Final report

1. Project details

Project title	FlareE - Measurement of Flare Destruction Removal Efficiency using Drones
File no.	640234-511826
Name of the funding scheme	EUDP 2023-II
Project managing company / institution	Explicit ApS
CVR number (central business register)	37 63 96 05
Project partners	Equinor ASA
Submission date	30 April 2025

2. Summary

Project summary:

The purpose of the project

Flaring is a significant source of methane emissions during oil and gas processing but also very difficult source to assess with existing measurement technology.

Project FlareE developed and demonstrated a novel drone-based measurement method for determining the Destruction Removal Efficiency of methane for various types of flares and how it could be reported.

Results, conclusions and perspective

The project FlareE achieved the following results:

- A novel drone-based method was developed to determine the DRE.
- The required technology was implemented and tested for different flare designs and flaring conditions in real operation environments.
- A new measurement system drone-payload was built and tested.
- Data collection, processing and reporting was integrated into Explicit*s cloud-based emissions datalab (E-Lab).
  - 97 individual measurements of flares were carried out during 3 campaign legs.
  - The technology and sampling method was demonstrated on elevated, single and multi-tip open flame and ground-level boxed flare designs.
  - The method showed to be applicable for sampling CH_4 and CO_2 emissions from flaring and to describe the DRE.
- The results showed the importance of considering spatio-temporal variations in the flare plume during sampling due to meteorological and operational variabilities.
- The flare plume needs to be assessed in its entirety to overcome gas dynamics.
- Meteorological and operational variabilities need to be considered when sampling.
  - Averaging of individual measurements reduces the uncertainty.
- Protocol was developed to express DRE for emission reporting purposes.
  - A scheme was suggested which describes an iterative sampling procedure and required additional data.
  - A path to express the representativeness of the found result was developed for the purpose of reporting.

The findings of this project are expected to complement existing measurement solutions for flaring efficiency by expanding the easy-of-use of such technologies and the scope of applicability.

Projektresumé:

Formålet med projektet

Fakkelafbrænding er en signifikant metankilde i oliegasproduktion, som er svær at estimere med eksisterende måleteknologi. Projekt FlareE har udviklet og demonstreret en innovativ dronebaseret målemetode til bestemmelse af destruktionseffektiviteten af metan i forskellige fakler, og hvordan denne effektivitet kan rapporteres.

Resultater, konklusioner og perspektiv

Følgende resultater er opnået i Projekt FlareE:

- Udvikling af en ny innovative dronebaseret metode til bestemmelse af fakkeleffektivitet (DRE).
- Teknologien blev implementeret og testet på forskellige fakkeldesigns og afbrændingsforhold i faktisk driftmiljø.
- Et nyt målesystem til montering på drone blev bygget og testet.
- Dataopsampling, behandling og rapportering blev integreret ind i Explicit*s cloud-baserede emissions-datalab (E-Lab).
  - 97 individuelle fakkelmålinger blev udført fordelt over 3 målekampagner.
  - Teknologien og prøvetagningsmetoden blev demonstreret på forskellige fakkeldesigns, både høj-siddende, enkeltstående og multitip fakler med åben flamme samt på indhegnede fakler i terræn-niveau.
  - Metoden blev påvist anvendelig til prøvetagning af CH_4 og CO_2-gasudledninger fra fakler i drift samt til at beskrive afbrændingseffektiviteten (DRE).
- Resultaterne viste også betydningen af at tage hensyn til tids- og stedlige variationer i fakkelrøgfanen under prøvetagning forudsaget af meteorologiske og driftsmæssige udsving.
- Røgfanen skal og bør måles i dens helhed for at overkomme gasdynamikker.
- Meteorologiske og driftmæssige variabler bør addresseres i prøvetagningen.
  - En gennemsnitsbetragtning over flere målinger reducerer måleusikkerheden.
- En protokol til karakterisering og rapportering af en fakkel's effektivitet (DRE) blev udviklet, herunder:
  - En interativ procedure for prøvetagning og dataindsamling.
  - En fremgangsmåde til udtryk af repræsentativitet i målingen til brug for rapportering.

Resultaterne fra projektet ventes at komplementere eksisterende måleløsninger til bestemmelse af fakkeleffektivitet gennem en udvidelse af tilgængeligheden af sådanne teknologier samt deres anvendelsesområde.

3. Project objectives

Flaring is as a high-temperature oxidation process to burn combustible components, mostly hydrocarbons, of waste gases from industrial operations. Out of these combustible components, methane is of particular interest in the oil and gas production due to its abundance and its potency as a greenhouse gas. If the combustion process at the flare is not complete it means methane is not fully destroyed to products with lesser climate impact such as CO_2 and released to the atmosphere.

The purpose of Project FlareE was to develop and demonstrate a new measurement methodology – based on in-situ sampling directly in the flare plume using drones equipped with gas analysers (also known as 'sniffer drones') – to measure and express flare Destruction Removal Efficiency, termed DRE, of methane (CH_4) in an operational environment. An illustration of the application of the method is presented in Figure 1.

Figure 1: Example of a drone-borne measurement for the calculation of DRE in the in-situ environment. The photograph in the upper-right corner shows the drone setup with sensors in greater detail.

The project was motivated by a requirement to report annualized DRE as part of the United Nations Environment Program's Oil & Gas Methane Partnership 2.0 (OGMP), a voluntary global reporting scheme focused on tracking and mitigating methane emissions in the oil and gas sector. Also, the first EU wide methane regulation[1] builds on the OGMP 2.0 framework and has been adopted in 2024. For this reason, there is an urgent need for monitoring solutions which will allow operators to accurately measure and report DRE from their flaring activities.

The project aimed to cover a variety of different flare types to study differences in emissions.

The project further expected to develop an open-source Flare Characterization Protocol (FCP) on DRE, which can be used by flare operators to more accurately calculate and report annual flare emissions to authorities and other reporting schemes. The aim of the FCP is to use spot measurements to adequately document individual flare efficiencies in their operational environment to allow annualized emissions extrapolation and potentially portfolio-wide assumptions on DRE for the purpose of methane reporting.

The project also contained critical research elements aimed at studying the applicability of certain in-situ sensor technologies in a flare plume environment as well as the variability in the flare plume itself, e.g. CH_4, CO_2 concentrations, temperature, wind velocity etc., under different operational conditions. The project should show how a direct in-situ measurement methodology is most optimally applied.

Summarized the Project FlareE had the following key objectives:

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[1] EU 2024/1787, "Regulation (EU) 2024/1787 of the European Parliament and of the Council of 13 June 2024 on the Reduction of Methane Emissions in the Energy Sector and Amending Regulation (EU) 2019/942 (Text with EEA Relevance)," Pub. L. No. OJ L, 2024/1787 (2024), https://eur-lex.europa.eu/eli/reg/2024/1787/oj/eng.

- To develop and demonstrate a working drone-based methodology for sampling CH_4 and CO_2 in flare plumes as well as other relevant atmospheric parameters under various operational conditions with the purpose of expressing a representative DRE.
- To develop a measurement protocol for how flare plumes should be characterized, and efficiencies expressed, including but not limited to addressing operational settings under which measurements should be performed, how to manage variability in the measurement environment, suitable for extrapolating results to determine annualized flare methane emissions.

4. Project implementation

4.1 Project evolution

The project contained four work packages which built the structure for the project's progress. These packages cover the technological and methodological development.

The first work package, WP1, covered the preparation. The purpose of this work package was to prepare a functional test setup and address any preparations needed for the subsequent testing phase. A payload with a sensor setup including CH_4 and CO_2 gas analysers based on tuneable diode laser spectroscopy (TDLS) and non-dispersive infrared spectroscopy (NDIR), respectively, as well as ultrasonic anemometers and radar altimeter has been developed, assembled and successfully tested in-house. We were able to build upon previous hardware and software developments also used for DFM flights. The built payloads were then tested in flight, traversing emission plumes from natural gas combustion at nearby gas production sites in Denmark. These tests had three major objectives:

1. Airworthiness of the assembly,
2. Initial characterization of the signal response to comparable emission sources,
3. Collection of initial data to develop suitable approaches to quantify DRE.

A series of flights was conducted between February and April 2024 for this purpose. The flights were a success with respect to the beforementioned objectives. The collected sensor data led to the conclusion that the project can commence with the following steps. With the test showing the drone setup was functional, the criteria of Deliverable 1 were fulfilled.

A further part of WP1 was the preparation of field tests in collaboration with the Norwegian multinational energy company Equinor. During these deployments the system was exposed to emissions from representative emissions from industrial flares for refinement of the sampling method and collection of data for the development of the Flare Characterization Protocol (FCP). Both partners decided to execute the measurements campaigns at the two Norwegian Equinor processing plants Kårstø and Kollsnes. The combination of both sites allowed for measurements at various design types of flares, i.e. 3 open single tip stack flares, 1 multi-tip tulip flare, 1 open double tip flare, and one boxed flare, as well as an incinerator for volatile organic compounds (VOCs). The preparation of these campaigns in terms of gathering flight permits and site access clearances fulfilled Deliverable 2.

