

Statistical Study of Carbon Intensities in the GOM and PB

Ama Motiwala, Dr. Huzeifa Ismail

Submitted date: 10/04/2020 · Posted date: 13/04/2020

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Citation information: Motiwala, Ama; Ismail, Dr. Huzeifa (2020): Statistical Study of Carbon Intensities in the GOM and PB. ChemRxiv. Preprint. <https://doi.org/10.26434/chemrxiv.12111480.v1>

In addressing carbon emissions as the primary contributor to climate change, a study was conducted to examine the total carbon dioxide equivalent (CO₂e) emitted into the atmosphere from the production of crude oil and gas in the two largest producing regions of the U.S: the Permian Basin (PB) and the Gulf of Mexico (GOM). The objective of this report is not to compare the carbon intensities between PB and GOM, but rather to understand the causes of deviations observed between the two Basins, particularly in the years 2016 to 2018. This report details the initiative, including the research of emissions and production data from three federal agencies: the U.S. Environmental Protection Agency (EPA), U.S. Energy Information Administration (EIA), and the Bureau of Ocean Energy Management (BOEM). High-level analysis was conducted on six greenhouse gases: carbon dioxide, nitrous oxide, methane, sulfur hexafluoride, perfluorocarbons, and hydrofluorocarbons. Some major findings of this study include the establishment of a clear trend in which GHG emission rates increase as production increases. The mean carbon intensity, derived from the log normal distribution, for PB production and GOM production was determined to be 14.83 ± 3.374 kg CO₂e/BOE and 7.86 ± 2.32 kg CO₂e/BOE, respectively, for the year 2018 with 95% confidence interval. While three years of data is not sufficient to conclude a trend, both GOM and PB experienced lower carbon intensity rates in 2017 compared to 2016 and a higher carbon intensity rate in year 2018 compared to 2017. The primary causes for the PB's higher carbon intensity are flaring practices, transportation, hydraulic fracturing and weather-related impacts, which will be further discussed in this report.

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Statistical Study of Carbon Intensities in the GOM and PB

Amatullah Motiwalaa and Dr. Huzeifa Ismailb

^aEnvironmental Engineer, ^bPrincipal Investigator

Chirality Research Inc.

ama@chiralityresearch.com, huz@chiralityresearch.com

ABSTRACT

In addressing carbon emissions as the primary contributor to climate change, a study was conducted to examine the total carbon dioxide equivalent (CO_{2e}) emitted into the atmosphere from the production of crude oil and gas in the two largest producing regions of the U.S: the Permian Basin (PB) and the Gulf of Mexico (GOM). The objective of this report is not to compare the carbon intensities between PB and GOM, but rather to understand the causes of deviations observed between the two Basins, particularly in the years 2016 to 2018. This report details the initiative, including the research of emissions and production data from three federal agencies: the U.S. Environmental Protection Agency (EPA), U.S. Energy Information Administration (EIA), and the Bureau of Ocean Energy Management (BOEM). High-level analysis was conducted on six greenhouse gases: carbon dioxide, nitrous oxide, methane, sulfur hexafluoride, perfluorocarbons, and hydrofluorocarbons. Some major findings of this study include the establishment of a clear trend in which GHG emission rates increase as production increases. The mean carbon intensity, derived from the log normal distribution, for PB production and GOM production was determined to be 14.83 ± 3.374 kg CO_{2e}/BOE and 7.86 ± 2.32 kg CO_{2e}/BOE, respectively, for the year 2018 with 95% confidence interval. While three years of data is not sufficient to conclude a trend, both GOM and PB experienced lower carbon intensity rates in 2017 compared to 2016 and a higher carbon intensity rate in year 2018 compared to 2017. The primary causes for the PB's higher carbon intensity are flaring practices, transportation, hydraulic fracturing and weather-related impacts, which will be further discussed in this report.

I. INTRODUCTION

Anthropogenic climate change is an existential threat to business-as-usual for the global economy and industry. The increasing global temperature is primarily due to the increased concentration of greenhouse gases (GHGs); GHGs trap solar radiation and warm the surface of Earth. The GHGs primarily responsible for this impact are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and various fluorinated compounds. According to the EIA, U.S. energy related CO₂ emissions are projected to decrease by 4% compared to 2019 by 2050 in an effort to mitigate climate change.

The energy industry comprises 76% of the United States total anthropogenic emissions profile, of which oil and gas producers are the largest emitters. This industry utilizes, emits, and manages these GHGs as part of standard operation. In general, the energy industry is undergoing a major transformation to meet the demands on the low-carbon economy. To retain relevance in this low-carbon future, oil and gas operators must demonstrate a commitment to satisfy the growing demand for energy while managing climate change impacts. In addition to complying with global mandates, oil and gas companies must strengthen their environmental, social, and corporate governance (ESG) to satisfy shareholders and to remain competitive. ESG ratings are directly connected to capital availability and business performance.

A robust, long-term plan that serves the best interest of shareholders and secures longevity for the oil and gas business is necessary and requires quantifiable metrics to measure impacts. Carbon intensity, reported as kg CO₂ equivalent per barrel of oil equivalent (kg CO₂e/BOE), is the generally accepted metric to quantify the level of GHG impact per unit fossil fuel; this value captures not only the embedded carbon but also that which is emitted during production. CO₂ equivalent (CO₂e) is a standardization of GHGs, which individually have varying heat capacities and climate change impacts. This is particularly

relevant for oil and gas operators as much of their emissions are in the form of CH₄, which is a more potent GHG than CO₂. CO₂e allows for a quantification of total global warming impact, independent of GHG species.

For each unit fossil fuel, the majority of GHG emissions are associated with consumption. According to EIA, burning fossil fuels contributes to 93% of total U.S. CO₂ emissions.⁹ As a starting point, though, oil and gas operators are focusing on operational emissions that occur during production which constitutes only 34.6% of the total emissions out of all oil and gas processes.³⁸

To begin working toward reducing emissions, it is critical to understand the magnitude, sources, and nature of GHG emissions from oil and gas production. Generally, bottoms-up approaches that quantify emissions from the production level, severely underestimate production carbon intensity. This work aims to use a top-down approach, wherein emissions data is compared to production rates to quantify the real carbon intensity.

In the year 2019, the United States' total crude oil production was 4.5 billion barrels (Gbbbl). Of this, Texas's production comprised over 40%. In Texas, the largest producing regions are the Gulf of Mexico (GOM) and the Permian Basin (PB) with 1.85 Gbbbl and 0.69 Gbbbl in 2019, respectively. Thus, these two regions were selected as they are the largest producing regions based on crude oil productions reported by the EIA.

To quantify the carbon intensity for the GOM and the PB using a top-down approach, this work utilizes open-sourced, public emissions data provided by three federal agencies. This study attempts to quantify the carbon intensity for each unit of oil produced at upstream, midstream, and downstream oil and gas facilities in the GOM and the PB as kg CO₂e/BOE. The CO₂e emissions data include the following greenhouse gases:

CO₂, N₂O, CH₄, SF₆, perfluorocarbons, and hydrofluorocarbons. No life-cycle analysis was conducted.

