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Comprehensive Study of Major Methane Emissions Sources from Natural Gas System and Their Dependency to Throughput

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Abstract— This paper presents a comprehensive study of various sources of methane emissions, assess the impact of each source on emissions, and their dependency to throughput, time, and events. The analysis builds upon prior work [1] positing that a cause-based, marginal approach to estimating methane emission impacts of change in natural gas use was more accurate than assuming that methane emissions vary one-for-one with throughput. The results show that there are many components in the natural gas system that emit the same amount of methane to the atmosphere regardless of their operational mode; meaning some emissions sources have no or only partial dependence on throughput. As a result, reducing natural gas consumption in the future will not yield a directly proportional reduction in the methane emissions. The results of this study will be used in future works to build a model using the marginal emission methodology to estimate the change in methane emissions of natural gas systems as system throughput changes. It is believed that the results of this study will help energy policymakers to understand better the effect of policies aimed at reducing natural gas use on greenhouse gas (GHG) emissions and where such policies should be applied.

Keywords—methane emissions, natural gas system, marginal methane emissions estimation, energy policymakers, GHG emissions

I. INTRODUCTION

According to the Environmental Protection Agency (EPA), 81% of greenhouse gas (GHG) emissions come from CO_2, 6% is comprised of nitrous oxide emissions. Both gases are produced by burning coal, natural gas, and oil. Another 10% of GHG emissions is comprised of methane, which is the primary constituent of natural gas [2]. Methane released in the atmosphere from producing, transporting, and using natural gas raises concern about the climate impacts of methane emissions. The atmospheric lifespan of methane (the short term due to a much larger radiative cross-section short term due to a much larger radiative cross-section (measure of GHG effect forcing) compared to CO_2 [3].

Methane emissions from various segments of natural gas infrastructure are mainly due to venting as part of standard operation and leakage from system components (known as fugitive emissions). The emissions from these components are divided into three categories: Vented emission, fugitive emission, and exhaust emission. Vented emission refers to the intentional release of methane in the environment for maintenance and for maintaining system safety. Fugitive emission is the unintentional leakage of methane from equipment, and finally, the methane that escapes from the exhaust of combustion sources is called exhaust emissions.

The amount of methane emissions from U.S. natural gas supply chain was first published in 1996 using 1992 as the base year in a multi-volume set of reports by the Environmental Protection Agency (EPA) and Gas Research Institute (GRI) [4]. Since then, EPA has released two reports annually: The GHG Inventory (GHGI) of U.S. GHG emissions and sinks, and the Greenhouse Gas Reporting Program (GHGRP) [5]. The GHGI annual report publishes U.S. GHG emission estimates from 1990 to two years before the published year while GHGRP collects greenhouse gas information from all facilities with emissions over the threshold rate of 25,000 metric tons of CO_2 equivalent per year. The emission factor (EF) and activity factor (AF) are the main components used by GHGI and GHGRP (developed in 1996 by EPA/GRI) in calculating the annual national emission rates. The emission factor is the methane emission rate per unit of activity factor for each component of the natural gas system while the activity factor assesses the extent to which each component is utilized (active) within the system. For some sources, such as pipelines, the activity factor has units of miles (length) or standard cubic feet (scf) for volume, whereas for others it is the number of active units (number) of an emissions source e.g., compressors, pumps, etc. Total emissions for each source are the product of the activity factor and emission factor (Emissions=AF*EF). Significant efforts have been made to improve the accuracy of estimated emissions. The Barnett Shale coordinated campaign supported by the Environmental Defense Fund

(EDF) is one of these major initiatives. The campaign funded 16 research projects to help more accurately estimate the emission of different components at the Barnett Shale field. Several papers published on these studies indicate that there are significant needs to update emission factors to more accurately account for emission of various components. Only a few studies have been published that relate emissions changes to the throughput. In some recent experimental works [6, 7], the relationship between site-level methane emissions and the gas production has been quantified to better understand the relationship between natural gas production and the resulting emissions. It was shown that measured site-level methane emissions decrease as throughput increases meaning that there is a negative correlation between throughput and the emissions. These results confirm that some components in the natural gas systems have leak rates that are not 100% throughput based, and as a result, emissions will not change in proportion to changes in throughput.