With the completion of WP1 and being ready to fly, the project also reached Milestone 1 of the FlareE project within the scheduled time.

The second work package, WP2, covered the further testing of the developed system both in an external test laboratory and the measurements at the Equinor processing plants. Previously collected data from earlier measurements were used as initial input material to define the according test plans (Deliverable 3)

The Research Institutes of Sweden AB, RISE, was chosen as the external laboratory where the gas sensors of two payloads were calibrated characterized in March 2024 according to the test laboratory standard ISO 17025 for CH_4 and CO_2 (Deliverable 4).

The field tests on the two sites were conducted on three occasions, where each one round of measurements was conducted at the Kårstø processing plant before and after the renewal of flare tips, in July and September 2024, respectively. The measurement campaign at the Kollsnes processing plant was conducted in October 2024 (Deliverable 5).

The development of the method and application was part of work package 3 (WP3) which was conducted alongside of WP2. The results from laboratory tests but foremost from the data and experiences gained from the deployments in the field, where the measurements were conducted in the true environment under real operation conditions, were used for continuous refinement of the method and the application.

The results showed which sampling approach should be applied to determine the DRE under real operation conditions of flares as well as the limitations of the applied method (Deliverable 6).

The algorithm to calculate the DRE on the bases of the sampled emissions data was developed and implemented as an application as part of Explicit's E-Lab. It uses the calculated net emission rates of CH_4 and CO_2 from the drone measurements as well as additional data from the flare operator regarding the gas compositions and gas flow rates supplied to the flare before combustion (Deliverable 7).

While the first measurement campaign at Kårstø was already executed in July 2024 and as such well within the foreseen period, the second measurement campaign at Kårstø as well as the measurement campaign at Kollsnes could not be conducted before the end of September, or the beginning of October, respectively, due to scheduled shutdown periods of processing plants. These later two campaigns were hence timed at and even past the foreseen end of the foreseen periods for WP2 and WP3 according to the project plan.

The late timing of these campaigns and the anticipated large amount of data to be processed had led to the conclusion that the project period would need to be extended by four more months until 30th April 2025. The request to change the project plan accordingly was granted by EUDP in September 2024.

The Danish national technology consultancy FORCE technology characterized the uncertainties of the calculated DRE based on the measured emission rates and supplied additional data from the flare operator according to the Guidelines to uncertainties in Measurement (GUM, DS/EN ISO 20988 Air Quality) (Deliverable 8).

The tests and the resulting reports underlined that there was a working method. The related commercial milestone, CM1, was reached before the end of 2024.

Work package 4 (WP4) covered the dissemination and reporting activities of the FlareE project. It includes the development of the recommended Flare Characterization Protocol (FCP) which is one of the main outcomes of the FlareE project besides the developed technology and sampling method. The FCP is described in more detail in the section 5.2.7 of this report (Deliverable 9). The publication of the FCP also fulfills the second commercial milestone (CM2). The results were reported to various stakeholders during conferences, workshops and web meetings, see section 5.4. The presentations and a platform for discussion were given to industrial representatives from the oil and gas sector as well as relevant authorities related to this field, e.g. the United Nations Environmental Program (UNEP). In this context, we would like to highlight the conference/workshop contributions to the Decarb Forum be Offshore Energies UK (OEUK) in November 2024, to the 2025 Methane Mitigation Europe Summit in February 2025, and to the ASMEA Flow Measurement Workshop in April 2025 (Deliverable 10).

The general project management was also part of WP4, covering also the project meetings, planning activities, accounting, the intermediate progress reports, etc. (Deliverable 11).

4.2 Risks associated with conducting the project

Several risks were foreseen at the beginning of the project.

A major risk regarding the development of a measurement method was that drones would not be allowed to operate at adequate altitudes to measure the emission plumes from flaring as the ceiling for standard flight operations for drones is at altitudes of 120 m and measurements at elevated flares could require to exceed this limit. This risk did not materialize. Explicit was able to acquire all necessary permissions needed for the fulfillment of the required operations.

A related risk was too limited access to test sites or the suppliable testing conditions were insufficient. But various suitable test sites were found with different kinds of flares which were measured during different operating conditions. The project's schedule was be adapted according to the accessibility.

A third method related risk was that the sensor performances would not be sufficient to measure the emitted concentrations with a sufficient signal-to-noise ratio and time resolution which would be required calculate the DRE with a satisfying precision. But the tests in the lab and especially those conducted in real flaring environments showed that the selected sensors fulfilled the requirements.

There also was a potential commercial risk of insufficient market feedback. However, we experienced a continuous and active request regarding our approach to an easy-to-deploy method as an alternative to state-of-the art methods. Requests about this approach came from both, oil and gas industry and relevant authorities in this field.

The risk of insufficient proof in an operational environment was overcome with the quantity of conducted flights and the quality of the obtained data to show the credibility with respect to commercialization.

The time to market was kept short, as the findings were iteratively adapted to a full-scale application alongside to the project's execution, ready to be introduced to the market.

5. Project results

5.1 Fulfilment of project objectives

The project has developed a method to calculate the DRE from flares in operative environments using sampled emissions from flaring by a drone-based measurements. The findings presented in the following sections show that drone-borne in-situ sampling technologies are applicable in real flaring environments. The results of this project also point out that the impact of spatial inhomogeneities in the emissions of plumes needs to be considered as well as the plume dispersion in relation to operational settings and atmospheric conditions. It provides a recommendation about how to measure emissions from flaring to determine the DRE. The original objectives of the project were obtained.

5.2 Developed method and technology

5.2.1 Method description

Project FlareE is an extension of the work done in a previous 2021 MUDP project[2], called Plane. In that project, Explicit developed and validated a novel drone-based technique for quantifying fugitive emissions of methane called the Drone Flux Measurement (DFM) method for which Explicit is accredited according to the test laboratory standard ISO 17025. This method has since been deployed on multiple oil and gas assets worldwide, e.g. across Europe, Australia, Asia and the US to quantify methane emissions from both onshore and offshore sites.

Project FlareE builds on several of the results from the Plane Project, including most of the drone payload hardware design, parts of the drone remote control software, and the basic data transmission infrastructure that allows the drone to communicate and transmit data directly to Explicit's cloud-based emissions lab, called E-Lab.

However, where the Plane Project was solely focused on quantification and only incorporated a single gas sensor for the quantification of CH_4, project FlareE included the design and validation of a dual sensor payload including both CH_4 and CO_2 gas analysers and the development of a new measurement methodology to express DRE through the measurement of gas ratios of CH_4-to-CO_2 and possible other parameters such as temperature variation, which is not part of DFM, and wind flow in the flare plume. DRE is thus an entirely separate and independent type of measurement application from the one covered in the Plane Project.

Figure 2 illustrates the data sampling of emission data from the flaring process. A drone is equipped with sensors to primarily measure gas concentrations as well as wind speed and wind direction aboard the drone together with other relevant parameters such as air temperature, barometric pressure and humidity. The measurements are conducted downwind of the targeted source, i.e. the flare. The flight during the sampling process itself is automatized. The drone follows a pre-defined pattern, which is set by the pilot before the flight. As illustrated in Figure 2, the drone follows a horizontal trajectory, which is defined by two or more waypoints. After the completion of each transect, the drone rises to the next altitude and follows the trajectory in opposite direction. Hence, the completed path describes a virtual, vertical area called "flux wall", which delivers a cross-section through the measured emissions plumes and a surrounding area.

Apart from the waypoints, the pilot sets the minimum and maximum altitudes, the altitude step and the speed-over-ground to complete the definition of the flight pattern. The distance is depending on structures and risk zones in the vicinity to be considered, and the levels of gas concentration to be measured as well as the extent of the emissions on the flux wall. Typical measurement distances to the flares are 30 to 100 m but can be longer if required. The wind speed should not exceed 12 m/s for the operability of the drone and should be higher than 1 m/s so that emissions traverse the flux wall. There are general limitations which might affect the drone operation such as heavy precipitation or high temperature, which could arise under massive flaring conditions.

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[2] Jon Knudsen and Laura De Rossi, "The Plane Project: Mapping and Quantification of GHGs from Diffuse Emission Sources Using Drone Technology and Vertical Measuring Walls" (The Danish Environmental Protection Agency, 2022), https://www2.mst.dk/Udgiv/publications/2022/04/978-87-7038-413-1.pdf.

