Recommended practices for CH_4 emissions detection and quantification — combustion efficiency and flaring destruction

RECOMMENDED PRACTICES FOR CH_4 EMISSIONS DETECTION AND QUANTIFICATION — COMBUSTION EFFICIENCY AND FLARING DESTRUCTION

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FOREWORD

This document was developed based on available data at the time of its preparation, and in dialogue with technology providers, academics and oil and gas operators. In addition, academic publications were reviewed. This report reflects the review of such information sources and is as accurate and robust as the data provided and to the extent of Carbon Limit's knowledge.

This report might not reflect the views of technology providers, and oil and gas operators that have been consulted during its preparation. For further information on their views, it is suggested direct contact with such persons or companies.

Methane emissions detection and quantification technologies is a fast-evolving field. This report relies on data, technology, and research available to Carbon Limits at the time of its preparation, is prepared on a commercially best effort basis, and has no intention of being exhaustive.

The project that resulted in this report has been conducted under the supervision of Offshore Norge. However, Carbon Limits has made the assessment independently and all precautions were taken to avoid any infringement of competition laws and to comply with best practices. No cost elements of the different technologies were shared by or with the participants.

This document has been developed as a follow up of the project and the report on *Recommended practices for methane emissions detection and quantification technologies – upstream*, performed for IOGP, IPIECA and OGCI. To ensure that this report can be read as a standalone document, some sections of the original report have been included in this document.

EXECUTIVE SUMMARY

This document has been developed as a follow up of the project to IOGP Report 661 *Recommended practices for methane emissions detection and quantification technologies – upstream*, performed for IOGP, IPIECA and OGCI, which aims to provide oil and gas operators with guidelines for selecting and deploying methane emissions detection and quantification technologies tailored to the situation at their sites, with the aim of improving upstream methane management and emissions reporting.

This document addresses technologies to quantify the emissions from flares, which are an important source of greenhouse gas emissions in the oil and gas industry. The report and an accompanying Technology filtering tool can be used to guide operators by asking questions to identify potentially relevant technologies to quantify emissions from flares. A series of detailed data sheets have been developed through input from various stakeholders, including technology providers, operators, and academic research.

This report also covers other measurement techniques and technologies important for flare performance monitoring, which include single and multi-sensor aerial methods (drones and aircrafts), stationary methods, and calculation-based methods (numerical models and Computational Fluid Dynamics (CFD)/predictive systems). Case studies are presented as a knowledge sharing exercise to address how the implementation of technology can be used to identify flaring emissions and inform emissions reduction. Therefore, the work presented in this report is complementary to initiatives to minimise or eliminate routine flaring.

1 INTRODUCTION

Flaring at oil and gas facilities is the process of burning undesirable or surplus gas in an open-atmosphere flame. Satellite data suggest that 152 billion m^3 of gas was flared in 2020 (EOG *Global gas flaring observed from space*). It is estimated that the energy that is wasted in this process could power the whole of Sub-Saharan Africa (The World Bank *Gas flaring explained*).

There are several types of flaring that may occur, including process flaring, production flaring and emergency flaring (McEwen et al. *Black carbon particulate matter emission factors for buoyancy-driven associated gas flares*). Due to the higher market value of oil and lack of infrastructure to gather and process associated gas in certain regions, oil-producing well sites may use continuously operating production flares to dispose of the associated gas (McEwen et al. *Black carbon particulate matter emission factors for buoyancy-driven associated gas flares*).

Flaring converts flared gases including methane into carbon dioxide. Flaring is preferred over direct venting of gas to the atmosphere to reduce greenhouse gas emissions, since methane has a global warming potential 82,5/29,8 times greater than carbon dioxide on a 20/100 years' time horizon (Forster et al. Chapter 7*: The earth's energy budget, climate feedbacks, and climate sensitivity*).

Even though flaring reduces the amount of methane emissions to the atmosphere compared to venting, flares are a source of greenhouse gas and other undesirable emissions. These include methane (the dominant component of natural gas and generally the largest component of flare gas at upstream production sites), and carbon dioxide. Incomplete combustion or inefficient flaring can result in the emission of other undesirable components such as unburned flare gas (Gvakharia et al. *Methane, black carbon, and ethane emissions from natural gas flares in the Bakken Shale, North Dakota*) (Johnson et al. *A fuel stripping mechanism for wake-stabilized jet diffusion flames in crossflow*), volatile organic compounds (Knighton et al. *Direct measurement of volatile organic compound emissions from industrial flares using real-time online techniques*), nitrogen oxides (Torres et al. *Emissions of nitrogen oxides from flares operating at low flow conditions*) and black carbon (Conrad and Johnson *Field measurements of black carbon yields from gas flaring*). It is estimated that 42 % of the black carbon that can be found on the ice of the arctic comes from flaring activities (Stohl et al. *Black carbon in the Arctic: the underestimated role of gas flaring and residential combustion emissions*), increasing snow and ice melt. Additionally, many of the products of inefficient flaring have adverse human health effects (benzene, nitrogen oxides, heavy metals, etc.) (HSC News, University of Southern California *Living near natural gas flaring poses health risks for pregnant women and babies*) (Blundell and Kokoza *Natural gas flaring, respiratory health, and distributional effects*).

In response to the climate crisis, numerous organisations, industries, and governments are undertaking initiatives to minimise or eliminate routine flaring. One such initiative is the World Banks *Zero Routine Flaring (ZRF) by 2030*, which was endorsed by the World Bank and the United Nations Secretary-General in 2015. Additionally, the Global Gas Flaring Reduction Partnership (GGFR) (Global Gas Flaring Reduction Partnership), comprising private investors from the World Bank, was established to support this objective. Routine flaring results in an annual economic loss of 55 billion US dollars (International Energy Agency (IEA) *Flaring emissions*). It is estimated that achieving a complete cessation of routine flaring would require an investment of over 100 billion US dollars (World Bank *Gas flaring explained*). Therefore, reaching zero routine flaring will result in a net positive economic benefit over the longer term.

Alongside these initiatives to reduce gas flaring, operators have an interest in improving and controlling the performance of their flares to minimise their impact on the climate and on people. Flare performance is often determined by its combustion efficiency (CE). Combustion efficiency of a flare may be defined in several ways but is most usefully defined as the carbon conversion efficiency (η), which evaluates the percentage of carbon mass in the hydrocarbon fuel stream that is fully reacted and converted to carbon dioxide. This may be expressed as:

$$\eta[\%] = \frac{mass\ of\ carbon\ in\ produced\ CO_2}{mass\ of\ carbon\ in\ hydrocarbon\ fuel\ stream} \times 100 \quad \text{(Eq.1)}$$

For cases where $\eta < 100$ %, this definition does not impose any restrictions on the composition or phase of incomplete combustion products. In general, these products may include gas phase species such as carbon monoxide and unburned or reformed hydrocarbons, as well as particulate phase soot. <u>However, CE is not directly related to methane emissions.</u> In some situations, it may also be useful to define a destruction removal efficiency (DRE) of any combustible species (for example, methane) in the fuel stream. Destruction removal efficiency can be defined for a species *i* (e.g. methane) as:

$$DRE_i\ [\%] = \left(1 - \frac{emission\ rate\ of\ species\ i}{flow\ rate\ of\ species\ i\ in\ the\ fuel\ stream}\right) \times 100 \quad \text{(Eq.2)}$$

Historically, it has often been assumed that all normally operating flares irrespective of design, operation or age perform at the same level of efficiency – with flares in production environments thought to have a CE of 98 % (API *Compendium of greenhouse gas emissions methodologies for the natural gas and oil industry*). That means that up to 2 % of methane being sent to flare would be lost to the atmosphere. A properly operating flare can operate well above 98 %, often above 99 % and approaching 99,9 %. Similarly, a flare may also operate at much lower efficiency, from ~50 % (McDaniel *Flare efficiency study*) or lower. An unlit flare is effectively achieving a CE of 0 %, which has been well documented (Plant et al. *Inefficient and unlit natural gas flares both emit large quantities of methane*) (Itziar Irakulis-Loitxate et al. *Satellite-based survey of extreme methane emissions in the Permian Basin*) (Itziar Irakulis-Loitxate et al. a) and b) Environmental Science & Technology Letters).

Many parameters may impact efficiency, including flare gas composition, gas flow rate, gas exit velocity from the burner, flare design, as well as crosswinds, as summarised in Table 1.

Table 1: Importance of measured parameters for flare CE/DRE

Parameter	Importance
Gas composition	The characteristics of gas being sent to flare plays a key role in how much methane may be emitted to the atmosphere. This includes the proportion of methane to other hydrocarbons, as well as other inert gases such as carbon dioxide or nitrogen. Gas composition is an indicator for flare gas parameters such as the heating value and air to fuel ratio of the flare gas
Environment	Each flare is subject to a unique mixture of local environmental conditions such as wind speeds, turbulence, and weather events. These conditions may extinguish the flare and result in unintentional venting of gas to the atmosphere or reduction of flare efficiency. Flares are also often placed at high elevations, on a boom over the water in offshore scenarios, and away from infrastructure or personnel for safety reasons due to the high temperatures. This makes accessing and performing measurements more challenging
Flare design	The design of the flare will have an impact on performance. Flare tips may be unassisted, assisted with steam or air, pressure, elevated or ground flares, single or multi-tip, etc. Flare ignition systems may be either using pilot gas lines (where the flare is continually lit using a low-flow, auxiliary fuel source and consists of a flare pilot, ignitor, and pilot flame monitor) or an on-demand ignitor that deploys a flame when required using a guide tube and pellet discharge system
Operation	The same flare may be used in very different operational conditions: I. Normal operation II. Low production flaring with higher fractions of purge gases III. Maintenance, start-up and shut-down processes IV. Emergency events where large amounts of gases are released over a short duration V. Initial flowback operations with high fraction of inert gases (including carbon dioxide or nitrogen) during, e.g. well testing or completions VI. Disposal of sulfuric (acid) gas Operational conditions will influence flow conditions such as homogeneous or cyclic rates
Age	Older flares may be more susceptible to performance issues. As a flare ages without proper maintenance, issues with ignitor or flame monitoring systems may increase Change in flaring conditions over the lifetime of a flare may occur. For example, when the flare system is designed, the knockout drum may be sized accordingly. Over the lifetime of the flare, conditions may change and the knockout drum may be undersized compared to the current activity needs However, satellite data suggest that even new flares have been shown to be a source of inefficient flaring (Itziar Irakulis-Loitxate et al. b) Environmental Science & Technology Letter)

Flare design, operation and age of any individual flare can vary significantly from flare to flare. Gas composition, operation and environmental conditions are also variables that will vary depending on the flare but will also vary over time as well. All these factors result in challenges to determine flare CE/DRE and subsequently methane emissions.

Research both recent and since the 1980s suggests that flares may be a source of methane emissions at oil and gas facilities, and efficiencies can fall well below the commonly assumed 98 %. The IEA estimates the average global CE to be around 92 % (World Bank *Zero routine flaring by 2030 initiative*), while other research determined onshore US flaring DRE to be approximately 91,1 % efficiency (World Bank *Zero routine flaring by 2030 initiative*), which both consider the prevalence of unlit flares. Thus, there is a need to move beyond a generic emission factor, to actual measurements and measurement-based quantification to properly quantify the emissions from flares.

Methane emissions can be calculated using the following equation:

$$\textit{Methane emissions} = \textit{Volume of flared gas} \times \textit{methane content} \times CH_4\ \textit{DRE} \qquad \text{(Eq. 3)}$$

Figure 1 shows the potential implications for methane emissions from global gas flaring (World Bank *Zero routine flaring by 2030 initiative*) depending on the efficiency of the flare, which ranges two orders of magnitude between ~4 $MtCO_2e$/y to >350 $MtCO_2e$/y. Even slight changes in efficiency can result in significant changes in methane emissions. For example, a flare operating with a CE of 99 % will result in –50 % emissions than if it were operating with a CE of 98 %. This highlights the significance that even a 1% change in efficiencies can have significant climate impact.