II. COMPUTATIONAL METHODS

Data Sources

The Environmental Protection Agency (EPA) supplied the GHG emissions data and the oil and gas production data for the corresponding facilities. In an effort to verify the EPA's production data, additional production data was collected from the Energy Information Administration (EIA), and the Bureau of Ocean Energy Management (BOEM). All three agencies provide public, open-source data for oil and gas production. These federal agencies are not affiliated with this report in any way and hold no commercial agenda.

The United States EPA provides facility level information on GHGs, derived using the FLIGHT tool that is managed and is utilized by multiple government organizations. This multipurpose environmental analysis system provides geographic resolution by region for GHG emissions from large facilities in the United States.

The United States EIA is a statistical and analytical agency within the US Department of Energy (DOE) that provides impartial production data from offshore and onshore facilities, including fossil fuel production from multiple sources.

The BOEM manages the exploration and development of offshore energy and marine mineral resources on the United States Outer Continental Shelf (OCS) where about 18 percent of domestic crude oil and four percent of domestic natural gas supply is produced. The BOEM provided oil and gas production data for GOM facilities. Both the EIA and BOEM data was used predominantly as an accuracy check for EPA production data.

Data Integrity Management

As illustrated in Figure 1, a detailed workflow was utilized to ensure data integrity across the analysis. The process began with exploration of the various data sources, which were subsequently extracted, manipulated, and standardized. These datasets were combined into a single dataset that was incorporated into multiple visualization tools to obtain insights on production and emission rates of operators in the GOM and the PB.

Following an online literature search to scope for reliable sources of CO₂e emissions and production data of crude oil and gas, available data was downloaded, vetted for accuracy and reliability, and databased. High-level data analytics on this dataset included sense-checking industry-wide knowledge, such as "U.S. wide barrel of oil equivalent (BOE) production per day" and "PB production for year 2018." In 2018, the PB produced approximately 3.7 million barrels of oil per day. If the downloaded data was not within 10 percent of this value, the source was discarded and not considered for this report. The downloaded data that passed the sense-check, including data from the EPA, EIA, and BOEM, was databased for the in-depth analytics required to calculate the carbon intensity rates for production from the PB and the GOM.

GHG Emissions

GHG emissions data was exported from the EPA website using the FLIGHT tool, which provided an excel file containing an organized schema of emissions data for all onshore and offshore operators across basins from 2011 to 2018. Emissions data from the PB was limited to that with Basin Code 430. The geographic locations of offshore operators were limited to the states of Alabama, Texas, and Louisiana to isolate GOM operators' emissions data. The combination of GOM and PB resulted in 759 emissions data points collected from 2016 to 2018.

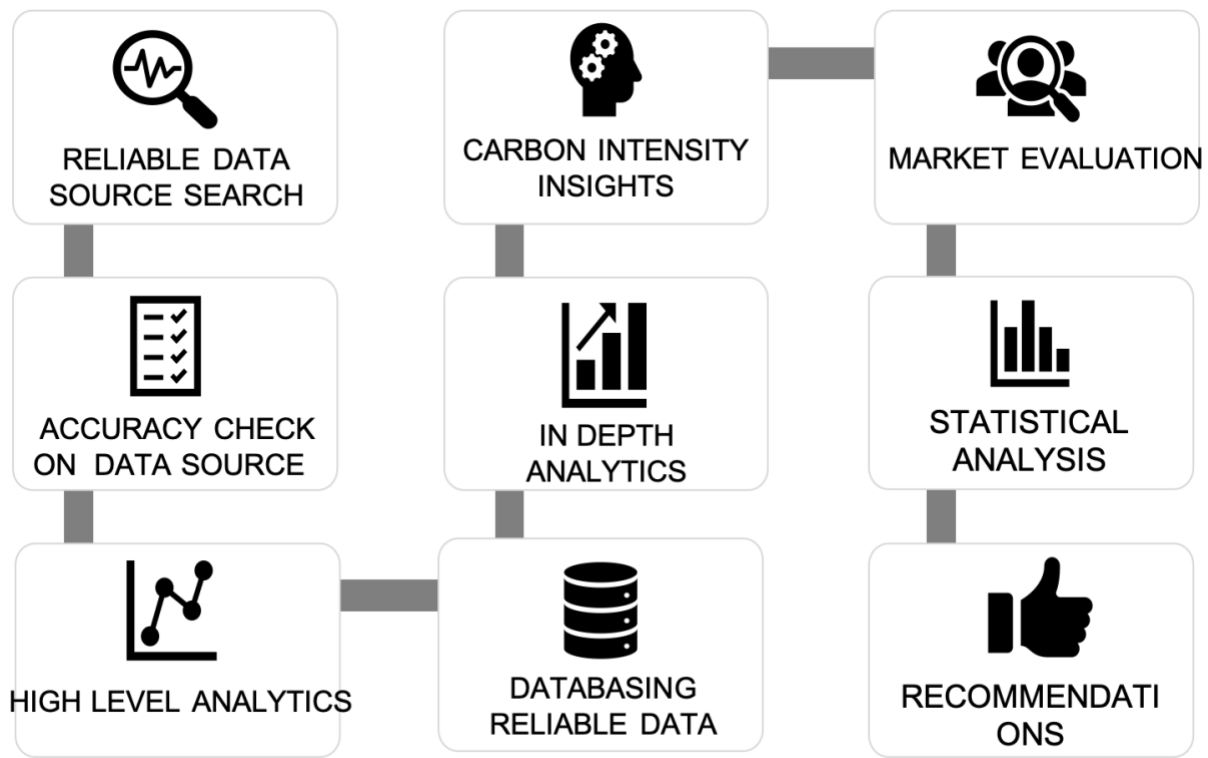


Figure 1: Overview of process workflow employed to perform statistical analysis on carbon intensity in the GOM and PB.

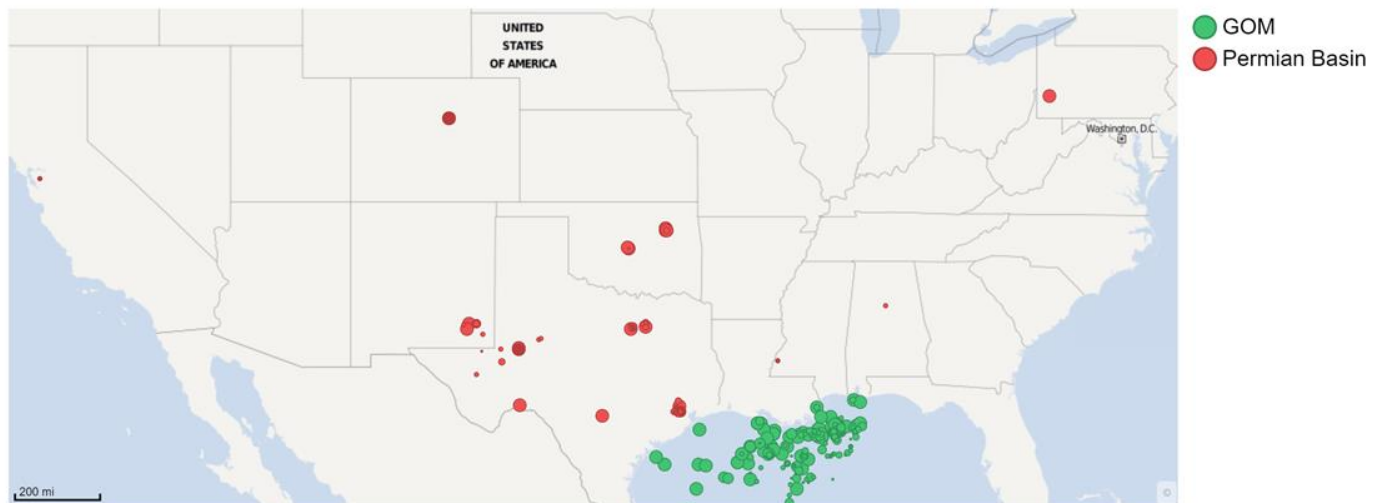


Figure 2: GOM and PB* operators considered in this report. For 2018, 137 GOM operators and 68 PB operators were considered, the latter of which are head office locations, not the operating facility.

