industry's environmental performance.[94] This partnership is also more industry driven, focusing on solutions that are technologically and commercially feasible and will result in the most emissions reductions. Company participation is voluntary and involves education workshops, collaborations, and action-oriented programs - including a leak detection and repair program.

Note on Large Operators

91 https://methaneguidingprinciples.org/
92 https://www.ccacoalition.org/en/activity/ccac-oil-gas-methane-partnership
93 https://www.ipieca.org/about-us/
94 https://theenvironmentalpartnership.org/who-we-are/

Finally, many of the largest oil producers often make promises to reduce methane emissions and focus on achieving climate goals,[95] but are accused of failing to follow through - a practice called "greenwashing." Major oil companies, such as BP, Exxon Mobil, and Shell are important supporters of many of the above initiatives, but data suggests some have actually increased flaring in recent years. According to *New York Times*[96] and *Unearthed*[97] investigative reports from October 2019, Exxon and BP both significantly increased the amount of gas they vented and flared in the US - both by as much as 70% since 2017 reports. BP flared significantly more in recent years by acquiring polluters in the Permian and allowing venting and flaring to increase. Aside from energy companies, independent petroleum producers that drill specifically for oil are also flaring at higher percentages, with Marathon Oil flaring more than half the associated gas produced at their Bakken wells in 2017 and continuing to increase.[98] An important exception to this trend is Chevron, which reportedly flared or vented less than three percent of associated gas by following strict internal rules around drilling in areas where gas can be economically captured.[99]

These numbers show that more than a voluntary environmental pledge is required for companies to significantly reform venting and flaring practices. Policy solutions and voluntary initiatives need to include requirements for transparency in both reporting and practices, as well as secondary verification and enforcement mechanisms.

95 announces progress towards methane target and new CCUS initiative to scale up actions towards climate goals - OGCI

96 Despite Their Promises, Giant Energy Companies Burn Away Vast Amounts of Natural Gas

97 Exxon and BP among worst for flaring in US oil fields despite green pledges

98 Ibid

99 Ibid

3. Oil and Natural Gas Market Dynamics

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3.2 Natural Gas Supply and Demand 32
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3.4 Costs of Gas Flaring Solutions 35
3.5 The Rise of ESG Integration as a Potential Strategy 36

This section delineates the structural economics of associated gas as a byproduct of oil production. The flaring issue originates with oil production. Oil prices influenced by dynamics of supply and demand worldwide play a prominent role, whereas the economics of natural gas has a more regional focus. Those dynamics will not only impact the status quo of gas flaring, but also provide implication of the future trend on flaring emissions.

3.1. Crude Oil Supply and Demand in the US

This section describes the oil demand and supply through analyzing market dynamics from the perspectives of short term shocks and long term forecasts.

Recent Oil Market Black Swan Events

COVID-19

There is an unprecedented decline in crude oil demand as a result of the COVID-19 pandemic. The United States as the largest crude oil producer in the world, is going to face the demand shock until the pandemic is terminated. There are several predictions made to speculate the duration of this pandemic, but no one can guarantee it until the day finally comes. Not only the impact of the pace of lockdown easing is unclear, but also there is a significant uncertainty amid a highly volatile market regarding the resumption of economic activities. However, one of the consequences that can be predicted is an unprecedented drop in global oil demand. As the impact of COVID-19 spreads around the world, oil demand contraction is expected. The travel ban imposed in many countries, the lockdown of hundreds of cities and areas, the disruption in the global supply chain all have a tremendous impact on oil demand. In response to the demand shock, the supply is likely to fall as limited storage is not a solution to the surplus. The trend of imbalances between supply and demand has already occurred in the market. Production must be cut as the oil supply is likely to exceed both demand and the capacity of storage. IHS Markit estimates that the shut in of world oil production will be 10 MMbpd from April to June 2020.[100] For the United States, the amount shale oil production reacts to a combination of the price change and demand shock. EIA forecasts the production will average 13 MMbpd in 2020 and

100 IHS Markit sees forced oil production cuts of 10MMbpd ahead

drop to 12.7 MMbpd in 2021.[101] The Bakken and Eagle Ford regions will contribute to the production declines as well as the Permian Basin is expected to have a flat growth. Consequently, the output of associated gas produced as a byproduct of wells drilled for the oil will likely to decrease along with the production cut. The impact of COVID-19 on the oil and gas market as well as the prices will be further discussed in the following section.

Saudi-Russia Oil Price War

Oil prices collapsed earlier this year as the forecast of oil demand went down sharply due to a pause of economic activity and restrictions on travel all over the world. In March, while OPEC+ countries led by Saudi Arabia voted in favor of a production cut of 1.5 MMbpd in response to the pandemic, Russia held off the decision and wanted to wait to evaluate the impacts of the demand collapse.[102] Unable to reach a consensus, oil prices slipped at an unprecedented rate, to the lowest prices since 2003. The disintegration of the OPEC+ alliance turns the oil market into free market mode. Although there were negotiations among major oil producers to cut production facing the demand crises, the amount they reached in agreement was inadequate to deal with storage capacity issues. There is a growing scarcity of oil storage space and will create a challenge for oil producers if they do not curb the production.[103] Even if they reach the consensus, oil producers will likely continue to extract oil as long as prices are above lifting costs. Oil surplus already occurs as a result of the supply surge and demand decline. The disruption brought by COVID-19 shifts the balance even further. Without production cuts, oil storage is less likely to solve the problem in the long run. The oil business is on track to change with the pandemic accelerating the pace. The boom of shale business enabled the United States to capture a larger market share from the OPEC+. The U.S shale business used to be very robust and competitive on the world stage because oil is still a commodity that is irreplaceable in the next few decades as it dominates in transportation fuel. However, the problem with oil storage creates uncertainty in the market as storage is filling up worldwide and American onshore tanks are nearly reaching their capacity.

On April 12th, Saudi Arabia and Russia finalized the deal by agreeing to make the biggest oil production cuts on record, 9.7 MMbpd, which is approximately 10% of global output.[104] The cut will start from May and continues with additional reductions until expiring in April 2022. Behind the deal was the efforts made by the United States and President Trump in order to stabilize oil prices and take a further step to influence the market. However, the cut falls far short of the demand destruction, which leads to an immediate price drop on the same day, $23 a barrel of West Texas Intermediate. With the plummeting prices, many American companies already have cut the output. Indeed, they reduced production in response to the demand destruction amid the COVID-19 pandemic outbreak. As a result, some small and indebted firms may have to suffer

101 Short-Term Energy Outlook - US Energy Information Administration

102 OIL MARKET BLACK SWANS: COVID-19, THE MARKET-SHARE WAR, AND LONG-TERM RISKS OF OIL VOLATILITY

103 Weekly US and regional crude oil stocks and working storage capacity - US Energy Information Administration

104 Opec secures record global oil cuts deal under US pressure

bankruptcies and yet there are merge and acquisition possibilities for bigger players in the energy industry.[105] This will lead to a consolidation of the oil and gas industry in the United States.

Long Term Forecasts

The Future of US Markets

The supply and demand will continue to be imbalanced as well as the impacts of both events will not disappear when the pandemic is over. Oil supply in the United States is sensitive to oil prices. The collapse of oil prices will cause a decline in oil production, lessening the output of associated gas. In the United States, oil suppliers reply on ample amounts of up-front capital investment. Private equity and private credit are the major players in funding oil companies, who are also considering broader ESG concerns. Thus, in order to respond to the investors' sentiment, oil companies have to carefully create a healthy balance sheet with positive return, meanwhile taking the flaring issue seriously. The surge of gas is flared as a result of the unrelenting growth of the extraction of crude oil. It is often cheaper to flare the gas than building pipeline infrastructure to transport gas to markets. Therefore, companies tend to flare the gas for economic and technical reasons.

In the United States, the oil and gas industry operates like a cyclical business. After the pandemic ends, the demand will bounce back to the previous level as the economy recovers. Looking into the future, it is more likely for the public market to provide capital as needed. Once the initial up-front capital is invested, costs for operation are relatively low, yet costs for shut in can be relatively high based on the research done by the Federal Reserve Bank of Dallas (table 3.1) As the demand recovers after the pandemic is over, the growth of the oil and gas industry will become more capitalized. The growth of oil production will continue contributing to the flaring gas issue.

In spite of the recent market turbulence, experts in the industry have a cautiously optimistic attitude towards the long-run regarding U.S shale oil production.[106] General growth in consumption for oil and gas is expected due to population growth and increased GDP, which will encourage energy use in all sectors.[107] However, possible commitments to mitigate climate change, such as renewable energy incentives and emissions regulations, might lead to more uncertainties in demand for oil.

105 Oil Nations, Prodded by Trump, Reach Deal to Slash Production
106 IEA (2019), *World Energy Outlook 2019*, OECD Publishing, Paris, https://doi-org.ezproxy.cul.columbia.edu/10.1787/caf32f3b-en. Figure 3.2
107 See the infographic: A race against the carbon clock

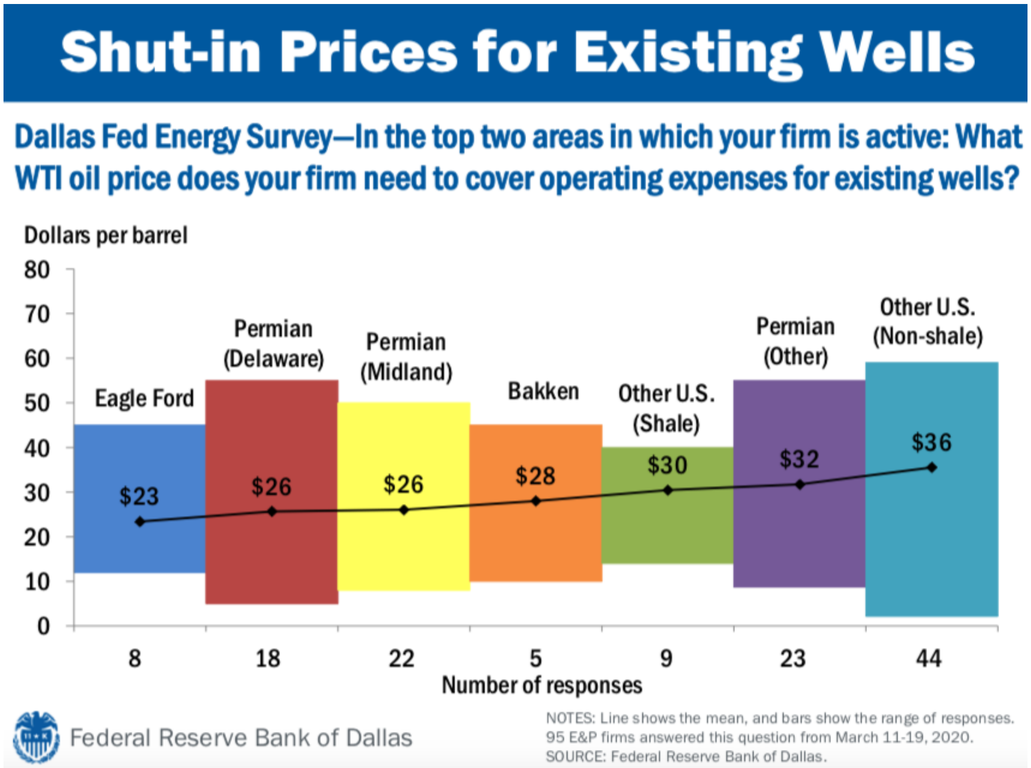

Table 3.1 Shut-in Prices for Existing Wells from Federal Reserve Bank of Dallas

Global Oil Prices

Oil is a global commodity so its price depends on world wide supply and demand. The main factors that affect oil prices are US shale oil production, US crude oil stocks, and OPEC oil supply. The US Energy Information Administration (EIA) forecasts that by 2025, the average price of a barrel of Brent crude oil will rise to $81.73/b. This figure is in 2018 dollars, which does not account for inflation.[108] Further, by 2030 world demand will drive oil prices to $92.98/b, and by 2040, prices are estimated to be $105.16/b, again quoted in 2018 dollars. At this point in 2040, cheap oil sources will have been exhausted, and it will be more expensive to extract oil. By 2050, oil prices will be $107.94/b. These projections are lower than EIA's previous price estimates from 2017, reflecting the stability of the shale oil market. EIA assumes that the global demand for petroleum flattens out after its peak in the next one or two decades as energy utilities in the future will rely more on natural gas and renewable energy.[109] From an economic standpoint, EIA assumes that the economy will grow around 2% per year while energy consumption will increase by 0.4%, which will drive up the price of oil as demand increases. The projected increase in oil price will incentivize shale oil producers to drill for more oil, which may in turn increase flaring emissions. However, in the short run, the crash of U.S. oil prices into negative territory in April will lead to a decline in oil production in 2020. This will imply a reduction in flaring emissions this year and next year as oil suppliers plan to curtail production to offset demand collapse amid COVID-19.

108 https://www.thebalance.com/oil-price-forecast-3306219#citation-35
109 Renewable Energy: Definition, Sources, Benefits, Future

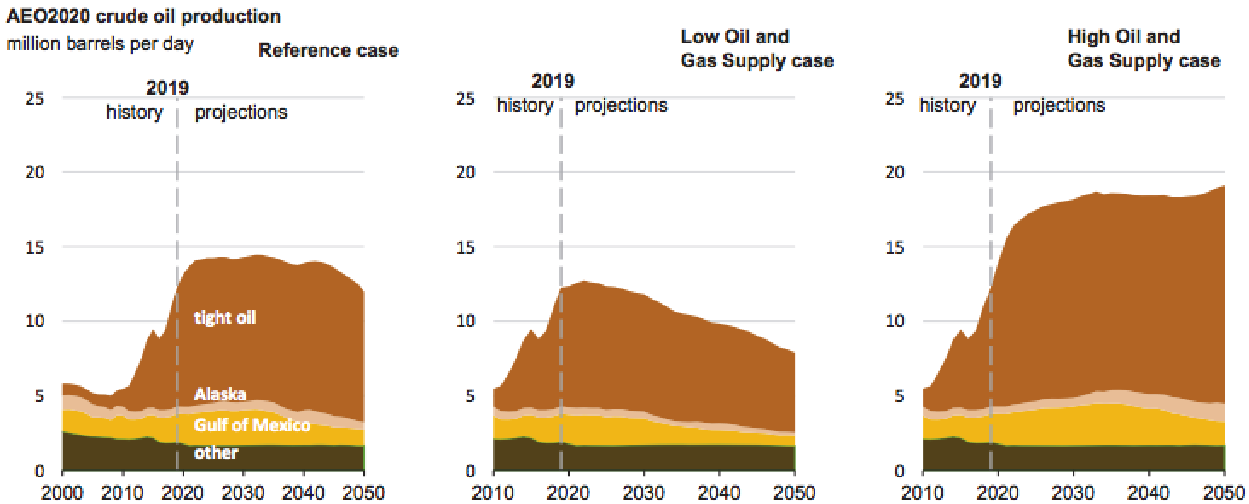

Table 3.2 2020 Crude Oil Production Forecast from US Energy Information Administration[110]

US Natural Gas Prices

Natural gas is consumed more on a regional level than oil, and its price makes a smaller impact on the supply and demand because gas is an inelastic product. The low price of coal makes it a competitor with gas in some countries, but rising environmental concerns hinder the use of coal. In terms of power generation, gas is less polluting than coal as a resource. The International Energy Association (IEA) forecasts on natural gas spot prices of the stated policies scenario at Henry Hub will be $3.3MMBtu in 2030 and rises to $4.4 MMBtu in 2040.[111] The increase of natural price gas may incentivize oil producers to sell the gas instead of flaring it, but the huge discrepancy between the profits of producing oil and gas will likely continue to hinder flaring reduction goals. Depressed US gas prices as well as the long distance to reach key markets that require infrastructure create a huge challenge for oil companies that have to take responsibility to the investors. Hence, technology and policy solutions are needed to encourage the reduction of harmful gas flaring.