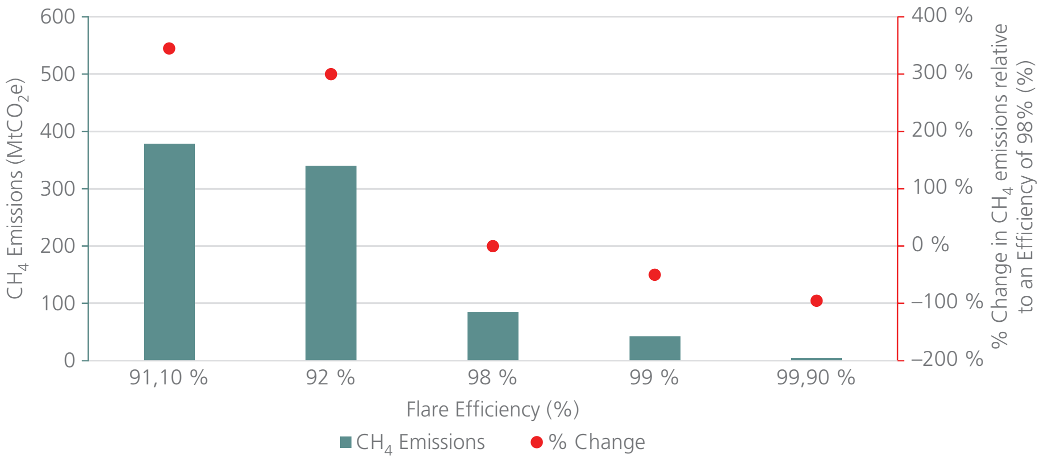


Figure 1: Methane emissions vs efficiency for global gas flaring

The parameters in Eq. 3 require calculation. Flared gas volumes may be measured using flow meters, while the methane content may be determined by analysis using gas chromatographs (GC), laboratory analysis, or online analysis. Eq. 3 also has inherent uncertainty associated with it. For all measured parameters, there are inaccuracies associated with these. Volume of flared gas may be measured using flow meters covered in 2.7.2. Gas composition of the flared gas is also measured using equipment covered in 2.7.3, which includes both the methane content as well as other combustible and non-combustible species. These may be generally described as the flare meter system. These parameters may vary over time, and as such require direct analysis. Since flare systems may not be subject to the same fiscal control as other oil and gas systems, it can be problematic to collect representative samples, reducing the opportunities to perform validation sampling. Furthermore, when gas composition is derived from sampling or inferred by other means, there is an associated uncertainty with this, as it assumes that the gas has a certain composition, which may vary from real-time conditions. Similarly, instantaneous flow rates may vary from time-averaged, hourly or daily flow rates. Variations in these parameters will also have an impact on efficiency and associated methane emissions, which also must be considered, particularly if these parameters are not directly measured, or inferred from other conditions that may not be wholly representative with an uncertainty stated with it.

2 TECHNOLOGY REVIEW

Development of technologies to quantify flare efficiency and emissions is ongoing, and there are now a range of technologies that are becoming available that allow for better quantification of emissions from specific flares. Identifying a flare that has lower efficiency than expected will also allow an operator to explore technical options to improve it and thus reduce emissions. The following sections describe general approaches to measuring flare performance. First, controlled experiments are described that look at testing of flares in controlled or semi-controlled situations. Then, technologies that measure both physical properties using *in situ* measurements of the flare plume (aerially deployed sensors) and wavelengths of light or electromagnetic radiation (spectrometry) are described. This is followed by modelling of flare CE/DRE using measured parameters such as gas composition and flared gas volume and flare burner design. Other systems using computational fluid dynamics (CFD) and predictive systems that monitor specific flares are also described. Finally, other measurement methods that are not directly quantifying CE but are providing useful tools/solutions to identify and reduce methane emissions from gas flaring will also be covered.

Additional resources can be found in the Methane Guiding Principles (MGP) Methane Flaring Toolkit (Methane Guiding Principles *Methane flaring toolkit*). The Methane flaring toolkit also covers other flaring situations beyond the scope of CE/DRE of flares included in this document, and more comprehensive descriptions and analysis can be found both in the Toolkit as well as the referenced links.

Technologies for the measurement of flare CE and DRE are a fast-evolving space. It is expected that technologies will continue to be developed and evolve over time. It should be noted that technologies assessed as part of this report only include those for which providers were available for interviews. Other technologies may be available, and others may be made available in the future.

2.1 CONTROLLED EXPERIMENTS

Controlled experiments are often done for research and experimental purposes by both academia and operators. While they are not directly useful for an operator to determine CE/DRE of specific flares, they may be used to test and train models, and to better understand flare performance.

2.1.1 Experimental scale

These experimental conditions are often scaled down flares. Examples include flares in wind tunnels (Bourguignon et al. *The use of a closed-loop wind tunnel for measuring the combustion efficiency of flames in a cross flow. Combustion and flame*) (Burtt et al. *A methodology for quantifying combustion efficiencies and species emission rates of flares subjected to crosswind*), or on vertical flares in laboratories (Corbin, and Johnson *Detailed expressions and methodologies for measuring flare combustion efficiency, species emission rates, and associated uncertainties*). The benefits of these experiments are that they allow for flare experiments to be performed in controlled conditions. However, flares operate in an open atmosphere and thus may be subject to a variety of atmospheric conditions. Experiments in wind tunnels offer the benefit of flares subject to atmospheric conditions such as turbulent crosswind.

2.1.2 Full scale

At testing facilities, the concept is to perform measurements on a full-sized test flare on the location site, where products of the plume are measured to determine CE and methane emission rates (McDaniel *Flare efficiency study*) (Torres et al. *Industrial flare performance at low flow conditions*). Flares can be measured using extractive samples that sample a point in the plume, or where the plume is entirely captured using a 'fume-hood' type sampler.

Tests of this nature allow for tests in a variety of conditions, which are both controllable (for example burner type and diameter, flare gas exit velocity and gas composition) and uncontrollable in nature (for example the presence of crosswinds).

Examples include the US EPA Flare Efficiency Study (US EPA *Flare efficiency study*), the Texas Commission on Environmental Quality (TCEQ) Flare Study (TCEQ *Flare study final report*), and ongoing work by bp in the process of publication (although not publicly available at the time of the publication of this report).

Other ongoing research is currently planned by the British Flame Research Committee (BFRC)[1] with support of its members to overcome the challenge of lack of defensible baseline data available for models. They believe they can overcome this challenge and test 'a flare in a box' at industrial scales, accurately simulating crosswind with all measured input and output parameters, including methane slip in the exhaust gas. Having this information should allow a more accurate indication of flare performance at its normal operating conditions thus providing invaluable information to flare suppliers, modelling/simulation providers and operating companies in how to design, operate and monitor flares to better understand, report and manage flare emissions.

2.2 AERIALLY DEPLOYED SENSORS

Aerially deployed sensors are those that are mounted and flown at altitudes around oil and gas operations to measure flare CE, CH_4 CE or CH_4 emissions directly. They are most often performed using two deployment methods: drones and airplanes. The following sections provide descriptions of the general methods and points of consideration. Aerially deployed technologies offer snapshot of emissions but may not be representative of all conditions.

1 The British Flame Research Committee (BFRC) brings together industry, academe and regulators looking to sustain the vital contribution of combustion in energy intensive industry by informing policy, stimulating research and disseminating knowledge across the commercial and academic sectors to support the UK's contribution to a 'global zero carbon future'. They have a number of active working groups, one of which is focusing on flare emissions and performance. Whilst many previous studies have investigated and validated flare performance, the majority have only considered full design firing conditions. However, for the majority of the time the flare operates at lower flow rates and it is in this area the BFRC flare working group are directing their attention. The group has already validated that a small reduction in combustion or destruction efficiency can result in a significant increase in CO_2e but as not all flared gas is methane it is equally important to consider the gas compositions when equating the emissions to a Climate Warning Potential value. For more information on the BFRC working group, please contact Richard Withnall at Greens Combustion Limited, rwithnall@greenscombustion.com, or for the BFRC in general, Roger Dudil, comms@britishflame.org.uk

2.2.1 Drone-mounted

The use of drones in the surveillance and maintenance of oil and gas installations has become increasingly widespread. In the case of flaring, they allow measurements to be taken in the flare plume. There are two measurement methods for these drones:

1. Single sensor drone to measure the concentration of methane:

This method uses a drone that is fitted with only one methane sensor that measures the methane concentration of flare plume. By taking many measurements, it is possible to estimate the quantity of methane that is released by the flare. Using the measured methane flow rates of the fuel stream (for example, using an ultrasonic flow meter), the CE also can be calculated. Care must be taken to isolate methane emissions from the targeted flare, since methane from other potential sources may also be identified using this method.

2. Multi-sensor drone to measure the concentration of methane and carbon dioxide:

If the drone is fitted with both methane and carbon dioxide sensor, the CE can also be calculated, and the carbon dioxide sensor allows measurement of carbon dioxide concentrations. Flare plumes will be more distinguishable from other emission sources at oil and gas facilities using this method since carbon dioxide is also measured and is not often found in plumes from other equipment sources. By evaluating the ratio between this amount and the measured flow rate of the fuel stream, it is possible to estimate the CE/DRE.

Although drones have a reduced complexity compared to other airborne solutions, they require very light sensors. Sensors mounted on drones may also pick up emissions from other methane sources at oil and gas facilities, or from neighbouring sources. Care must be taken to isolate methane emissions from the targeted flare. Methods have been developed to perform inversions to isolate a methane plume at multiple flight altitudes (Conley et al. *Application of Gauss's theorem to quantify localized surface emissions from airborne measurements of wind and trace gases*) or in 'curtain-like' paths where a drone will fly starting at the lowest altitude to the highest, to completely envelope any emissions from the source.

2.2.2 Aerial measurement of flare efficiency

This solution is based on the same concept as the drone one, but with sensors mounted on airplanes or helicopters. Planes can be equipped with single methane sensor or both methane and carbon dioxide sensors. These aircraft are manned and will typically have longer flight times and cover more distance per flight. They can take measurements over a wide area downwind of the flare.

One aspect that must be considered is the potential for other, non-flare sources of emissions (or multiple flares) that may be measured downwind. Therefore, it is important that the emissions from flares are isolated. This may be done by flying in closer proximity (while adhering to safety requirements), or by isolating the flare emissions. For example, this can be by comparing concentration spikes of methane and carbon dioxide (in the case of measurements of multiple concentrations simultaneously, since non-combustion sources will not typically be a source of both methane and carbon dioxide emissions), where possible.

Examples in the literature include thoseby Zavala-Araiza et al, Gvakharia et al, and Caulton et al.

2.3 SPECTROMETRY

2.3.1 Video imaging spectral radiometry (VISR)

VISR is a remote sensing technology that provides real-time measurement of the flare CE. CO_2 and unburnt hydrocarbons concentrations of the flare are estimated using a spectral analysis of the image of the flare in the infrared spectrum. It can also provide information on the amount of heat released by the flare and therefore the amount of gas burnt. VISR can be used as a stationary solution, to continuously monitor one particular flare (or various flares in its line of sight) or as a mobile device for the inspection of a site as part of a maintenance and repair programme.

Examples of this method include the work by Duck et al (*PERF Project 2014-10 results and analysis of the VISR method for remote flare monitoring*), and Zheng (*Review of differential absorption lidar flare emission and performance data*).

2.3.2 Active laser spectrometry

Active laser spectrometry is a remote sensing technology that provides real-time measurement of the flare CE, and that allows quantification of emissions. The range of measurements is large, as it can take measures up to one kilometre away.

The idea behind active laser spectrometry is to send a laser beam of tuneable wavelength to the area of the flare. The laser will reflect on a particular type of particle (methane, carbon dioxide, etc.) depending on its wavelength. By calculating the intensity of the light returning to the sensor, it is possible to estimate the concentration of the different particles in the flare. DIAL (differential absorption LIDAR (light detection and ranging)) is an example of this technology.

A report by the UK Environment Agency provides a comprehensive review of the DIAL technique (Few et al. *Review of differential absorption lidar flare emission and performance data*). More details can be found in the report.