Prior works funded by EDF have mostly focused on assessing the accuracy of measured emissions without analyzing the causes and drivers of emissions. This paper tries to gain insight into casual drivers of methane emissions and how changes in the system affect those drivers. [1] reports that the percentage dependency of emission sources upon natural gas system throughput has never been quantified in detail. Further research is needed to fully characterize the effect of throughput change on total system emissions. As described in [1], a clear understanding of the change in emissions with incremental increase or decrease in consumption of natural gas is essential in determining its environmental impact. The goal of this study is to expand the characterization of components in the natural gas system. This is the first building block needed to determine the impact of changes in natural gas throughput on the total methane emissions. These results will be used in future works to calculate total system emissions from methane. The marginal methodology for estimating methane emissions changes is especially important as natural gas throughput will be flat or declining in most policy scenarios in some states, e.g., in California due to renewable energy outgrowing other sources of energy.

II. METHODOLOGY

Emissions from each component of the natural gas system are attributed to several factors and therefore calculating their causal dependencies is a very complex process. In order to simplify, these factors are divided into three categories as suggested in [1]: Throughput-based, time-based, and event-based. Equation (1) shows how the marginal approach calculates the total emissions for each individual emissions source in terms of its dependency upon time, event and/or throughput, where E_T, E_E, and E_{TP} are emissions rates driven by time, event, and throughput respectively, and a, b, and c are the marginal emissions coefficients of time, event, and throughput, respectively.

$$E= aE_T+ bE_E + cE_{TP} \quad (1)$$

Comprehensive literature review is conducted to assess these marginal emission coefficients, as explained in detail in the following sections. These coefficients are then used in our future works to build a model using the marginal emission methodology to estimate the change in methane emissions of natural gas systems as system throughput changes.

A 2018 EPA/GHGI report identifies 129 emissions sources for the U.S. natural gas system [2]. Over 20 individual methane emission sources have been evaluated in the literature. In the current study, some of the major methane emissions sources have been investigated to assess their dependency on throughput and other factors. Specifically, ten key factors that have significant impact on the total emission have been examined closely.

Fig. 1 shows the distribution of the emissions percentage from each component of the 2018 EPA report. The “other” in represents all methane emissions sources in the natural gas system with emissions less than 3%. 27% of 2016 total emissions from the US natural gas system come from gathering and boosting stations themselves. There is not enough information for all the emitting components in the gathering and boosting stations, which makes it impossible to marginally assess this source. The authors suggest that future research and measurement campaigns may need to be focused upon this sector of the natural gas system.

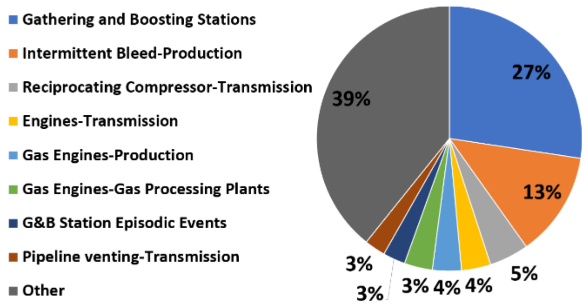

Fig. 1. The distribution of emissions percentage from each component of the natural gas system for the 2016 base year (data from [2])

III. RESULTS AND DISCUSSION

Major sources of methane emissions from natural gas systems are outlined in 2018 EPA/GHGI [2]. These sources are carefully studied and categorized as throughput, event, and time dependent and are outlined in Table I. Further experimental work is needed to evaluate the dependency of each source on throughput, event, and time. This will help improve the accuracy of the estimated total emissions of the system using the developed model.