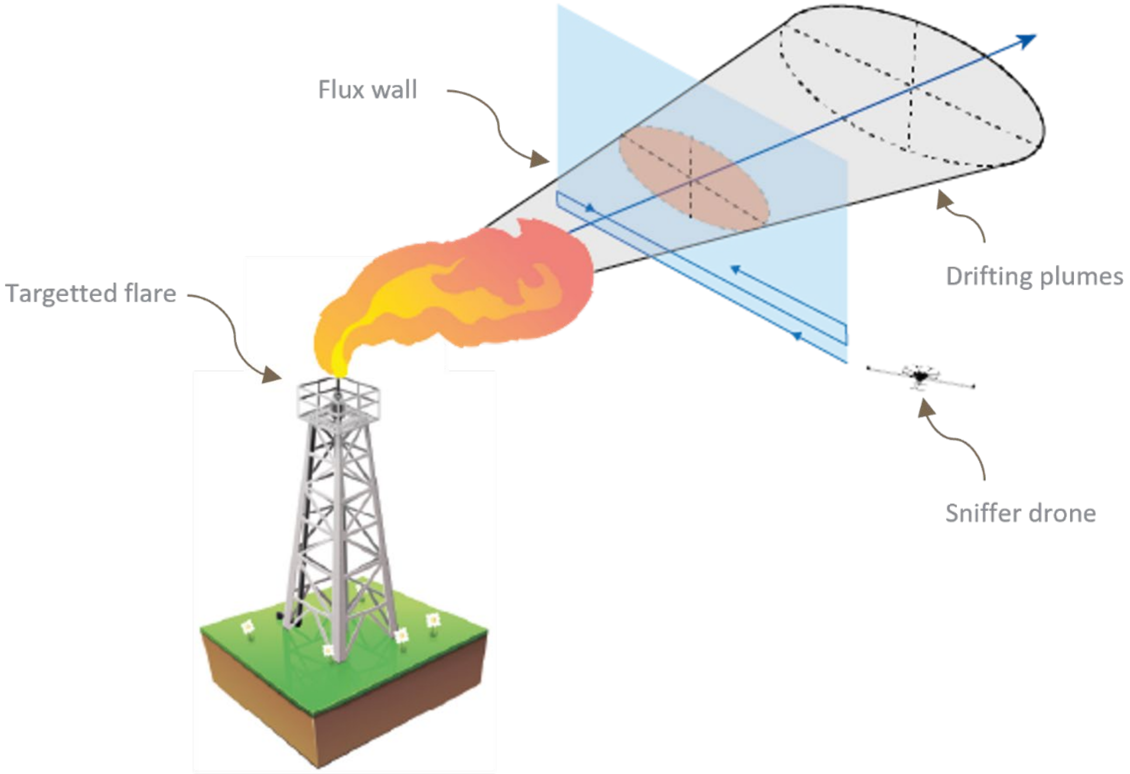

Figure 2: Illustration of data sampling for the calculation of the flaring efficiency using the Drone Flux Measurement (DFM) method. The sniffer drone is equipped with all relevant sensors, i.e. sensors to quantify gas concentrations and anemometers for the quantification of wind speed and direction, etc. All data is continuously sampled while the drone is following a pre-defined path along a horizontal trajectory downwind of the source. The drone repeatedly follows this trajectory at different altitudes, thus erecting a virtual flux wall on whose area the sampled data can be referenced. Emissions from the flare are transported by the wind through the plane of the flux wall.

Gas concentrations, wind speed and direction, the drone's position and navigation data are continuously transmitted to the controller and logged with a sampling rate of 2 Hz. The data, e.g. distribution of the measured gas concentrations, is directly visualized on the controller to assist the pilot's navigation during the flight and for preparation of the next flight. After the flights, the data is encrypted and transferred to the E-Lab. The E-Lab combines the collected data for an initial, automatic calculation of the measured emission rates, which are for the project FlareE used to calculate the DRE.

The DRE is fraction of CH_4 that has been destroyed (removed) by flaring as compared to the total amount CH_4 fed to the flare.[3,4] The leading principle of calculation applied in this project is to substitute the amount of CH_4 in the pre-combusted gas stream based on measurements of emission rates of CH_4 and CO_2 from the flaring

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[3] Scott C. Herndon et al., "Application of the Carbon Balance Method to Flare Emissions Characteristics," *Industrial & Engineering Chemistry Research* 51, no. 39 (October 3, 2012): 12577–85, https://doi.org/10.1021/ie202676b.

[4] Darcy J. Corbin and Matthew R. Johnson, "Detailed Expressions and Methodologies for Measuring Flare Combustion Efficiency, Species Emission Rates, and Associated Uncertainties," *Industrial & Engineering Chemistry Research* 53, no. 49 (December 10, 2014): 19359–69, https://doi.org/10.1021/ie502914k.

and information about the gas composition of the flared gas before combustion. This principle has been exercised and published in flare emission studies by Caulton et al. (2014)[5] and Gvakharia et al. (2017)[6].

The sampled emission data is used to calculate the DRE according to Eq. 1, which shows the definition of the DRE (to the left) and the approximation (to the right) used in the studies referred to above and in the herein presented method. In combination with information about the gas composition of the gas fed into the flare, the CO_2 is used to estimate the amount of the destroyed CH_4 from the feed gas to the flare.

$$DRE = 1 - \frac{emission\,rate\,of\,CH_4\,to\,the\,atmosphere}{flow\,rate\,of\,CH_4\,in\,the\,fuel\,stream} \cong 1 - \frac{f(CH_4)}{X \times \frac{M(CH_4)}{M(CO_2)} \times f(CO_2) + f(CH_4)} \qquad \text{Eq. 1}$$

Here, $f(CH_4)$ and $f(CO_2)$ are to the measured emission rates expressed in units of kg/h, and $M(CH_4)$ and $M(CO_2)$ are the respective molar masses. The parameter X is the fraction in the distribution of carbon atoms attributed to CH_4 in the pre-combusted gas which are emitted in form of CO_2 after the oxidation by the combustion process from flaring. The value of X is directly derived from the gas composition. It accounts for all carbon containing species in the fuel stream which would produce CO_2 if ideally combusted.

This approach assumes that the carbon containing species in the gas flow to the flare are forming CO_2 by combustion in the flare with a similar likelihood. A second assumption is that carbon species produced from the combustion process other than CO_2, e.g. CO or soot, can be neglected. The results of the studies by Pohl et al.[7], Allen and Torres[8], and Umukoro and Ismail[9] support this assumption showing that the relative abundance of CO or soot, respectively, in the emitted flare plume was found to be much lower than CO_2 in their studies.

5.2.2 Uncertainty budgeting

The uncertainty of the DRE method was evaluated by FORCE Technology as a third party and according to the Guidelines to uncertainties in Measurement (GUM, DS/EN ISO 20988 Air Quality). The uncertainty budget considers the uncertainties of the individual measurements of the emission rates of CH_4 and CO_2 which are used as input variables together with the uncertainty of the carbon fraction attributed to CH_4 in the feed flow to the flare.

Generally, emission plumes are not evolving steadily in a real, ambient atmosphere. Hence, the uncertainty of the measured emission rates using the DFM method has been assessed empirically based on blind controlled release tests. They characterized the uncertainties of the resulting emission rates in dependence on the noise-to-signal ratio and the number repeated flights. The uncertainties of the calculated CH_4 and CO_2 emission rates decrease significantly with the number of repetitions as shown in Figure 3.

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[5] Dana R. Caulton et al., "Methane Destruction Efficiency of Natural Gas Flares Associated with Shale Formation Wells," *Environmental Science & Technology* 48, no. 16 (August 19, 2014): 9548–54, https://doi.org/10.1021/es500511w.

[6] Alexander Gvakharia et al., "Methane, Black Carbon, and Ethane Emissions from Natural Gas Flares in the Bakken Shale, North Dakota," *Environmental Science & Technology* 51, no. 9 (May 2, 2017): 5317–25, https://doi.org/10.1021/acs.est.6b05183.

[7] John H. Pohl et al., "Combustion Efficiency of Flares," *Combustion Science and Technology* 50, no. 4–6 (December 1986): 217–31, https://doi.org/10.1080/00102208608923934.

[8] David T. Allen and Vincent M. Torres, "TCEQ 2010 Flare Study - Final Report," 2011, https://downloads.regulations.gov/EPA-HQ-OAR-2012-0133-0047/attachment_32.pdf.

[9] G. Ezaina Umukoro and O. Saheed Ismail, "Modelling Emissions from Natural Gas Flaring," *Journal of King Saud University - Engineering Sciences* 29, no. 2 (April 2017): 178–82, https://doi.org/10.1016/j.jksues.2015.08.001.