3.1. Natural Gas Supply and Demand

Due to oversupply, the price of natural gas is not attractive compared to the profitable oil business. Oil companies have low incentives to sell gas that comes out with oil production due to the high cost of infrastructure. Thus, the flaring issue becomes more serious as oil production increases.

110 AEO2020 - Petroleum

111 IEA (2019), *World Energy Outlook 2019*, OECD Publishing, Paris, https://doi-org.ezproxy.cul.columbia.edu/10.1787/caf32f3b-en.

The oversupply of natural gas market

Natural gas is the biggest source for generating electricity in the United States, accounting for 44%.[112] Therefore, power generation determines price elasticity for gas demand. The boom of power generation from renewable energy sources is due to a more competitive price compared to natural gas power plants. Furthermore, subsidies from the government become another incentive for electricity producers to make a transition from natural gas to renewable energy resources. For example, investment tax credit, production tax credit, and state-level policies all encourage renewable energies. Along with ESG concerns, sustainable energy will be the key in the future. The oversupply of natural gas becomes an issue.

While oil price determines its production, it is a totally different situation for gas. Because oil is more valuable than gas, oil drillers are insensitive to low gas prices, and spontaneously incentivized to produce oil. Natural gas industry faces an oversupply issue which explains why the price of gas is so low. The demand for natural gas depends on weather, economy and petroleum prices. The warm weather leads to a decrease in consumption of gas, causing the price to be even lower. Demand for both power generation and building consumption in residential and commercial sectors fall due to a relatively higher temperature compared to the year before and the economy shows a sign of fatigue amid COVID-19 pandemic. The lower price discourages producers to drill natural gas.

On the supply side, the EIA forecasts that U.S. natural gas production is expected to decrease by 5% in 2020 by cause of the recent fall in consumption in response to COVID-19.[113] Natural gas production in the United States set records in 2018 and 2019 is mainly attributed to the boom of shale and tight oil production. Thus, the prices of natural gas dropped and the volume of gas in storage increased. The production of associated gas from oil wells is expected to decrease because drilling levels of oil will decline. Producers plan to curtail capital spending and production as both prices of oil and natural gas decreased In March and April.

Flaring

Oil production and prices play a more pivotal role than the price of gas in terms of solving the flaring issue. Flaring occurs during upstream production, which dominates with 90.6% of all flaring.[114] The primary reason for the abundance of flaring associated gas is the lack of pipeline capacity to ship gas to markets. Oil producers seek to mitigate the constraints of gas takeaway capacity through building more pipeline infrastructure.[115] They also have the options to delay the completion of new wells or slow down production rate to hold up oil-centric operations. Flaring in the Permian declined to 700 million cubic feet of natural gas per day during the first quarter of 2020, down from a peak of nearly 900 million cubic feet per day in the fourth quarter of 2019.[116]

112 National Energy and Petrochemical Map

113 https://www.eia.gov/todayinenergy/detail.php?id=43755

114 https://www.sciencedirect.com/science/article/pii/S2211467X17300962

115 Natural Gas Flaring and Venting: State and Federal Regulatory Overview, Trends, and Impacts

116 https://texasenergyreport.com/newsclips-2/

The reduced output from oil-directed wells under the influence of two black swan events curb the output of associated gas flaring consequently.

3.2. Breakeven Prices for Oil and Gas Companies

Breakeven price

The breakeven cost of production is the average natural gas price at which a producer would need to sell its production to neither lose money nor make a profit.[117] The characteristics of production basins determine the breakeven cost. It is possible to have a negative price depending on the wells because natural gas is produced as a byproduct of oil drilling. Two notable examples are Permian Basin and Eagle Ford. There is a difference in the breakeven cost of wet and dry gas. Wet gas contains a significant amount of natural gas liquids. For example, the breakeven price for the Marcellus Wet well is $1.77/MMBtu, while a dry well has the price of $2.43.[118] Producers of wet gas have economic advantages when encountering a low gas price compared to their counterpart of dry gas. Nevertheless, the number of wet gas wells is not enough to meet the demand for natural gas. Dry wells are the key players to set market price based on the marginal cost. Low gas prices disincentivize oil producers to bear the costs of building pipelines and sell the gas they produce when drilling the oil. For them, it is commercially viable to flare gas rather than collect and sell it.

Breakeven price for oil

The price of oil needed to profitably drill a new well varies depending on the region. The chart below shows a research done by the Federal Reserve Bank of Dallas to study the different breakeven prices for drilling new wells. The cost to produce shale oil in the United States is much more expensive compared to that of OPEC+ countries, which means American oil producers are more vulnerable to price shocks. On the other hand, OPEC countries, especially Saudi Arabia have advantages of cost of production, but they have a limited tolerance of low oil prices as most of their countries' GDP and revenue rely on oil. For individual American oil producers, they will suffer from low prices and prices have a direct impact on determining future production. Below is a chart of breakeven prices for new wells according to the survey conducted by the Federal Reserve Bank of Dallas.[119] Oil prices will have to be higher than the breakeven prices in order for producers to make profits, especially for drilling new wells. The number of new wells is critical to the amount of increasing flaring emissions because the number of gas pipelines is not enough for both new wells and existing wells. If new wells continue to grow at a rate faster than pipeline infrastructure, the flaring rate is likely to increase.

Nevertheless, with the oil price collapse, the shut in of oil production is possible to happen for smaller companies that are threatened to lower prices and if they are not making profits. Some companies may leave the business because the low oil price is no longer profitable to them. Yet,

117 Are Natural Gas Prices Below $3 Sustainable?
118 *Ibid* Are Natural Gas Prices Below $3 Sustainable?
119 Energy Slideshow - Dallas Fed

if OPEC+ countries all agree to reduce the rate of production, the price will likely be driven up eventually.

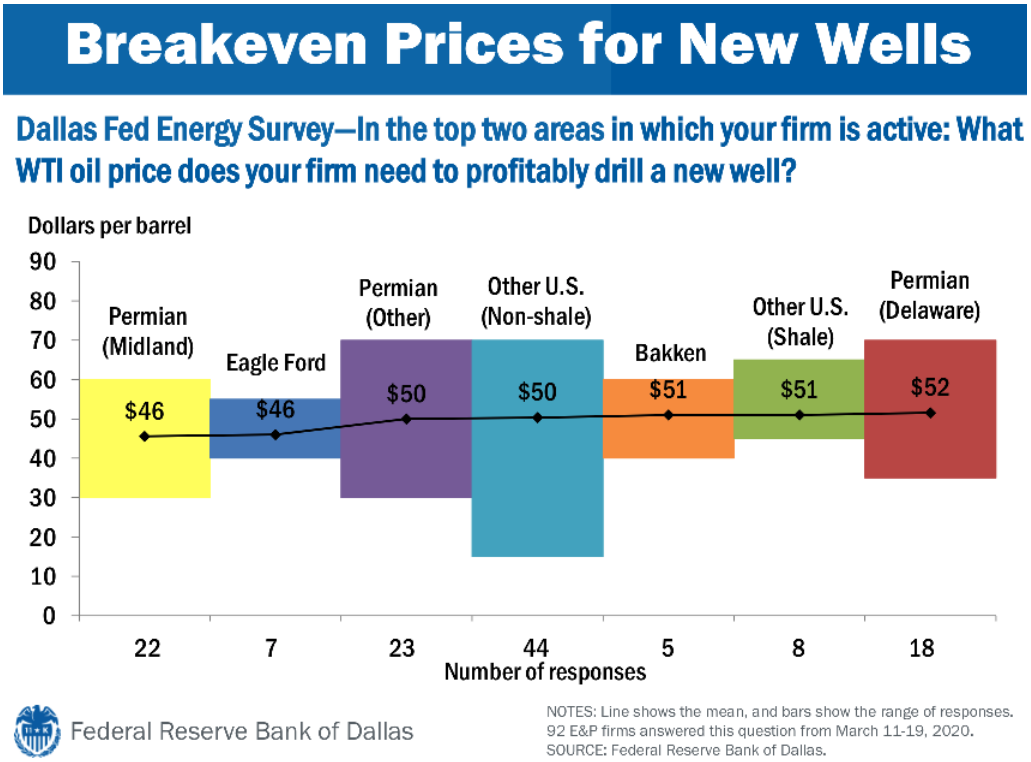

Table 3.3 Breakeven Prices for New Wells from Federal Reserve Bank of Dallas

3.3. Costs of Gas Flaring Solutions

In order to solve the gas flaring issue, significant capital investment will be required. Building more pipelines and reinjecting the gas are two ways that are helpful, but are not necessarily commercially viable solutions. This section describes the obstacles of the two solutions from an economic perspective. The following sections will present technology and policy solutions that are more feasible to reduce harmful gas flaring for industry leaders and policy makers to consider. The challenges of building more pipeline infrastructure to collect, transport, and sell gas are mainly economical. Gas reinjection also has bottlenecks when it comes to the returns of oil production.

Building more pipelines

Building more pipelines will reduce pressure on flaring gas, but it can be costly. In order to calculate the cost, the distance of the pipeline has to be multiplied by the diameter of the pipe. Costs per mile increases with the pipe size. Average diameter of an interstate pipeline is between 24 inches and 36 inches, or an average of 30 inches.[120] A large diameter pipeline costs around 90,000 USD/inch-mile for 30 to 36 inches. Indeed, the infrastructure may take several months to one year before approval is given and construction finished.[121]There are several costs to be considered for pipeline infrastructure. The construction and operating costs of natural gas pipelines and the costs of gathering, transmission, and distribution pipelines all contribute to the balance sheet.[122] Also, the cost increases if the pipeline goes through residential areas, roads, or highways, meaning costs are largely dependent on location, terrain, and population density.[123]

For example, the recent Permian Highway Pipeline is projected to cost about $2 billion, but completion of the project is constrained by considerable uncertainty. The project may be postponed due to recent developments in the volatile market environment, legal battles with regulators, and the security of dividend returns. Companies are responding to this market and investment uncertainty by reducing capital investments and cutting costs.[124] The first big gas pipeline to enter service in the Permian in recent years was Kinder Morgan's $1.75 billion Gulf Coast Express in September 2019. This project provided the region with much needed takeaway capacity to the Gulf Coast. Because Gulf Coast Express was already filled to its 2.0-bcfd capacity, the market will have to wait until early 2021 for a relief. Consequently, Kinder Morgan expects to put the 2.1 bcfd Permian Highway gas pipe into service.[125]

Reinjection of gas

Shale enhanced oil recovery delivery through gas reinjection technique works well, yet the industry faces bottlenecks on returns in the short term. By drilling new wells, companies are safe to get returns in the first year. This gas reinjection technique may take up to two year to make full returns due to the cost to fill up the depleted wells with gas after the first injection cycle.[126] The scarcity of gas compressors contributes to the reluctance of using this method for companies. Therefore, in consideration of the long-term vision, oil producers need to redistribute time and resources to the effort. This explains why the reinjection alternative is not deployed on scale by many companies from a profitability standpoint.

3.4. The Rise of ESG Integration as a Potential Strategy

The rise of ESG integration can serve as a financial incentive to encourage companies to address flaring issues. Investors have been incorporating ESG metrics into investment policies for the past few decades, and they have indeed valued the sustainability impact of an investment in recent years with a particular focus on climate change. Given the catastrophic consequences COVID-19 pandemic has caused, investors will have to put greater focus on ESG metrics to

120 What Does Natural Gas Pipeline Construction Cost per Mile
121 Improving utilization of associated gas in US tight oil fields - p9
122 https://docs.house.gov/meetings/IF/IF03/20200205/110468/HHRG-116-IF03-20200205-SD006.pdf p26
123 Natural Gas Value Chain: Pipeline Transportation
124 Phillips 66: Red Oak, Liberty, ACE Pipelines Deferred by Cost Cuts
125 Kinder Morgan Uncertain About Permian Pass Pipeline
126 Shale EOR Delivers, So Why Won’t the Sector Go Big?

mitigate risks. Industry itself also seeks green transition with ESG integration responding to the demand.

Investors' sentiment

In recent years, the concept of Environmental, Social, and Governance (ESG) has gained popularity within the energy industry for a variety of reasons. According to the World Bank, "ESG investing incorporates environmental, social, and governance issues into the analysis, selection and management of investments".[127] ESG is yet to be defined by any official regulatory agencies, and different industries and companies have their own approach to ESG. ESG framework covers a wide range of issues from environmental, social and governance perspectives, such as climate change, diversity, and management structure. There is growing evidence showing these nonfinancial factors have an impact on the business, which can reduce volatility and have better returns for investors in the long run.[128] Although some have made progress to incorporate more ESG metrics, more need to be done in order to further reduce flaring.

Evolving needs from investors' side leads to a green transition in the energy sector for many oil and gas companies. Those ESG-conscious investors motivate companies to begin making a change in their business model towards sustainability. For example, Kimmeridge, a private equity firm with a focus on oil and gas assets, published a report calling for a change of business model in the exploration and production sector. The whole industry is facing a capital flee with lower investment rate. Despite the fact that a lower investment rate will cause a lower production and in turn a lower rate of flaring, this is not a solution for the development of the industry in the long term. Along with other changes in social and governance, Kimmeridge specifically points out a change to reach target zero flaring of gas from the environmental perspective.[129] Therefore, for investors' in the energy space, there is a trend to make sustainable investment. Under the demand of investors, this will be a market force to drive transformation for the oil and gas industry to embrace ESG initiatives.

There is a trend for the investors' community to invest sustainably and will continue to thrive. Factors such as carbon pricing, climate-related supply chain disruptions, and shifts in consumer demand, all of which may change the underlying economics.[130] Companies look for transformation because the current business model that may seem profitable in the short term, is not sustainable in the long term. An increasing number of companies addresses environmental concerns when making investment decisions as they believe ESG will bring positive returns in the long run. However, the current challenge that the oil and gas industry faces to incorporate ESG metrics is similar to other industries in terms of information disclosure and setting standards. More and more industries and companies have begun to consider ESG integration, yet

127 http://documents.worldbank.org/curated/en/913961524150628959/pdf/125442-REPL-PUBLIC-Incorporating-ESG-Factors-into-Fixed-Income-Investment-Final-April26-LowRes.pdf

128 https://www.unpri.org/Uploads/g/t/y/ESG-Factors-and-Risk-Adjusted-Performance.-A-New-Quantitative-Model.pdf

129 Preparing the E&P Sector for the Energy Transition: A New Business Model

130 https://energypolicy.columbia.edu/research/commentary/boosting-esg-finance-post-covid-19-world#_ednref11

they have their own definitions and rules about ESG metrics each is a little different from others. In order to encourage ESG reporting, one of the essential tasks is to set industry wide standards for every participant to follow and agree on. In particular, for the purpose of mitigating flaring, issues with measurement and reporting discussed in this paper may contribute to the creation of widely accepted standards and requirements or further regulatory practices.