A. *Pneumatic Controllers*

As it can be seen from Fig. 2(a), in intermittent vent controllers there is a gas release to the atmosphere when the valve needs to be open from the closed condition [8]. The amount of gas release depends on the actuation frequency, the supply gas pressure, the age, the type of process flow being control, and the condition of the equipment. On the other hand, since no seal exists between the actuator and the supply gas in the continuous bleed controllers there is always a continuous gas flow through the orifice. When the system is depressurized, there is a constant gas flow venting to the atmosphere [8]. When more pressure is required toward the actuator and the valve needs to be closed, the bleed port will partially cover the block resulting in less gas release. As soon as the actuator receives the input signal to reduce the built-up pressure, the block starts uncovering the bleed port and as a result, temporarily increasing the amount of gas emissions until it settles and reaches the steady-state condition. These two sudden increases and decreases in gas emissions will cancel out each other resulting in a continuous rate independent of the process being control as shown in Fig. 2(b). The continuous bleed controllers are also categorized as high and low bleed controllers based on the emission rate (emissions higher than 6 scfh over 50 Mcf considers high bleed devices according [9]). The devices that need to control process flow very quickly should have a large orifice hole and as a result, the bleed port would be large resulting in higher emissions.

EDF funded study [10] measured the emissions rate from 377 natural gas powered pneumatic cotrolleres majority at the natural gas production sites throughout the U.S. It was found that the level controllers used in the seperators and the compressors have the highest emissions rate compared to others (well head, plunger lift, process heaters, dehydration system, flare, sales) as well as dependency of the emissions rate to the production region (the Rocky Mountains region has the lowest amount of emissions and the Gulf Coast has the highest amount of emissions). This suggests that controllers's emissions rate are strongly dependent on the type of the service, the process being served, the region and etc. The charactristics of 40 highest emsisons rate controllers were examined and it was found that the cause of high emissions rate for most of the controllers was due to equipment issues. Overall, it may be concluded that the intermittent controllers emits when the control valves open and close and as a result they are event based. At the same time when these controllors need to process more gas flow (throughput), the actuation rate will get high, resulting more venting to the atmosphere. This may cause the emissions rate to be partially dependent on the process gas flow rate or throughput. Note that this is only the case when the process being controlled is natural gas. For the continous bleeding controllers, it is clear they fall into time based controllers and are independent of the process flow.

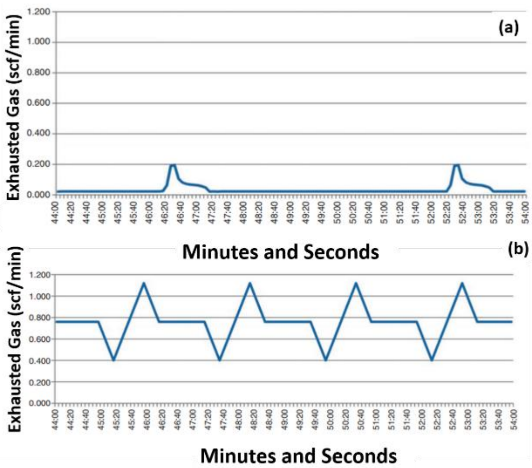

Fig. 2. Theoretical exhaust rate: (a) Intermittent-vent; (b) Continuous-vent [8]

B. Engine

Methane emissions from the exhaust of compressor engines are one of the significant sources of emissions resulting from incomplete combustion of natural gas. As part of the EDF funded series of studies Johnson et al. conducted audits of emissions in three compressor stations and two storage facilities [11]. The goal of the study was to compare their measured emission factors with those of AP-42 [12], the 1996 EPA/GRI [13], and Allen et al. [14]. From data collected in this study, it was shown that 46% of overall emissions are from engine exhaust, 5% from crankcase and the rest are from other component leaks and venting. The sites employ a combination of four-stroke lean-burn (4SLB), two-stroke lean-burn (2SLB) engines, and gas turbines. The measured engine exhaust reported in [11] varies significantly compared to calculated results from AP-42. For example, measured emission for G3512 engine is 5.7 (kg/h) while the calculated value is underestimated by 23% at 4.4 (kg/h).