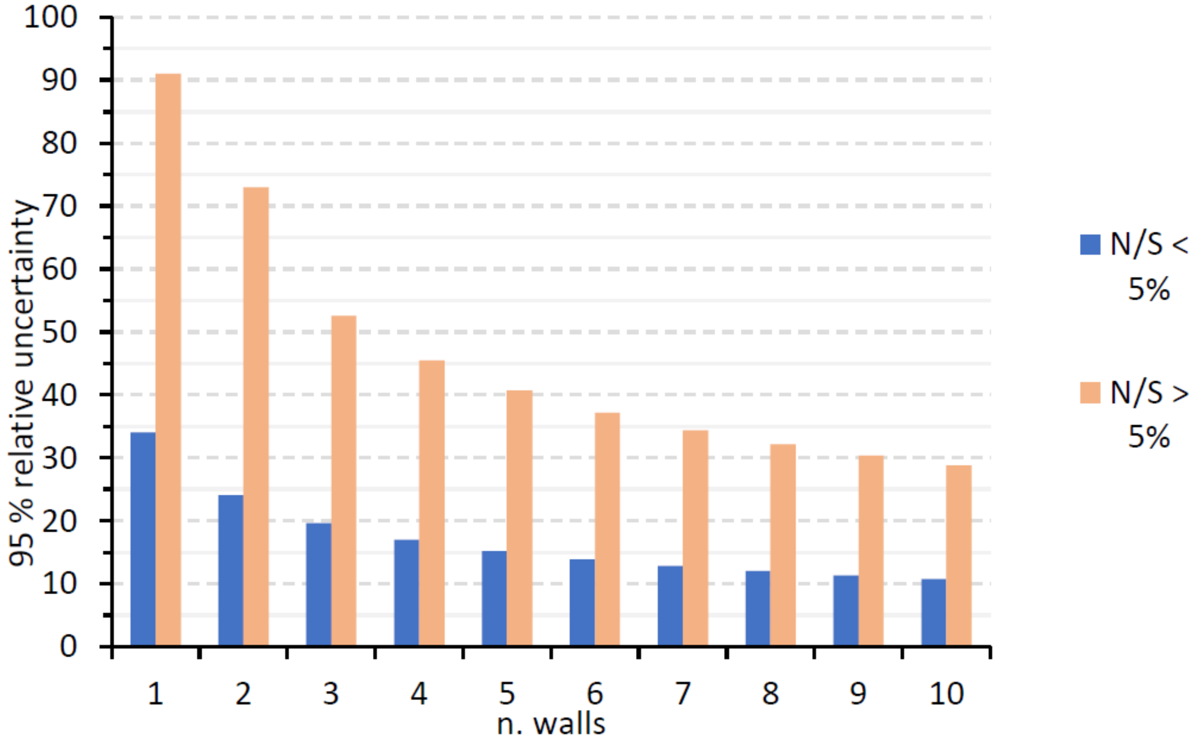

Figure 3: FORCE Technology's estimate of uncertainty as function of walls from empirical blind controlled release tests in the field. N/S refers to the noise-to-signal ratio of the gas concentration measurement. A N/S value of 5% corresponds to a flux value of approximately 1 kg/h of CH_4, depending on wind conditions and distance from source.

The DRE calculation includes emission rates of CH_4 and CO_2 for simultaneously sampled data. Hence, dependency between the variables can be expected as both are affected by the meteorological variations. Only the contributions of the individual sensors to total uncertainty are statistically independent. However, as the dependent uncertainties are part of the nominator and denominator in Eq. 1, the law of propagation can be regarded as a conservative approach. Hence, the uncertainty can be calculated by Eq. 2.

$$unc(DRE) = f(CH_4) \times f(CO_2) \times X \times \frac{M(CH_4)}{M(CO_2)} \times \sqrt{\frac{\left(\frac{unc(f(CH_4))}{f(CH_4)}\right)^2 + \left(\frac{unc(f(CO_2))}{f(CO_2)}\right)^2 + \left(\frac{unc(X)}{X}\right)^2}{\left(X \times \frac{M(CH_4)}{M(CO_2)} \times f(CO_2) + f(CH_4)\right)^4}} \qquad \text{Eq. 2}$$

The uncertainties of the emission rate of CH_4, unc(f(CH_4)), and the emission rate of CO_2, unc(f(CO_2)), are outputs of the DFM calculation, see Figure 3. FORCE Technology estimated the relative uncertainty of X, unc(f(X))/X, to be 0.03 based exemplary flare gas compositions from flare measurements.

5.2.3 Developed Technology

One of the main outcomes of the project is the developed hardware for the measurement of emissions from flares for the calculation of the DRE.

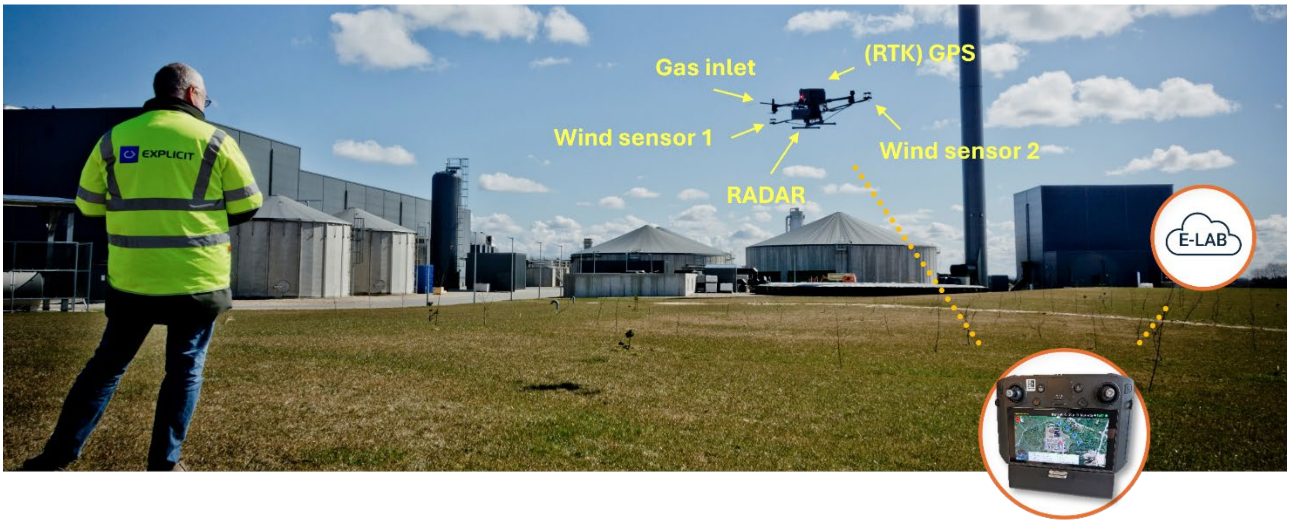

Figure 4: Deployment example of the DJI Matrice 350 RTK drone equipped with the sensor payload in the field. The collected data is transmitted in real time to the controller and can be uploaded to the cloud-based E-Lab for further analysis which also delivers direct feedback to the pilot with calculated emission rates after each flight.

Figure 4 shows the sensor payload attached to a DJI Matrice 350 RTK drone. The dimensions of the payload including the wind arms are 250 cm x 22 cm x 18 cm and it weighs approximately 2.5 kg. The gas is sampled through the inlet in front of the drone. It is transported through the gas analysers by pumps. In this setup, the gas concentrations of CH_4 are quantified by an Axetris LGD Compact A-1 module using tuneable diode laser spectroscopy (TDLS). The concentrations of CO_2 quantified by a Senseair K30FR CO_2 sensor using non-dispersive infrared spectroscopy (NDIR).

Two 3D ultrasonic anemometers are laterally mounted to the payload each on either side and placed outside the influence of the downwash from the rotors. Apart from measurements of the air flow in all three directions, it also delivers data about temperature, humidity and barometric pressure. The results of both two sensors are generally used for better accuracy and quality assurance.

The distance to ground is measured radar mounted at the bottom of the payload to complement the built-in altitude assessment of the drone for lower flight altitudes up to 50 m.

All sensor data as well as position and navigational data is sampled with a frequency of 2 Hz. It is transmitted in real-time to the controller, where it is displayed and logged. Hence, the pilot has direct feedback, which is visualized on the controller, about any relevant information, such as gas concentrations and temperatures. This helps the pilot to recognize regions of interest with respect to the measured target. Further, the data are an important indicator in case the drone approaches areas with potentially dangerous levels of CH_4 or temperatures which might impact the integrity of the drone in the vicinity of hot flares.

For this project, two payloads were calibrated by the Research Institutes of Sweden AB. The calibrations were carried out according to ISO 17025. The precision of the gas sensors was also assessed during the calibration. The CH_4 and the CO_2 gas analysers showed a precision of around 3% at a confidence level of about 95% (k=2) relative to the measured value in the concentration range between 2 to 20 ppm in the case of CH_4, and a concentration range between 400 to 3000 ppm in the case of CO_2.

5.2.4 Test of concept

The concept and technology were initially tested during flights at nearby gas production plants in Denmark between January and April 2024. The targeted objects was an emission stack and an elevated flare. These objects were used as initial targets to validate the suitability of the developed instrumentation and the applicability of the sensor setup and payload design. Further the collected data was to develop and refine the measurement approach. Also, the collected emission data and retrieved gas composition data was used to prepare a measurement scheme and algorithm for the field tests in corporation with Equinor.

The flare was measured on three different days under the prevalent operation conditions. Figure 5 shows the distribution of the measured concentrations along the different traces of the flux wall downwind of the flare for one exemplary flight. It shows that the concentrations levels above background of the measured emissions in this case with up to 4 ppm for CH_4 and 30 ppm for CO_2 in about 70 m distance to the flare are distinguishable from sensor noise. And second that the shape of both signals indicates a comparable response time of the CH_4 and CO_2 sensors which appears fast enough resolve individual peaks. A set speed-over-ground of 1.5 m/s and a sampling frequency of 2 Hz yields a spatial separation between two adjacent data points of 0.75 m.