ESG considerations also gain prominence for rating agencies in assessing issuer credit quality. There are a number of established rating agencies and index providers focused specifically on ESG metrics with rigorous research processes to evaluate companies, such as Sustainalytics, MSCI, Refinitiv, and ISS. They measure corporate performance based on ESG criteria by using their own research methodology. They provide the information and assessment as a great reference for investors in the decision making processes. Traditional rating agencies, such as Moody's, Standard &Poor's, and Fitch Ratings also enter the field as investors show enormous interests in ESG. They start to include ESG related non-financial data in addition to ranking companies based on financial factors and those data have taken on an increased importance in credit rating. ESG analysis is not systematically integrated into credit risk assessment yet. One potential suggestion for policymakers is that they should lay down rules to set an explicit and systematic industry standard given ESG's growing importance.

Industry transformation

On the industry side, some efforts have also already been made to reduce flaring. For example, the CEO of Cimarex energy, an exploration and production company with a base in Texas, Oklahoma, and New Mexico, announced their 2020 corporate goals to set numerical targets for the purpose of reducing company emissions and the incidence of flaring. The performance in regard to those goals will be directly linked to executive team compensation.[131] This is an effort that can be a paradigm for other people in leadership positions to consider. The impact may not be as quick and obvious, but the effectiveness of linking compensation is likely to be expected if decisions are made from c-suite people who actually care about the flaring issue and are determined to do so.

Sustainability Accounting Standards Board (SASB), Global Reporting Initiative (GRI), and Task Force on Climate-related Financial Disclosures (TCFD) are three non-profit organizations that publish reports to set standards for industries. They outline a framework for companies to disclose information regarding sustainability disclosure topics and accounting metrics for industries like oil and gas. SASB has a focus more on the investors' side, while GRI and TCFD provide a reference for the industry. Investors increasingly weigh ESG criteria when evaluating companies and making investment decisions. Hence, this will likely provide a financial incentive for oil and gas companies to value and incorporate ESG reporting. The lack of broadly accepted standards across the industry becomes a problem. Policy makers or leaders in the industry have to think about the question of how to set an industry-wide standard or even pass a law, so that everyone can follow the rules without disagreement. Furthermore, as discussed in this report, the difficulty of measuring flaring emissions makes it an obstacle for policy makers to incorporate it into ESG metrics. However, once flaring measurement is figured out through creating rules and

131 Colorado oil company ties executive pay to cutting emissions, flaring

standards, it should become of the criteria as flaring issue raises more and more concerns among investors and the industry.

Many big companies in the industry have already started the effort in ESG. Flaring emissions is a critical part of these companies. For example, Exxon Mobil was committed to reduce flaring by 25 percent globally by 2020.[132] BP also upgrades its Permian wells that could eliminate much of its flaring and it will not start new wells in the area unless they have access to gas pipeline infrastructure, which will be extremely helpful to flaring reduction.[133] Unfortunately this year, some smaller shale oil producers may face financial difficulty as a result of the demand shock and low price. The likelihood of them filing bankruptcy is expected this year and next year. Some merge and acquisition transactions are also likely to happen for some of those producers. Large companies tend to have more focus on ESG because they have a variety of income sources and can devote more resources into ESG. As the industry becomes consolidated with large companies that remain in the business, the integration of ESG metrics for those companies will grow. They will continue to make progress on ESG. Incorporating flaring into ESG metrics can potentially be an effective tool to reduce flaring.

132 Despite Their Promises, Giant Energy Companies Burn Away Vast Amounts of Natural Gas
133 ibid.

4. Technology Solutions

Methane Measurement Technologies **40**
Introduction of current flow meters
Satellite data
Flaring Efficiency Technologies **45**
Flaring efficiency monitoring
Typical designs to improve the flaring efficiency
Gas Utilization Technologies **48**
Compressed liquified natural gas (CNG)
Small-scale liquified natural gas
Gas-to-liquids
Blockchain and bitcoin mining

This section presents several of the technological solutions to gas flaring in the market today. We conducted a research analysis to better understand this industry, its challenges, and its main components, focusing on the five essential technological practices to reduce flared gas:[134]

- Increase direct measurement of flared gas volumes: mass flow meters need to be widely installed at the flare for measuring flared volumes directly;
- Improve the flaring efficiency: robust flaring monitoring to ensure the flares operate at the required level is essential, as is deploying technologies that can improve the combustion efficiency of flare;
- Apply gas utilization technologies: capture methane/gas at the business level and build more small facilities;
- Keep the gas in the reservoir: apply technologies that can keep the associated gas underground to avoid further need for flaring/reinjection of gas;
- Develop timely infrastructure: oil/gas companies, governments and investment communities need to prioritise the development of pipeline capacity and gas processing.

In the previous section, we discussed associated natural gas infrastructure development and reinjection technologies. We will further discuss methane measurement, flaring efficiency, and gas utilization technologies in this section.

4.1. Methane Measurement Technologies

134 Flaring emissions – Tracking Fuel Supply – Analysis

Flow Meters

Existing industry regulations and standards provide helpful guidelines by defining the acceptable accuracy limits for flare flow meters, especially in EPA[135]. However, it is challenging to reveal the flowmeter inaccuracy and minimize errors in flare flow measurement. There are inherent challenges to measure and monitor gas including the flow variation, complexity of gas composition and location accessibility.

Aside from the measurement of the flared gas, it is often necessary to monitor flare flow at various points within a complex run of pipes including the actual flare stack. Flow meters provides the user with an understanding of the gas source flowing to the flare, as well as a relative flow rate. In the current market, there are two kinds of flow meters, mass flow meters and volumetric flow meters. In volumetric flow meters, the flow rate is calculated by measuring the volume of a substance through a device over a given period. In mass flow meters, the flow rate is calculated by measuring the amount of mass of a substance passing through a device for a given amount of time. [136] Mass flow technology has an inherent advantage over volumetric flow technology by its very nature since it accounts for absolute measurements, while volumetric air flow is less reliable than mass flow to account for absolute measurements because changes in temperature and pressure affect the gas density and thus reduce the accuracy. Direct thermal mass flow controllers and insertion-type thermal mass flow meters, on the other hand, offer customers direct gas mass flow measurement without pressure or temperature sensors or flow computers. Coriolis flow meters are the only other technology that measures mass flow rate directly with no secondary flow computers.[137] To reduce the flared gas, we need to improve the direct measurement of gas. Therefore, we'll only discuss mass flow meters in this chapter. Here is a chart about current mass flow meter technologies:

Name	Characteristics	Cost
Thermal Flowmeters	• **Direct Measurement:** Measure gas mass flow directly without the need for additional need pressure; • The most economical technology for direct measurement of the flared gas; • **Calibration:** Thermal mass flow meters measure heat transfer and relate heat transfer to mass flow based on the calibration. Since various gases have different heat transfer properties, the thermal mass flow meter must be calibrated with the specified gas to accurately measure the flow rate. • One disadvantage of Thermal Flowmeters: By using thermal ones, engineers need to know the composition	Vary by types

135 Technical Guidance Document: Compliance Assurance Monitoring, Revised Draft: https://www.epa.gov/sites/production/files/2016-05/documents/cam-tgd.pdf
136 Mass Flow vs. Volumetric Flow Meters
137Volumetric Flow Rate Versus Mass Flow Rate Technology | Sierra Instruments

	of gas they're measuring. This can be a problem measuring stack gas emissions from the main flow header in refineries and chemical plants where the gas composition can vary. ● Wide Rangeability: Thermal flow meters can have a rangeability of 1000:1, still lower than ultrasonic flowmeters, but allow thermal ones to accommodate large flow swings and extreme flow conditions.	
Sage Thermal Flowmeter	● Special Calibration: The first thermal mass flow meter to utilize graphical displays, a hybrid digitally driven circuit, a hybrid digitally driven circuit and the industry's first in-situ calibration verification system;[138] ● The Sage Metering (SAGE) flow meters are calibrated using the actual gas mixture (or a mixture as close as possible to the specified composition).[139] This method of calibration is more accurate than using air with correction factors for different gases which is another commonly used calibration practice.	Approximately $5,000 with the potential of the price being lowered in the future[140]
TF Hudgins TFH 1000 Thermal Gas Flowmeter	● **It is the only thermal mass flow meter on the market that performs a calibration validation test under actual operating conditions, in-pipe and at normal flow;** ● It provides high-precision, direct measurement of gas flow rate in standard units without the need for temperature or pressure compensation.The compact, robust unit also provides accurate measurement of process gas temperature;[141] ● **It exceeds the accuracy requirements defined by the EPA rule.**	N/A
Ultrasonic Flowmeter	● Ultrasonic flowmeters are more widely used for flared gas ● It is more accurate than thermal flowmeters (see the chart below) ● Reliability: ultrasonic flow meters have no moving parts and require less maintenance than some other meters	Can range from $50,000-$100,000[143] per installation with the

138 Sage Natural Gas Flow Meter and Thermal Mass Flow Meters
139 Flare Gas Measurement Using Sage Thermal Mass Flow Meters
140 *Ibid* Flare Gas Measurement Using Sage Thermal Mass Flow Meters
141 TFH 1000 Thermal Gas FlowmeterBrochure
143 Sage Natural Gas Flow Meter and Thermal Mass Flow Meter https://sagemetering.com/

	• **Wide rangeability**: some meters can have the rangeability as high as 2000:1[142]. Because the flowrate in a gas stack can be very low at times, while sometimes can have a high velocity.	potential of price being lowered in the future
Coriolis mass flowmeter	• It relies on the Coriolis effect to measure fluid mass flow rates; • Not commonly used for flared gas: Coriolis flow meters are applicable for mass flow measurement in liquids as well as gases, but are prominently used for liquids as a high-density fluid is required to maintain the momentum of oscillation which is critical for measuring the mass flow rate.	N/A

Table 4.1 Current Typical Mass Flowmeters

The table 4.1 illustrates two main flowmeters for flaring gas, thermal flow meters and ultrasonic ones. Ultrasonic flowmeters are more accurate than thermal flowmeters. Many scientists have conducted research on these two flow meters for flare applications.

	Actual volume	Standard volume	Mass
Case 1—Propane increased			
Differential pressure meter	34%	34%	25%
Thermal flowmeter	2-15%	2-15%	35-45%
Velocity meter (optical, ultrasonic, vortex)	0%	0%	0%
Case 2—Hydrogen added			
Differential pressure meter	31%	31%	45%
Thermal flowmeter	100-300%	100-300%	300-700%
Velocity meter (optical, ultrasonic, vortex)	0%	0%	112%
Case 3—CO_2 increased			
Differential pressure meter	9%	9%	8%
Thermal flowmeter	2-5%	2-5%	15-20%
Velocity meter (optical, ultrasonic, vortex)	0%	0%	15%

TABLE I: ERRORS RELATED TO USING A FIXED COMPOSITION*

*The approximate measurement error under constant flow conditions when using a fixed composition of 1% CO2, 0.9% H2S, 97% methane, 1% ethane and 0.1% propane and the flare composition changes to:

Case 1: 0.53% CO2, 0.47% H2S, 51.08% methane, 0.53% ethane, 47.39% propane
Case 2: 0.4% CO2, 0.36% H2S, 38.8% methane, 0.4% ethane 0.04% propane, 60% hydrogen
Case 3: 12% CO2, 0.8% H2S, 86.22% methane, 0.89% ethane, 0.09% propane

Source: API MPMS 14.10

142 Flow Technologies for Measuring Flare Stack Emissions

Table 4.2 Errors Related to Use of Fixed Composition for Different Meter and Calculations Type[144]

From the chart above, the ultrasonic meter (velocity meter) is the optimistic choice for addressing environmental concerns. However, the current version of ultrasonic flow meters is ranging from $50,000-$100,000 per installation,which could be expensive for some buyers. Another more affordable and common technology is the Sage Thermal Flow Meters (Sage), which is approximately $5,000 with the potential of the price being lowered in the future. Sage technology is calibrated using the actual gas mixture (or a mixture as close as possible to the specified composition). Sage is able to predict the variations in performance based on the different gas compositions. This method of calibration is more accurate than using air with correction factors for different gases which is another commonly used calibration practice.

The flow meter technology including both the ultrasonic and the thermal flow meters are developing. There are new technologies coming up in the market. A self-verification system is introduced to flow meters and can help avoid calibration costs. Usually, in the oil/gas industry, flowmeters must be calibrated periodically and removed to comply with governmental regulations. Performing self-verification on a flowmeter can extend calibration cycles by a factor of 10 or higher. In some cases, it may even be possible to replace wet calibrations completely with self-verification. Another improvement is wireless capabilities and the real-time data. Today's flowmeters can already have wireless, Bluetooth and web server capabilities, which means flowmeters can be accessed, probed, configured and diagnosed over smartphones, tablets and handheld devices.

The main challenge of flow meter technologies doesn't come from the technology itself, but from the target customers. Challenges result from inadequate regulatory incentives and financial concerns. In the future, these are the two main factors that market players need to face. Real-world problems like inaccuracies and high costs of the flaring measurement are still hard to be solved without flow meter technology being applied to the whole value chain.

Satellite Data

A set of methods are presented for the global survey of natural gas flaring using data collected by the National Aeronautics and Space Administration/National Oceanic and Atmospheric Administration NASA/NOAA Visible Infrared Imaging Radiometer Suite (VIIRS). The accuracy of the flared gas volume estimates is rated at ±9.5%.[145] Because of the lack of systematic reporting from flare operators and the remote nature of many flare locations, satellite sensors are an attractive option for global monitoring of gas flares. However, in the past, none of the existing sensors have been designed specifically for the detection and monitoring of gas flares. While recently, a technology company called Kayrros, a Paris-based tech start-up company has released their recent findings about the "methane emissions inventory database" or "methane tracker". It

[144] "Manual of Petroleum Measurement Standards, Chapter 14 - Natural gas Fluids Measurement, Section 10 - Measurement of Flow to Flares", Table 5, API, MPMS, 14.10, June, 2012

[145] "Methods for Global Survey of Natural Gas Flaring from Visible Infrared Imaging Radiometer Suite Data", Christopher D. Elvidge 1,*,Mikhail Zhizhin 2,3,Kimberly Baugh 2,Feng-Chi Hsu 2 andTilottama Ghosh, MDPI, 2016

was a breakthrough announcement because it created a system focusing on the detection and monitoring of methane and gas flares. Methane emissions can now be detected on a global scale, which represents a major step-change in the ability to work towards the reduction of man-made emissions.[146] The data shows that there are around 100 high volume-emitting events at any one time around the world. Together, in the course of one year, they are releasing 20 megatons of methane which is equivalent to 1.8 gigatons of CO2 in the first twenty years. Though there are still skeptical concerns about the accuracy of satellite data, it is still one of the most accurate and objective technologies for methane monitoring and measurement. One challenge for those companies doing satellite technology on flared gas is how to incorporate the methane tracking system into investment like ESG, company's portfolio or even emission trading system. Companies like Kayrros are building their business models by quantifying ESG rating standards and offering environmental supervision and real-time data for buyers, which is very promising for those satellite data companies.

4.2. Flaring Efficiency Technologies

It is difficult to accurately gauge the extent of emissions coming from flare stacks. Although it is widely assumed that they operate with 98% efficiency, there is widespread concern that this number is not entirely accurate.[147] This will lead to considerable underreporting of the emissions.[148] The flaring efficiency depends primarily on three key parameters: the CH4 fraction in the waste gas, the flare jet velocity, and the wind speed. Based on this, I listed two kinds of technology to address the flaring efficiency issues. One is the flaring monitoring technology and another one is to increase the efficiency in flare gas and air mixing.