Figure 2 displays a map of GOM operators and PB operators considered in this report. This map was constructed using latitudes and longitudes provided by the EPA. As clearly illustrated, PB locations are scattered across the United States even though the PB only covers a region in west Texas and New Mexico. Hence, PB locations were assumed to be the operators' headquarters or reporting offices, whereas GOM locations are the actual operating facilities. This was indicative of data quality discrepancies with GHG reporting to the EPA from onshore versus offshore operators.

Production Data

Production data, where available, was extracted from EPA for all reporting facilities between the

years 2011 and 2018. For the purpose of this report, all facilities that did not report any production data were voided from any analysis. No gas production or respective gas-to-oil ratios (GOR) values were reported between 2011 to 2014 – only oil production – so a BOE value was not obtained. In addition, none of the GOM operators reported any production data to EPA for the year 2015. Therefore, only data from 2016 to 2018 was considered for facilities that reported both production and emissions data.

Table 1 summarizes the number of facilities that reported both emissions and BOE data and the resulting carbon intensity calculations.

Table 1: Summary of emissions and BOE production reported to EPA by operators in GOM and PB facilities from 2016 to 2018 and the resulting arithmetic mean carbon intensity calculations

Year	Region	Total EPA Reporting facilities	# facilities with production data	Emissions* (kg CO ₂ e)	BOE	Carbon intensity (kg/BOE)
2018	PB	68	68	2.30×10^{10}	1.55×10^9	14.84
2018	GOM	137	124	6.64×10^9	8.53×10^8	7.79
2017	PB	62	62	1.56×10^{10}	1.06×10^9	14.65
2017	GOM	133	122	6.28×10^9	8.74×10^8	7.18
2016	PB	64	64	1.33×10^{10}	8.89×10^8	14.96
2016	GOM	122	116	6.40×10^9	7.69×10^8	8.32

*emissions limited to facilities that also reported production data

Analytical Methods

The extracted oil and gas production values from the EPA underwent a data accuracy check. A variance percentage was calculated between the production data from EPA and BOEM and EPA

and EIA. Table 2 summarizes the different production values reported in all three sources for GOM for the year 2018. In 2018, GOM had 124 facilities that reported both emissions and production data to the EPA out of 137 total GOM facilities.

Table 2: comparison of production data reported by EPA, EIA, and BOEM for GOM for 2018. All three sources report a production value within less than 5% variance, which verifies the accuracy of the main data source for this report, EPA.

Year	Basin	Source	Crude oil production (barrels per day)	% variance from EPA
2018	GOM	EPA	1.72×10^6	-
2018	GOM	EIA	1.80×10^6	4%
2018	GOM	BOEM	1.76×10^6	2%

This process was employed for all years for GOM and PB, which resulted in similar outcomes. Hence, EPA was determined to be an accurate data source for the purpose of this report.

On an absolute basis, PB production levels are much higher than GOM production levels. To normalize the data for statistical analysis and to remove bias from underperforming facilities, weighting factors were assigned to each operator based on its production. Equation (1) was utilized to mathematically assign appropriate weightage to each facility in GOM and PB.

$$W_i = \left(\frac{BOE_i}{\text{Min (BOE/yr/basin)}} \right) \quad (1)$$

Where, $i = 0,1,2,3, \dots, n$

These weights were applied to the production values for each facility and used to calculate the arithmetic mean of carbon intensity using equation (2). Similarly, all other statistical parameter calculations – such as geometric mean, median, IQR, and quartiles – incorporated the weights within the carbon intensity of each facility, and the final, normalized dataset was used to create the box plot, histogram, and the probability density curve.

$$AM_{BOE} = \left(\frac{\sum W_i CI_i}{W_i} \right) \quad (2)$$

Where,

AM = arithmetic mean

W_i = weightage

CI_i = carbon intensity

This entire schema was imported into SQL and embedded into visualization tools such as spotfire, igor, and rstudio ide in preparation for analysis on the data. A statistical analysis was performed using the python library scipy stats on the dataset so that GOM and the PB could be analyzed based on a statistical foundation.

Statistical analysis was performed on the emissions data set to comprehend carbon intensities of GOM and PB for 2016, 2017, and 2018. For a data set where some data points are larger than the rest of the data, indicating outliers and a right-hand tail, a log-normal distribution is considered ideal. This was the case with the GOM and PB data sets as illustrated by the histograms in Figure 3.