The significant estimation difference of emissions in AP-42 is likely due to the calculation only relying on fuel input as the only parameter. Another major source of emissions that is not considered in AP-42 calculation is the leaks from the engine's crankcase. As shown by Johnson and Covington [11], considering the effect of emission from both exhaust and crankcase significantly reduces the difference between the measured and calculated emissions. Specifically, for sites that employ new 4SLB technology, after adjusting for crankcase emissions, measured emissions were only on average 11.4% lower than AP-42 estimates. [11] proposed a new method for estimating the total site emissions based on correlating the total site emissions and throughput. The measured site emission rate over engine throughput from a limited number of sites that employ 4SLB technology was plotted against total site throughput as shown in Fig. 3. It was shown that the total measured emission rate has a high degree of negative correlation with the throughput with an R-squared value of 89%. Stations with higher throughput have lower emissions per engine throughput. Therefore, the measured response can be used to model the emissions based on the station's throughput and can be applied to reliably estimate the total emission of sites that employ 4LSB technology. Based on the results reported in [11], creating a library of measured emission and station throughput for sites that use 4SLB technology can provide an invaluable tool for estimating the total emissions of various sites nationally. Based on this, we suggest that engine emissions are 90% throughput-based due to the burning of natural gas and 10% time-based due to the leaks associated with pressurized operation.

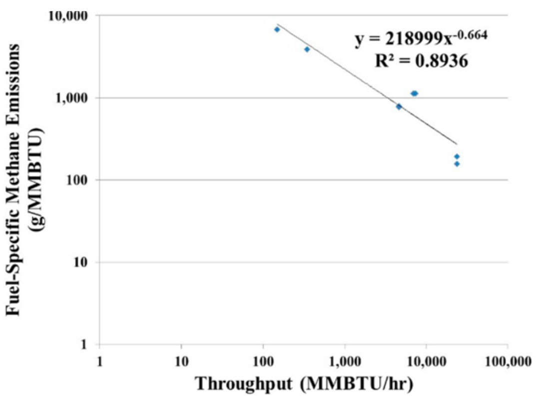

Fig. 3. Fuel-specific methane emission vs. site throughput for 4SLB engines [11]

C. Liquid Unloading

Allen measured methane emissions from 107 wells sampled from four different natural gas production regions [15]. 32 gas wells without plunger lift and manually triggered and 74 well with plunger lift both automatically and manually triggered. It was found that unloading with plunger lift results in lower emissions per event compered to unloading without plunger lift. The frequency of the event in an unloading with plunger lift is higher (>200 events per year) compared to without plunger lift (<10 events per year). In [15] the statistical analysis between gas well characteristics (age, depth, and static shut-in pressure, surface flow line pressure, volume, and gas production SCF per day) and measurements data (event duration, event per year, annual emissions, emissions per event) was done. The goal was to identify the relationship between well characteristics and annual emissions and explain the high variability of the frequency of unloading events. It was found that the correlation between the annual emissions and the event frequencies are significant and there is a positive correlation between the event frequencies and the age of wells, suggesting that gas wells with older age have more unloading. There is also a negative correlation between the annual emissions and the depth of the gas, suggesting gas wells with higher depth have lower annual emissions. It can be concluded that the younger wells have higher depth and lower number of events resulting in lower total annual emissions.

The relationship between the gas well age and the gas production rate (scf/day) was conducted using measurements data from [15]. As it is shown in Fig. 4, there is a positive correlation between them, meaning that older gas wells have less gas production rate.