Flare Efficiency Monitoring

In 2014, Providence Photonics Technology[149] developed an innovative technology to remotely measure the combustion efficiency of an industrial flare, which gained funding and grant support from the EPA. The Providence Photonics flare monitor utilizes a specially designed, multi-spectral high speed Infrared (IR) imager to measure relative concentrations of unburned fuel and combustion products in every region of the flare flame. These measurements are then used to determine real-time flare combustion efficiency and provide metrics to measure the presence of smoke and the level of steam assistance. With these process parameters, operating conditions can be adjusted to keep the process flare combustion optimized without excessive use of secondary resources, such as auxiliary fuel gas and steam. Additionally, the flare monitor can be installed several hundred feet away from the flare further reducing the complexity of installation and

146 Kayrros and Copernicus Images Allow Quantification of Global Methane Leaks Equivalent to 1.8 Gigatons of CO² Emissions

147 "Methane, Black Carbon, and Ethane Emissions from Natural Gas Flares in the Bakken Shale, North Dakota", Alexander Gvakharia, Eric A. Kort, Adam Brandt, Jeff Peischl, Thomas B. Ryerson,Joshua P. Schwarz,Mackenzie L. Smith, Colm Sweeney, Environmental Science & Technology, 2017

148 Kleinberg, Robert. "Greenhouse Gas Footprint of Oilfield Flares Accounting for Realistic Flare Gas Composition and Distribution of Flare Efficiencies." Preprint. Earth and Space Science Open Archive, December 16, 2019. https://doi.org/10.1002/essoar.10501340.1.

149 https://www.providencephotonics.com/flare-monitoring

maintenance costs. At that time, there are not many technologies applied to the measurement and monitoring of flare efficiency. But recently, many companies like Siemens, Honeywell, Zeeco are also developing similar kinds of technologies.

Recently, big companies are taking an active part in the flaring monitoring market. For instance, Providence Photonics, recently partnered with Lockheed Martin and Surface Optics to manufacture Mantis, a video imaging spectral radiometry, or VISR, flare monitor. The product is used by BP businesses to manage methane emissions at oil and gas production facilities. It's the first readily deployable monitoring solution that directly measures methane emissions entering the environment. However, like the report that Texas Railroad Commission published in February, the "flaring intensity" is becoming significant, which means the mid-size and small-size companies can also contribute a lot to the flared gas amount. How to ensure those companies enter into the flaring monitoring and efficiency market is the key question in the near future.

The Callidus Hemisflare

Conventionally, the flare gas exiting from the cylindrical pipe of the flare head expands as a free jet into the atmosphere and sucks in the air necessary for combustion.[150] To improve the flaring efficiency, the new Callidus Hemisflare utilizes a patent pending Coanda bowl [151]design to inspirate more air. When flare gases can be presented in a thin sheet, more of the gases come in contact with the air, increasing the likelihood of complete combustion. This is achieved using the Coanda Effect.

The new bowl design uses raised vertical ridges around the outside of the bowl, significantly increasing the surface area of the bowl. Increased surface area improves the gas/air mixing, which improves the flare's smokeless capacity. The bowl profile has also been enhanced through computational fluid dynamics modeling, and physical testing, to optimize the bowl shape and dimensions for the best combustion characteristics. In this way, the Callidus design adds additional surface area, expands the contact between air and flare gas, and increases the mixing efficiency.

150 REF # 2 Degree Of Conversion Of Flare Gas In Refinery High Flares
151 Callidus Hemisflare - Offshore and Onshore Production Flare

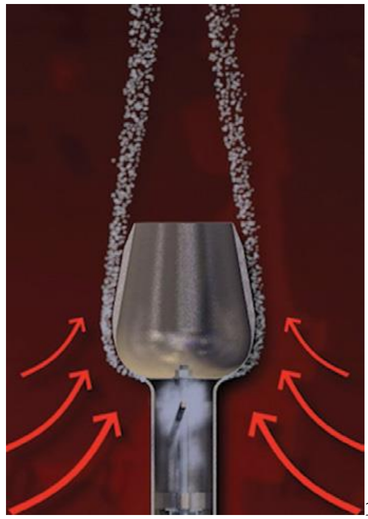
[152]

Table 4.3 The Callidus Hemisflare Coanda Bowl

The Callidus Hemisflare tip design is a breakthrough in modern flare technology.The incorporation of the Coanda design with enhanced ridges has increased the flare gas and air mixing while enabling longer tip lifespan. With this new tip design, the flare steam consumption has been reduced, the steam control system has been simplified, and the smokeless efficiency is improved. In general, the Callidus Hemisflare tip is a vast improvement over current steam technologies.

There is no public data about the costs of those efficiency technologies. However, we learned from our interview with Dr. Eric Kort from University of Michigan, that this kind of burner tip has a low cost, which can be affordable for the industry.
[153]

The 2019's Flare Monitoring Market Report[154] claims that the flaring monitoring industry is anticipated to register significant revenue over the estimated time period, between 2019 and 2035. Especially when more technology providers, service providers, research organizations, PE and VC firms are joining, this can be achieved. However, a key challenging factor for the growth of the said market is the technological challenges resulting from the adherence to regulatory norms while bringing down the overall cost of systems.To make technologies commercialized, regulatory and policy incentives are essential for end users.

4.3. Gas Utilization Technologies

Compressed Natural Gas: GE's CNG in a box

152 *Ibid* Callidus Hemisflare - Offshore and Onshore Production Flare

153 Our group had an interview with Dr. Eric Kort on March 26th, 2020

154 https://www.marketwatch.com/press-release/flare-monitoring-market-2019-recent-industry-trendstop-manufacturers-market-growthshare-historical-background-and-future-forecast-2019-08-29

GE's "CNG in a Box" system was launched in 2012.[155] It can solve the inaccessibility of well sites and help reduce the flared gas. Specifically, it allows E&P companies to use and monetize more of their produced gas, even at wells in inaccessible off-grid locations. The first stage of the development of the CNG In A Box system was directed to natural gas vehicle (NGV) refueling, but with a few simple improvements, it turned out to be well suited to "virtual pipeline" applications. "Virtual pipeline" refers to a moveable gas solution rather than a traditional pipeline system. GE offers their clients a modular "plug-and-play" CNG solution when combined with trucks to move gas. The same technology can be used to flare gas, enable onsite power generation and be suited for on-road transportation fueling of NGVs because of the modularity and flexibility of the design.

According to HartEnergy[156], this particular technology can reduce natural gas flaring in North Dakota by 1.6 MMcm/d (60 MMcf/d), or 20%, and has the potential to play a critical role in flare gas reduction in wells beyond the Bakken, including expanding gas processing capability and powering production.

Mini Facilities: Small-scale LNG

There is a growing number of companies doing small-scale LNG projects now. The Cryobox Mobile LNG station by Galileo Technologies [157]is one of them. It can provide LNG fuel for remote industrial facilities, mining operations, or distant communities, even further than 250 miles away, and transform the polluting gas-flaring into value-added liquid fuel. This kind of technology is also called "virtual pipeline." It has some advantages compared to traditional LNG plants:

- Low Energy Consumption: With an energy consumption of 300 kW at the gas conditioning stage and 400kW at the liquefaction stage.[158] This process offers one of the lowest energy consumption levels in the market: 0.7 kilowatt-hours per LNG kilogram (kWh/kg);
- Quick peak time: Peak production is reached in 10 minutes. (for traditional LNG plants are about 18 hours);
- Less processing and commissioning time: The rig can be moved between wells and can be up and running within an hour of arriving on site.The transfer of LNG to storage tanks can be completed without the use of pumps. Through the priority panel, LNG can be sent from those tanks to distribution trailers, to industrial vehicles or to equipment for immediate consumption;
- Much less capital costs than mega/normal LNG projects;
- Multiple fuels for flexible needs: Besides producing LNG, the Cryobox offers Compressed Natural Gas (CNG) or Compressed Biomethane (Bio-CNG) on demand. After reaching the required BTUs scheduled in a regular LNG production plan, the Cryobox is also able to produce up to 80,000 standard cubic feet/hour[159] of CNG for

155 https://www.hartenergy.com/exclusives/thinking-inside-box-176379
156 https://www.hartenergy.com/exclusives/thinking-inside-box-176379
157 https://www.galileoar.com/us/small-scale-distributed-lng-production/
158 *Ibid* Distributed LNG Production
159 https://www.verdek.com/nano-lng-station.htm

fleets or for retail fueling, allowing for maximum uptime and additional revenue. Another advantage is there is no additional installation of CNG compression components under Galileo's dual-mode capability.

The challenge of small-scale LNG projects is from the demand. There are three major end uses for small-scale LNG: marine fuel (bunkering), fuel for heavy road transport, and power generation in off-grid locations. In the US's northeastern region, small-scale LNG facilities have been operating for years, chiefly providing a source of fuel for electric power plants in the winter months, when fuel demand is high. The market structure of small-scale LNG in the Gulf Coast region is different. Small-scale LNG serves the overseas market, especially in Latin America and for the bunkering market. For instance, with the IMO 2020, NuBlu Energy's Port Allen Liquefaction facility, a 30,000 gal/d project situated along the Mississippi River near Baton Rouge, Louisiana, about 140 miles north of the Gulf of Mexico is looking at the overseas market.[160]

Compared to conventional LNG plants, small-scale LNG is more flexible. But at the same time, it suffers from more volatilities. Small-scale LNG is developing with short-term LNG contracts, which are not linked to the oil price. Short-term LNG contracts usually use spot prices, which are more risky for LNG suppliers. The demand market needs to be guaranteed in LNG contracts. This is why the current small-scale LNG is growing fast in high-demand countries like China. Operational challenges in the small-scale LNG market refer to companies' integrated operational abilities across the whole value chain. It would be difficult for a supplier to maintain their business if they only have small-scale LNG without other integrated business. According to PWC's report in 2017,[161] the winning players in small-scale LNG industry need to be active across all segments of the industry, from the supply of gas, to transportation and distribution, right down to the point of direct commercial relationships with end-users (where sizable). Players should focus on the core activities, while outsourcing the low-value-added activities that require specific local presence and knowledge of national regulations, such as bunkering, "last-mile" transportation, and scouting of smaller off-grid potential users. Equally, companies should leverage their key competencies in commodity hedging to reduce the price risk for end users in the initial market development phase. Leading companies in the small-scale LNG market like Gazprom, Shell, Equinor and BP reflect the importance of operational abilities.

Overall, small-scale LNG technology can be a practical way to solve the flared gas in North Dakota and Texas, while the key step is to find the customers of applying this technology and where does the LNG demand lie in: Mexico, Northeastern US or other markets.

Gas to Liquids

In industry, methane is typically used in the syngas process, which converts steam and methane to a mixture of carbon monoxide and hydrogen, known as synthesis gas, at ~900°C. The synthesis gas can then be reacted over a catalyst in a second step, also at high pressures and temperatures, to produce methanol. Methanol can then be used directly as a fuel or as a precursor for high-value chemicals. The syngas route is energy-intensive as it requires high temperatures

160 Small-scale LNG projects make market inroads in US - Platts Insight
161 https://www.strategyand.pwc.com/fr/fr/media/small-going-big.pdf

and pressures. In addition to operating at lower temperatures and pressures than existing technologies, OxE Gas to methanol technology[162] process has demonstrated tolerance to sulfur impurities common in natural gas, which will reduce the cost of purification prior to the reaction.

OxE's initial studies demonstrated that methane could be efficiently oxidised to a methanol derivative using inexpensive salts in a process termed oxyesterification (OxE) with minimal (<2%) production of CO2. With this, 40% yield was reported with more than 97% selectivity for the desired product.[163] Further investigation into the process indicated that the partial oxidation is efficient because the product is protected from unwanted over-oxidation. This cutting-edge process provides a potential route to use natural gas more productively than the traditional GTL technology.

OxE technology can reduce costs through the purification process. In addition to operating at lower temperatures and pressures than existing technologies, the OxE process has demonstrated tolerance to sulfur impurities common in natural gas, which will reduce the cost of purification prior to the reaction. Another strength of this technology is no gas pipelines are required, which can lower costs: facilities for the OxE process are projected to be less costly than current technologies, enabling natural gas conversion at the wellhead rather than requiring pipeline construction to bring the natural gas to large chemical plants.

Same as the gas to methanol technology, GTL is also expensive. The GasTechno Technologies has invented a Portable Mini-GTL system that converts methane to methanol in one step. It is designed to monetize small scale sources of stranded gas from 50 thousand standard cubic feet per day (mscfd) to 30 million standard cubic feet per day (mmscfd); a market representing 80% of the global stranded and flared gas market. [164]

Blockchain, Bitcoin Mining, and Data Centers

Crusoe Energy Systems, as a pioneer, announced that it would install data centers at shale sites, generating electricity from the surplus gas to mine Bitcoin. The company has eight operations across the US, with plans for an additional 30 in the first half of 2020, and now it wants to use the electricity generated from these centers to power data centers to mine Bitcoin.[165] Steady electricity output and high tech improvement: Crusoe said it plans to use the computing capability generated from those centers to develop an artificial intelligence cloud-computing service. The report said that Crusoe plans to set up 70 units in 2020, each with a maximum electric output of 1 MW, which the company said would keep approximately 10 MMcf/D of gas from being flared.

Blue Marble Gas, a midstream gas gatherer and blockchain technology company will place a power-generation and Bitcoin-mining system next to a gas pipeline. The business plan is simple: use pipeline gas to generate electricity and sell that electricity to the owner of the Bitcoin-mining

162 https://energypost.eu/new-gas-to-methanol-technology-oxe-could-end-oil-well-flaring/
163 https://energypost.eu/new-gas-to-methanol-technology-oxe-could-end-oil-well-flaring/
164 GasTechno® GTL Gas-to-Liquids
165 Data Science and Digital Engineering: Company Bets Bitcoin Mining Can Ease Flaring

operation. In this case, Blue Marble gets paid for the energy conversion while its private equity backer holds onto the Bitcoin wallet.[166] Blue Marble estimates that a single unit of gas used to make one Bitcoin, which today is valued at around $9,000, would bring a return of $8 to $15 at current commodity prices. [167]The first installation taking shape this year is estimated to convert 30 MMscf/D into nearly $270,000. This will require at least 100 MW of power, generated by four GE-built trailer-mounted gas turbines.

5. Natural Gas Flaring and Venting Regulation

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5.1. Current state of Federal and Local Regulations

The following chapter presents an outlook on the state and local regulations to address natural gas flaring and venting that exist in the U.S. and a brief analysis of best practices and failed programs that exist today. Under the U.S. Federal system, each State has the jurisdiction and authority to implement its own regulation, or to set specific goals, milestones, and objectives to reduce natural gas flaring. There is no Federal framework the states must follow to address, but the Environmental Protection Agency (EPA) oversees the implementation of the Clean Air Act (CAA) which regulates all air emissions, controls hazardous pollutants, including greenhouse gases, and sets general standards to protect the public health and welfare.[168] This chapter

166 Wikipedia: Bitcoin Wallet, which is also called the Cryptocurrency wallet, is a device, physical medium, program or a service which stores the public and/or private keys and can be used to track ownership, receive or spend cryptocurrency.