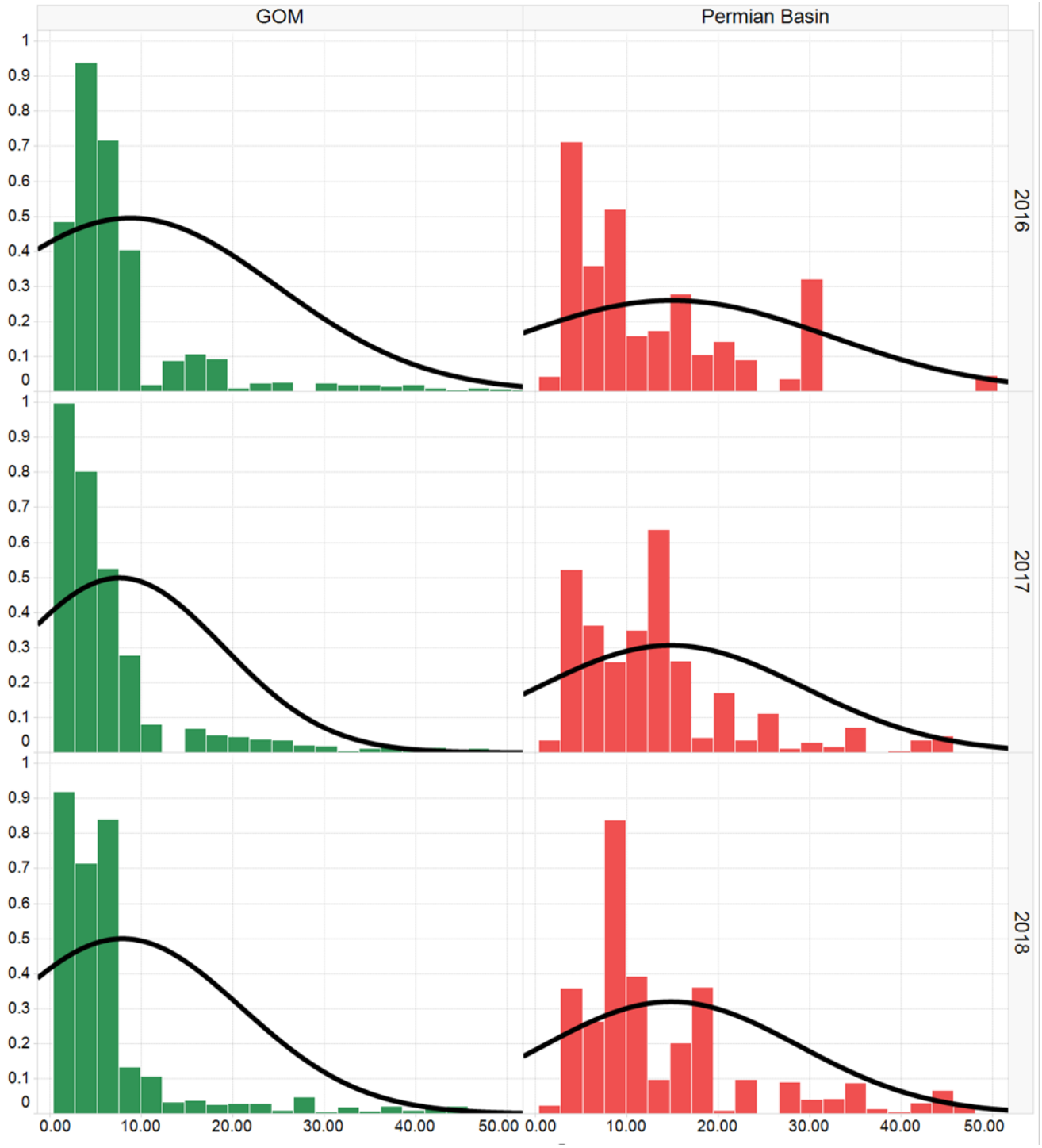


Figure 3: Histogram and a probability density curve for carbon intensity in GOM and PB by year. The difference in the shapes of histograms for GOM and PB is highlighted by the fitted curve. GOM's steeper slope of the curve shows that the carbon intensity among the operators is concentrated around the lower end, whereas PB's flatter curve indicates greater dispersion in carbon intensity data among operators.

Aside from the log-normal distribution, other distributions such Weibull, Gamma, and Normal distributions were also applied to the dataset. Additionally, since the data contained approximately 10% outliers, a normal distribution without the outliers was also tested.

A sample of the fitting results are provided in Figure 4 for the 2018 data set for PB. While all distributions followed a similar shaped fitted curve, a log-normal curve best represented the dataset as established before. The calculations of CO₂e emissions were based on data and tools from the EPA, EIA, and BOEM and limited to only those facilities in GOM and PB that reported

both production and emissions data between 2011 to 2018 to EPA. Six GHGs were considered: carbon dioxide, nitrous oxide, methane, sulfur hexafluoride, perfluorocarbons, and hydrofluorocarbons. Emissions of other GHGs that may contribute to climate change were not included in the calculations. Life-cycle analysis was not conducted.

A box and whisker diagram, Figure 5, was also constructed using the data set which visualized GOM and PB data for the years 2016 to 2018. Figure 5 also provides the associating statistical parameters. The parameters that were the most insightful include the interquartile range (IQR) and the mean.

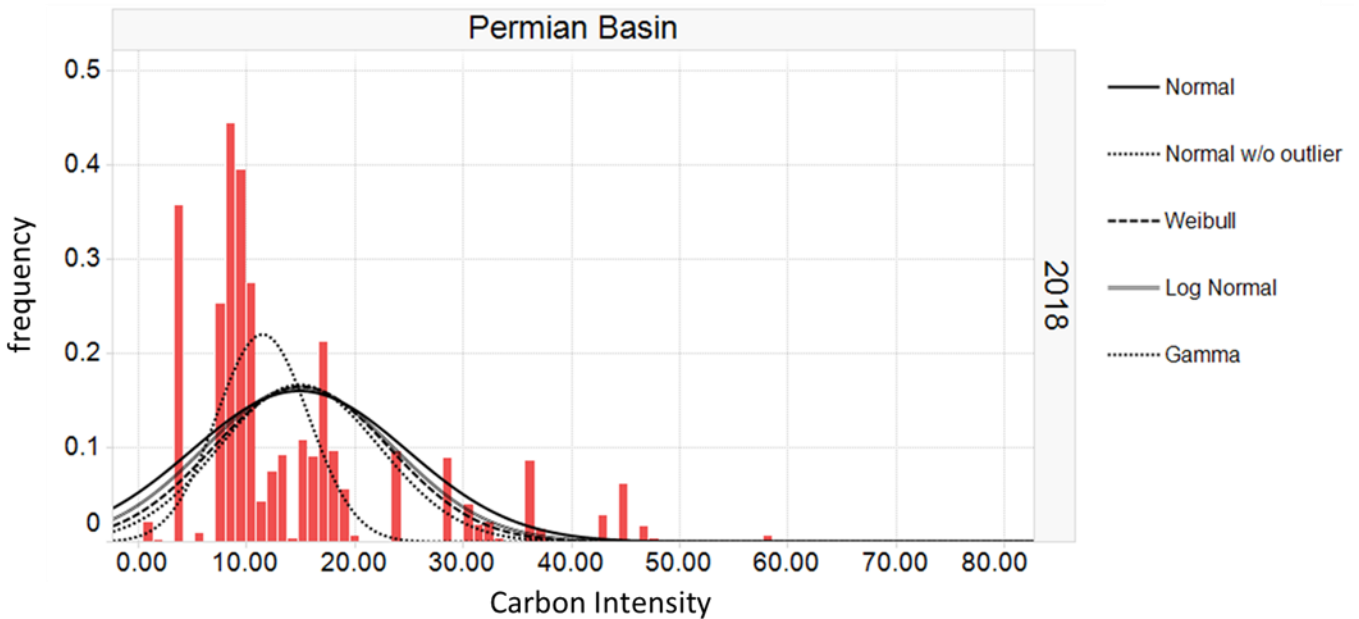
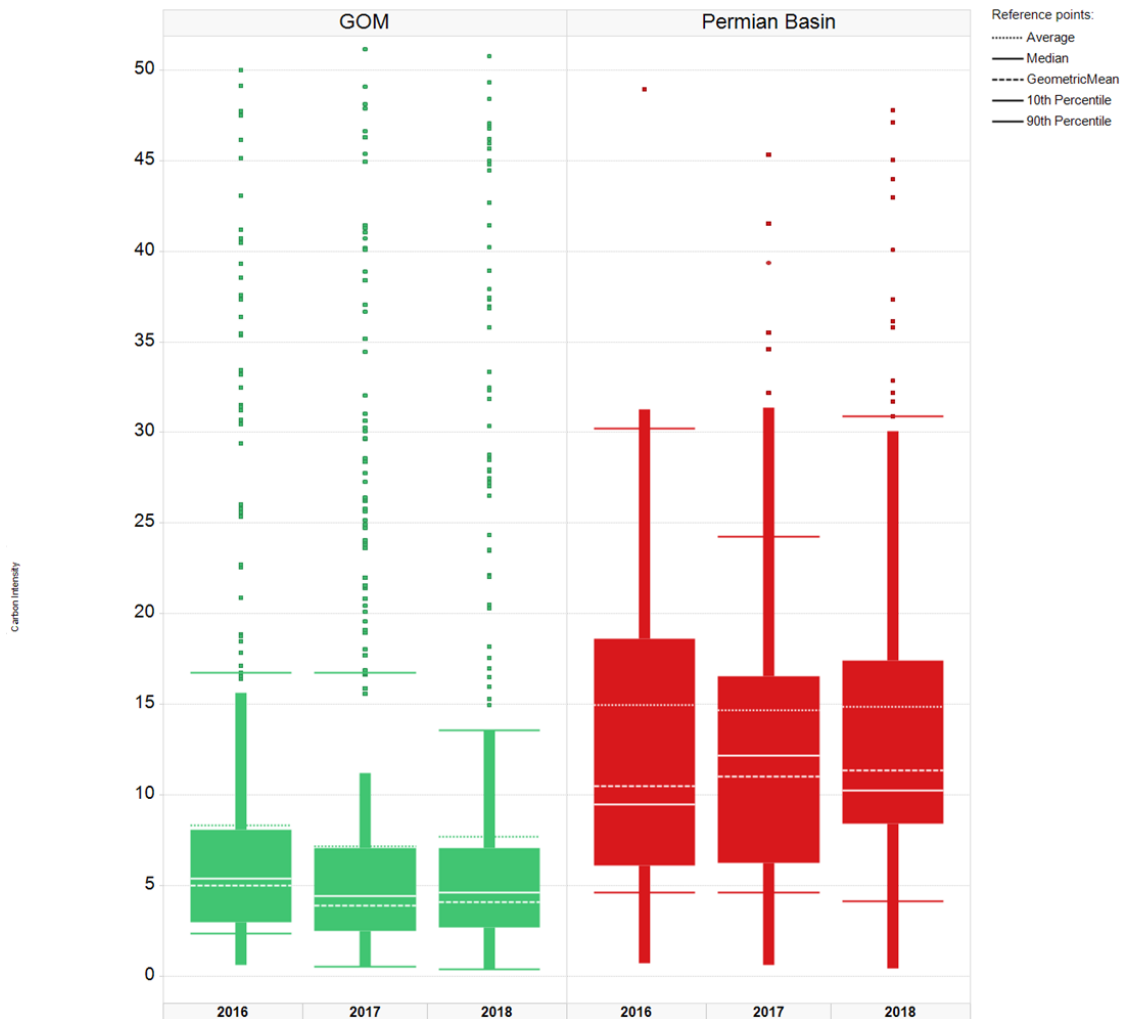