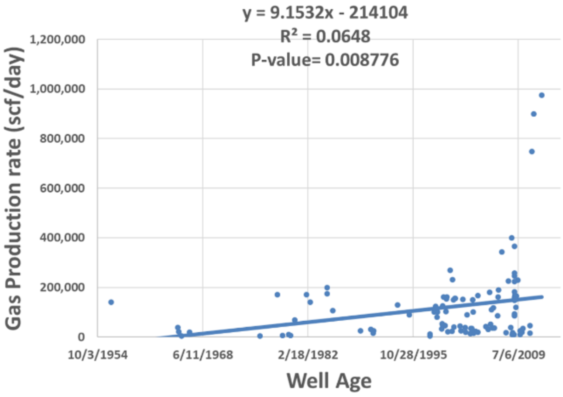

Fig. 4. Gas wells production rate vs age based on measurements data from [15]

In order to show the dependency of emissions on unloading event and throughput, a statistical analysis has been done using measurement data from [15]. Since EPA/GHGI reports two separate sources for unloading, with and without plunger, the data was divided by these two categories. For unloading with plunger, the correlation between: 1) well methane production (scf/day) and annual methane emission (scf); 2) well methane production (scf/day) and normalized emission (annual methane emission/annual methane production); 3) annual unloading event and annual methane emission; 4) unloading event and emission per event were calculated. Data also is categorized based on well characteristics: 1) well with only manual plunger; 2) wells with only automatic plunger; 3) all conventional wells; 4) all unconventional wells; 5) all tight reservoirs; and 6) all shale gas, to show the dependency of well-specific characteristic to the throughput and unloading events. It was found that there is not any significant relationship between well methane production and methane emissions and between well production and normalized emissions. Although, there is a significant relationship between annual methane emissions and unloading events (all with p-value less than 0.05) and overall dependency of annual emissions to events is around 13.83% for plunger wells. Among 7 different group of wells, the group with the highest percentage of manual loading (100%) have highest dependency to the event frequencies while wells with automatic plunger don't have any correlation to the event frequencies. The combination of well formation, conventional/unconventional, age and many other factors determine the total dependency to the unloading events. According to measurement data [15] and the nature of the unloading event it can be thought that unloading emissions are mainly event based and a small portion is throughput based, since more extraction from well causes more gas to flow through the wellbore and lead to unloading events. It should be noted that the measurements data from [15] only sampled 107 wells out of 60158 throughout the whole U.S., but it is still the only broad and large set of measured data for unloading among the literatures.

D. *Compressor*

Depressurized compressors have zero fugitive emissions and their only emissions come from blowdown valve that vent to atmosphere [16]. Fugitive emission leaked from pistons and its housing is present and cannot be avoided even in newly and properly installed reciprocating compressors [17]. As compressors age and the shafts and seals of the compressors wear down from friction and heat, fugitive emissions increase. Considering the complexity of calculating various factors affecting emissions over time due to pressurized leaks, leakage per stroke, and frequency of pressurization, most analyses in literature only measure emissions over a short period of time and assume continuous constant leakage. It can be concluded that for component-based emissions from reciprocating compressors that the amount of gas escaping from the system through the gaps is strongly function of the gas pressure and speed. Therefore, increasing throughput will increase the emissions from one specific reciprocating compressor, but compressors usually operate at a constant speed at the compressor station and it can be thought that the dependency of emissions to the throughput is weak. At the same time the gaps between various packing cups and rods even in newly installed system indicate that there is a constant leakage that accumulates over time. As a result, it is believed that emissions from reciprocating compressors are time based.

Wet seal centrifugal compressors block the voids by circulating oil at high pressure around the surface of the shaft and sealant rings [18]. The sealing oil overtime traps gas and needs to be cleaned to maintain its lubricative properties. The process of purging oil from the trapped gas, degassing, produces gas which usually is vented to the atmosphere and is the primary source of emissions in wet seal centrifugal compressors [18].