167 Innovators Seek To Transform Flaring Into Money and Power

168 Supreme Court of the United States of America, "Massachusetts v. EPA, 549 U.S. 497 (2007)," Justia Law, accessed May 7, 2020, https://supreme.justia.com/cases/federal/us/549/497/.

separates the U.S. states into two groups, the major oil and gas producers and the rest of the states as an entity using the EIA considerations. The state producers are: Alaska, Arkansas, California, Colorado, Idaho, Kansas, Louisiana, Montana, New Mexico, North Dakota, Ohio, Oklahoma, Pennsylvania, Texas, Utah, West Virginia, and Wyoming.

In the U.S. the regulation acknowledges the importance of flaring for safety measures and during the first stages of the oil production. In this sense, it is unlikely that flaring or venting will ever disappear, or that 100% of associated natural gas could be efficiently captured and channeled to target markets.[169] The U.S. the legislation has approached the problem twofold. First, the air quality regulation which aims to maintain air pollution, including greenhouse gases, below hazardous thresholds and to protect human health in the short and long terms. Second, the permits and operation framework which establishes the administrative procedures that the oil and gas industry must follow to operate its business in the U.S. Such regulation establishes the minimum requirement to operate an oil well, how to dispose of waste, in some states it contains specific thresholds and goals for natural gas flared.

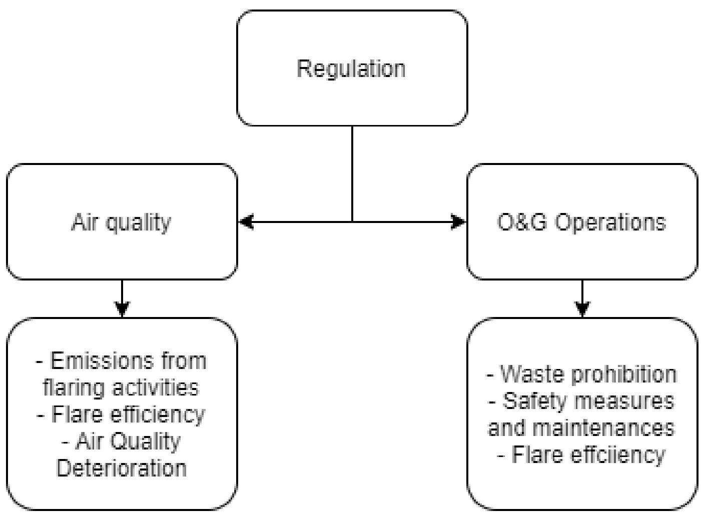


Diagram 5.1 Regulatory Approaches to Gas Flaring and Venting

As a consequence of this dual approach, the legislatures in North Dakota, New Mexico, Louisiana, Pennsylvania, West Virginia, Arkansas, Montana, and Ohio have divided the roles monitoring and reporting of gas flaring related issues between two government agencies: one that overlooks air quality issues and other that deals with operators, safety, permits and ground

169 U.S. Energy Department, "Natural Gas Flaring and Venting: State and Federal Regulatory Overview, Trends, and Impacts" (Office of Oil and Natural Gas, June 2019), https://www.energy.gov/sites/prod/files/2019/08/f65/Natural%20Gas%20Flaring%20and%20Venting%20Report.pdf.

activities.[170] The rest of the oil producing states have put these responsibilities on a single entity that deals with the entire problem. In this situation, the government entity tends to follow the "ground" approach to the gas flaring and regulates the owners and operators of the oil wells.

It is important to recognize that Federal and State legislations evolve at a different rhythm than the oil and gas industry, causing a lag in between these two. In the past, oil and natural gas prices pushed for major capture efficiency and productivity in this industry, natural gas was a scarce resource with a higher value than it has today. The boom of unconventional shale gas and tight oil has changed the paradigm creating an oversupply of natural gas and the consequent waste of associated gas in the new oil wells.[171] As mentioned in Chapter 3, there are multiple factors maintaining natural gas prices in low ranges in the U.S. and discouraging the capital investments required to to capture associated gas and to use it efficiently.

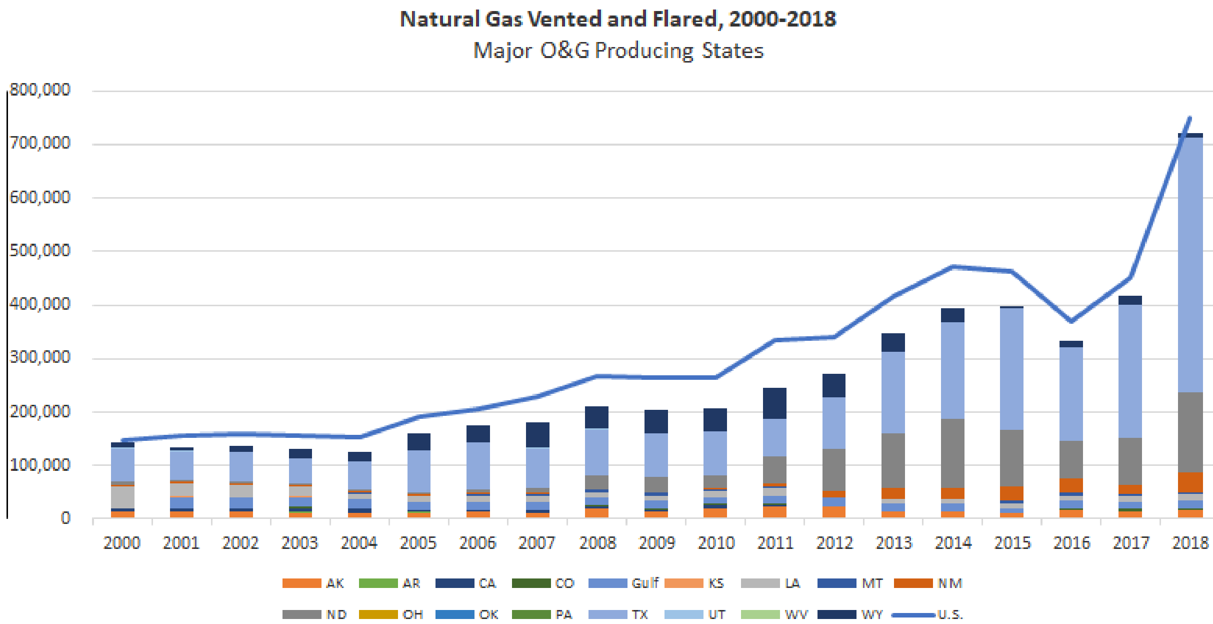
Natural gas flaring and venting increased since 2005 as a result of tight oil production. Graph 5.2 shows that natural gas flaring and venting was constant between 2000 and 2004, and increased right after. Natural gas flaring and venting increased 413% according to the U.S. Energy Information Administration (EIA) data between 2000 and 2018, a dramatic increase for a developed country.[172] The legislation has been lagging behind the industry in terms of production trends, requirements, and available technology, but some states have addressed the problem more

170 Office of Oil & Natural Gas U.S. Energy Department, "Arkansas Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/Arkansas.pdf; Office of Oil & Natural Gas U.S. Energy Department, "Louisiana Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/Louisiana.pdf; Office of Oil & Natural Gas U.S. Energy Department, "Montana Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/Montana.pdf; U.S. Energy Department, "Natural Gas Flaring and Venting: State and Federal Regulatory Overview, Trends, and Impacts" (Office of Oil and Natural Gas, June 2019), https://www.energy.gov/sites/prod/files/2019/08/f65/Natural%20Gas%20Flaring%20and%20Venting%20Report.pdf; Office of Oil & Natural Gas U.S. Energy Department, "New Mexico Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/New%20Mexico.pdf; Office of Oil & Natural Gas U.S. Energy Department, "North Dakota Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/North%20Dakota.pdf; Office of Oil & Natural Gas U.S. Energy Department, "Ohio Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/Ohio.pdf; Office of Oil & Natural Gas U.S. Energy Department, "Pennsylvania Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/Pennsylvania.pdf.

171 Marianne Kah et al., "Columbia Global Energy Dialogue: Natural Gas Flaring Workshop Summary," April 2020, https://energypolicy.columbia.edu/research/global-energy-dialogue/columbia-global-energy-dialogue-natural-gas-flaring-workshop-summary; Hiroko Tabuchi, "Despite Their Promises, Giant Energy Companies Burn Away Vast Amounts of Natural Gas," *The New York Times*, October 16, 2019, sec. Climate, https://www.nytimes.com/2019/10/16/climate/natural-gas-flaring-exxon-bp.html; International Energy Agency, "Flaring Emissions," IEA, accessed April 25, 2020, https://www.iea.org/reports/tracking-fuel-supply-2019/flaring-emissions; Lori Edwards, "LMOP Workshop: Financial Considerations and Incentives Discussion," n.d., 15.; U.S. Energy Department, "Natural Gas Flaring and Venting: State and Federal Regulatory Overview, Trends, and Impacts" (Office of Oil and Natural Gas, June 2019), https://www.energy.gov/sites/prod/files/2019/08/f65/Natural%20Gas%20Flaring%20and%20Venting%20Report.pdf; Rystad Energy, "Permian Gas Flaring Hits All-Time Highs," accessed May 7, 2020, https://www.rystadenergy.com/newsevents/news/press-releases/Permian-flaring-record/.

172 International Energy Agency, "Flaring Emissions"; U.S. Energy Information Administration, "Natural Gas Vented and Flared."

effectively than others. The following lines will compare these regulations and their impact on the industry over the past ten years.



Graph 5.2 Natural Gas Vented and Flared Data from EIA

The data shows that Texas, North Dakota, and New Mexico contribute largely to the flaring problem in the U.S. The rest of the country presents low volumes of natural gas flared or vented. In addition to time evolution, state Regulations tend to differ in their definitions, treatments, extent, and complexity, states with intensive O&G industry developed a more flexible regulation to accommodate different kinds of activities and practices and to foster new technologies.173 However, these regulations tend to be soft on flaring and venting procedures for the same reasons, they want to encourage the industry by reducing bureaucracy and monitoring procedures that might frighten investments.

Some experts have shown their frustration over the lack of concrete actions to address this issue seriously in the U.S. and they have called for more energetic actions from the regulators and from the industry too.174 In addition, state legislators have tried to address venting and flaring without reducing tight oil production in the country. An investigation on the Texan case showed that the local regulator has approved all flaring permits submitted by the operators. The report points out the agent-principal situation in which the Texas Railroad Commissioners' campaigns are heavily funded by the oil and gas industry, creating opposing incentives for the

173 U.S. Energy Information Administration, "Natural Gas Vented and Flared.": Kah et al., "Columbia Global Energy Dialogue: Natural Gas Flaring Workshop Summary."

174 Kah et al., "Columbia Global Energy Dialogue: Natural Gas Flaring Workshop Summary."

Commissioners to apply the state legislation on flaring.[175] This approach is common in other parts of the country and creates a complicated system that has diffuse incentives to reduce harmful natural gas flaring and venting while trying to protect the O&G industry.

Following the twofold regulatory approach described before, current regulations have separated the efforts to address natural gas flaring. On one side, states placed the responsibility of monitoring air quality on specific Departments of Environmental or Air Quality Divisions, eight out of 17 state producers have created such government offices to monitor and enforce air quality regulation. On the other side, all of these seventeen producer states have created a regulatory framework around operational permits and their corresponding government office to oversee and enforce such regulation or explicit restrictions on the unnecessary or excessive waste of natural gas.[176] Even between these policies, some are stricter than others, for example, Kansas, Louisiana, Montana, New Mexico, Utah, Oklahoma, and Texas and have specific thresholds to determine if a company has to report the amount of gas flared or vented and whether they need additional permits to do so.[177] In other states where the oil production is high, the regulation only bans the uneconomic waste of this hydrocarbon, but there is no detailed information on what that means, what are the thresholds for flaring and venting, or what qualify as unnecessary waste.

5.2. Emissions Abatement Goals

The urgency to control natural gas flaring and venting has increased as climate change risk rises and reducing all kinds of greenhouse gas (GHG) emissions has gained popularity among some government stakeholders. In states like Colorado, North Dakota and New Mexico, the governors have issued executive orders or regulations to address and reduce GHG) emissions, including those emitted by the O&G industry.[178] Such measures have reinforced the role of governors and

175 Deon Daugherty, "Unrestrained Permian Gas Flaring," August 2019, http://www.energyintel.com/pages/worldopinionarticle.aspx?DocID=1044758.

176 U.S. Energy Department, "Natural Gas Flaring and Venting: State and Federal Regulatory Overview, Trends, and Impacts."k

177 Office of Oil & Natural Gas U.S. Energy Department, "Kansas Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/Kansas.pdf; Office of Oil & Natural Gas U.S. Energy Department, "Louisiana Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/Louisiana.pdf; Office of Oil & Natural Gas U.S. Energy Department, "Montana Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/Montana.pdf; Office of Oil & Natural Gas U.S. Energy Department, "New Mexico Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/New%20Mexico.pdf; Office of Oil & Natural Gas U.S. Energy Department, "Oklahoma Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/Oklahoma_0.pdf; Utah State Legislation, "R469. Natural Resources; Oil, Gas and Mining: Oil and Gas.," Pub. L. No. R649 (2018), https://oilgas.ogm.utah.gov/pub/Rules/Rules_R649_All.pdf; Office of Oil & Natural Gas U.S. Energy Department, "Texas Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/Texas.pdf.

178 Michelle Lujan Grishman, "Executive Order on Addressing Climate Change and Energy Waste Prevention.," Pub. L. No. Executive Order 2019-003 (2019), https://www.governor.state.nm.us/wp-content/uploads/2019/01/EO_2019-003.pdf; Becker et al., "House Bill 19-1261," Pub. L. No. 1261 (2019); North Dakota Industrial Commission, "Order 24665," Pub. L. No. Order 24665 (2018),

state agencies in the process of controlling natural gas flaring. However, these measures do not directly address associated gas flaring or venting, but the overall GHG emissions so there are multiple other solutions that could be implemented to reach such targets that will not reduce gas flaring or venting, bur rather attack carbon dioxide, nitrous oxide , hydrofluorocarbons, perfluorocarbons, nitrogen trifluoride, and sulfur. From the oil and gas producer states North Dakota, New Mexico, Colorado, and Pennsylvania set specific targets to cut back greenhouse gas emissions, but only North Dakota created a schedule to increase natural gas capture in the state.[179]

State	**Goals**
North Dakota	Gas capture goals established by the N.D. industrial Commission: - 74% October 1, 2014 through December 31, 2014 - 77% January 1, 2015 through March 31, 2016 - 80% April 1, 2016 through October 31, 2016 - 85% November 1, 2016 through October 31, 2018 - 88% November 1, 2018 through October 31, 2020 - 91% beginning November 1, 2020
New Mexico	Reduce GHG emissions at least 45% by 2030 compared to 2005 levels.
Colorado	Reduce GHG emissions 26% by 2025, 50% by 2030, and 90% by 2050, relative to 2005 levels.
Pennsylvania	Reduce GHG emissions 26% by 2025 and 80% by 2050, relative to 2005 levels.

Table 5.3 Greenhouse Gas Emission Reduction Goals per Oil & Gas Producer State

A particular problem with the current regulations is that only Louisiana, Montana and Wyoming mandates companies to differentiate between natural gas flaring or venting on their reports, the rest of the major state producers do not require such distinction, even when the industry and the regulation understand the different impacts each of these processes have on the environment.[180] The New Mexico Oil Conservation Division also requires the distinction between these two

https://www.dmr.nd.gov/oilgas/GuidancePolicyNorthDakotaIndustrialCommissionorder24665.pdf.; U.S. Energy Department, "Natural Gas Flaring and Venting: State and Federal Regulatory Overview, Trends, and Impacts."