Figure 4: fitting results for various distribution curves tested on the 2018 PB data set.



Year	Basin	Mean	Median	Q1	Q3	P10	P90	IQR
2018	PB	14.85	10.26	8.43	17.42	4.14	30.91	8.99
2018	GOM	7.67	4.60	2.66	7.06	0.37	13.57	4.40
2017	PB	14.64	12.14	6.25	16.53	4.62	24.26	10.28
2017	GOM	7.17	4.41	2.50	7.06	0.50	16.76	4.56
2016	PB	14.95	9.49	6.10	18.60	4.59	30.21	12.50
2016	GOM	8.32	5.36	2.96	8.09	2.36	16.76	5.13

Figure 5: Box and Whiskers plot and the associated statistical parameters for CO₂ emissions in the GOM and the PB. The most valuable insights based on the statistical parameters for 2018 are: (1) the IQR and median indicate higher dispersion in the PB, likely due to a greater number of higher producing facilities (2) the arithmetic mean is higher compared to the mean obtained from log-normal distribution due to the data set being biased towards higher producing facilities

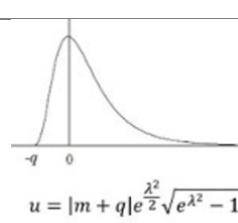
III. RESULTS AND DISCUSSIONS

Carbon Intensities

A log-normal distribution was applied to fit the data and the mean carbon intensity for GOM was determined to be 8.00 to 7.86 kg/BOE and PB ranged from 14.69 to 14.83 kg/BOE for the years 2016 to 2018 respectively, as summarized in Table 3.

The interquartile range represents the middle 50% range of a data set and serves as an indicator of statistical dispersion. It is the difference between 75th and the 25th percentile. Hence, the closer this value is to the median point, the less disperse a dataset is considered. For the year 2018, PB's IQR for carbon intensity was 8.99; compared to the median, which was 10.26, a higher degree of dispersion in PB data was evident.

Table 3: Summary of results of a log normal distribution which were applied to the dataset.

Production Region	Year	Distribution	Mean (μ)	Standard Deviation (σ)	Median	Shape
GOM	2018	Log Normal	7.86	13.03	4.07	
	2017		7.29	11.63	3.87	
	2016		8.00	10.03	4.99	
PB	2018		14.83	12.44	11.36	
	2017		14.52	12.44	11.03	
	2016		14.69	14.41	10.50	

The IQR for GOM in 2018 was 4.40, and its median was determined to be 4.60 indicating less dispersion in the GOM's data. This essentially represents the production profiles of PB, where the difference between the lowest producing facility and the highest producing facility is greater than the difference between the lowest and highest producing facilities in GOM.

The arithmetic mean for PB in 2018 was determined to be 14.85 kg CO₂e/BOE and for GOM the arithmetic mean was calculated to be 7.67 kg CO₂e/BOE. In comparison, the log-normal distribution produced a mean of 14.83 kg CO₂e/BOE for PB and 7.86 kg CO₂e/BOE for GOM for the year 2018. The difference in mean by the log-normal distribution and the box and whiskers plot is caused because the log-normal accounts for the higher value data points and removes bias towards them whereas the box plot does not. Since, PB had a greater number of high

producing facilities, the box plot mean values were higher comparatively.

Also, the arithmetic mean communicates a lower carbon intensity in the year 2018 compared to the year 2016 for both GOM and PB. Alternatively, the means obtained from log-normal distribution shows a slight increase in carbon intensity for PB from 2016 to 2018.

The statistical analysis concluded that PB data is more dispersed with a greater range between the lowest and highest producing facilities, which could contribute to a higher carbon intensity arithmetic mean calculation. Also, while three years of data is not sufficient to conclude a trend, both GOM and PB experience lower carbon intensity rates in 2017 compared to 2016 and a higher carbon intensity rate in year 2018 compared to 2017.

Implications

As expected, CO_{2e} emissions increase as production increases. However, as production increases, carbon intensities also increase. Much of this disparity in emissions can be attributed to the differences in flaring practices between offshore (GOM) and onshore (PB) production. Figure 6 provides a high-level summary of the

production and CO_{2e} emissions data for GOM and PB for the years 2016 to 2018, in which the sizes of the bubbles are directly proportional to the carbon intensity values. A trend of increasing production and related emissions is evident in the PB; production levels in GOM, however, have remained consistent, and thus, the emission rates over the years have also remained constant.