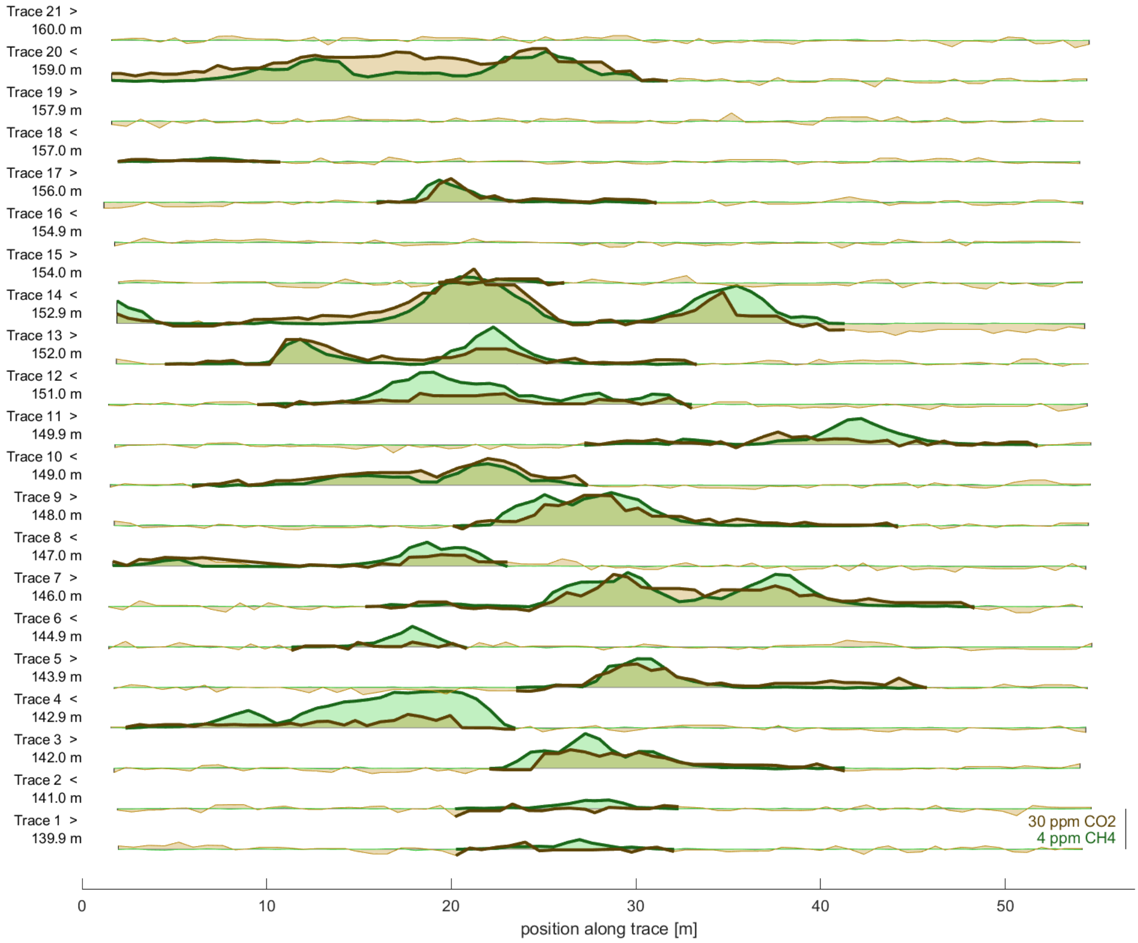

Figure 5: Example of measured gas concentrations along the transects of a flux wall measured downwind of a real flare. The respective background values are subtracted from the concentrations. The baseline represents the altitude according to the altitude steps displayed on the left hand side of the figure. The distance between two adjacent altitude steps corresponds to 30 ppm of CO_2 or 4 ppm of CH_4, respectively. The respective flight direction along the traces is accordingly indicated by the symbols ">" or "<".

Further, atmospheric instability needs to be taken into account. The variances of the atmospheric conditions lead to a dynamic dispersion of the emission plume from the measured flares. The depicted simulation in Figure 6 shows the effect of wind variations to an assumed constant release of particles and how these particles would be seen along a cross-section at the distance of the flux wall. The particles can be regarded as substitutes for molecules. The simulation shows the effect of the atmospheric variability to the spatial displacement and concentration variations along the propagation and the temporal variance of observed concentrations at any fixed distance along the line of propagation. Atmospheric variations are a dominating impact on emission measurements. Therefore, the sampling design must address the spatio-temporal variance in flare plumes. This also shows the importance of simultaneous wind measurements at the drone during the gas sampling.

The above reflects the findings from the empirical measurements to establish the uncertainty budget for the measured emission rates using the DFM method, see section 5.2.1. There it is shown that the uncertainty can be reduced significantly through repetitions. The recommended target are three repetitions to reduce the uncertainty of the emission rate measurements to about 20% given noise-to-signal ratio above 5%.

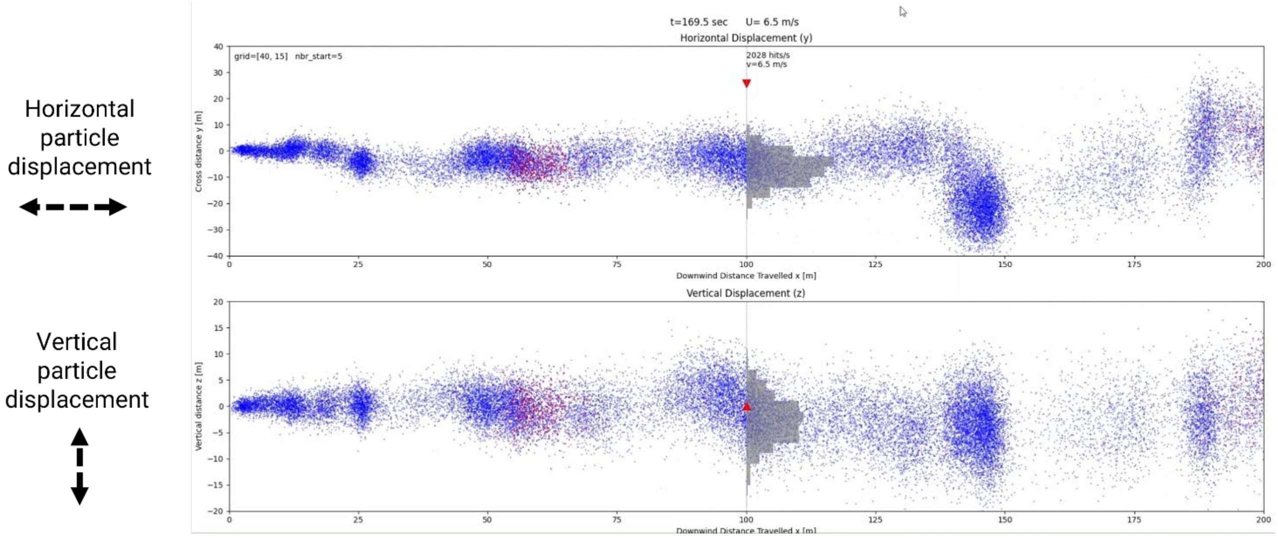

Figure 6: Simulation of the effect of atmospheric variations to plume propagation and measured concentration levels. The simulation uses wind data from real measurements obtained during the measurement of a flare plume. The displayed particles are continuously "released" with a constant rate at a point source to the left, as seen from above (top panel) and from the side (bottom panel). The gray bar graph represents the distribution pattern at a cross-section at a distance of 100 m from the source.

5.2.5 Measurements under real conditions in different scenarios

The flights for the first field test were carried out at the Kårstø processing plant between 23rd and 25th July 2024. The measurements targeted the four flares at the site, whereof three are elevated single-tip flares and one is an elevated double-tip flare. Additionally, an incinerator for volatile organic compounds (VOC) was measured.

A second campaign at the Kårstø processing plant took place after shutdown period during which flare tips were replaced with measurements being conducted between the 26th and 30th September 2024. These measurements were focused on the flares at this location only.

With the third campaign conducted at the Kollsnes, two further types of flares were assessed. A boxed flare at ground level was measured on 3rd October 2024 and an elevated multi-tip tulip flare was targeted on 7th October 2024.

The emissions of the flares were measured at their present conditions and requested conditions with increased flow rates. The increased flow rates affected the composition of the flared gas and Equinor shared their monitored flow data and conducted gas samples for gas composition analysis in their laboratory. Also, the gas flows and gas compositions of the flare pilot burners are considered, as they also contribute to the overall flaring process and the total emission from it. The reported data from the operator contributed to the DRE calculation of the carbon fraction which is attributed to CH_4 in the fed gas stream X in Eq. 1.

In total, 101 individual measurement flights were carried out at the individual flares (97 measurement flights) and the VOC incinerator (4 measurement flights) to validate and refine the method to determine the DRE. The measurements of the flares can be separated into 27 cases, i.e. combinations of individual flares and distinguishable operating flow conditions.

In the following, the key findings from the conducted measurement campaigns with respect to the development of the method are presented.

The conducted flights were conducted at a speed-over-ground of 2 m/s to 4.5 m/s which translates in a granularity of about 1.0 m to 2.3 m considering the data sampling frequency of 2 Hz. The higher speed-over-ground setting might be advisable at extended sources where larger flux walls need to be created to cover the full extent of the emissions. It is a result of balancing the limited flight time of up to 25 minutes defined by the battery capacity and the power usage and the extent of the flux wall. This was the case for the boxed flare at the Kollsnes processing plant. Similar considerations were taken to set the altitude steps, which were in a range of 1 m to 4 m. The collected gas concentrations indicate that this range was satisfying regarding the measured cases.