179 North Dakota Industrial Commission, Order 24665; U.S. Energy Department, "New Mexico Natural Gas Flaring and Venting Regulations"; Lujan Grishman, Executive Order on Addressing Climate Change and Energy Waste Prevention.; Pennsylvania Department of Environmental Protection, "Methane Reduction Strategy," Department of Environmental Protection, December 17, 2019, https://www.dep.pa.gov:443/Business/Air/Pages/Methane-Reduction-Strategy.aspx.

180 U.S. Energy Information Administration, "Natural Gas Vented and Flared"; U.S. Energy Department, "Alaska Natural Gas Flaring and Venting Regulations"; U.S. Energy Department, "Louisiana Natural Gas Flaring and Venting Regulations"; U.S. Energy Department, "Montana Natural Gas Flaring and Venting Regulations"; Office of Oil & Natural Gas U.S. Energy Department, "Wyoming Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/Wyoming.pdf.

processes, but the rule is not strictly enforced. This situation creates a larger problem because the public data collected and published by different organizations rarely differentiate gas flaring from venting. Under these circumstances, tackling a specific process becomes very difficult and companies tend to operate as if both processes have the same warming potential in the atmosphere, when in fact they do not.

Until recent years, the regulators relied only on the operator's or owner's data, but the appearance of new monitoring technologies such as satellite measurements and ground sensors that can estimate natural gas flaring and venting will change policy enforcement and evaluation in future years.[181] Satellite data can be an effective complement to the operator's data to reconcile the information reported by the operators. However, no regulation has included these technological advancements, nor considered their potential effects for future monitoring and enforcement. These solutions can be cost-effective alternatives for the monitoring process since they provide reliable estimates on the real size of the problem, but the legislation should take them into consideration and evaluate potential ways to use them in the future. The technological alternatives for surveillance and monitoring GHG emissions will increase the pressure on companies to correctly disclose their emissions and their procedures to reduce harmful waste of resources.

In the past, stakeholders have pointed out the importance of assessing the real impact of flaring and venting, arguing that there is no way to completely abate gas flaring or venting and this problem can only be managed and eventually reduced. According to some stakeholders," flaring intensity" (quantity of gas flared per barrel of oil produced) is a better measurement since associated gas is proportional to oil production, so the phenomenon increases as total oil production rises. In 2020, Ryan Sitton, Commissioner of the Texas Railroad Commission (RRC) published an article pushing for the use of flaring intensity as the appropriate index to measure unnecessary gas flaring. This indicator presents the associated gas flared as a percentage of the oil production obtained so it could be used as a performance benchmark between oil producers in the U.S. and other countries.[182] Beyond the debate on which is the best indicator for natural gas flaring, it is important that state legislations are based on a common measurement if the industry aims to tackle this problem effectively.

Sitton's approach would discourage research and development to address this problem. It is true that associated gas is intrinsically linked to oil production, but there are multiple operational practices that could reduce this problem in the short and long terms. Adopting the Commissioner's perspective would give the industry permission to flare or vent natural gas as a percentage or their production, creating mixed signals from a regulatory standpoint. The current regulation has assumed a vision, at least in paper, of zero tolerance of flaring above certain thresholds and for other reasons beside safety measures. We consider that this approach has better chance to effectively address the problem and to incentive real solutions to use the associated natural gas

181 Christopher D. Elvidge et al., "Methods for Global Survey of Natural Gas Flaring from Visible Infrared Imaging Radiometer Suite Data," *Energies* 9, no. 1 (January 2016): 14, https://doi.org/10.3390/en9010014.
182 Ryan Sitton, "2020 Texas Flaring Report Q1" (Texas Railroad Commission, February 2020), https://www.rrc.state.tx.us/media/56420/sitton-texas-flaring-report-q1-2020.pdf.

5.3. The Ideal Regulation

Considering the current state of the regulation, this research identified the best practices in place and the pieces of legislation that could improve the overall reduction for gas flaring and venting in the local environment. These characteristics are based on what we consider the Ideal Regulation to measure, monitor, and reduce natural gas flaring and venting in the U.S. Such Ideal Regulation would be difficult to approve as a whole in any state considering the current state of these legislations, but it is a useful exercise to see where these regulations are today and what could be improved to address this problem. There are three major components of an effective regulation: routing flaring prohibition, accurate and mandatory measurement differentiating necessary from unnecessary flaring and venting, and third party monitoring. These elements can be the basis of model legislation, with the goal of modernizing and harmonizing state laws to effectively address natural gas flaring and venting.

Diagram 5.4 Components of the Ideal Natural Gas Flaring Regulation

The Ideal Regulation exercise is useful to discriminate the current state regulations on natural gas flaring and venting and to determine which states are closer to the desired scenario (Best Practice) and which still have room for improvement (Undesired Practice). The criteria to categorize these regulatory frameworks as Best Practices are how comprehensive, detailed and concise the laws are written and how close the wording of the laws is to the desired regulation. For example, a state regulation might mandate the operators to measure and report their volumes of natural gas flared or vented, but the wording of the regulation must be clear on the requirements and the periodicity of the report to be considered a Best Practice.

This exercise also discriminates the wording that synthesized better the needs of each category and compared it to the rest of the state legislations that regulate such categories too, considering that concise regulations leave less room for legal interpretation that the operator can use in their favor to infringe the law. Using the same methodology, it is possible to come up with a categorization that identifies Undesired Practices in the state legislations. The discerning criteria is the following:

1. Routine Flaring Prohibition: The ideal regulation must prohibit routine flaring and carefully circumscribe exceptions to that prohibition, such as emergencies, upset conditions, well maintenance activities, testing, liquids unloading, among others.
2. Mandatory Measurement and Reporting: The local regulation must explicitly ask for the owners/operators to measure the volume of associated gas produced, separated, vented and flared throughout the production chain. In the best case the report should be submitted to the authority on a monthly or quarterly basis.
3. Flaring and Venting Differentiation: The regulation must mandate a clear distinction between these two processes. This is crucial for environmental and air quality control since each one has different global warming potentials and impact on the environment. Where failure to capture is allowed, flaring must be allowed before venting and venting should be allowed only when absolutely necessary for safety purposes.
4. Clear Definition of Safety and Unnecessary Flaring: The regulation must distinguish between unnecessary and necessary (for safety or maintenance purposes) flaring and venting. The distinction is important because it gives the operators the necessary margin to operate a well. However, the regulation must establish a maximum period after which flaring or venting cannot be considered for safety.
5. Flaring threshold. The regulation must set a specific volume threshold to distinguish what constitutes safety or acceptable flaring from unnecessary waste.
6. Waste Definition: The regulation must contain a cohesive and concise definition of what constitutes waste in the oil and gas industry. This is imperative to avoid owners or operators using this classification to dispose of natural gas that would otherwise be consumed or commercialized. Today each state legislation has its own legal definition creating an intricate system independent from other regulations, which makes it very difficult to coordinate or integrate them in a way that will properly address the problem.
7. Third Party Monitoring: The local laws should incorporate the use of new technologies to measure natural gas flaring and venting from above to validate the operator's and owner's data.

The Ideal Regulation would theoretically close any backdoor for the operators to keep unnecessary gas flaring and venting. Some of the major states producers have already included these Best Practices in their regulatory framework , but no state has included them all. Table 5.5 presents the outstanding states in each category, and in bold caption the one that we identified having the Best Practice of them, along with a brief description of the regulation and its qualities.

Category	States	Best Practice
Routine Flaring Prohibition	California Colorado Idaho New Mexico Ohio Texas West Virginia	No state has an explicit prohibition, they strictly ban the waste of natural gas instead and give no room for waste.
Mandatory Measurement and Reporting	Arkansas Colorado North Dakota Texas Utah **Wyoming**	Wyoming Oil and Gas Conservation Commission. Chapter 3. Sec. 39. *Authorization for Flaring and Venting of Gas.* The regulation encourages the use of practical technologies to minimize venting and flaring of natural gas and requires monthly reports of this processes including: (i) Duration and total estimated volume of gas; (ii) Circumstances that resulted in flared or vented gas; (iii) Identification of whether gas was vented or flared; (iv) Identification of whether the gas volume is based on metered flow, Gas/Oil Ratio (GOR) (v) Owners/Operators with wells venting or flaring shall submit a compositional analysis of the gas.
Flaring and Venting Differentiation	**Louisiana** Montana Wyoming	Louisiana Administrative Code. Title 33: III, Environmental Quality: Air This state regulation includes a subchapter K that limits volatile organic compounds and not only it differentiates between venting and flaring, but the different types of flaring and their admissible thresholds.
Safety and Unnecessary Flaring Differentiation	Alaska Colorado Idaho Kansas Ohio Pennsylvania Texas Utah **Wyoming**	Wyoming Oil and Gas Conservation Commission. Chapter 3. Sec. 39. *Authorization for Flaring and Venting of Gas.* The regulation includes the report of natural gas flared for safety measures and it also requires for the operator to disclose the circumstances that resulted in the flaring procedure.
Flaring Threshold	Louisiana Montana Idaho Kansas Louisiana Montana Oklahoma **Pennsylvania** Texas Utah	Oil and Gas Conservation Act. Laws of Pennsylvania. The regulation uses the parameters defined in the Code of Federal Regulations Title 40. Protection of Environment to determine the threshold to define a safety flaring process from unnecessary or excessive flaring.

Waste Definition	Alaska Arkansas Colorado Kansas Montana New Mexico **Oklahoma**	Oklahoma Administrative Code. Title 165: Corporation Commission. Chapter 10: Oil and Gas Conservation This regulation defines waste in a comprehensive way, including economic waste and it recognizes specifically the associated gas produced from common sources and the vented gas as well. It also considers waste the flaring of tail gasoline, pressure maintenance and recycling plants where markets are available. A distinction that separates these procedures from unnecessary waste of natural gas.
Third Party Monitoring	No State considers it	

Table 5.5 Best Practices in the Producer States' Regulation

This analysis showed that only Louisiana, Montana and Wyoming legislations require the differentiation of flaring and venting.[183] On the contrary, most of the producing states have included in their regulatory framework some requirements on measurement and reporting, differentiation between safety and unnecessary flaring, some kind of flaring threshold, and a waste definition. This means that a first step to harmonize state legislation would be pushing for them to include a clear distinction on the natural gas that is flared versus the volumes that are being vented. The other components of the Ideal Regulation are present in most of the regulatory frameworks, but they could also be upgraded towards the Best Practice.

Wyoming has the only state regulation that includes two Best Practices, one is its requirement on "Mandatory Measurement and Reporting" and the other on "Safety and Unnecessary Flaring Differentiation". The Wyoming Oil and Gas Conservation Commission has established specific requirements for the operators to measure natural gas flaring and venting and report these volumes to the Commission including an explanation on the circumstances that led to these practices. The legislation also requires the operators to separate natural gas flaring and venting for safety measures from the unnecessary disposal of this hydrocarbon.[184] The wording of these regulations is concise and clear leaving no room for interpretation that can lead to the infringement of these laws.

The analysis throws an interesting case, Texas has a clear and detailed regulation on gas flaring, it also concentrates the authority on this problem in a single regulatory agency, the Railroad Commission. The state legislation clearly defines what constitutes safety flaring and what does

[183] Wyoming Oil and Gas Conservation Commission, "Chapter 3. Operational Rules, Drilling Rules" (2016), https://docs.google.com/a/wyo.gov/viewer?a=v&pid=sites&srcid=d3lvLmdvdnxvaWwtYW5kLWdhc3Rlc3R8Z3g6NzE2ZjM3ODg3NmU5ZWQzYg; Louisiana State Legislation, "Louisiana Administrative Code. Title 43. Natural Resources." (2020), https://www.doa.la.gov/Pages/osr/lac/LAC-43.aspx; Office of Oil & Natural Gas U.S. Energy Department, "Montana Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/Montana.pdf; Office of Oil & Natural Gas U.S. Energy Department, "Wyoming Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/Wyoming.pdf.

[184] Wyoming Oil and Gas Conservation Commission, Chapter 3. Operational Rules, Drilling Rules; U.S. Energy Department, "Wyoming Natural Gas Flaring and Venting Regulations."

not and it has specific thresholds to differentiate between these processes.[185] These characteristics place the state regulation among the outstanding cases, but the volumes of natural gas flared and vented grew 644% between 2000 and 2018.[186] This case is proof that regulation should consider multiple factors to properly address this problem. This document recognizes that regulation interacts with market forces, technological changes, and political agendas, so it is only logical to analyze these three factors together to understand the circumstances behind natural gas flaring and venting. It is Interesting that the best practices do not come from states with high flaring rates such as Texas, New Mexico and North Dakota, but from states that contribute less to the problem such as Wyoming, Pennsylvania or Louisiana.

Using the same methodology this research has identified undesirable regulations that create room for improvements. This exercise analyzed the state legislations to identify the more obscure, ambiguous or simply inexistent regulations in terms of natural gas flaring and venting and organized undesirable traits that could be significantly improved using the Best Practices from other state legislations as an example, Table 5.6 shows the result from that analysis.

Topic	States	Undesirable Practice
Routine Flaring Prohibition	**Alaska** **Arkansas** **Kansas** **Louisiana** **Montana** NorthDakota **Oklahoma** Pennsylvania Utah Wyoming	No state has an explicit prohibition. The states in bold are those that prohibit some kind of waste but they give the operators a space to flare or vent for different reasons, as long as they stay below a certain threshold.
Mandatory Measurement and Reporting	California **New Mexico** Oklahoma Pennsylvania	New Mexico Administrative Code. Title 19, Chapter 15. Subsection 18 *Production Operating Practices. Metered Cashing Head* The owner of the lease is not required to measure the exact amount of casinghead gas the owner produces and uses for fuel purposes in the lease's development and normal operation. The owner of the lease shall meter and report casinghead gas produced and sold or transported away from a lease, except small amounts of flare gas, in cubic feet monthly to the division.

185 Katherine Ann Willyard and Gunnar W. Schade, "Flaring in Two Texas Shale Areas: Comparison of Bottom-up with Top-down Volume Estimates for 2012 to 2015," *Science of The Total Environment* 691 (November 15, 2019): 243–51, https://doi.org/10.1016/j.scitotenv.2019.06.465; Office of Oil & Natural Gas U.S. Energy Department, "Texas Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/Texas.pdf; Railroad Commission of Texas, "Texas RRC - Flaring Regulation," accessed April 15, 2020, https://www.rrc.state.tx.us/about-us/resource-center/faqs/oil-gas-faqs/faq-flaring-regulation/.