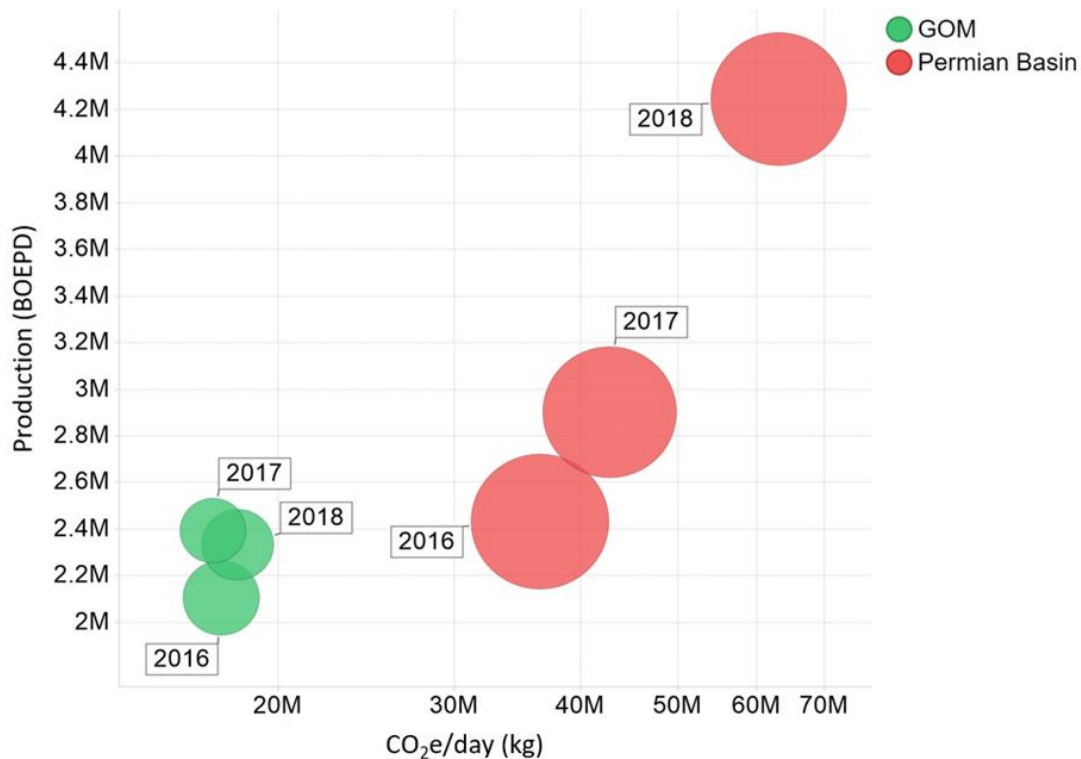


Figure 6: Production and emission summary bubble chart for GOM and PB. The y-axis is production in units of barrels of oil equivalence per day (BOEpd). The x-axis is carbon dioxide equivalence in units of kilogram (CO_{2e}/day). The size of the bubbles are directly proportional to carbon intensity values. A trend of increasing production and related emissions is evident in the PB, whereas production levels and emission rates have remained consistent over the years in GOM.

Flaring – Maximizing Production

Flaring is a practice in which excess natural gas is combusted at the point of production or along the pipeline, releasing CO₂. Though there are many reasons that a product might flare, a common operational strategy is to maximize oil production. When gas production exceeds the

capacity of the pipeline, the excess is removed to allow maximum oil production. Oil production in the PB has a considerable amount of associated gas because its oil is high in American Petroleum Institute (API) gravity, a measure of how heavy or light a petroleum liquid is compared to water. The higher the API gravity of crude, the lower its density. Oils with higher API gravity, such as in

PB have higher gas to oil ratio (GOR). Standing's equation summarized the relationship between API gravity and the GOR^{15,16} of an oil as follows:

$$R_s = \gamma_g \left(\frac{p}{18 \times 10^6} \right)^{1.205}$$

where:

- R_s = solution gas/oil ratio, scf/STB,
- γ_g = gas specific gravity, -,
- p = pressure, psi,
- $y = 0.00091 T - 0.0125 \text{ } ^\circ\text{API}$, and

It is evident from this equation, that with all parameters being equal, the oil with the higher gravity oil will result in a lower value of y and therefore a higher GOR. Lighter crudes with a high API have a large gas fraction. Venting, in which gas escapes as methane, or flaring of high API crudes results in higher emissions during the upstream processing stage of its production. As demonstrated in Figure 7, a very light, gassy crude oil that is mismanaged will experience its highest emissions in the upstream process of production, whereas a heavier oil will have most emissions downstream.¹⁰

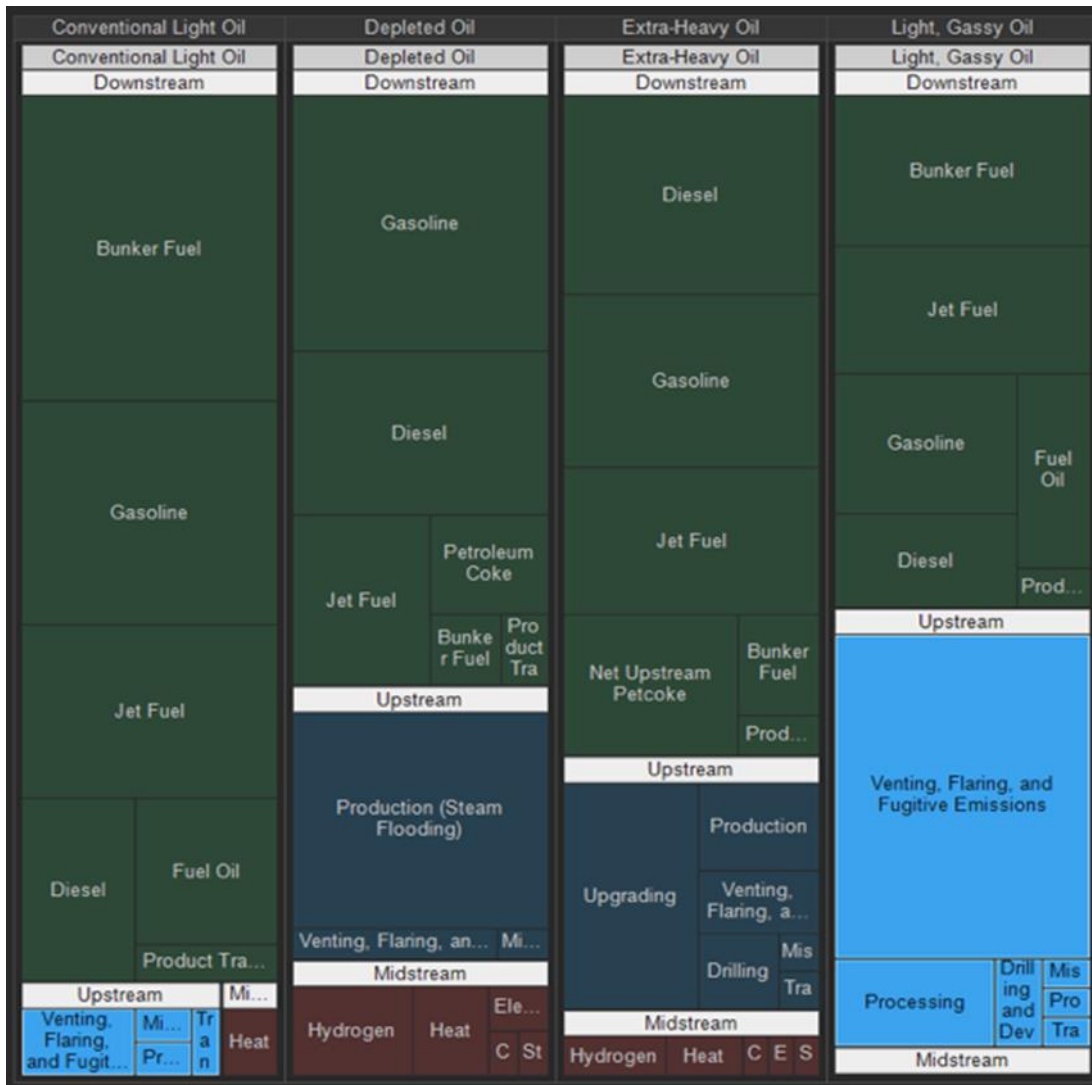


Figure 7: sources of emissions broken down by types of crude oil produced in midstream, upstream, or downstream facilities and sized by the quantity of GHG emitted. PB produces light, gassy oils, and as illustrated, the largest source of emissions for upstream PB operators is caused by flaring.