2.3.3 Passive Fourier transform infrared (PFTIR) or hyperspectral spectrometry

This technology is based on passive spectroscopy method. It receives the continuous spectrum of emissions that hot gas emit in the flare and analyses it mathematically to identify the signature of the different elements of the plume. It allows the quantification of the amount of carbon dioxide, hydrocarbons and carbon monoxide that is emitted from the flare. The complexity of this system requires specialist operators and is not suitable for long-term deployment.

2.3.4 Pyrometer

A pyrometer is a remote sensing technology that provides real-time temperature measurements. By measuring the change in light intensity, it can determine the presence or absence of a flame at the extremity of the flare tip. Pyrometers are often used alongside thermocouples for an extra layer of monitoring, for example, if the flare is lit. Temperature can sometimes be taken as a proxy for CE, where changes to the temperature may be indicative of lower efficiency. However, they are not able to directly measure CE/DRE or methane emissions and may also be correlated to other changing parameters like the volume of flared gas.

2.4 NUMERICAL MODELLING TO ESTIMATE FLARE CE AND CH_4 EMISSION RATES

By using measurable parameters of a flare, such as gas composition, flared volume and burner diameter, the efficiency and methane emission rates of flares may be calculated by using numerical models. Over the past 20 years, several models to estimate flare CE and methane emissions from flares have been developed. They are summarised as follows:

- Flare CE applicable to flare from 0,5 – 2 inch burner diameters – Eq. 1;
- Flare CE applicable to flares from 2 – 4 inch burner diameters – Eq. 2;
- Flare CE applicable to flares with large amount of inert gas – Eq. 3, and
- Flare CH_4 emission rates applicable to flares from 2–4-inch burner diameters – Eq. 4.

The following sections provide a description of each of these models, including required input parameters, how they can be used to estimate flare CE or methane emission rates, and any potential limitations or considerations to take when using these equations.

2.4.1 Empirical models to estimate flare efficiency

Johnson and Kostiuk (*A parametric model for the efficiency of a flare in crosswind*) presented a parametric model to estimate flare CE for multiple flare diameters and natural-gas-based fuel compositions:

$$1-\eta = A\frac{\exp\left(B\frac{U_\infty}{(gV_jD)^{1/3}}\right)}{LHV_m^3} \qquad \text{Eq. 4}$$

Where U_∞ is wind speed, g is the gravitational constant, V_j is the flare gas exit velocity from the flare stack, D is the inner flare stack diameter, LHV_m is the mass-based lower heating value of the flare gas, $A = 156,4\left(\frac{MJ}{kg}\right)^3$ and B = 0,318.

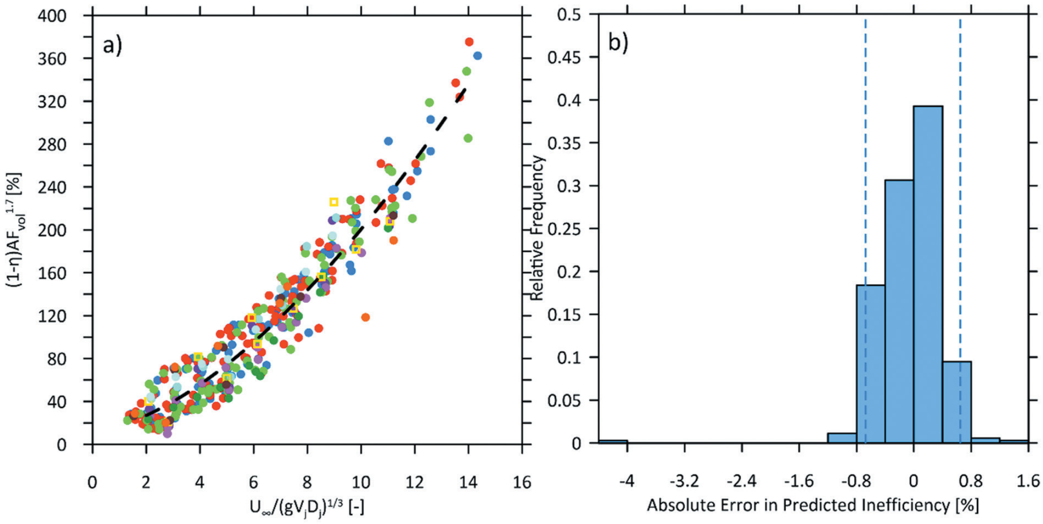
This practically motivated model used heating value as an easily obtainable parameter to represent flare gas compositions, to scale data in combination with the empirical relationship of Kostiuk et al. (Scaling of wakestabilized jet diffusion flames in a transverse air stream). Separate empirical coefficients A and B were determined for either natural gas- or propane-based (not shown here) fuels from 0,5–2-inch diameter flares using a closed loop wind tunnel.

More recently, experiments were performed using a closed loop wind tunnel and resulted in a published methodology to calculate flare efficiency and emission rates (Burtt et al. *A methodology for quantifying combustion efficiencies and species emission rates of flares subjected to crosswind*). The empirical model presented below considers hydrocarbon flare gas mixtures with less than 20 % inert diluents 2–4-inch burner diameters, with exit velocities between 0,5 and 2 m/s:[2]

$$(1-\eta)\,AF_u^{1,7} = 4,54\left(\frac{U_\infty}{(gV_jD)^{1/3}}\right)^{1,615} + 13,53 \qquad \text{Eq. 5}$$

2 Conditions that are representative of Alberta, Canada

AF_{υ} is the stoichiometric air to fuel ratio of a volumetric basis, U_{∞} is wind speed, g is the gravitational constant, V_j is the flare gas exit velocity from the flare stack, and D is the inner flare stack diameter. Figure 1 plots the suggested empirical model for scaling carbon conversion inefficiency data using $AF_{\upsilon ol,stoic}$. The 95 % confidence interval on the predicted inefficiency is –0,679 % to +0,6907 % (absolute).



General Model	Coefficienct (w/ 95% coefficient bounds)	Goodness of fit
$(1-\eta)AF_{vol}^{1.7} = a(U_{\infty}/(gV_jD_j)^{1/3})^b + c$	a = 4.54 (3.12, 5.96) b = 1.615 (1.495, 1.735) c = 13.53 (6.389, 20.67)	SSE: 1.347E+5 R^2: 0.9292 Adjusted R^2: 0.9288 RMSE: 19.4092

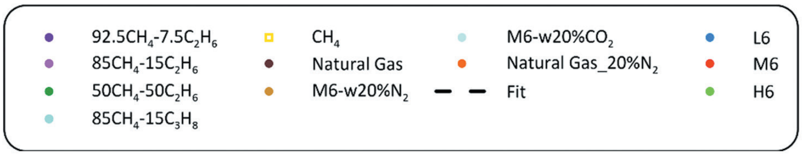
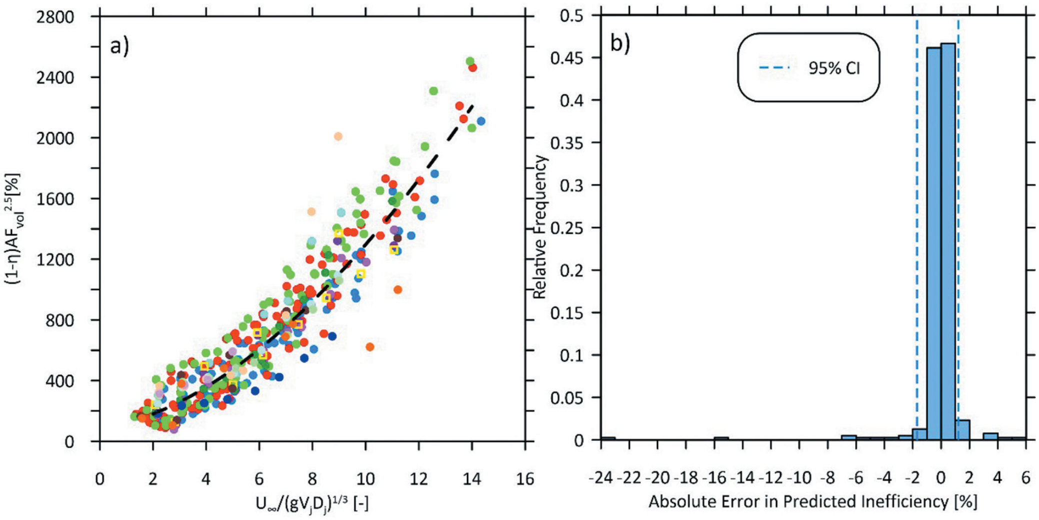


Figure 2: Flare efficiency

Flares in certain applications, such as those associated with gas treatment processes, may include large amounts of inert species in the flare gas. For these cases, an empirical model has been derived using data for flare gas mixtures with up to 70 % inert species (i.e. CO_2 or N_2), as:

$$(1-\eta)AF_{\upsilon}^{2,5} = 25,13\left(\frac{U_{\infty}}{(gV_jD)^{1/3}}\right)^{1,678} + 100,3 \qquad \text{Eq. 6}$$

As shown in Figure 2, a model based on $AF_{\upsilon ol,stoic}$ is again applicable, predicting the flare inefficiency within an absolute difference with a ~–1,7 % to +1,2 % at 95 % confidence.



General Model	Coefficienct (w/ 95% coefficient bounds)	Goodness of fit
$(1-\eta)AF_{vol}^{2.5} = a(U_\infty/(gV_jD_j)^{1/3})^b + c$	a = 25.13 (23.64, 26.62) b = 1.678 (1.655, 1.701) c = 100.3 (92,09, 108.5)	SSE: 2.345E+5 R^2: 0.9974 Adjusted R^2: 0.9973 RMSE: 24.585

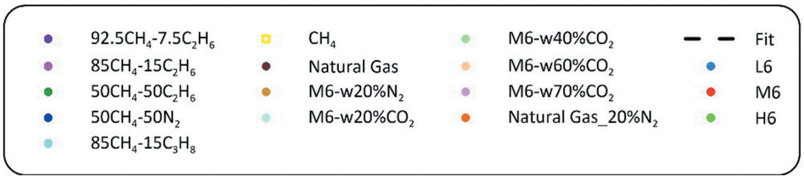


Figure 3: Inefficiency for flares, including highly diluted flare gas compositions

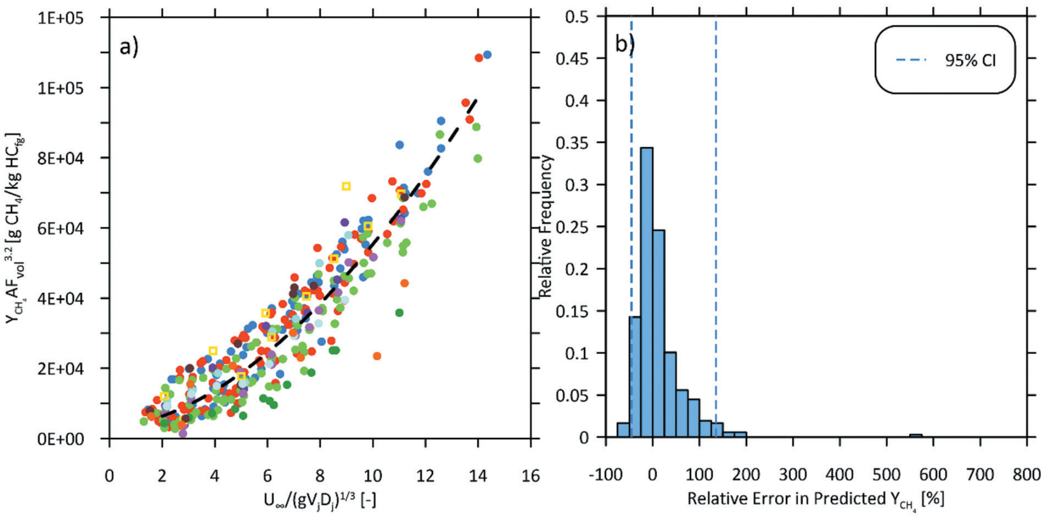
The equations in Figure 3 are made up of parameters that are relatively simple to obtain (constants, air to fuel ratio or heating value from gas composition analysis, flare gas exit velocity using metered flow rates and the known flare diameter, and wind speeds from, e.g. local meteorological stations or on-site wind speed measurements). A note of importance is that the tested burner diameters used to develop Eq. 2 partially overlaps with field-scale burners, and the model can scale burner diameters above 3 inches, which offers promise for applicability to larger burner diameter sizes not included in testing. However, there is higher uncertainty on the accuracy of the model to be applied outside the range of the tested conditions, and it should be used with caution, particularly for gases with high dilution of inert gases.