186 U.S. Energy Information Administration, "Natural Gas Vented and Flared."

Flaring and Venting Differentiation	California **New Mexico** Utah West Virginia	New Mexico Administrative Code. Title 19, Chapter 15. Subsection 18 *Production Operating Practices. Metered Cashing Head* The owner of the lease is not required to measure the exact amount of casinghead gas the owner produces and uses for fuel purposes in the lease's development and normal operation. The owner of the lease shall meter and report casinghead gas produced and sold or transported away from a lease, except small amounts of flare gas, in cubic feet monthly to the division.
Safety and Unnecessary Flaring Differentiation	New Mexico Oklahoma **Pennsylvania**	Pennsylvania Law. Oil and Gas Conservation Law The Oil and Gas Conservation Commissions from the Department of Mines and Mineral Industries have the authority to execute investigations and Inspections of owners or producers records, including the unnecessary or excessive surface loss or destruction or oil and gas. However, there is no clear distinction on what constitutes "unnecessary destruction" in the regulation.
Flaring Threshold	Arkansas California North Dakota Ohio Oklahoma **Pennsylvania**	Pennsylvania Law. Oil and Gas Conservation Law The law forbids any kind of waste of oil and gas in the state, and waste is described as "The unnecessary or excessive surface loss or destruction of oil and gas". There is no clear and effective threshold to separate safety measures from unnecessary flaring or venting.
Waste Definition	California **North Dakota** Texas Wyoming	North Dakota Administrative Code. Title 43. *Chapter 3. Oil and GAs Conservation* Waste is clearly prohibited to all producers, contractors, owners, drillers, carriers, gas distributors, service companies, pipe pulling and salvaging contractors. However, there is no definition of Waste in the regulation, leaving this prohibition to interpretation.
Third Party Monitoring	No State considers it	

Table 5.6 Opportunity Areas in the Producer States' Regulation

The Best versus Undesired practices exercise throws an interesting result, while California has a very ambiguous legislation for natural gas flaring and venting their emissions represented only 2.3% of the total gas flared or vented in 2011, the last year this state reported their volumes to the EIA.[187] On the contrary, Texas has a very clear and specific regulation around natural gas flaring and venting, but their emissions have risen significantly since the shale revolution started in that state.[188] As mentioned before, the legislations evolved at a different, usually slower, pace than the industry, that is one possible answer to this paradox. Other hypotheses suggest that the geology in these states is very different causing the oil wells in California to present less associated gas compared to the plays in Texas. Finally, another explanation is the political one, which suggests that when the Legislator does not trust the political will of the enforcing

187 U.S. Energy Information Administration, "Natural Gas Vented and Flared."
188 Sitton, "2020 Texas Flaring Report Q1"; U.S. Energy Department, "Texas Natural Gas Flaring and Venting Regulations"; Railroad Commission of Texas, "Texas RRC - Flaring Regulation."

regulatory agencies it tends to write a more extensive, detailed and specific law to limit the agencies actions.

It is difficult to determine which hypothesis explains both atypical cases as California and Texas, but given the available information, these two cases reinforce the idea that the regulation interacts with many other factors that determine the volumes of natural gas flared or vented in the U.S. However, it is important to have a solid regulatory framework that encourages operators to cut their emissions and to have a more efficient waste disposal process. Having a loose regulation can allow higher flaring and venting volumes.

5.4. Definition of Waste

The definition of waste is particularly relevant in the fight to reduce natural gas flaring and venting since it can open a backdoor for operators to catalogue part of their associated gas as waste and dispose of it without reporting this volume as flaring or venting. Having a common definition of waste could be a solution to distinguish whether natural gas can be categorized as waste or not, and what would be the policy to dispose of it safely. Today states' legislations have their own waste definition and specific rules to treat and dispose of it according to environmental and safety standards. However, states like North Dakota, Texas and Wyoming do not properly define waste in their oil and gas regulation opening the door for legal interpretation or confusion, at least.[189] In 2020, Commissioner Ryan Sitton from the Texas Railroad Commission asked around his colleges their definition on waste but he could not find a consensus, even when they all agreed that having the term defined is an important issue to address natural gas flaring. Besides the states mentioned before, the rest of the oil producing states have a definition on waste, but the wording varies significantly creating different approaches to this issue.

Some state regulations categorically prohibit the waste of oil and natural gas in their territory which increases the urgency of having an appropriate definition to give the operators legal certainty on what they can and cannot do with their associated gas. As mentioned before, the main reason why natural gas is not captured is that it is uneconomical to sequester it, process it and place it on the market, particularly as the price of this hydrocarbon remains low. This is relevant because some legislations also prohibit economic waste, meaning the inefficient use of this hydrocarbon in the operation of the well or its placement in a target market. Kansas legislation defined as:

General Rules and Regulations for the Conservation of Crude Oil and Natural Gas

189 Wyoming Oil and Gas Conservation Commission, "Chapter 3. Operational Rules, Drilling Rules" (2016), https://docs.google.com/a/wyo.gov/viewer?a=v&pid=sites&srcid=d3lvLmdvdnxvaWwtYW5kLWdhc3Rlc3R8Z3g6NzE2ZjM3ODg3NmU5ZWQzYg; North Dakota Mineral Resources, "North Dakota Mineral Resources," January 2020, https://www.dmr.nd.gov/oilgas/DMR_Fact_Sheets.pdf; Office of Oil & Natural Gas U.S. Energy Department, "North Dakota Natural Gas Flaring and Venting Regulations," May 2019, https://www.energy.gov/sites/prod/files/2019/08/f66/North%20Dakota.pdf; Stephen Rassenfoss, "Texas Railroad Commission, Executives Hold Hearing To Explore Production Quotas," April 16, 2020, https://pubs.spe.org/en/jpt/jpt-article-detail/?art=6895; Railroad Commission of Texas, "Texas RRC - Flaring Regulation," accessed April 15, 2020, https://www.rrc.state.tx.us/about-us/resource-center/faqs/oil-gas-faqs/faq-flaring-regulation/.

Article 7. Production and Conservation of Natural Gas
57 - 702 Definitions

(...) Economic waste shall mean the use of natural gas in any manner or process except for efficient light, fuel, carbon black manufacturing and repressuring, or for chemical or other processes by which such gas is efficiently converted into a solid or a liquid substance.

The definition of economic waste is still defined by operational standards rather than market drivers, which excludes the main reason natural gas is flared or vented today. A better definition of waste to reduce natural gas flaring should include the prohibition to dispose of this hydrocarbon to obtain one of higher value such as oil. Following this logic, some experts have proposed introducing a tax on flaring to address this issue and to put a price on the environmental damage caused by this activity. Jason Bordoff, has proposed to use a tax large enough to encourage capital investment on infrastructure to transport gas to the markets and reduce the flaring ratios in the U.S.[190] However, it is still unclear what would be an acceptable range for such a tax and how it could impact the production of oil in the medium and long terms.

As in 2020, there are seven state regulations that share a common basis of their waste definition: Alaska, Arkansas, Kansas, Montana, Ohio, Oklahoma, and West Virginia. These regulations separate oil and natural gas wastes and define depending on its location in the production chain. The previous analysis recognized Oklahoma's waste definition as the Best Practice because it clearly separates what constitutes waste along the production chain and differentiates oil from natural gas. This regulation can guide the harmonization of other state regulations, in particular in the states that share the same basis, mentioned before.

Title 165: Corporation Commission. Ch 10. Oil and Gas Conservation.
Definitions

"Waste" means:
(A) As applied to the production of oil, in addition to its ordinary meaning, "shall include economic waste, underground waste, including water encroachment in the oil or gas bearing strata; the use of reservoir energy for oil producing purposes by means or methods that unreasonably interfere with obtaining from the common source of supply the largest ultimate recovery of oil; surface waste and waste incident to the production of oil in excess of transportation or marketing facilities or reasonable market demands." [52 O.S.A., 86.2]
(B) As applied to gas, in addition to its ordinary meaning, shall include economic waste; "the inefficient or wasteful utilization of gas in the operation of oil wells drilled to and producing from a common source of supply; the inefficient or wasteful utilization of gas in the operation of gas wells drilled to and producing from a common source of supply; the production of gas in such quantities or in such manner as unreasonably to reduce reservoir pressure or unreasonably to diminish the quantity of oil or gas that might be recovered from a common source of supply; the escape, directly or indirectly, of gas from oil wells producing from a common source of supply into the open air in excess of the amount necessary in the efficient drilling, completion or operation thereof; waste incident to the production of natural gas in excess of transportation and marketing facilities or reasonable market demand; the escape, blowing, or releasing, directly or indirectly, into the open air, of gas from well productive of gas only, drilled into any common source of supply, save only such as is necessary in the efficient drilling and completion thereof; and the unnecessary depletion or inefficient utilization of gas energy contained in a common source of supply." [52 O.S.A. §86.3]
(C) The use of gas for the manufacture of carbon black or similar products predominantly carbon, except as specifically authorized by the Commission, shall constitute waste.

190 Jason Bordoff, "A Flaring Tax Can End This Wasteful and Damaging Practice," March 3, 2020, https://www.ft.com/content/beae788e-5c9d-11ea-ac5e-df00963c20e6.

(D) The flaring of tail gas at gasoline, pressure maintenance, or recycling plants where a market is available.[191]

The Oklahoma regulation covers most of the backdoors that could lead to legal interpretation favouring excessive gas flaring and venting. This definition can also improve by including a more comprehensive approach to the term "economic waste", as it is currently defined, it refers to the inefficient utilization of natural gas in the operation of oil wells rather than its potential to create economic value itself. Nevertheless, this is an excellent starting point to redefine other regulations or to use a basis for a federal definition of waste that compels the local legislation to observe a broader definition of what constitutes economic waste. Having a shared definition on waste is relevant to maintain the flaring and venting standards in the industry, today's situation opens the window for legal interpretation and offers a back door for operators to classify excess gas as waste and burn it or vent it.

Having a more strict and specific definition on waste would require adjusting the waste prohibition in some states, because it could create an inoperable situation in which oil and gas companies would not have a margin to conduct their work. The requirements on flaring and venting for safety measures would have to be adjusted so they give the operators the required range to conduct their business without breaking the law. This would require the waste definition to include a range or a specific threshold so the operators can distinguish between safety procedures and waste management.

5.5. Future Regulations for Natural Gas Flaring and Venting

The recent development of measurement technologies puts pressure on the operators to check their measurement procedures and sensors. The discrepancies between satellite data and the operators' reports raised concerns about what measures are more accurate and what should be taken into consideration to understand and address this problem. Using data form the National Oceanic and Atmospheric Administration (NOAA) Earth Observation Group satellite data, EDF compared this measurement with the operator's report in the U.S. and discovered that only in 2017 the burned gas detected by the satellite doubled the operators' report in the Permian basin.[192] Standard and Poor's (S&P) arrived at the same conclusion after they compared the information collected by state agencies with the satellite data from NOAA and discovered that operator's data might be under-reporting volumes of natural gas flared and vented. S&P highlighted some of the benefits for satellite data over the ground reports saying that the former is a more sophisticated, accurate and timely assessment of the phenomenon than the later. Additionally, satellites are non-invasive technologies that reduce the time and resources needed to measure the problem. Additionally, the date process algorithm developed by NOAA has

191 Oklahoma Legislature, "Oklahoma Administrative Code | Chapter 10 - Oil and Gas Conservation | Casetext," § Chapter 10. Oil and Gas Conservation (2019), https://casetext.com/regulation/oklahoma-administrative-code/title-165-corporation-commission/chapter-10-oil-and-gas-conservation.

192 Colin Leyden, "Satellite Data Confirms Permian Gas Flaring Is Double What Companies Report," Energy Exchange, January 24, 2019, http://blogs.edf.org/energyexchange/2019/01/24/satellite-data-confirms-permian-gas-flaring-is-double-what-companies-report/.

proved to be very accurate with a +/- 9.5% standard error.[193] Both organizations consider that having this technology monitoring natural gas flaring and venting could help closing the gap between the available data and having a better measurement of the real problem.

S&P used NOAA data to calculate the natural gas flared as a percentage of the total production of this hydrocarbon. This index can be useful to understand what are acceptable flaring ratios, but it is also relevant to identify the plays and the operator that are struggling with this problem.[194] Having something close to real-time data is a tool that regulators can use to enforce the law, while service companies can use it to provide specific solutions for the operators to tackle this problem. In terms of the regulation, what matters is the capability of the law to capture the variations and standard errors of satellite data into consideration. Nevertheless, the regulation should contemplate that gas flares share specific characteristics that give them away:

1. Gas flares tend to form circular light features in the sky with bright centers and wide arms;
2. Many gas flares present color in blue, green, and red images;
3. These flares tend to be isolated or far from urban areas, which makes them more visible at night.[195]

These characteristics have been identified by the experts in this topic so the regulation could use them to define what constitutes a gas flare not only in technical terms, but from the regulatory standpoint. It is also important that the regulation delineates the basic principles to include new measurement as references to enforce the law, while it creates spaces for innovation and the development of new measurement techniques.

Including new real-time data measurement in the regulation requires an adjustment of the legal framework itself: the mandatory distinction of flaring and venting, defining what constitutes flaring for safety, what is the threshold to consider unnecessary flaring, and defining what constitutes waste and how it can be treated. The legal framework should be prepared for satellite estimations that could challenge the operators' data and it should find a way to reconcile them soon or it will have to deal with a third party questioning the data reported.

An effective regulation should open windows for technological innovations and legal procedures to incorporate them in the legal framework. However, forecasting where innovation will come from is very difficult, so a better approach could be to create a mechanism to force the legislation to periodically review the new technologies available in the market and their potential impact on the oil and gas industry. In the past, several experts have pointed out the unintended barriers for innovations created in the regulation and their adverse effects on the development and improvement of the industry. In 2017, Robert Kleinberg pointed out that the Emission Standards for New, Reconstructed, adn Modified Sources Reconsiderations of the EPA discouraged technological innovation in methane leak detection because it limited the approved methods for

193 Brian Collins, "Are Some Shale Producers Under-Reporting Gas Flaring to Keep Oil Flowing?," October 24, 2018, https://platform.mi.spglobal.com/web/client?auth=inherit&sf200858251=1#news/article?id=47199929&cdid=A-47199929-12062.

194 Collins, "Are Some Shale Producers Under-Reporting Gas Flaring to Keep Oil Flowing?"

195 Christopher D. Elvidge et al., "A Fifteen Year Record of Global Natural Gas Flaring Derived from Satellite Data," *Energies* 2, no. 3 (September 2009): 595–622, https://doi.org/10.3390/en20300595.

methane leak detections to specific technologies, leaving the rest of the options out of the discussion.[196] Future regulation should be open to new technologies and it should be flexible with technological improvements in the oil and gas industry.

5.6. Lessons from Mexico

Mexico does not have a reputation for enforcing environmental laws, but over the past decade the government developed a strategy to reduce gas flaring and improve the performance of the major oil and gas operator, Pemex. In 2009, the Ministry of Energy (SENER) and the National Hydrocarbons Commission (CNH) developed a strategy with Pemex to reduce associated gas flaring in Mexico, that year the official estimations showed that the oil and gas company was losing $3.1 billion dollars due to this activity. The strategy set milestones for Pemex to reduce its flaring and monitor its progress over the years. The plan included a detailed investment Calendar and operational improvements that Pemex should implement to achieve the goal.[197] This approach worked out in Mexico and the natural gas flaring contracted after the regulation started.[198] Over the years, the regulator worked closely with Pemex to address this problem using the "shaming approach" rather than penalizing the company.