Figure 7 shows two examples with high correlations of measured CH_4 and CO_2 emissions to illustrate the comparable performance of the sensors to follow changes in the measured signals. The measurements were conducted at the elevated open, double-tip flare but on different dates. The distance and orientation with respect to the flare stack is comparable. The two flare tips were in line with the wind direction and there is no clear separation of the two sources based on the displayed concentration distribution. The measured CH_4 and CO_2 concentration show a very high correlation in this case indicating a well-mixed emission plume. The respective concentration ranges in the presented examples differ by orders of magnitude. But the signals follow each other well in both cases indicating a comparable signal response of the two gas analyzers. There is a system-related delay between the responses though. But this does not affect the results due to the mathematical integration of the signals as part of the emission rate calculation.

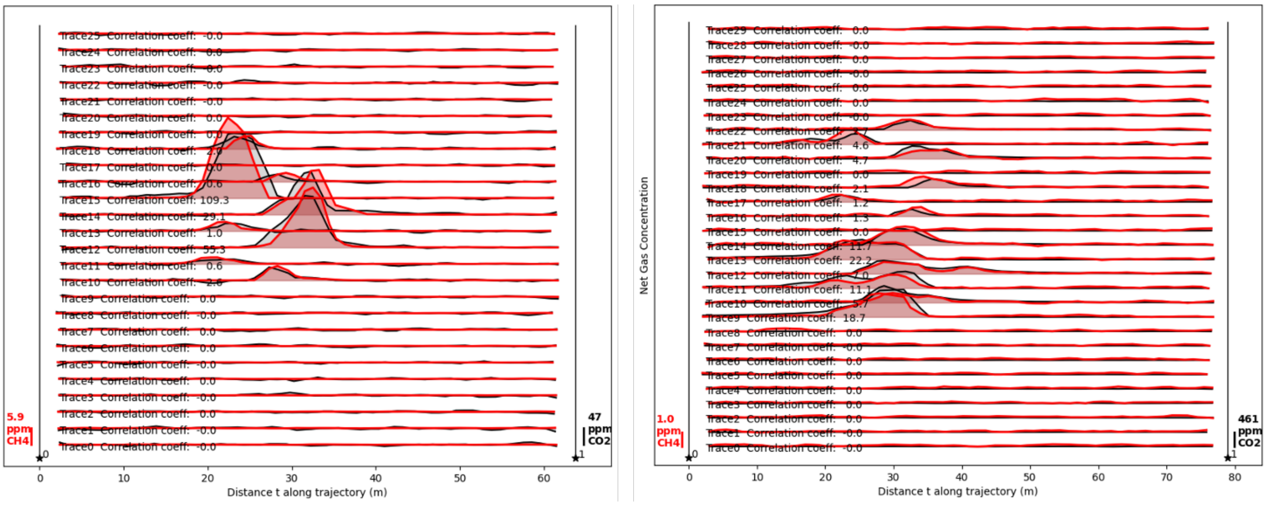

Figure 7: Background corrected net concentrations of CH_4 and CO_2 as measured along the transects of two flights from the same elevated open, double-tip flare measured on different occasions and different operational conditions. The respective scaling factors are shown in red to the left of each graph for CH_4 and respectively to the right of each graph for CO_2. The mean wind speed during the measurements were 8.7 m/s and 6.1 m/s, respectively.

There are two implications from the above. First, these result support with the findings of the initial tests showing that the elected sensor setup is suitable to track the concentration changes that can be expected from high-emission sources with small spatial footprints, such as flares. Second, the capability of this approach to separate individual flare tips that a located next to each other is limited. In the provided example the emission and DRE calculation would represent an average of the contributions from the two flare tips.

However, the distributions of CH_4 and CO_2 do not necessarily correlate. Causes for separated and poorly correlated emission patterns could for example be different combustion processes with different efficiencies which for example could due to multiple burners, or separate pilot and flare emissions, etc. An example is shown in Figure 8 where such separation becomes obvious and, in this case, led to a layered distribution with uncombusted CH_4 emissions dominating at lower altitudes while high CO_2 concentrations from the combustion process dominate at higher altitudes.

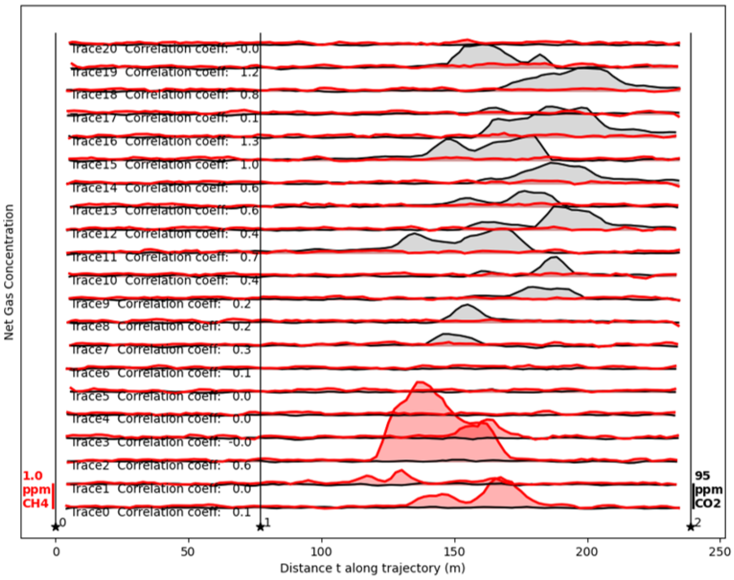

Figure 8: Background corrected net concentrations of CH_4 and CO_2 as measured along the transects of a flight at the boxed flare. The respective scaling factors are shown in red to the left of the graph for CH_4 and respectively to the right of the graph for CO_2.

Inhomogeneous DRE distributions along the flux walls could also be caused by wind gusts as higher wind velocities could cause uncombusted gas to be stripped from the combustion zone.[10,11,12]. This would also reduce the correlation between the measured CH_4 and CO_2 distributions but not necessarily lead to a layered pattern in the resulting flux distribution.

With the process of creating three repeated flux walls and calculating the emission rates as integrals over the entire peak area, both, the impact of spatial inhomogeneities and temporal variations are considered and lead to averaged values. Hence, the DRE which is calculated upon the resulting emission factors is an average that takes the spatio-temporal variances in flare plumes into account.

The visualization of the results as shown in Figure 9 supports the attribution of the measured emission to the respective source. The displayed temperature provides an additional indication about the flaring state. Though the temperature is measured at the location of the drone, it can be used to confirm combustion and exclude

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[10] Peter Evans et al., “Full-Size Experimental Measurement of Combustion and Destruction Efficiency in Upstream Flares and the Implications for Control of Methane Emissions from Oil and Gas Production,” *Atmosphere* 15, no. 3 (March 7, 2024): 333, https://doi.org/10.3390/atmos15030333.

[11] M.R Johnson and L.W Kostiuk, “Efficiencies of Low-Momentum Jet Diffusion Flames in Crosswinds,” *Combustion and Flame* 123, no. 1–2 (October 2000): 189–200, https://doi.org/10.1016/S0010-2180(00)00151-6.

[12] M. R. Johnson, D. J. Wilson, and L. W. Kostiuk, “A Fuel Stripping Mechanism for Wake-Stabilized Jet Diffusion Flames in Crossflow,” *Combustion Science and Technology* 169, no. 1 (August 1, 2001): 155–74, https://doi.org/10.1080/00102200108907844.

the release of gas without combustion, when a significant increase is measured which coincides with a peak in the measured CO_2 emissions.

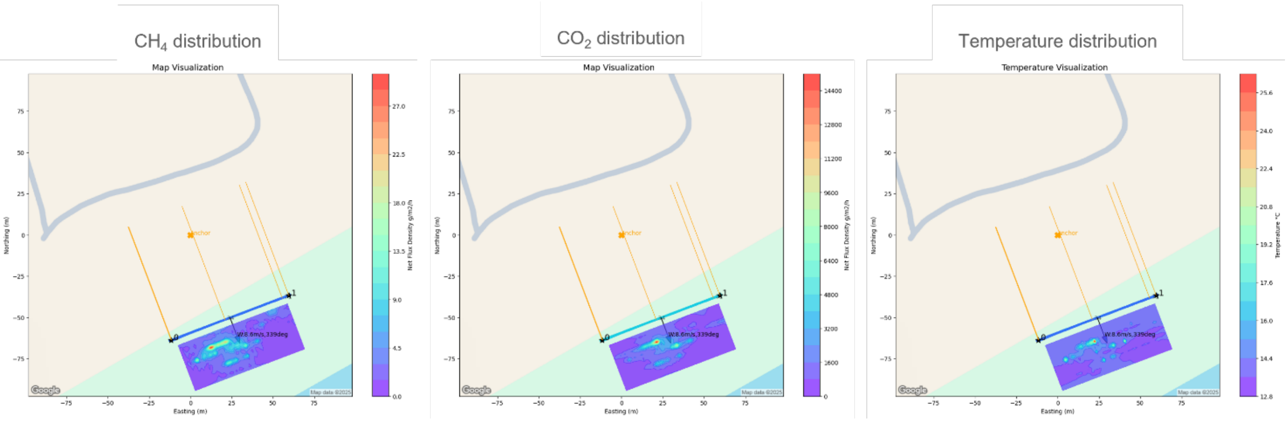

Figure 9: Example of visualized distributions CH_4, CO_2 and air temperature at the location of the drone as contour plots projected on a map. The flight trajectory is defined by the waypoints “0”, “1”, etc. and indicated by black star symbols. The anchor point represented by the orange “x” shows the location of the flare. The thin orange lines indicate the mean wind direction, which was measured during the flight.