2.4.2 Empirical model to estimate methane emission rates

From a greenhouse gas perspective, a model to specifically predict methane emissions rather than bulk inefficiency would be useful. The same team at Carleton developed an empirical model for predicting methane yield (Y_{CH_4}, defined as g CH_4 per kg of hydrocarbons in the flare gas) scaled using $AF_{\upsilon ol,stoic}$ and defined as:

$$Y_{CH_4}AF_{u}^{3,2} = 911,3\left(\frac{U_{\infty}}{(gV_jD)^{1/3}}\right)^{1,757} + 3283 \qquad \text{Eq. 7}$$

Figure 3 (Kostiuk et al. *Scaling of wake-stabilized jet diffusion flames in a transverse air stream*) presents a model using $AF_{\upsilon ol,stoic}$ as a correlating parameter to predict methane yields within –45 % to +140,1 % at 95 % confidence. Again, the given equations are made up of parameters that are relatively simple to obtain (constants, air to fuel ratio from gas composition analysis, flare gas exit velocity using metered flow rates and the known flare diameter, and wind speeds from, e.g. local meteorological stations or on-site wind speed measurements). However, there is higher uncertainty on the accuracy of the model to be applied outside the range of the tested conditions, and should be used with caution, particularly for gases with high dilution of inert gases. The model was shared as a current best attempt to predict methane yields due to the significance of gas flaring and the need to develop a practical model in the absence of better available data, and to move beyond a common assumption of 98 % CE.



General Model	Coefficienct (w/ 95% coefficient bounds)	Goodness of fit
$Y_{CH_4}AF_{vol}^{3.2} = a(U_\infty/(gV_jD_j)^{1/3})^b+c$	a = 911.3 (547.1, 1276) b = 1.757 (1.603, 1.912) c = 3283 (960.7, 5605)	SSE: 1.78E+10 R^2: 0.8892 Adjusted R^2: 0.8885 RMSE: 7.06E+3

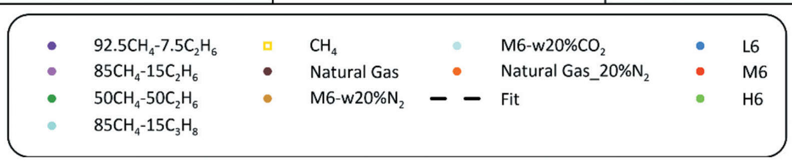


Figure 4: Methane emission rate

2.5 COMPUTATIONAL FLUID DYNAMICS AND PREDICTIVE SYSTEMS

Predictive analytics system for flares uses a method based on a parametric model and CFD studies with input data coming from flare gas composition, flow rates, flare design (pressure and temperature as well as flare tip shape and diameter) and environmental factors such as wind speed and/or humidity. These systems can be used to maintain continuous and efficient combustion. They can also be permanently installed or theoretically as a digital twin, independently of flare vendor or control system (Laing & Black National Engineering Laboratory).

Parameters of influence are measured for the flare, including temperatures, pressures, flow rate, exit velocity, flare diameter, purge rate and gas composition. Algorithms are based on previous experimental studies. Combustion efficiency is inferred based on readings compared to controlled, experimental data.

The systems can be deployed both onshore and offshore, for a variety of flare types (e.g., assisted, or unassisted, high pressure vs. low pressure). However, the use of a flow meter on the flare line is needed to gather data and integrate the systems with the flare control system. The accuracy of the flow meter is also essential to ensure the calculated efficiency is accurate. The quality of measured parameters can affect flare efficiency uncertainty (Gibson *Validation of the CFD method for determining the measurement error in flare gas ultrasonic meter installations*). For example, the placement of a flow meter on the flare line may result in suboptimal measurements of flare gas flow rate, which will have further implications when determining CE or methane emissions from flares. Flow simulations in the flare gas line may be undertaken using CFD software packages such as Fluent.

Interviews with the BFRC shed light on their ongoing plan to embark on a comprehensive CFD programme. This programme aims to understand how different flare designs operate under various weather conditions, starting from the out-of-the-box supplied design condition up to the point just before replacement due to mechanical failure. Unfortunately, after some trial studies, BFRC felt that CFD would not be able to provide a suitable prediction tool. This was due to a surprising lack of defensible baseline data that the models could use for the extrapolation of differing designs and conditions. This lack of accurate data to provide CFD with the initial defensible model needed, prior to scaling into the actual operating scenario, was a major hurdle that BFRC felt needed overcoming.

2.6 IDENTIFYING UNLIT FLARES AND PERFORMANCE ISSUES

This section captures other measurement methods that are not directly quantifying CE but are providing useful tools/solutions to identify and reduce methane emissions from gas flaring. Identification, measurement, and subsequent mitigation of unlit flares is an important aspect of methane emissions management, as an unlit flare will effectively have a CE of 0 %, emitting all methane to the atmosphere.

2.6.1 Satellites

Satellites can be used to measure methane emissions from space. Methane in the total atmospheric column is measured using multispectral imaging. They therefore must have a very high sensitivity to be able to distinguish a surface methane plume from the background methane concentrations in the atmosphere. Since they are generally not able to identify the distribution of emissions within the total column, (i.e., the vertical extent of a plume), they provide information only in two dimensions. However, depending on their orbit, they allow for continuous or frequent measurement, and therefore add a time dimension. The orbit type determines the geospatial and temporal coverage of a remote sensing satellite. Most methane-capable satellites operate from a low Earth orbit, with an altitude between 500 and 1000 km above Earth. Depending on the satellite's field of view and the latitude of the site, satellites may have a site revisit frequency between 1 and 14 days. Therefore, satellites offer a snapshot of emissions but may not be representative of all conditions, similar to aerially deployed sensors.

Many satellites are currently available, some with publicly available data and some privately operated. Satellite resolution also varies and may provide estimates from a regional scale down to scales approaching site level, where individual plumes are identifiable. This has an impact on the ability to identify the emission source, such as a flare. Minimum detection thresholds of methane also vary significantly, from approximately 100 kg/h up to >1000 kg/h. Additionally, satellite measurement requires daylight and low cloud coverage, while quantification accuracy depends on wind speed and the flow rate of gas being flared. Satellites also have difficulty performing measurements over water. New techniques are being developed that use sun glint[3] reflected off a water surface to detect and quantify emissions. Currently early in development, this technique could improve the ability to detect and quantify methane emissions over bodies of water. Satellite measurements of both CH_4 and CO_2 are currently not available.

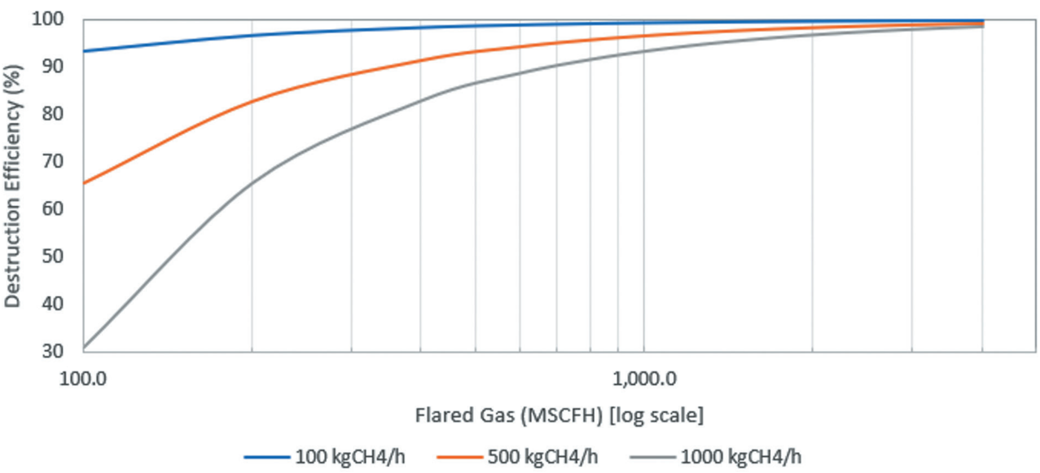


Figure 5: CH_4 DRE vs volume flow rate of flared gas for three methane emission rates

Figure 5 presents a comparison of methane DRE vs the volume of flared gas from a single flare for three theoretical satellites with detection thresholds of 100, 500 and 1000 kg/h. The lower the detection threshold of the satellite, the smaller the flare that will be detectable (looking vertically along a single flare gas flow rate), while the emissions from flares with smaller flared gas volumes will be more detectable (looking horizontally along a single DRE).

Satellites can also be used to identify unlit flares (which have a CE/DRE of 0 %). Satellites can therefore be an effective means to either confirm the absence of unlit flares, or to identify flares with performance issues that may go undetected otherwise. Identifying these potentially large emission events is crucial from an emissions standpoint.

3 Glint is the specular reflection from the surface of water and occurs when the sun angle and view angle are equal and in the same principal plane.

2.6.2 Optical gas imaging (OGI)

When a flare has a combustion performance issue, the unburnt hydrocarbons (composed mainly of methane) are going to create a plume that can be detected with an infrared camera. This technology is also used for leak detection and repair (LDAR) activities. However, it is not able to directly quantify methane emissions from lit flares due to the heat release of the flare but can be used to identify unlit flares or performance issues. Examples include work by Lyon et al (*Concurrent variation in oil and gas methane emissions and oil price during the COVID-19 pandemic*) and Zavala Araiza et al (*A tale of two regions: Methane emissions from oil and gas production in offshore/onshore Mexico*). Several OGI cameras are available, which are covered in more detail in IOGP Report 661 – *Recommended practices for methane detection and quantification technologies* by OGCI, IOGP and Ipieca.

2.6.3 Alarm systems[4]

Other aspects of a flare system can be incorporated into flare monitoring to determine when a flare is unlit, or potentially dealing with performance issues. Options could include one or more of the following:

– Optical camera or thermal imaging camera that can be viewable from a control room by site personnel, or connected to an alarm system that may signal operational status or provide performance warnings.
– A thermocouple attached to a flare can monitor the heat from flaring, where a low temperature reading may signal that a flare has become unlit.
– Acoustic monitoring systems can also be used that respond to the sound signature of a pilot flame as it travels along the pipe works and signal the operating status of the flare.
– Flame ionisation detection alarm systems uses ionisation of the gas during combustion to generate a measurable current that can also signal the operating status of the flare.

2.7 OTHER ASPECTS OF FLARE MONITORING

This section captures other measurement methods that do not directly quantify CE but provide useful tools/solutions for flare monitoring, to identify and reduce methane emissions from gas flaring.

2.7.1 VIIRS

A subcategory of satellites is the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi NPP and NOAA-20 satellites. The technology measures visible and infrared imagery in the near and short-wave infrared spectrums at night to identify flared gas volumes. The satellite has high resolution and publicly available data. However, it is not a direct measurement of efficiency or methane emissions and can be inaccurate when several flares are captured in a single pixel. It also cannot identify unlit flares and is impacted by high cloud coverage.

4 Information is a summary of the Methane Flaring Toolkit. Please refer to https://flaringmethanetoolkit.com/ for a comprehensive overview.

2.7.2 Measurement of the flare gas volumed – flow meters

Flow meters measure the rate of gas sent to flare. Many different types of flow meters exist and are used in the oil and gas industry, including ultrasonic flow meters, Coriolis mass flow meters, thermal mass flow meters, differential pressure flow meters, positive displacement flow meters etc.

A note of importance is that only ultrasonic and thermal mass meters are suitable for flare lines: inserting an obstruction in a flare line is not possible, while inserting thermocouples and sample probes must be as short as possible and undergo wake frequency calculations to ensure their stability.

While not able to directly measure flare efficiency, they provide crucial metering of gas sent to flare, and can be an input to a system that will estimate flare efficiency, such as in CFD analysis. The MGP Methane Flaring Toolkit contains a comprehensive review of flow meters, and more information can be found in this resource.