To maximize oil production, more flaring will occur with oils that have a higher GOR¹⁴.

Data collected by the EIA between 1985 to 2019 indicates the GOM has a weighted average API gravity that varies from about 29 to 34.¹¹ In contrast, since 2018 PB has been producing more than 50% of its production with greater than 40 API degrees gravity.¹²

Flaring has been called out by governments and advocacy groups as a harmful and wasteful practice. Though largely classified as a safety measure, there are a number of adverse effects of flaring. This practice wastes natural gas that could be used for power generation, emits CO₂ with no peripheral value, and contributes to air pollution through the formation of soot and smog. The lack of compelling value proposition for natural gas and the high demand for oil has exacerbated the prevalence of flaring. In addition, insufficient planning to accommodate the additional gas production and inadequate regulations may also be contributing factors.

The volume of gas flared by Texas in 2007 was 101 billion cubic feet (bcf) and has significantly increased since 2010. There is, however, some discrepancy between reporting agencies. The National Oceanic and Atmospheric Administration (NOAA) reported approximately twice the amount that EIA reported. According to the Environmental Defense Fund (EDF), the PB flared 104 bcf of natural gas, and 12.5 bcf was vented and flared in the GOM in 2007.¹²

In order to further validate the data provided to these federal agencies and measure accuracy of what is reported by the facilities, emissions data from satellite monitoring is recommended. Various companies in the market offer column density mapping of single species in mol/m² of major GHGs such as CO₂ and CH₄ using satellites. These satellites are equipped with a high-resolution spectroscope that measures light absorbed at specific wavelengths correlated to GHG concentration. Accuracy of these satellites are high as they record hundreds of thousands of

measurements at a single source location with resolution in tens of meters.¹⁸

Considering overall GHG emissions from the oil and gas industry between 2016 and 2018, it was reported that methane emissions had decreased between 2016 and 2017; however, CO_{2e} emissions increased during this period.²⁰ This increase in GHG emissions coincided with the reported increase in flaring of gas from oil wells, which had increased nationwide from 2016 to 2017.

Flaring – Infrastructure

A significant proportion of the increase in methane emissions over the past decade has been attributed to hydraulic fracturing, also known as fracking. Some estimates suggest that shale-gas production in North America may be responsible for more than half of the increased methane emissions from fossil fuels²⁵. U.S. shale gas accounts for 89 percent of global production. Furthermore, in the time required for shale gas to be extracted from the ground to its destination, methane gets released into the environment, which is equivalent to the quantity of methane released when fuel is burned.

Some studies show that methane emissions could be almost twice the amount that the EPA estimates. Because methane is a more potent GHG than carbon dioxide, this is a significant source of CO_{2e} emissions.²⁶ The global GHG intensity map from a satellite source will significantly help validate EPA data.

Another reason flaring occurs is when insufficient pipeline infrastructure exists. Hydraulic fracturing dramatically increased gas and oil production in the PB. However, infrastructure did not grow with production, and when there is no pipeline to handle the excess gas in the PB, the gas is flared off as a safety measure and to maximize oil production. Since the GOM consists of offshore facilities, it was required to have a well-established pipeline infrastructure to transport gas to onshore processing facilities, and

in some instances, the gas is utilized for power generation or temporarily re-injected to enhance oil recovery¹⁷. For these reasons, the amount of CO₂e emissions due to flaring is considerably higher in the PB than in the GOM.

The rapid growth of production from hydraulic fracturing in the PB has resulted in growth of over 2 million barrels per day in just under a decade. This accelerated growth has contributed to the significant increases in requirements for additional pipeline infrastructure and transportation capacity. The existing pipeline infrastructure cannot cope with the increased amount of associated gas produced, which is approximately 5 bcf/day.

In 2018, the daily production from the PB was 3.7 million barrels per day and is expected to reach 7 million barrels per day by 2022.²⁷ The GOM is expected to grow as well with its mid-price production estimate for 2022 to be 3.7 million BOE a day compared to a production of 2.3 million BOE per day in 2018.²⁸

Transportation

Another factor contributing to higher levels of emissions per barrel of oil in PB is transportation. As oilfields in the PB are more accessible, the need for planning adequate pipeline infrastructure is not as restrictive as that of offshore facilities. Therefore, more oil can be produced by drilling more wells, after which the product can be stored in tanks and trucked away to its destination.

As an overall contributor to CO₂ emissions, freight and passenger transport accounted for 20% of emissions in 2011.²¹ Emissions from freight transport accounted for approximately one-third of the total emissions originating from transport. Emissions can occur not only from the burning of fuel but also during the transportation of liquid hydrocarbons.

One point of emissions during transportation is the loading and unloading of trucks, whether performed by atmospheric trucks, pressure

trucks, or pressure tanks on atmospheric trucks. Petroleum products can spill or leak when the hoses between trucks and tanks are connected and disconnected, particularly where there are holes or faulty seals or when parking brakes and wheel chocks are not used. Also, a failure to ensure enough tank space or to stop flow in time can result in an over-full tank, causing fuel to drip off the nozzle or spill when the hose is placed back onto the pump. One way to prevent odorous emissions during the unloading process is pressurize loading. However, loading under pressure decreases load capacity by 10 to 30 percent because truck tanks reach a pressure limit before the volume limit, resulting in the necessity for more trucks to carry the same volume. Also, pressurized loading is not currently applicable to tank cleaning and de-sanding.

Depending on the type of truck, the type of connection that is used in the loading operation also impacts emissions. An atmospheric truck needs only a quick-connect type of coupling. However, pressure trucks require hard-piped or flanged connections, limiting their capacity to 10 to 30 percent less than that of atmospheric trucks. Therefore, while leaks and emissions occur with both types of trucks and connections, pressure trucks are further complicated by the fact that they require more trips than atmospheric trucks to transport the same quantity of liquids.²³

Liquid storage tanks can be a source of emissions, especially carbon dioxide and methane. Although methane does not remain in the environment as long as CO₂, it contributes considerably more to GHGs while it is present in the atmosphere. Emissions from storage tanks can be categorized as working, breathing and flash emissions.¹⁰ Working emissions occur from any turbulence or the displacement of existing vapors within the tank. Breathing emissions result from the expansion and evaporation of the liquids during normal changes in daily ambient pressure and temperature. Flash emissions can occur when a stream of high-pressure liquid is introduced into a tank that was previously at atmospheric pressure. Additionally, a major

source of storage tank emissions is evaporation through faulty seals, manholes, gauge pipes, and hatches and the extent of leakage depends on the design and can be exacerbated by wind conditions.²² Leak detection and repair (LDAR) regulations were put into place by the EPA to monitor and manage these leaks, and several initiatives by oil & gas producers focus on this class of emissions.