Emissions were well distinguishable from background in the applied cases. However, upwind measurements can be advised if background sources should not be clearly separatable. The resulting net emission rates from the upwind measurements should then be subtracted from the net emission rates measured downwind of the sources.

5.2.6 Implementation of the DRE calculation

The measurements were used to extend the cloud-based analysis of emission rates by Explicit, called E-Lab, with a module for the calculation of the DRE. This module combines the results of the measured emission rates of CH_4 and CO_2 for a series of flights, with a target of 3 repetitions, under the steady flaring conditions maintained by the flare operator. It also uses relevant gas flow and composition data provided by the flare operator for the calculation of the CH_4-related carbon fraction. Several gas flows feeding the flare can be considered accordingly.

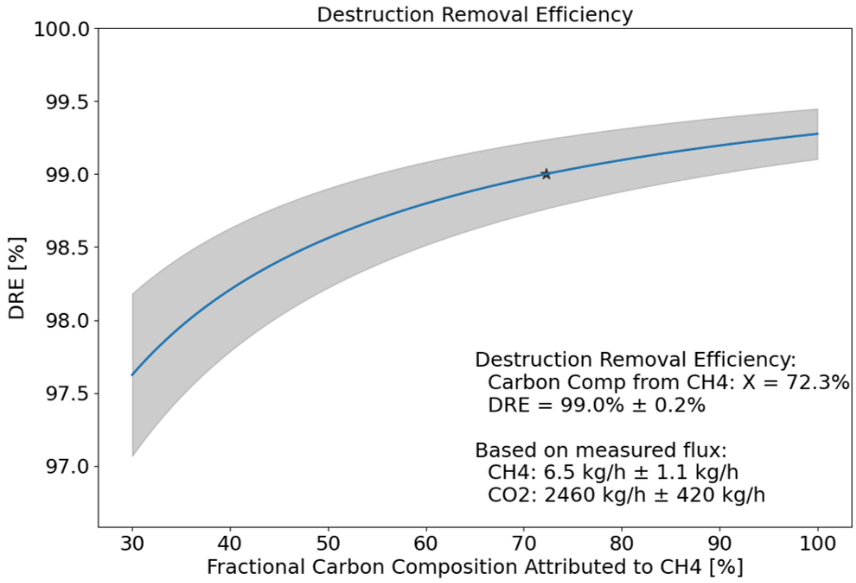

Figure 10: Result of a DRE calculation as produced by the added DRE module to Explicit's E-Lab. The DRE is shown in dependence to the CH_4-related carbon fraction (variable X in Eq. 1). The star shows the DRE for the according to the gas composition present at the time of the measurement. The grey area shows uncertainty. All provided uncertainties are expressed at 95% confidence.

The output is a calculated result for the DRE and its uncertainty. The dependency of the DRE on variations of X are visualized in a graph. This can be a useful indicator in case the composition is not exactly known and a range of X would need to be assumed. An example of the graphical output is shown in Figure 10.

5.2.7 Flare Characterisation Protocol

The measurements conducted by the drone are conducted during a limited time frame and can represent only a limited set of operational conditions. A flare characterisation protocol (FCP) was developed, with which the spot measurements can be used to adequately document individual flare efficiencies in their operational environment to allow annualized emissions extrapolation and potentially portfolio-wide assumptions of the DRE for the purpose of methane reporting.

The flow rate of the gas feeding the flare and the gas composition are the main drivers of the combustion process. Regarding the gas composition, it needs to be considered that a high fraction of inert gases such as N_2 or CO_2 in the pre-combusted gas stream might inhibit combustion itself as they reduce the net heating value (NHV) of the gas mixture. Previous studies found a critical limit of the NHV of the flared gas to be about 300 BTU/scf below which the efficiency deteriorates.[13] The NHV values of the flared gas during the conducted measurements ranged between about 680 BTU/scf to nearly 8400 BTU/scf, so that the driving factor related to the flare operation for the combustion was the flow rate.

The suggested procedure is to set up the sampling as an iterative process as shown in Figure 11. The operator's flare control sources historical data of flow rates and gas composition about targeted flare (F1). The time frame of the data should be representative for an entire year. The time resolution should be high enough to represent typical process variances. We suggest it to be in the order of 1 min. This data is used typical range of flow rates and as reference for reporting. The following step (F2) uses the historical data to define an. applicable and stable start condition at the low end of the range of the flow rates. The flare control logs the flow rate and takes a gas sample for composition analyses (F3) while the emission rates of CH_4 and CO_2 from

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[13] Evans et al., "Full-Size Experimental Measurement of Combustion and Destruction Efficiency in Upstream Flares and the Implications for Control of Methane Emissions from Oil and Gas Production."

the flare are sampled (E1). The sampled emission rates are used to calculate the DRE which might be just an estimate if gas composition is not accurately known yet (E2). Then the resulting DRE is compared to the results of earlier iterations related to lower flow rate conditions. If significant changes of the flow rate do result in a significant change of the DRE (Q), the flare control increases flow rate (F4) and the flow chain F3-E1-E2-Q-F4 is repeated until no significant changes at reasonable high flow rates can be detected anymore. Estimated results for the DRE will be refined (E3) using the true gas composition data from the analysis of the gas samples collected during step F3.

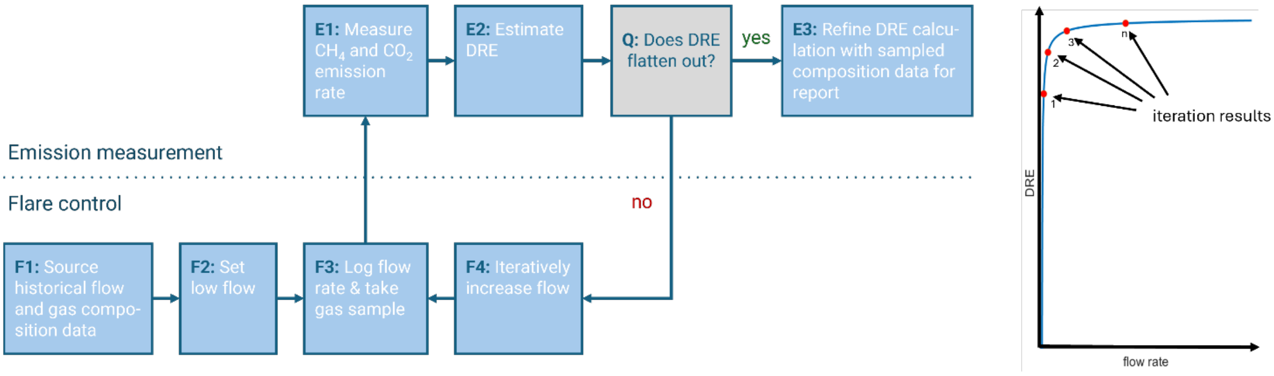

Figure 11: Flare Charactersation Protocol (FCP) sampling procedure.

The right-hand panel in Figure 11 shows the expected dependence of DRE to flow rate which are also apparent from the measurements conducted in this study. The DRE quickly increases with flow rate until it asymptotically approaches 100%. An example in case of the measured ground-level boxed flare is shown in the left panel of Figure 12 which covered a wide range of calculated DRE values.