2.7.3 Measurement of the flare gas composition

While flare gas composition is not the only influence of flare performance, it is an important parameter to measure to be able to calculate the CE/DRE of a flare. For example, 2.4 details how the gas composition may influence the calculated CE or methane emission rate of a flare.

Many types of measurements may be made to calculate gas composition, including gas chromatography – mass spectroscopy (GC-MS), on-line sampling, lab analysis, as well as a host of others. A complete list can be found in the MGP Methane Flaring Toolkit. As well as providing the pros and cons of each method, it provides information on the effectiveness of samples based on the probe type selected.

3 CRITERIA FOR FLARE TECHNOLOGY SELECTION PRESENTED IN THE ONLINE DATABASE AND TECHNOLOGY DATA SHEETS

To help the operators understand which technologies may be most suitable for their sites, a technology filtering tool and a series of technology data sheetss were developed and are provided in conjunction with this report.

Using the interactive technology filtering tool, the operator answers a set of questions, selecting preferences for a wide range of criteria, to assess which technologies could be most suitable for the operator's site(s) and purpose(s). The operator may answer only parts of the questions depending on the specific characteristics of the need. The technology filtering tool is, by nature, simplifying complex assessments, and operators are always invited to refer to the technology data sheetss for a more detailed assessment.

Detailed technology data sheetss have been prepared for each technology assessed under this project. The information used in the technology filtering tool comes from the technology data sheetss, with a focus on the filtering criteria.

The following sources and validation aspects were used to develop the technology filtering tool and technology data sheetss.

Source and validation classification

Sources:

[1] Information from peer-reviewed paper prepared by an independent party (such as academia).

[2] Information from independent third party (such as operator).

[3] Information from technology provider (including peer-reviewed paper from technology provider).

[4] Certification against a standard (e.g.: OGI, US EPA OOOOa etc.).

[5] Carbon limits assessment.

Validation :

(a) Tested by independent academic researchers.

(b) Tested by fully blind tests performed with third party (e.g.: operator, academia), Fully blinded tests are when the technology provider has no knowledge of controlled releases being performed and are the most representative of real-world oil and gas sector surveys.

(c) Tested by partially blind tests performed with third party (e.g. operator, academia), Partially blinded tests are when the technology provider is aware of controlled releases, but not of the characteristics of the release, such as the location or the magnitude.

(d) Technology providers' in-house testing.

This section presents the information and criteria used in the technology filtering tool and technology data sheetsss and provides the reader with background information on how to use them. Some categories are used as filters in the database, i.e. those containing 'tool filter' in their title. All criteria listed in this section are detailed in the technology data sheetss, whether they are used as tool filters or are only covered in the technology data sheetss.

This document has been developed as a follow up of the project to IOGP Report 661 *Recommended practices for methane emissions detection and quantification technologies – upstream*, performed for IOGP, IPIECA and OGCI. To ensure that this report can be read as a standalone document, some sections of the original report have been included in this document.[5] Given the differences between measuring flare CE/DRE from methane emissions from other potential sources at upstream oil and gas facilities, the existing technology filtering tool has been expanded to include a separate filtering sheet for technologies to measure CE/DRE of flares specifically.

3.1 OPERATOR PREFERENCES

Methane emissions detection and quantification technologies can take many forms and may be deployed in different ways. The nature of the technology can be selected depending on the operator's preferences and constraints with regards to site access, business model, deployment method and the output of the sensor (visual/non-visual). The following sections provide details on each of these filters.

Depending on the nature of the filter questions, the operator can choose multiple options, or single options. For single option filter questions, the default is 'All'. In this case, technologies applying to all option types will be visible in the final technology table. For multiple option filter questions, the user can check or uncheck the boxes depending on the characteristics that the operator wishes to exclude, thus narrowing the technology choices that will be displayed by the technology filtering tool.

3.1.1 Deployment method (tool filter)

Technology deployment methods can vary significantly. These include equipment mounted on drones or airplanes, fixed sensors on tripods, elevated mounting systems or permanent process instrumentation. This factor can be important if certain deployment methods are challenging for a given facility, for example, plane-mounted solutions will not be possible for facilities located in a no-fly zone.

The technology filtering tool asks the operator to indicate the different deployment methods that may be considered. The operator should check all boxes that they wish to consider in the assessment.

3.1.2 Sensor classification and type (tool filter)

Though not presented as a filter for the user, the tool also classifies the sensors by type. Technologies to quantify flare efficiency range from *in situ* measurements to optical, remote methods. Sensors may be broadly classified as using *in situ*, remote sensing, or calculation

5 Note that criteria for technology presented in the Data Sheets have been adapted from a previous recommended practices document Report 661 *Recommended practices for methane emissions detection and quantification technologies – Upstream* performed for IOGP, IPIECA and OGCI. There are similarities between these reports, as structures and options for the Data Sheets are similar. Criteria have been edited where applicable to apply to flare efficiency measurement technologies.

software-based techniques. Sensors requiring direct contact with the plume are classified as *in situ*. Sensors that can remotely measure efficiency are classified as remote-sensing methods. Calculation software-based technologies will also require additional, external inputs (such as gas composition, gas flow rate etc.) that will be used to determine a flare's performance.

3.1.3 Business model (tool filter)

Technology and service providers generally offer two main business models:

– Instruments are purchased and used by the operator's staff.
– Technologies are offered as a data product, whereby the technology is deployed or installed by the technology provider, who subsequently provides data analysis/reports.

Some technologies can be deployed using either business model, while others are only available under one of these arrangements. Operators can choose the 'both instrument and data product' option to filter technology providers who offer both options. Turnaround times and specific services offered can vary significantly and have been documented in the Technology data sheetss when known.

3.1.4 Frequency of technology deployment (tool filter)

The recommended frequency of deployment may be specified by the operator, depending on several parameters, though only from a technical perspective.

Technologies have been classified as one of the following:

– Continuous monitoring: this could be at site level, equipment level or component level. (It should be noted that continuous monitoring can be affected by gaps in network connectivity or environmental conditions, leading to occasional gaps due to downtime of the system.)
– Periodic monitoring: this concerns technologies such as handheld devices and aerial monitoring. Such technologies may require the operator's or provider's assistance in deployment. The actual frequency is then selected by the operator.

3.1.5 Sampling frequency during operation

During measurements, technologies may take samples at different time frequencies, for example, more than every second, every minute, every 10 minutes etc, and can be useful information to understand how 'continuous' a methane sensor is. This section will provide further information regarding the sampling frequency of a technology while it is deployed.

3.1.6 Response time on CE/DRE quantification

Flare technologies or techniques may perform readings constantly, but the response time for how frequently flare CE/DRE is calculated and output may be longer, for example, due to averaging or processing time. This section details the response time between when a measurement is taken and when combustion or CE is output.

3.1.7 Requires access to site (tool filter)

Some technologies may require site access to perform e.g. periodic measurements around site equipment. Otherwise, site access may also be required for installation or deployment, e.g. a permanently installed sensor on a fixture that requires placement and setup. Permits may be required for some of these technologies. Other technologies can be deployed without access to the site, for example if they are remotely operated at sufficient distance from equipment. Possible responses in the technology data sheets are as follows:

– Yes: site access is required for deployment or installation
– No: site access is not required for deployment or installation

3.1.8 Operating regions

For some technologies, providers may not have availability in all areas, due to international restrictions, lack of demand or limited personnel availability. This section of the technology data sheet covers specific areas where the technology is currently deployed or is available for use or purchase.

3.1.9 Operational since

This section of the technology data sheets presents the age of the technology, to provide an indication of the technology provider experience.

3.2 FLARE QUANTIFICATION/MONITORING

Flare measurement technology for quantification and monitoring may provide outputs in specific formats, including CE, DRE or CH_4 emissions. Where possible, it will be specified which parameter is being measured and output by the technology. It is important to remember in this section which parameters are being monitored. For the differences between CE, DRE, and methane emissions, see in section 1 for more information.

3.2.1 Quantification performance (tool filter)

Quantification performance may be based on different operating conditions of the flare, wind speeds, and/or distances of measurement technology from the source, all of which can have an impact on quantification performance. Robust, parameterised, and publicly available analyses of quantification performance increase transparency regarding the abilities of technologies. Technologies that have published results for these parameters offer a more reliable indication of performance than those for which results are not publicly available.

Many factors can affect the ability of a particular technology to detect or quantify methane emissions and flare CE/DRE. Therefore, technology providers that have published results of quantification performance typically provide a range of emission rates for which the technology is able to perform quantification and a quantification uncertainty at a specified emission rate either under typical operational conditions or, for example, in terms of wind speed. Providing this type of information helps users better understand the performance envelope of the technology. Where available, more details on the technology's quantification performance are presented in the relevant technology data sheets.

The technology filtering tool allows the operator to select whether the technology should quantify:

- CH_4 emissions from flares (Yes/No);
- Combustion efficiency of flares (Yes/No), and
- Destruction removal efficiency of flares (Yes/No).

3.2.2 Quantification performance validation (tool filter)

To improve transparency regarding existing third-party validation of technologies reviewed as part of this project, technologies have been assessed against several types of validation, that have been presented in the data sheets. The database helps operators select technologies based on the validation performed. This criterion may be especially useful for operators who are not planning to perform internal technology validation.

For the purposes of this project, 'validation' means that tests have been conducted and that the results are publicly available. It does not necessarily mean that the tests found that the technology performed 'as advertised'. Note that the validation criterion is completely independent from the performance criteria.

Four different technology validation options are available in the technology filtering tool:

- Not applicable for this technology: Applicable filter for technologies that can either perform detection or quantification. For example, some technologies are only able to detect methane but not to quantify it, in which case verification of quantification performance is not relevant.
- Not Tested: Tests may have been performed by the technology provider, either in the lab or field, with the presence and size of the emission source either known or unknown to the technology operator. Care should be taken when considering the conditions under which in-house testing took place, since these may not always reflect field conditions. For the purposes of this document, technologies are considered 'not tested' if they have only undergone in-house testing. Technologies are also considered 'not tested' if test results are not publicly available.
- Tested: Testing has been done by peer-reviewed paper prepared by independent academic researchers, or validation done using partially or fully blinded tests performed with a third party such as academics, independent researchers or by oil and gas operators. In the data sheets, further information has been provided about the type of validation done. The following categorisations have been presented in the data sheets, apart from the ones specified above.
- Tested – Academia: The information comes from a peer-reviewed paper prepared by independent academic researchers and may also include the results from either fully or partially blind testing (see below).
- Tested – Partial/fully blind tests: Testing can be done using partially or fully blinded tests performed with a third party such as academics, independent researchers or by oil and gas operators. For fully blind tests, the presence, location, and size (if any) of the controlled test release(s) were unknown to the technology provider at the time of the test. This is the closest approximation of field conditions, with the least amount of inherent bias. For partially blind tests, the technology provider was aware that controlled release testing was taking place but was unaware of the size or location of the release. Partially blind tests offer improved validation of technology performance over scenarios where the emission source size was known but may still introduce

bias. For instance, the operator performing the test may have taken more proactive steps than it normally would have done to detect or quantify emissions.

It is important to keep in mind that some validation work is ongoing. This means that the Technology filtering tool and Technology data sheetss ideally should be regularly updated to take into account the results of new test results and research. The following cases are highlighted:

– For some technologies, testing already may have been performed, but the results not yet made public. Information about such cases, where known, are indicated in the technology data sheets. However, the technology will still be considered 'not tested' for the purposes of this report, since the results were not yet publicly available at the time of publication. This does not imply anything regarding performance, but only the availability of the information.
– For some technologies, some validation may have been performed, but there are no plans to make the results public. In such cases, the technology has been classified as 'not tested', even if the results of such validation were communicated orally. This does not imply anything regarding performance, but only the availability of the information.
– Where relevant, information in the technology data sheetss is provided regarding the layout of the testing site, environmental conditions, and limitations of the validation performed. The user should carefully consider the test conditions and setup relative to those in which the technology is likely to be used (see also 3.4 on Environmental Conditions). For example, a partially blind test performed in a desert with a single point emission source may not be relevant if the operator intends to use the technology for multiple, small sources in dense foliage.