Dry seal centrifugal compressors employ a ring press around the shaft to seal the voids in the rotating shaft. The ring relies on the pressure difference and springs to prevent the process gas from escaping. Dry seals can be more efficient in preventing emissions at a lower cost compared to wet seals [19]. Similar to reciprocating compressors, it could be challenging to estimate emissions associated with impeller speed and frequency of pressurization. In terms of causal based emissions analysis for centrifugal compressors it can be said that the small percentage of the leakage from the wet seal is related to fugitive emissions at the seal face and this can be thought as time-based emissions since even newly installed wet seal compressors leak. On the other hand, most of the gas leakage happens at the vent from degassing unit which is directly proportional to the throughput meaning higher throughput require more oil circulation and degassing. Therefore, the main cause of emissions change is the change in throughput.

E. Other Emissions Sources

Blowdown: According to data recorded by EPA, approximately 65% to 70% of operators maintain the station pressure while the compressor is idle while the rest will use the blowdowns to depressurize the compressor to atmospheric pressure [20]. In some processing plants, blowdown lines are routed to a flare to limit emissions. This option is almost never available in the transmission sector. One solution to reduce emissions in the transmission sector during shutdowns is to keep compressors mostly pressurized. This approach reduces the amount of gas released to atmosphere in the blowdown process. The drawback of mainlining the pressurized compressor is that this will cause emissions from compressors rod packing and closed blowdown valves [21]. Blowdowns mainly occur during emergencies and maintenance and, emissions caused by blowdowns are event based. Increasing throughput and usage could increase the need for regular maintenance. As a result, it can be argued that emissions from blowdowns can have a small throughput-based cause. Despite this reasoning, some of observations at gas wells and compressor sites show no instances of blowdowns for an extended period, suggesting that blowdowns should only be considered an event-based source of emissions.

Storage Wellhead and Wellbore: The failure of mechanical seals in the wellhead sealing in which separate each layer of different casing can cause the gas from the production casing leaks through an open annulus valve. If the annulus valve is closed, then gas pressure can build up in the annulus and cause more failures and issues. The second source of the leakage occurs within the wellbore due to the fracture in the production casing wall and letting gas inside the case escape and finds its way up to the surface. The last source of emissions occurs when the pressure of the surface casing surpasses the yield strength of the surrounding lithology. This causes the gas to change its direction and instead of moving upward through the wellbore, finds a less resisted way to escape. As a result, gas can travel to another storage field or could move up to the surface where it is then emitted to the atmosphere [22]. In terms of causal based analysis, it can be concluded that the methane emissions due to the failure of mechanical seals can be categorized as equipment leaks. Thus, as long as the wellhead is pressurized, there is a continuous leakage of methane to the atmosphere therefore, these emissions are time based. Methane emissions due to the other two sources from storage wells are mainly event-based since many factors can cause the fracture in the production casing, such as earth movement or heavy production operations close to the storage sites [22].

Storage Tank: The amount of emissions from the storage tank depend on the pressure difference between the tank and the separator and the liquid flow rate. Depending on the segment (production, processing, and transmission) the amount of emissions may be different for the same throughput. It can be concluded that high pressure difference between tank and the separator results in higher emissions. Regardless of the pressure difference for a specific facility, it is clear that the main cause of the emissions is throughput. The more throughput to the facility creates more flash and working losses (fully describe in [23]) from the liquid tanks. At the same time depending on the seasonal and daily changes in temperature and pressure, some portion of the emissions can be considered as event based. In order to prevent the underestimation of emissions from the condensate tank, the emissions from malfunctioning separator dump valves are measured as a separate source of emissions under condensate tank vents in the EPA/GHGI report [23].