One of the experts interviewed for this investigation mentioned that CNH's first regulations had no penalties for the Pemex if it did not cut gas flaring. However, the Commission began publishing the volumes of associated gas flared by Pemex on a monthly basis creating a reputation risk for the company, in particular in a context where the public opinion not only saw the volumes flared, but also the market value of such waste. Another interviewee corroborated the effectiveness of such strategy and the source also mentioned that the CNH continuous monitoring and random audits to the production sites have contributed to the effectiveness of the project. Table 5.7 shows the plays that flared below their year goal and how it took them to go back in the abatement track.[199]

196 Robert Kleinberg, "Regulations.Gov - Comment," accessed May 12, 2020, https://www.regulations.gov/document?D=EPA-HQ-OAR-2017-0483-0760.
197 Reuters, "Mexico Orders Pemex to Reduce Natgas Flaring," *Reuters*, November 26, 2009, https://www.reuters.com/article/mexico-energy-idUSN2537400520091126.
198 SENER, "Regulación de La CNH a La Quema y El Venteo de Gas," accessed May 15, 2020, http://sie.energia.gob.mx/bdiController.do?action=cuadro&subAction=applyOptions.
199 SENER, "Regulación de La CNH a La Quema y El Venteo de Gas," accessed May 15, 2020, http://sie.energia.gob.mx/bdiController.do?action=cuadro&subAction=applyOptions.

Play	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Abkatun-Pol-Chuc	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Bellota-Jujo	OK	OK	OK	Fail	OK	OK	OK	Fail	Fail	OK
Cantarell	Fail	OK	OK	Fail	OK	OK	OK	Fail	Fail	OK
Cinco Presidentes	OK	OK	Fail	OK	OK	OK	OK	Fail	Fail	OK
Ku-Maloob-Zaap	OK	OK	OK	Fail	Fail	OK	OK	OK	OK	OK
Litoral de Tabasco	OK	Fail	Fail	OK	Fail	OK	OK	OK	OK	OK
Macuspana-Muspac	OK	OK	Fail	OK	OK	OK	OK	Fail	Fail	OK
Poza Rica-Altamira	OK	Fail	OK	OK	Fail	OK	OK	Fail	Fail	OK
Samaria-Luna	Fail	OK	OK	Fail	OK	OK	OK	Fail	Fail	OK
Aceite Terciario del Golfo	Fail	OK	OK	OK	OK	OK	OK	Fail	OK	OK
Veracruz	Fail	Fail	Fail	Fail	OK	OK	OK	Fail	Fail	OK

Table 5.7 Regulatory Compliance per Play

In 2015 and 2016, the goals regulator was flexible with the goals to reduce flaring as a consequence of the fall in the price of crude oil that happened at the end of 2014, the same arrangement occurred in 2019 as a government response to the negative financial results of Pemex. The regulation allowed the CNH to set goals per year so it can adjust the target when it is needed. One of the interviewees mentioned that this strategy has been effective reducing natural gas flaring, but its strength has decreased since 2017 due to the pressure on Pemex investment capital. The source pointed out that upstream activities have been postponed as a result and the program to abate gas flaring has taken the hardest hit over the past years.

According to both experts, the case-to-case approach has worked in Mexico because the federal government has the authority to impose a general regulation, sanction the player when they do not reach the goals, but also because the legislation is flexible enough for the regulator to adjust the strategy when is needed and to collaborate with the operators when they are struggling following the plan. This case-to-case approach could be an alternative for state regulators in the U.S. to adapt their abatement goals and strict legislation on flaring with the regulatory flexibility required to adjust the strategy when the circumstances change. However, for this approach to work properly, said one of the interviewees, it is important that the regulator is independent enough from the industry to act as a mediator and a law enforcement organization.

6. Recommendation

There is no quick fix for the problem of gas flaring due to its global prevalence, unknown extent, and widespread implications. Based on our analysis we believe the best path forward is a combination of technology and policy solutions, with measurement and reporting accuracy as the first priority. Governments should increase and enforce their requirements for complete, accurate reporting that is differentiated by flaring, venting, fugitive leaks, and safety. Industry should invest in on-site technology solutions to make measurement easier and more accurate. Nonprofits and independent researchers should continue working to bridge the gap between satellite and reported data, working with both industry and governments to understand the full extent of the problem.

Solutions will result from combinations of

- Policy -
  - accurate reporting, enforcement, economic incentives
- Industry Actions -
  - infrastructure, operational, technology application
- Environmental NGO Actions -
  - research, compliance, enforcement, measurement support, education
- Research and Development -
  - Technology innovation,

1. Expanding our understanding of the problem

- Prioritize accurate measurements
  - Independent flaring/venting coalition to implement measurement systems and track emissions
  - Can employ multiple measurement tools and update them as technology improves
    - Smart flow meters to send data directly to database
  - Reports data to governments instead of self-reporting from companies
  - Subscriber system to gain support and participation from companies
    - Companies pay to have emissions independently measured and verified
    - Saves companies money with less measurement and reporting time and tools
    - Can easily alert members to problems (leaks, unlit flares, emergencies etc)
  - Can report up to date flaring data online (see below)
  - Definitely requires transparency and representatives from all stakeholders
  - You can’t manage it if you can’t measure it
- Standardize reporting requirements
  - Reporting of safety vs waste or excessive flaring
  - Flaring vs venting

    - Include leaking/fugitive emissions and unreported categories of release
    - Forcing companies to report all data will help them and the public be more aware and can lead them to solve the problem, and secure social license to operate
- Less of a burden to implement than a tax or infrastructure
    - Infrastructure is expensive and time consuming
    - Trying to implement a tax or cap and trade scheme without accurate measurement and reporting will be impossible
- Investment/capital sector support -
    - ESG ratings tie in,
    - concrete data for analysis
- Possible industry incentives/implications of accurate measurement and timely reporting
    - Up to date data transparency may increase competition between companies to achieve the best practices and lowest emissions
    - Cost savings from streamlined reporting,
    - Quickly fixed leaks improve safety and save resources, (more) accurate analysis of economic value

2. Design gas capture requirements that would set firm limits on the percentage of gas that companies are allowed to flare across the basin

- Cannot monitor or enforce compliance without accurate measurements
- Gas capture percentage relies on many factors
    - including ratio of oil and gas,
    - operator and well size,
    - location,
    - access to infrastructure
- Need a methodology for determining ideal capture amounts
    - North Dakota goal was 90-95% by this year, which they are not going to meet
- Several technologies for cap capture and utilization
    - On-site power generation -
        - if there is not infrastructure/pipeline access, associated gas can be captured to be used to generate power locally,
        - Used to power drilling and well equipment
        - sell location-based access to power - Bitcoin mining or cloud computing
    - Sell through pipeline
    - Sell through LNG, gas to liquid
    - Reinjection

3. Extend gas production tax to flared gas (from project description)

- Cannot implement a tax without accurate measurements -
    - No way to know how much each company owes or estimate revenue, no way to enforce
    - If the tax is implemented before issues with reporting are solved, companies will have even less incentive for accurate reporting and measurement.

    - May be able to gain measurement/reporting regulation support from the industry if a tax is taken off the table (at least temporarily)
    - Use accurate reporting to implement best practices, use fines/shutdowns for operators who don't comply,
- Flaring Cap and Trade system
    - Allows companies without access to infrastructure to purchase "emissions permits" from companies with access
    - Can be an efficient way to reduce emissions with less economic burden on producers
    - There's a lot of research for pollution and the reduction of acid rain
    - Still requires accurate measurement and reporting

4. Display up-to-date flaring data online (from project description)

- Need real-time detection and measurement reporting -
    - ALFa LDS, VIIRS, smart meters
- Regulations currently require reporting on forms to different states -
    - A central database would be easier and cost effective for operators, governments, and researchers
- Removes the multi-tiered system of operator-state-national-world
- Also removes the 9+ month delay for data
    - Companies flare in real time and respond to immediate/short term demand, but flaring data is not available for researchers/policy makers for almost a year
        - A lot can change in a year
- Side-by-side comparison of satellite vs reporting can help close the gap between the two forms of data

5. Ensure that innovation and new data streams such as satellites are incorporated into policies (from project description)

- How can satellite data be incorporated into regulations without operator-level data?
    - Operator level data is needed for enforcement and compliance
    - Satellite data can be used to set goals or for comparison, unclear how it could be used effectively to reduce emissions directly through policy
- Other forms of new data streams
    - High resolution satellites
    - Leak detection

6. Regulation improvements and goals

- Accurate data - can't regulate from satellite data because you can't differentiate operators
    - Satellites can provide an overall overview or goal
- Crack down on leaking/fugitive emissions

- Increase data sharing practices between emissions reporting agencies (EPA) and production reporting (BLM/BSEE)
  - Require more frequent/accurate emissions inspection
- Problem of enforcement -
  - Even where regulations exist there is little oversight or enforcement
  - Fines for incorrect or late reporting
  - Random site inspections
- Participation in a climate initiative could be made mandatory -
  - At least a commitment level could be mandatory,
  - enforcement is still a problem
- Remove reporting exceptions from legislation
  - everything should be measured and reported
  - even if the loss is unavoidable
- Create model legislation
  - With supporting information, which can be used as a vehicle to modernize state laws.
  - For reporting requirements, flaring/venting regulations, and emissions
  - Tactic often used by conservative groups[200]

7. Public awareness/education campaigns

- Educate the public in critical states about the role of flaring/venting and how it affects pollution, health, climate change etc.
- Avoid greenwashing of flares: "Flares help reduce the amount of pollution released into the environment by burning and destroying the gas instead of allowing it to vent directly into the atmosphere." [201]
  - Not wrong but rather misleading:
- Avoid greenwashing of natural gas
  - Natural gas is cleaner than oil and coal but it's not a clean alternative energy
  - Still produces carbon

8. Operational solutions

- Leasing electric and natural gas powered equipment instead of purchasing[202]
  - Reduces reliance of diesel fuel
  - Allows associated gas to be used on site to power equipment
  - Reduces up front investment for new drilling equipment
- Improve safety with better leak detection
  - MONITOR and METEC at CSU research to test low-cost methane sensing technologies to help reduce methane leaks

200 Resolution Concerning EPA Proposed Greenhouse Gas Emission Standards for New and Existing Fossil-Fueled Power Plants

201 Flaring at Oil and Natural Gas Production Sites (RG-457)

202 Carbon limits pg 21

    - Offers quick return on investment
- Green completion
    - Practices to reduce casinghead gas emissions during drilling and completion
- Easier for major companies to implement
- Companies can tie executive variable compensation to reducing emissions through flaring and methane metrics[203]

9. Technology-specific solutions

- Flare efficiency technology
    - More policy/regulatory incentives are needed for flare efficiency technology applications
    - Grants and funds from federal level on encouraging flare efficiency technologies are essential
    - Oil/gas investment projects are encouraged to include flaring monitoring and efficiency as criteria of environmental concerns
- Measurement:
    - Future flow meters can have real-time measurement data, wireless capabilities and self-verification systems, which can be applied to larger lines. Companies can access the flow rate in a second and link the data to their internal database
    - Satellite data can be utilized for parent companies to supervise their branches on environmental behaviors or for companies to supervise their regional offices
- Gas Utilization:
    - Integrated E&P companies are encouraged to develop pilot small-scale LNG projects as the storage backup near the drilling well or alternatives for pipelines
    - North Dakota and Texas should adopt more flexible oil/gas business models and portfolio strategies on selling gas
    - Data centers for cloud computing, blockchain and bitcoin mining could be a future trend for gas power generation

10. Maintaining the Status Quo by not directly intervening in flaring

- The production boom in the US may only last a few more years, some regulators and operators want to "wait it out"
    - Quote from TRRC chairman "that's just what happens in a boom"
    - Allows states to benefit from increased revenue while it lasts
    - Governments and operators save infrastructure and technology costs
- Cons of maintaining the status quo:
    - continued emissions are very bad for environment and climate change
    - don't know exactly how long boom will last - could be many more years
    - Results in wasted natural resources

Meanwhile:

203 Chevron Greenhouse Gas Management — Chevron.com

- Implement programs for carbon offsets or credits
    - Can help industry move towards carbon neutrality and offset effects
    - Compile a living list of qualifying programs, research, and technologies for companies to invest or participate in
- Invest/promote the scaling up of alternative clean energy to reduce reliance on oil and gas
    - Market solution intervention - money talks
    - May help incentivize producers to capture more/become ESG rated
    - Incorporate ESG metrics into credit rating
    - Provides opportunities for oil companies to invest and develop/transition to clean energy
    - Large companies are more aware of/put efforting into resolving flaring issue
    - Reduced oil and gas demand means that existing infrastructure may suffice, can temporarily shut down highest flaring fields

7. Questions raised and further research

Off-Shore

- We didn't address offshore drilling in this report, but flaring is also a problem on offshore rigs.

How to expand to other countries?

- International flaring/venting/emissions treaty among major producing countries and consuming countries
  - One of the most successful environmental treaties in history was the Montreal Protocol, which successfully eliminated the international use of chlorofluorocarbons and related substances which were causing the "hole" in the ozone layer of the atmosphere. The Montreal Protocol can provide a framework for effective cooperation, enforcement, and monitoring of an international gas flaring treaty.
  - Can use satellite data to monitor country-level, and eventually company-level compliance
    - Montreal Protocol used atmospheric CFC measurements to successfully locate and stop non-compliant producers
- World Bank Initiatives, International NGOs, etc
  - Participation and compliance is voluntary
  - Increase "naming and shaming" when participating companies/countries don't comply
    - Can use satellite data for country level, but not for individual operators or companies
    - Only works if countries/companies are affected by "shame"
- Private operators with an international presence
  - Use incentives for large companies to standardize their own practices internationally, at least internally
  - ESG ratings

Further Research Ideas

Research for standardized reporting and measuring

- Research and invest in infrastructure for high resolution detection
  - Global satellite data does not detect/measure intermittent or small flares
  - Network of both high resolution gas detection for venting and infrared imaging for flares

    - A technology from LANL is focused on NO and SO_2 detection instead of methane/CO_2 emission,[204] but it may be able to be adapted/applied
        - Aerosol Absorbing Index (absorbing soot/smoke vs scattering aerosols) might be interesting for flares. The 500 m pixel size is relevant.
    - ALFa LDS - Autonomous, Low cost, Fast Leak Detection System[205]
- Create a central reporting database that is user-friendly for all stakeholders
    - Precedent for a centralized, non-governmental reporting/monitoring system
    - EU "Independent Institution", proposed at 20 March 2020 workshop
- Draft common legislation language to help local governments and convince them to use/buy in to a central system
    - Draft legislation so they're all reporting the same way - industry might help lobby for that, eases their reporting time/costs
- Smart meters? If they can install a smart meter on every apartment in NYC, there must be a way to use similar real-time measurement with flowmeters
    - In industry this is called SCADA: supervisory control and data acquisition
    - Can then be calibrated/measured against emissions detection

Research for operational/safety interventions

- Help reduce emissions from fugitive leaks and (possibly) reduce necessary flaring for safety purposes
- ARPA-E program called MONITOR, including METEC at CSU are developing and testing technologies for onsite detection of methane leaks
- Possible input/collaboration from major industry players
- Research to reduce gas lost during initial drilling stages
    - EPA Green completions IPIECA
- Real-time VOC sensors
- Improve emergency sensors and prediction/tests
    - Redundancies for power outages

204 NACHOS
205 https://www.lanl.gov/discover/news-stories-archive/2019/July/0710-alfa-lds-technology.php

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9. Interviews

Interviewees	Position	Date
Jason Bordoff	Founding Director of the Center on Global Energy Policy at Columbia University	April 16, 2020
Marco Cota	CEO Talanza Energy	May 1, 2020
Adamelia Burgeño	Director of the National Center of Hydrocarbons Information at the Mexican National Commission of Hydrocarbons	May 13, 2020
Eric A. Kort	Associate Professor Atmospheric, Oceanic and Space Sciences, and Applied Physics at the University of Michigan	March 23, 2020
Donald Hickmott	Researcher at Los Alamos National Laboratory	February 22, 2020

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