The technology filtering tool allows the operator to select technologies where the presented quantification uncertainty is validated.

3.2.3 Accuracy on CE/DRE quantification

Accuracy on CE/DRE quantification refers to the ability of technologies to give measurement values that match the actual measurements from a trusted method, such as extractive sampling described in section 2. In the ideal situation, the linear regression between measurements and the reference method is a unit-slope line.

3.2.4 Repeatability on CE/DRE quantification

Repeatability is a measure to evaluate how repeatable results are under a set of similar conditions. Technologies with high repeatability and low variation provide more confidence in the quantification of flare CE/DRE and is a measure of the uncertainty of the measurement.

3.2.5 Uncertainty on quantification

Quantification performance depends on various factors such as flare stack diameter, flow rates (which determine gas exit velocities), composition, and wind speeds. These factors can significantly impact the accuracy of quantification. To enhance transparency in evaluating technology capabilities, it is beneficial to have robust, parameterised, and publicly available analyses of quantification performance. Technologies that have published results for these parameters provide more reliable performance indications compared to those without public data.

Several factors can influence a technology's ability to determine flare efficiency. Therefore, technology providers that share quantification performance results typically provide a range of characteristics in which the technology can perform quantification, along with a quantification uncertainty at a specific emission rate. This information is often provided under typical operational conditions or specific wind speed scenarios. Such details help users understand the technology's performance limits.

The technology filtering tool allows operators to select technologies with validated quantification uncertainties. If available, additional information on the technology's quantification performance can be found in the relevant technology data sheets.

It is important to note that even if a sensor is highly precise, the quantification method incorporating that sensor may still have a higher degree of uncertainty. Technologies that state uncertainties consider quantification algorithms, environmental conditions, and emission rates. Quantification uncertainties can be reported as 1σ or 2σ uncertainties, representing the 68 % and 95 % confidence intervals, respectively, either in relative or absolute values. It is crucial to exercise caution when evaluating uncertainties.

3.2.6 Unlit flare monitoring

This section indicates whether the technology can identify flares that are unintentionally venting flare gas to the atmosphere without the presence of a flame. Note some flares may have other means to identify unlit flaring events. In some cases, flares may be installed with no flare tips and are effectively cold vents. Some of these technologies may monitor for this, while others assume that the gas is being combusted. Other methods may also be used, such as pilot flare monitors, or methods as simple as thermocouples at the burner connected to a control room system that will trigger an alarm if the burner temperature drops, but these technologies are not specifically covered in the current version of the tool. Possible options are as follows:

– Yes: unlit flare monitoring is possible with the technology.
– No: unlit flare monitoring is not possible with the technology.

3.2.7 Smoke index (tool filter)

The smoke index of a flare is a measurement or rating system used to assess the smoke or visibility produced by a flare. A higher smoke index refers to a denser and more visible flare. Smoke index may be dependent on combustion characteristics such as gas composition, environmental conditions such as wind speed or, in the case of assisted flares, the amount of steam- or air-assist. A smoke index outside of a desired range may indicate an issue that is resulting in higher-than-desired emissions and would trigger the need for a change in operation. Possible options are as follows:

– Yes: smoke index monitoring is possible with the technology.
– No: smoke index monitoring is not possible with the technology.

3.2.8 Flame stability (tool filter)

Flame stability of a flare is an indicator of the flare to maintain consistent and controlled burn for its intended operation. It is dependent on burner design, fuel composition, or environmental conditions such as wind. A stable flame may be used as an indication of a more efficient flame and can be monitored as a surrogate for CE/DRE, where low stability may indicate performance issues of the flare. However, note that a flame with high stability may also have high or low CE/DRE depending on other operating parameters, and should be treated with care. Possible options are as follows:

– Yes: flame stability monitoring is possible with the technology.
– No: flame stability monitoring is not possible with the technology.

3.2.9 Heat release (tool filter)

Heat release of flares indicates the thermal energy emitted by a flare during combustion. It is typically measured in terms of thermal power. Heat release is influenced by volume of gas, gas composition and oxidizing mixtures within the flare. Possible options are as follows:

– Yes: heat release monitoring is possible with the technology.
– No: heat release monitoring is not possible with the technology.

3.2.10 Flame size (tool filter)

Technologies may monitor flare flame size. Small flame sizes may indicate flares with low gas flow rates being combusted, and potentially with low efficiencies or becoming extinguished. Possible options are as follows:

– Yes: flame size monitoring is possible with the technology.
– No: flame size monitoring is not possible with the technology.

3.3 OFFSHORE USE CASE

Technologies can be affected by local conditions. This group of criteria allows the operator to evaluate technologies based on conditions at the site.

The first criterion (offshore applicability) enables the operator to filter technologies based on their suitability for offshore locations. Other criteria relate to a site's environmental/weather conditions. For each criterion related to an environmental condition, technologies have been classified in the Technology filtering tool and Technology data sheetss according to the following options:

– Applicable: the technology's performance is slightly affected or not affected by the environmental condition.
– Not Applicable: the technology cannot be used in those environmental conditions, or the performance is affected.

In the data sheets, an additional criterion for 'Applicable but higher detection threshold and/ or uncertainty' is included and, where possible, detailed to indicate that the technology can be used in an area where the particular or environmental condition applies. However, its detection threshold might be higher under such circumstances (e.g. it may not be able to detect values as low as its usual detection limit), its probability of detection lower, and/or its quantification uncertainty higher in those conditions.

3.3.1 Offshore relevance (tool filter)

Safety and accessibility aspects can be very different between onshore and offshore facilities. This criterion reflects the overall applicability of a particular technology to offshore conditions, which is a combination of two different considerations: technical applicability and certification for such conditions.

Technical applicability to offshore conditions: For some technologies, the capability to monitor offshore facilities depends on sensor type. Some technologies perform less effectively over bodies of water than they do on land (Jacob et al. *Quantifying methane emissions from the global scale down to point sources using satellite observations of atmospheric methane*).

Technologies that are technically ready and certified for offshore deployment are categorised as 'Applicable' in the technology filtering tool. The tool will classify as 'Technically applicable', technologies, at the prototype phase or not yet certified, for which the provider is currently exploring technical and computational improvements to take offshore conditions into consideration. Further details on this are presented in the technology data sheets.

Certification (e.g. ATEX rating, class 1, div 1 certification) may be required for the deployment of certain technologies at offshore facilities. Some technologies may be technically suitable but still waiting for certification to ensure safe use at such facilities. The Technology data sheetss and technology filtering tool present the status of certification at the time of the publication of this report. This element is likely to evolve over time, so operators may wish to obtain an update on certification status from the technology provider directly. Users should not use this filter if the certification status is not important for their selection.

3.3.2 Access to platform required?

Platform access may be required for deployment/installation and operation/maintenance of technologies at offshore facilities. Hot work permits may be required, and other logistical or safety measures may be required, such as the practicalities of platform access and space constraints. Some deployment does not require access to the platform. This section will provide more detail, where specified by the technology provider or other third party, on a case-by-case basis.

3.4 ENVIRONMENTAL CONDITIONS

3.4.1 Wind

Wind speed is one of the dominant factors causing uncertainty in detection and quantification of methane emissions in general and DRE measurement. While many of the technologies reviewed as part of this project require the presence of at least some wind to transport the methane from the source to the sensor, they usually will not perform equally well at all wind speeds. Knowledge of prevailing wind speed and direction are important for understanding the applicability and placement of such technologies around the site. Having a local weather station, on site, that provides wind direction and intensity may inform the applicability of technologies. Wind direction and speed can also be impacted by obstacles, such as equipment or buildings, which can influence uncertainty.

Wind speeds also affect quantification of methane emissions, depending on sensor type and deployment method. Variation in wind speed and/or direction will also impact the uncertainty of measurements. When available, these results are presented in the technology filtering tool. Operators need to carefully consider wind direction and speed when interpreting of the results of a given measurement.

Wind condition is not a direct filter in the technology filtering tool. However, recommended wind speeds and further details about the effects of wind on technologies are provided in the technology data sheets.

A minimum and maximum wind speed are also listed in the technology data sheets, which provide an operating envelope in which the technology will be able to reliably perform to determine a combustion or CE.

Prevailing wind conditions should also be considered. By evaluating the wind direction prior to measurement, an optimal measurement location may be identified that will increase the likelihood of the technology to measure flare CE/DRE reliably and consistently, while also avoiding interference of emissions from other non-flare sources.

3.4.2 Recommended – max/min ambient temperature

Here, minimum, and maximum ambient temperatures of a technology are listed based on technology specifications, where the technology will be able to operate safely and reliably. This could have an impact on certain geographical regions where extreme temperatures may be applicable.

3.4.3 Daylight (tool filter)

Some technologies, such as shortwave infrared sensors, measure spectrally resolved back-scattered solar radiation to detect methane emissions. Such technologies cannot be used at night because they require ample sunlight for detection and quantification.

If an operator wishes to consider technologies that can also operate at night, non-relevant technologies can be filtered out using this criterion in the technology filtering tool.

3.4.4 Readings near bodies of water (tool filter)

As noted already, some technologies require light to reach the sensor in order to perform measurements. Bodies of water, e.g. around offshore facilities, are a dark surface and often do not provide enough reflected radiance to allow certain optical technologies to detect methane emissions. This is typically more challenging for remote sensing technologies that require light reflection than for *in situ* sensors, which are not affected. However, new techniques are being developed that use sun glint[6] reflected off a water surface to detect and quantify emissions. Currently at an early phase of development, this technique could improve the ability to detect and quantify methane emissions around bodies of water.

The effect of water in the technology filtering tool is taken into consideration generally in the offshore applicability filter (see above), while the technology data sheets provide additional information on the specific challenges of reflected light near bodies of water.

6 Glint is the specular reflection from the surface of water and occurs when the sun angle and view angle are equal and in the same principal plane.

3.4.5 Cloud cover (tool filter)

Cloud cover reduces the observational ability of some technologies, for example by reducing the reflected sunlight that passive sensors use to detect methane, while also increasing uncertainty. This issue specifically applies to aerial technologies. Cloud cover could also affect continuous monitoring technologies that require solar power as a source of power to operate. This must be anticipated to have enough power backup (e.g., batteries) to operate solar-powered technologies when the meteorological conditions are not ideal.

3.4.6 Snow cover (tool filter)

Snow coverage will impact surface reflectivity, affecting the ability to make observations using some laser-based technologies, for example by increasing detection thresholds and/or the uncertainty levels for quantification. This can affect both aerial and fence-line monitoring technologies.

Snow can also affect continuous monitoring systems that use solar panels as a source of power for operation, as the snow can cover the panel and prevent the charging of the battery unless preventive/mitigation measures are implemented.

If relevant for them, operators can filter out technologies affected by snow coverage in the tool. In addition, further details on how the technology is affected by snow coverage is provided in relevant technology data sheets.

3.4.7 Precipitation (tool filter)

Some technologies can be affected by water droplets, which will scatter light and reduce instrument sensitivity, potentially reducing the technology's ability to detect or quantify emissions. Precipitation may also increase the level of uncertainty in quantification. This can be the case particularly for laser-based solutions. For offshore installations, precipitation may also be in the form of sea spray for boat-mounted equipment, Floating Production Storage and Offloading (FPSO) or platforms in high wind conditions where sea spray may interfere with measurements.

The presence of rain or snow at the time of detection can also affect the methane plume itself, including its direction and concentration. Quantification in these circumstances could result in a higher level of uncertainty.

3.5 DEPLOYMENT

Technologies may be deployed for different purposes or in the context of different methane management processes. Criteria in the technology filtering tool allow the operator to identify technologies that meet deployment objective(s).

3.5.1 Time for deployment

Time for deployment provides additional information regarding initial setup, lead times for installation, and other temporal aspects of a technology. This may include battery lifetime and charging time (if applicable), time for maintenance etc.

3.5.2 Ease of deployment

Some technologies may require a site to be assessed manually for emissions, where personnel would arrive on site and deploy the technology for a given period. Others may require access to site for installation, maintenance or data collection or offloading from a system. Depending on safety certifications, this could require obtaining hot work permits.