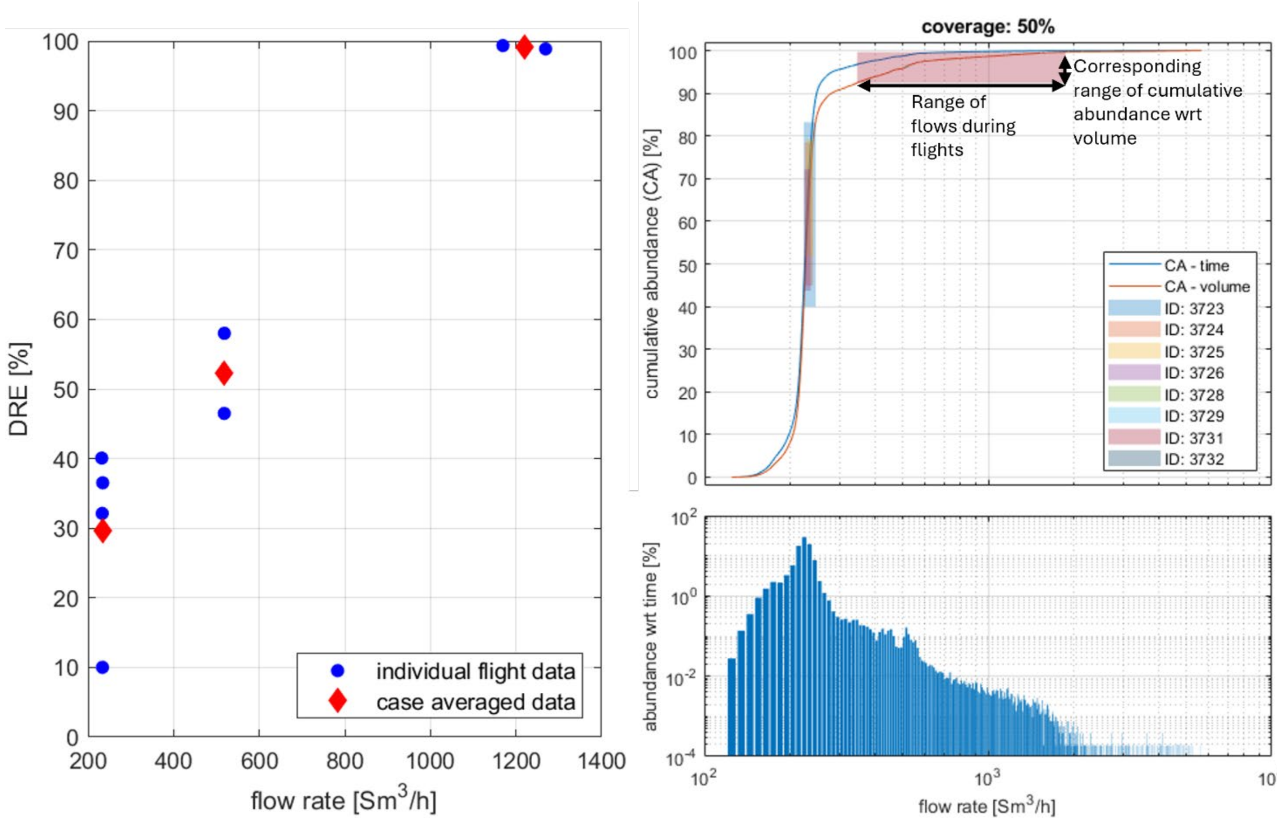

Figure 12: Representativeness of obtained results in an annualized context based on measurements of the boxed flare. Left panel: calculated values from measurements for the DRE over total gas flow rates to the flare. Bottom right panel: relative abundance of flow rates with respect to time rates over a 1-year-period. Top right panel: cumulative abundance of flow rates with respect to time and to the total volume of flared gas. The boxes displayed in the graph show the fraction of flow rates which was covered during the measurements of individual flights and how it compares to the overall abundance.

The obtained gas flow data for the provided case from the flare operator according to step F1 is shown in form of a histogram in the bottom-right panel in Figure 12. The upper right panel transposes the relative abundances over time into a cumulative abundance with respect to the fraction of the total emitted volume for this flow rate over the course of a year (solid red line).

The measurement series started at the lower range of the reported flows which also corresponds to the most prevalent condition. The variations of the flows for the different flights translate into corresponding ranges of cumulative abundances. Adding up the non-overlapping intervals of these ranges yields a coverage which is a measure of representativeness of the regarded operational scenarios that were observed.

The key information that is reported comprises the DRE in relation to the operational data, i.e. flow rate of all gas flows to the flare including pilot gas, as well as the respective gas compositions. Because of the known impact of cross wind to the flaring process[14] the wind conditions are a relevant parameter and need to be reported. The wind conditions can be put in context to historical data similar to above to assess the representativeness of the conditions present during the collected series of DRE measurements.

In case of assisted flares, this could be handled accordingly, provided that data of the assisting steam or air flow rates is available.

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[14] Damon C. Burtt et al., "A Methodology for Quantifying Combustion Efficiencies and Species Emission Rates of Flares Subjected to Crosswind," *Journal of the Energy Institute* 104 (October 1, 2022): 124–32, https://doi.org/10.1016/j.joei.2022.07.005.

5.3 Commercial implementation

The developed equipment and method to determine the DRE of flares reached a state where they can be used commercially including an applicable protocol has been developed as part of the FlareE project.

The outcomes of this project can be used across the industry by oil and gas operators, i.e. any national, international and/or global energy operator with flaring activity as primary target group. A secondary target group are other energy producers such as biogas plants and other facilities with flaring activity.

The developed measurement technique adds value as an independent verification service that provides oil and gas operators with a more cost-efficient and easy-to-deploy alternative to assessing and reporting DRE from multiple operational environments, both on- and offshore. Current measurement techniques for measuring DRE on individual flares are mainly based on optical remote sensing techniques such as FTIR or DIAL. However, because of their limitations, they do not have broad market penetration. Instead, the field is still characterized by early research adoptions, general immaturity, and no clear competitors, even in the US where flaring is more prevalent than in Europe and the monitoring market therefore presumably larger. This fact is recognized by the OGMP itself, which characterizes the status of current direct measuring techniques as ‘emerging’. Various capture techniques (*e.g.,* Tedlar sampling bags) have historically also been attempted but only for research purposes and not in a commercial context.

By contrast, the presented drone-based method is easy to deploy, versatile and has the potential to overcome several of the limitations of the optical methods. The developed technology is also not limited by geography but has global potential.

An alternative to the remote sensing technologies are quantitative analysis and verification using computational fluid dynamics (CFD) modelling. However, these models are also highly costly and generally struggle with validation. For this reason, CFD models are typically used for research purposes only or to address a specific flare design challenge and are not used routinely by operators according to OGMP 2.0.

5.4 Relevant project dissemination activities

The background and outcomes of the project were presented to relevant stakeholders on the occasions presented in Table 1.

Table 1: Disseminations of project FlareE.

Date	Dissemination activity
20 November 2024	Presentation of project’s found methodology and key findings at the Decarb Forum be Offshore Energies UK (OEUK) (web-based)
20 November 2024	Presentation and discussion of project’s found methodology with United Nations Environmental Program (UNEP) as a leading global authority of the Oil & Gas Methane Partnership 2.0 (web-based)
18 December 2024	Presentation and discussion of project’s found methodology with industrial stakeholders on a web-based meeting with BP
12-14 February 2025	Presentation of project’s found methodology and key findings at the 2025 Methane Mitigation Europe Summit in Amsterdam
29-30 April 2025	Presentation of project’s found methodology and key findings at the ASMEA Flow Measurement Workshop 2025 in Abu Dhabi

6. Utilisation of project results

The DRE measurement methodology developed through the FlareE project is commercialised by Explicit as a standalone measuring application. Explicit is currently experiencing significant growth within the global oil and gas industry thanks to its DFM method. The addition of DRE measurements is seen as a natural extension of this offering.

Explicit further aims to - ultimately - add the new application to its existing ISO/IEC 17025 accreditation as a separate test method. It currently holds an ISO accreditation for a drone-based gas sensing DFM method. This status provides a unique competitive advantage as any accredited monitoring solution will hold added value to clients and authorities. The more 'pieces' of the overall OGMP reporting scope that operators can demonstrate is encompassed by ISO quality standards, the stronger the credibility of the measurements. Here, the quantitative measurements with DFM and measurements of DRE complement each other. However, any accreditation activity was not part of the scope of this project.

The developed FCP for how to measure and report on DRE is presented to the oil and gas community and the OGMP. As an open protocol, the FCP is seen as an enabler for any subsequent market take-up of a new direct DRE measurement technique.

The outcomes of the FlareE project already led to commercial contracts with clients in the oil and gas industry.

7. Project conclusion and perspective

The project FlareE developed a novel drone-based technology and method to assess the DRE of flares and provided a scheme to be used for reporting the measured results.

The results of this project show that in-situ drone-based methods can be used to measure DRE from flaring activities and provide a recommendation about its application regarding emission reporting purposes.

The assessment of the DRE from flaring using the presented drone-based method builds upon Explicit's validated and accredited DFM method. The DFM method is applied to measure the emission rates of CH_4 and CO_2 in flare emissions, which are key parameters for the calculation of the DRE. The technology and method developed in this project were demonstrated for the use on elevated and ground flares. The equipment can be easily transported and deployed even at challenging locations such as offshore platforms. In contrast to other state-of-the-art technologies, e.g. spectrophotometers, for the determination of DRE from flaring there is no requirement on the flame to be lit or a line of sight to the flame.

The results from the FlareE projects highlight also the importance cover the spatial variability by sampling the entire plume, which is inherent in the applied DFM approach for the quantification of the emission rates of CH_4 and CO_2. The DFM approach also addresses the variability in time of the combustion process and plume propagation through averaging.

A Flare Characterisation Protocoll (FCP) was developed as part of the FlareE project. Recommendations were provided about how spot measurements can be carried out and put into an annual context.

A next step is the integration and quantification of additional gas analysers to determine and study impact of other combustion products such as CO. Also, the impacts of wind and flare assist systems would be worth to study in more detail in a future project.