Extreme Weather

One consequence of climate change is the increasing temperature of oceans, which in turn increases the number of hurricanes. Simulation experiments performed by the National Aeronautics and Space Administration (NASA) predicted that by doubling the amount of CO₂ in the atmosphere, the frequency of tropical storms and hurricanes over the GOM would increase by 50 percent.²⁹

In considering the impact of weather on oil production and carbon emissions, hurricanes have been known to cause extensive damage to offshore production facilities in the GOM. Therefore, operators tend to respond to approaching storms by shutting production until the storm passes. However, during hurricane season, onshore facilities are only affected marginally, if at all, and can continue daily production of hydrocarbons uninterrupted. Operational interruptions along the supply chain including power outages, maintenance, and loss of equipment integrity, though, may result in flaring if production continues.

Another consequence of weather on oil production and carbon emissions is the formation of ice crystals, or hydrates, that can form when water and natural gas react together under certain pressures and low-temperature conditions. Hydrates are particularly prevalent in the winter months where there is a drop-in temperature due to cold fronts, especially in PB, where they can cause blockages and flow assurance issues in pipelines.

A common method of dealing with hydrates is to add methanol to the production fluids, which acts as an anti-freeze to prevent the ice crystals from forming. However, methanol is only added in the presence of hydrates, and hydrates often form before operators have a chance to inject methanol. This delay may result in a blockage in a pipeline downstream of a treating facility, leading to a buildup of hydrocarbons in the pipeline. Rather than shutting in wells until the blockage is remedied – which could take a significant amount of time and production loss – the produced fluids are redirected to the flare stack. This redirection converts a tremendous amount of hydrocarbons into CO₂e emissions that would otherwise be transported through the pipeline. The alternative method, which is to successfully inject methanol before hydrates are formed, still contributes to total carbon emissions because methanol is itself a hydrocarbon. For every gallon of methanol that is burned, 9.1 pounds of carbon dioxide is produced.³⁰

In comparing the impact of hydrates on the Basins, the contribution to CO₂ in the PB due to methanol is consequently more than GOM, partly because of the differences in pipeline infrastructure and partly because of the use of chemicals in offshore facilities. Offshore facilities incorporate the use of low-dosage hydrate inhibitors, which considerably decrease the volume of methanol than is required on land. Also, because the PB is distributed over a large area, the carbon emission “land print” is larger than GOM facilities that are concentrated around a relatively smaller area where numerous oil wells produce into a single platform or FPSO. Although the area of hydrocarbons production is the same for GOM and the PB, the more widely distributed PB is more prone to higher carbon emissions from weather-influenced factors.

Critical questions for CO₂ Management

Most GHG emissions in the United States result from the consumption of oil and gas products. The social cost of carbon (SC-CO₂), which is an

estimate of the adverse economic consequences of incremental increases in carbon emissions, is applied to the total estimated greenhouse gas emissions. It is in the best interest, economically and environmentally, for oil and gas companies to manage their CO_{2e} emissions. This work only attempts to quantify GHG emissions magnitudes for operators in GOM and Permian. However, there are a number of key questions being considered in the context of CO₂ management by oil and gas operators in the country.⁴

1. What are the company's strengths, weaknesses, opportunities, and threats that influence strategic responses to climate change issues?
2. How reliable is the GHG emission and other climate change information gathered for management's decision-making and for the disclosure to capital markets and governments?
3. What is the strategy for responding to physical risks arising from climate change?

Oil and gas companies are responding in various ways to the demand for lower carbon emissions from policies and regulations, competition from renewables, and investors. The building block is investing in new approaches to reduce emissions; the next step is supporting new technologies through R&D and/or venture capital. The most comprehensive action is developing non-oil and gas projects. To date, the investment in reducing carbon emissions has been relatively small compared to overall capital spending. However, the growing trend toward carbon reduction is providing new opportunities and potential alternatives to help companies adapt to the global energy transition, including electric vehicle charging, electrification, hydrogen, direct air capture, offshore wind, and carbon capture and sequestration.⁵

IV. SUMMARY

To address climate change, the total carbon dioxide equivalent (CO_{2e}) emission rate for the

production of crude oil and gas was determined in the two highest producing regions of the United States which are the Permian Basin and the Gulf of Mexico. The objective of this report was to address the difference in carbon intensities between these basins and consider reasons contributing to this deviation. Carbon intensity rates were calculated using open-source data from federal agencies such as EPA, EIA and BOEM. A statistical analysis performed on the data concluded that the mean 2018 carbon intensity for PB and GOM was 14.83 ± 3.374 kg CO_{2e}/BOE and 7.86 ± 2.32 kg CO_{2e}/BOE, respectively. These numbers are based on a log-normal distribution which provided the best fit curve due to the presence of high performing facilities in the data set. A clear trend is established that the carbon intensity rate is directly proportional to the rate of production. Also, while three years of data is not enough to conclude a trend, both GOM and PB experienced lower carbon intensity rates in 2017 compared to 2016 and a higher carbon intensity rate in year 2018 compared to 2017.

Flaring practices, transportation requirements, hydraulic fracturing and weather-related impacts are various causes considered in this report to explain PB's higher carbon intensity. PB's oil extraction process have higher emissions compared to GOM's production due to the lack of pipeline infrastructure in the PB. The accelerated growth in production in PB enabled by hydraulic fracturing requires additional pipeline infrastructure and transportation capacity. In the absence of these; to maximize oil production and for safety reasons all excess gases associated with high-PI crudes are flared off. Additionally, offshore facilities are built to accommodate higher levels of drilling and production and are not impacted by the implications of additional land transportation resulting in less emissions.

Lastly, the rise of global temperatures has increased the frequency of hurricanes which impacts GOM severely while PB is only

marginally affected. This results in the offshore facilities shutting down production when a storm is approaching, minimizing its emissions while the PB operators continue uninterrupted daily production and emissions accordingly. A life-cycle analysis and a carbon intensity calculated based on mole balance accounting will largely improve accuracy of the results of this study.

The carbon intensities of the GOM and PB provide important awareness of environmental impacts and input in future business strategy and decision-making. Based on the observations presented in this report, it is recommended for future work to continue flare analytics between onshore and offshore facilities. The statistical analysis conducted in this report should be extrapolated to include data since 1980 and for other U.S. basins. Finally, a component level analysis for other GHG sources such as CH₄, CFCs, etc. is also recommended for the next phase of the project. EPA's data quality and accuracy can be greatly improved by implementing real-time reporting instead of annually and standardizing the reported values for both production and emissions between onshore and offshore operators. Data from EPA, EIA and BOEM should be further validated using satellite GHG mappings. Lastly, operators should report emissions to EPA using mole balance based on crude quality of the oil produced for cleaner emissions accounting, as opposed to reporting emissions as a mass.

ACKNOWLEDGEMENTS

Chirality Research Inc. acknowledges Kosmos Energy for the funding of this research as well as the contributions of the following organizations that make this work possible by providing open-source data and tools for public consumption: Environmental Protection Agency, Energy Information Administration, Bureau of Ocean Energy Management, and Carnegie Endowment's Energy and Climate Program. Jamila Yamani, PhD is also acknowledged for

her contribution and subject matter expertise in this study.

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