In the case of aerial monitoring, such as with drones or airplanes, the safety of the pilot and the site operators must be considered. This could require permits, as well as significant coordination on the part of the operator. These requirements differ by country. Ease of deployment provides additional information on the potential factors to consider when deploying the technology.

3.5.3 Training required

Consideration must also be given to any operator training required for deployment. This is likely to be closely associated with the business model of the technology provider. Some technology providers handle everything from installation to post-processing of data. In such cases, the operator would receive the estimated emissions data from the technology provider, so minimal training would be required for the staff of the oil and gas operator. On the other hand, some technology providers train the operator to use their technologies or software and integrate it into an existing system, for example in a control room. The training time that is required will vary, depending not only on the equipment but, for example, on staff experience and field/site characteristics.

3.6 INCLUSION IN DECISION TREES

Report 661: Recommended practices for methane emissions detection and quantification technologies - Upstream includes a series of decision trees, which cover additional factors that must be considered for technology deployment, beyond the selection of appropriate technologies for a given purpose. The decision trees are as follows:

- Tree 0: a general decision tree that organises the different processes into a coherent framework.
- Tree 1: screening of components and sites.
- Tree 2: quantification of emissions at source level.
- Tree 3: quantification of emissions at site level.
- Tree 4: reconciliation for a single site.
- Tree 5: reconciliation for a group of sites and/or a single site with multiple measurements over time.

This scope of work has been designed so that flare technologies may be integrated and considered in the decision trees of the Report 661 document. The inclusion of flare technologies fills an important gap in selecting technologies for deployment to detect and quantify methane emissions from upstream oil and gas. Details and examples of this are included in Annex A.

4 CASE STUDIES

4.1 OFFSHORE FLARE MEASUREMENTS

A study of two production regions on the UK Continental Shelf and two regions on the Norwegian Continental Shelf was performed by Shaw et al. *Flaring efficiencies and NOx emission ratios measured for offshore oil and gas facilities in the North Sea*. Flight measurements in this work were made using the UK's Facility for Airborne Atmospheric Measurement (FAAM) BAe-146 atmospheric research aircraft. Measurements of CO_2 and CH_4 were performed using a cavity ringdown laser spectrometer from Los Gator Research Inc. and C_2H_6 using a tuneable infrared laser direct absorption spectrometer from Aerodyne Research. Flare plumes were identified by correlating enhancements in expected gas phase components of the flared hydrocarbon gases compared to their background concentrations. Plumes that did not contain correlations of the components were discarded as originating from other oil and gas sources, other than flare plumes.

Fifty-eight plumes from 30 facilities were identified as containing emissions from gas flaring. A median CE, of 98.4% (96.6% - 99.4%) with C2H6, and 98.7% (97.2% - 99.6%) without C2H6 was recorded, which is aligned with the commonly assumed value of 98% used by many emission inventories for flaring CE. Destruction removal efficiencies (DREs) were also calculated for CH_4 and C_2H_6 in each plume, using fuel gas composition data. Median DRE values were 98,5 % (96,6 %, 99,5 %) for CH_4 and 97,9 % (96,5 %, 99, 2 %) for C_2H_6.

The skewed distribution of combustion efficiencies found in the study indicate that many flares assessed in the North Sea operate below the assumed standard efficiency for combustion. They also note inefficient combustion, together with the prevalence of unlit flares that directly vent CH_4 to the atmosphere, contribute to large CH_4 emissions. Hence, improving natural gas disposal and flaring practices represents a viable strategy for mitigating carbon emissions from the oil and gas sector.

4.2 BP FLARE STUDY

Bp have performed experiments at the John Zink Facility. The experimental tests fill the void of a general lack of available test data for natural gas flares combusted using pressure assisted flare designs used in upstream oil and gas production. Tests were performed on three different flare tips: a 14-inch straight pipe tip, a restricted orifice tip, 8-inch single arm pressure assisted tip, and an 8-inch multi-arm pressure assisted tip. Testing covered a matrix of 80 cases with various British thermal units (BTUs) and flow rates, natural gas and nitrogen gas composition mixes and wind speeds from 0 to ~6 m/s. While extensive test results are not yet published, several general results have been made publicly available in conference presentations by Panametrics. The DRE measurements using Flare.IQ generally agree with the DRE measurement using the control method (similar to as described in 2.1.2) at net heating values (NHV) >300 BTU/standard cubic feet (SCF). The uncertainty of the measurements was evaluated using direct error propagation and Monte Carlo simulation. At lower heating values, discrepancies between DRE measurements of Flare.IQ and the control method also increased, as the uncertainty of both measurement methods simultaneously increase. Preliminary results from this study reinforce the ability of technologies to measure flare DRE more accurately at optimal operating conditions. As DRE reduces, uncertainty will increase. While lower efficiency flares are more challenging to measure accurately, it should not deviate from the fact that the identification of flare inefficiencies are also an identification of performance issues. Lower-than-optimal flaring should be addressed through mitigation, either by replacing flaring with other gas utilisations where possible, optimising flare conditions of the existing flare, or through engineering design (such as flare repair or replacement).

4.3 PERMIAN METHANE ANALYSIS STUDY

The Environmental Defense Fund (EDF) conducted a series of surveys in the Permian region to assess the status of oil and gas flares and emissions (EDF *Flaring aerial survey results*). They used geospatial analysis of data from the SkyTruth Global Flaring Dataset, pinpointing potential flare locations. Leak Surveys Incorporated, a methane leak detection service provider, then conducted surveys with custom infrared cameras mounted on helicopters. Eight surveys looked at over 2 500 active flares and were performed between February 2020 and November 2021.[7] These surveys were aimed to identify malfunctioning (lit flares with combustion issues) and unlit flares, along with emissions from diverse oil and gas infrastructure.

The results showed that ~11 % of flares in the survey were malfunctioning, and around 4–6 % were unlit and venting, although these percentages varied across surveys. When looking at all well sites – including lower-production, 'marginal wells' – flare malfunctions jumped from 29 % to 36 % in randomised surveys of routine-flaring.

Two surveys targeting primarily midstream facilities found that 5,9 % flares were completely unlit while 4,3 % of flares had a combustion issue.

Additionally, a repeat area survey covering 200 km^2 found nearly 60 % of malfunctioning flares failed more than once during a week, while others had intermittent issues. The measurements for this study are expected to be variable over time, and may not be representative of current emissions. However, this study provides insights into the state of flaring and emissions in the Permian region, facilitating informed environmental monitoring and mitigation initiatives.

These types of surveys allow coverage of many flares, pinpointing unlit or malfunctioning flares. However, the trade-off of this type of study is that it does not allow for the quantification of CE, and instead demonstrates the ability to do large surveys of flares to identify issues such as unlit and malfunctioning flares, rather than quantification of flare efficiency.

4.4 USING COMPUTATIONAL FLUID DYNAMICS TO IDENTIFY MITIGATION ACTIVITIES

One oil and gas operator contracted Element Digital Engineering to develop a methodology using CFD to predict the methane destruction efficiency of a flare in current operation at an offshore oil and gas facility. The purpose was to use a CFD analysis to predict CH_4 DRE of the flare across a range of operating conditions, and to assess if there was an opportunity to improve upon the reported emissions of their flare.

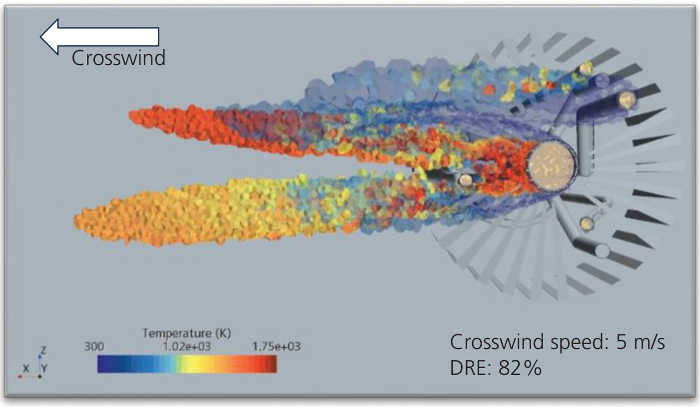
Element Digital Engineering built a computational model of the operator's flare, which included a 3D representation of the geometry surrounding the flare including high pressure (HP) and low pressure (LP) flare tips, ignition sources (pilots), wind fences and platforms.

7 Emissions are expected to be variable with time. Therefore, past data may not be representative of the Permian Basin's current emissions.

The HP flare tip had three equidistant pilots surrounding it, while the LP flare tip did not have a dedicated pilot. Crosswind speeds were also evaluated at the flare tip based on measurements at the platform level, using an atmospheric boundary layer profile of velocity and turbulence. A transient calculation of species transport that incorporated a complex chemistry combustion model was used to predict the performance of the flare with regards to destruction efficiency and to capture the chemistry of the reaction process accurately. Combustion reactants and products were analysed within the CFD model domain to ensure a steady or time averaged CH_4 DRE was obtained, and all methane is accounted for, rather than relying on extrapolation from limited sampling points.

The model was used to evaluate the flare at a range of operating conditions that would be expected during real scenarios, including normal operating conditions, start-up and at the extreme operating conditions (intermediate and maximum blowdown). The analysis identified CH_4 DRE between 52 % and 95 % for 25 simulated operating conditions. At mean operating conditions, the exit velocity from the HP flare tip was 0,58 m/s. The CH_4 DRE was found to be highly sensitive to crosswind conditions: as crosswind speed increases, the CH_4 DRE reduces. The correlation between exit velocity and crosswind speed observed agrees with previous research that suggests the combustion inefficiencies (and hence CH_4 DRE) are strongly connected to the interaction between the exit velocity of the flare and the crosswind speed (Johnson and Kostiuk *Efficiencies of low-momentum jet diffusion flames in crosswinds*).

Visualisations of the combustion profile, showing temperatures on areas above the lower flammability limit, are shown in Figure 6 for 5 m/s and 13,8 m/s crosswind velocities. The image on the left at a crosswind of 5 m/s shows a large region within the flammability limits, with high temperatures (>1000 K) indicating larger regions of combustion and higher CH_4 DRE. The image on the right at a crosswind speed of 13,8 m/s has a much smaller region of flammable gas and temperatures at the extents of this region are much cooler, indicating that the methane is dispersed by the crosswind, rather than combusting. Such images from computational analysis provide insight into the mechanisms that can impact CH_4 DRE.



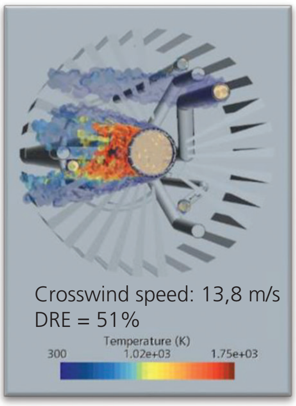


Figure 6: Temperature profiles and CH_4 DRE of the flare stack at crosswinds of 5 m/s (left) and 13,8 m/s (right) (provided by Element Digital Engineering)

The analysis also identified an area for improvement with the flare tip design. From the top-down view of the flare stack, it was observed that under certain conditions considerable methane from the LP flare remains unburnt. A dedicated, appropriately positioned pilot for the LP could deliver improved CH_4 DRE. Figure 7 demonstrates an example of the negative impact of the LP flare.

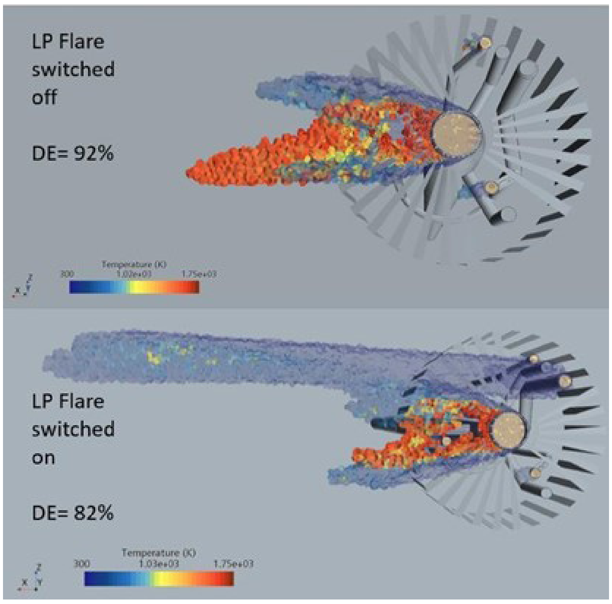


Figure 7: Temperature profiles and CH_4 DRE of the flare stack when the LP flare is switched off (top) and on (bottom) (provided by Element Digital Engineering)

CFD analyses are limited to the input parameters provided and their ability to be validated against real scenarios. However, they can provide the operator with predictions and insight into the CH_4 DRE of their flare stack at various operating conditions it may see during operation, which are variable and frequently much lower than the 98 % to 99 % typically assumed. The findings of studies like this can help to develop plans to reduce greenhouse gas emissions and inform improvements that could be made to the flare stack, or understanding which operating conditions cause the greatest contribution to emissions.