Dehydrator: The dehydration unit is used to remove the water from the gas and make it ready for the pipelines. The dehydrators usually use liquid triethylene glycol (TEG) to remove the water from the wet natural gas due to its property to absorb the water. Gas-assisted glycol pumps, in which Kimray is a leading manufacturer, in the natural gas industry are being studied in [24]. Since EPA/GRI 1996 report uses two different approaches to calculate emission and activity factor for dehydrators and gas-assisted glycol pumps, EPA/GHGI reports dehydrators and Kimray pumps as two separate methane emissions sources even though in both methane is vented to the atmosphere through the same venting line. The parameters affecting the amount of emissions from a dehydrator unit were studied using ASPEN/SP model in [25]. It was found that when the glycol to gas ratio is held constant, the glycol circulation rate is proportional to the gas flow rate meaning increasing in the gas throughput yield more glycol circulation rate. As a result, the amount of emissions are linearly proportional to the glycol circulation rate as shown in Fig. 5, which makes the dehydrators a throughput-based emission source.

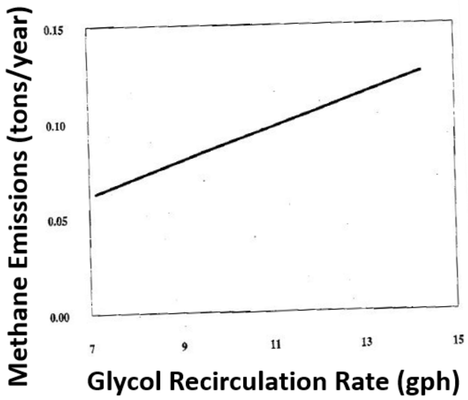

Fig. 5. The effect of glycol recirculation rate on methane emissions rate [25]

Equipment Leaks: The leaks from valves, connectors, flanges, open-ended lines, and scrubber dump valves can occur due to improper installation, manufacturing defect, corrosion, excessive temperature, vibration, and other factors resulting in tear and wear [26]. Although each component plays a small role in adding to the total emissions, they collectively create a significant amount of emissions. Some in the literature suggest that emissions caused by component leaks are random and only frequent inspection and utilizing the detection equipment can reduce them [26]. These components have continued leakage over time and therefore, a big portion of the emissions are considered time-based. Furthermore, gas leakage increases as the gas flowing through them increases and as a result, another portion of the leakage from the equipment is considered throughput based.

The final estimated coefficients for the investigated sources are presented in Table I. As outlined in Table I emission sources have dependency upon more than one casual based factor, and can have dependency to throughput, time, and/or events at the same time. The partial dependency or complete independency of these sources to throughput indicates that system emissions do not proportionally change with the change in throughput. These estimated coefficients will be used in our future work to assess methane emissions change with the change of the throughput based on the marginal methodology.

Table I. Marginal Emissions Assessment Coefficient

	Time Based (*a*)	**Event Based (*b*)**	**Throughput Based (*c*)**
Liquid Unloading	0%	80%	20%
Continuous Pneumatic	100%	0%	0%
Intermittent Pneumatic	0%	80%	20%
Dehydrator vents	0%	0%	100%
Blowdown vents	0%	80%	20%
Reciprocating compressors rod packing	90%	0%	10%
Centrifugal Compressors (Wet Seal)	20%	0%	80%
Centrifugal Compressors (Dry Seal)	90%	0%	10%
Storage tank	0%	10%	90%
Storage wellhead	30%	70%	0%
Gas engine	20%	0%	80%
Equipment leaks	90%	0%	10%

IV. Conclusions

The marginal emission coefficients are determined through a comprehensive study of the literature and an engineering assessment of the mechanisms for the tripartite distribution (event based, time based, throughput based). Results from this work suggest that major emission sources within the natural gas system do not show emissions change one-for-one with changes in throughput. For some components, increasing or decreasing throughput will not change the emissions at all. It is expected that this approach provides a more accurate method compared to the constant-emission-factor method to calculate the change in emissions of the natural gas system as throughput changes.

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