5 CONCLUSION

5.1 TECHNOLOGY AVAILABILITY

At the time of publication, a limited number of technologies were identified and included as part of this report[8] for monitoring of flare performance using CE and DRE measurements. Technologies range from continuous monitoring solutions using visual-based products, and predictive monitoring systems that use external inputs to predict efficiency based on measurable parameters. Section 2.0 of this report also covers other measurement techniques and technologies important for flare performance monitoring, which include single and multi-sensor aerial methods (drones and aircrafts), four stationary methods, and three calculation-based methods (numerical models and CFD/predictive systems). Technologies available for flare efficiency measurement are far less than for the detection and quantification of methane emissions from oil and gas. For example, 51 technologies were identified for the *Report 661* document for methane emissions detection and quantification technologies.

5.2 TECHNOLOGY OUTPUTS

Technologies provide a range of outputs, that include measurements of direct CH_4 emissions, flare CE, or methane CE. While each of these parameters provide quantification of flare performance in different outputs, some of these technologies may be able to derive other outputs (i.e., CE/DRE/CH_4 emissions), provided auxiliary information is available (flow rates, gas compositions etc.).

5.3 QUANTIFICATION PERFORMANCE

Many technologies show strong accuracies at high combustion efficiencies. However, with the introduction of other factors such as higher wind speeds, low energy content of flared gases, flare performance will be reduced, resulting in more inefficient flares and higher methane emissions. In parallel, quantification accuracy can become more challenging. It is important to be more accurate at these low efficiencies when emissions are expected to be highest.

5.4 VALIDATION/VERIFICATION

Validation of measurement technology for flares is more difficult than for other sources of methane emissions. To Carbon Limits knowledge, there is no universal standard for performing validation of flare measurement technology. For blinded evaluation of flare performance, testing must be done in comparison to a control method. Implementation of this can be done at dedicated facilities such as the John Zink Flare Test Facility. Considerable effort must be put into the instrumentation and testing to set up and run, for example,

8 The list of applicable technologies may not be fully exhaustive. Technologies were only included if they were identified and the technology provider responded to interview requests for the development of data sheets. Other technologies may also be applicable that were not included due to lack of response, and other technologies may also be applicable but were not identified.

blinded evaluations. Flare performance will vary based on many parameters such as flare gas flow rate, burner type and diameter, gas composition, presence, or absence of assisting fluid, in addition to the environmental conditions that have been covered throughout this report. For example, wind speed and direction are transient parameters. Therefore, these parameters must also be monitored to understand their impact on flare performance. There are also requirements of time, investment, and resources. To summarise, many parameters that impact flare performance must be monitored, which provides an additional challenge to be able to compare third-party testing, and to evaluate whether these conditions are representative and applicable to a flare in the field.

5.5 ONGOING INDUSTRY EFFORT

An important note to make is that work is ongoing for development of experimentally derived models and results (Allen and Torres *Flare study final report*). Measurement-based calculations and models are becoming available that rely on techniques that ingest external parameter input to provide a better estimate of flare performance than an assumption of 98 % CE. For example, in 2021 Offshore Norge updated emission factors for flares on the Norwegian Continental Shelf based on measurement campaigns. bp is in the ongoing process of developing ongoing work for steam and air assisted flares, that in the future may be made publicly available (case study presented in 4.2). Efforts at the BFRC and research institutions such as Carleton University are ongoing to derive experimentally based empirical models to predict flare performance over a range of conditions. With increased focus on methane emissions and flaring and ongoing work, increased understanding and development of robust models is expected to continue to improve in the future.

Yet, measurement of flare performance and other parameters of a flare system provides much more useful information than a default assumption of CE. When flare performance is poor, it indicates an area of focus for mitigation. This could be through replacing flaring with other gas utilisations where possible, optimising flare conditions and flow rates of the existing flare, or through engineering design (such as flare repair or replacement).

This work is closely related to other ongoing initiatives such as Oil and Gas Methane Partnership (OGMP) 2.0, and the World Bank *Zero routine flaring by 2030* initiative, which have been introduced to tackle emissions from flaring. Valuable resources such as the Methane Flaring Toolkit provide additional, practical information on not only quantification, but flare monitoring and other aspects of flare systems that must be considered.

Table 2: Summary of assessed technologies

Purpose	Type	Deployment method	Sensor	Use	Datasheet developed	Independent validation	Frequency
Quantification of emissions	Technology	Aerial (Drone/aircraft)	Single sensor	Methane quantification	Not (yet)		Periodic
			Multi-sensor	Combustion efficiency quantification	Not (yet)		Periodic
		Stationary	VISR		Yes	Yes	Continuous
			Active laser		No		Periodic
			PFTIR		No		Periodic
			Bi-spectral cooled OGI		Yes	No	Continuous
	Calculation-based	Numeric modelling	Various – operational and environmental parameters	Methane quantification	No (included in report)		Continuous
				Combustion efficiency quantification	No (included in report)		Continuous
		Computational Fluid Dynamics and Predictive Systems			Yes	No	Continuous
Unlit, malfunctioning flares	Technology	Satellite	Multi-spectral imaging	Unlit, Malfunctioning Flares	No (included in report and initial scope)		Periodic
		Stationary Handheld	OGI camera		No (included in report and initial scope)		Continuous
	Alarm systems	Process data	Optical camera, thermal camera, thermocouple, acousitc alarm, Flame ionization, pyrometer		No (included in report and initial scope)		Continuous

ANNEX A
INCORPORATING SPECIFIC FLARE TECHNOLOGIES INTO DECISION TREES

The following sections present how specific flare technologies may be incorporated into the decision trees that are provided in the IOGP, Ipieca and OGCI *Recommended practices for methane emissions detection and quantification technologies – upstream*.

A.1 TREE 1: SCREENING OF COMPONENTS AND SITES

Flares should be included and considered in the screening of components and sites depending on the presence or absence of flare(s). Based on section 2 of the tree, flares should be systematically included in an exhaustive list of all emission sources based on routine and process emission sources (for example, regularly operating flares), or non-routine emissions and incidents (for example, unlit flares).

In section 3 of the tree, continuous improvements of emission sources can be performed on a continual basis, either through continual emission reductions, follow up from reconciliation, or the addition of potential emission sources as they are identified.

A.2 TREE 2: SOURCE-LEVEL QUANTIFICATION

Since detection and quantification of methane emissions from flares is a discrete source, measurements of flare efficiency and CE would fall under the scope of Tree 2: Quantification of emissions at source level, where emissions from individual sources are quantified and summed to produce a single value. The goal of the decision tree is to identify appropriate quantification methods for each source at a facility. Depending on the goal of source-level inventory development, the recommended method to quantify emissions may vary from generic emission factors, measurement-based emission factors, engineering calculations and measurements. Decision tree 2 can be followed to determine the appropriate quantification method.

If the goal of the inventory is a simple, source-level inventory, generic emission factors may be used. However, these may result in higher uncertainty and error, without providing accurate results. It may be appropriate in limited situations, such as a first, high-level assessment when developing a baseline inventory that would then be supplemented by additional quantification methods in the future.

If the goal is to develop a source-level inventory based on measurements or engineering calculations, or to perform reconciliation with site-level, measurement-based quantification, a more detailed approach should be taken. If flares are material sources, a more source-specific quantification approach is recommended.

If the source is material, it must be determined if it is possible to reliably measure emissions. If the methane emissions cannot be measured for technical reasons, it is recommended to rely on engineering calculations to quantify. Engineering calculations can be preferred if taking measurements could be unsafe, expensive or difficult. Engineering calculations could rely on derived models previously identified in 2.4 of this report. The validity of applying these models to flares depends on the flare conditions and are recommended for use only when the models cover representative conditions. Whenever it is not prohibitively challenging to do so, it is recommended to perform measurements.

When measuring, variability should be considered to inform the measurement timing and to assess total emissions over the relevant time frame. If the flare operates in a continuous or near-continuous manner, measurements can be performed anytime and extrapolated over the full period of operation.

If the flare operation is cyclical, with various operations such as normal operation, periodic maintenance or variable flow rates, measurements should be taken at different times in the cycle and attributed to the different operating modes of the source.

If the flare is intermittent or event-based, such as in the case of an unlit flare or a safety flare that intermittently combusts large volumes of gas during facility start-ups or shutdowns, and it is possible to know the frequency, duration and timing of such emissions, measurements should be performed to capture volume, frequency, and duration. All these factors must also be considered when using the technology data sheetss and selecting a flare technology using the Technology filtering tool.

A.3 TREE 3: SITE LEVEL QUANTIFICATION MEASUREMENT

The main goal of the site level quantification measurement tree is to perform a total site level measurement of potential sources of methane emissions. This is not flare specific and will include all potential sources. Depending on the objective of site level quantification and considerations of technology constraints outlined in the tree, a site level quantification technology can be selected from the technology database. Depending on the technology selected, as well as the specific operating conditions of the flare, a site level measurement technology may detect methane emissions resulting from one or more flares and may be able to attribute the emissions to the flare or as part of the cumulative site level emission rate. It is important to note that the timing of the site level measurement may result in varying operating conditions of the flare at that point.

A.4 TREES 4 AND 5: RECONCILIATION FOR A SINGLE SITE AND MULTIPLE SITES/ MEASUREMENTS

To perform a reconciliation for a single site, emissions from flares present at the time of the site level measurement should be evaluated, and the expected emission rates of the flares at the time. This can be informed by the quantification method used for the flare. Depending on the results of the source and site level measurement estimates, in particular flares should be evaluated to understand if they represent a discrepancy, either due to being unintentionally unlit or other maintenance, upsets or malfunctions occurring. Root cause analysis of the source-level quantification may be necessary and relevant for emissions from flares. If the flare is quantified using emission factors or methods that do not account for time variability or have large uncertainty, it may be necessary to improve source-level quantification with additional measurements or calculation methods. This would be in addition to the review of the site level measurement technology, and the steps outlined in the two decision trees.

ANNEX B
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ANNEX C
ABBREVIATIONS

Abbreviation	Meaning
ATEX	equipment for explosive atmosphere
BFRC	British Flame Research Committee
BTU	British Thermal Units
CE	combustion efficiency
CFD	computational fluid dynamics
DIAL	differential absorption light detection and ranging
DRE	destruction removal efficiency
EDF	Environmental Defense Fund
EPA	Environmental Protection Agency
FAAM	Facility for Airborne Atmospheric Measurement
FPSO	Floating Production Storage and Offloading
GC	gas chromatograph
GC-MS	gas chromatography mass spectrometry
GGFR	Global Gas Flaring Reduction Partnership
HP	high pressure
IEA	International Energy Agency
IOGP	The International Association of Oil & Gas Producers
IPIECA	International Petroleum Industry Environmental Conservation Association
LDAR	leak detection and repair
LIDAR	light detection and ranging
LP	low pressure
MGP	methane guiding principles
MWG	EI Methane Working Group
NHV	net heating value
OGCI	Oil and Gas Climate Initiative
OGI	optical gas imaging
OGMP	Oil and Gas Methane Partnership
PFTIR	passive Fourier transform infra-red
SCF	standard cubic feet
TCEQ	Texas Commission on Environmental Quality
VIIRS	visible infrared imaging radiometer suite
VISR	video imaging spectral radiometry
ZRF	Zero Routine Flaring

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