

Methane emission measurements of natural gas operator sites

TNO 2023 R12713 – 9 January 2024

Methane emission measurements of natural gas operator sites

Author(s)	I. Velzeboer, G.J. de Bruin, W.C.M. van den Bulk, D. van Dinther
Classification report	TNO Public
Title	TNO Public
Report text	TNO Public
Number of pages	48 (excl. front and back cover)
Number of appendices	0
Project name	Methane emission measurements of natural gas operator sites
Project number	060.57112

All rights reserved

No part of this publication may be reproduced and/or published by print, photoprint, microfilm or any other means without the previous written consent of TNO.

© 2023 TNO

Contents

Contents

Contents	3
1 Introduction.....	4
2 Experimental procedure	5
2.1 Mobile plume measurement with the TILDAS laser spectrometer.....	5
3 Study area	9
3.1 Germigny sous Coulomb (STORENGY).....	9
3.1.1 The wellheads	10
3.2 Montoir de Bretagne (ELENGY)	11
3.3 Prinquiau (GRTgaz)	12
3.4 Chémery (STORENGY)	13
3.4.1 The wellheads	15
4 Results and discussion	17
4.1 The Germigny sous Coulomb site.....	17
4.1.1 The wellheads	21
4.2 The Montoir de Bretagne site.....	23
4.3 The Prinquiau site	28
4.4 The Chémery site.....	33
4.4.1 The wellheads	39
5 Conclusions and outlook.....	45
References.....	48

1 Introduction

GRTgaz RICE is preparing a top-down methane emission study on behalf of ELENGY (LNG company, affiliated to ENGIE), on one of their LNG terminals (Montoir de Bretagne LNG Terminal) and on behalf of STORENGY on two of their underground gas storage (UGS) sites (Germigny and Chemery) and for GRTgaz interconnection site Prinquiau. Therefore, they aim to meet the emission quantification through a site level bottom-up approach, preferable using a tracer gas release method. Based on a literature study of Lopez *et.al.* (2021), a follow-up controlled release study and contacts with TNO, GRTgaz requested TNO to do the measurements. To quantify methane (CH_4) emissions from a site, TNO provides the Mobile Tracer Dispersion Method (MTDM), using nitrous oxide (N_2O) as a tracer. By measuring the methane concentrations together with the N_2O concentration (of which the source strength, i.e. emission level, is known) downwind of the facility, the methane emission can be quantified.

Within this project, methane emissions of four sites were quantified. TNO has joined the measurement campaign from 12 to 21 June 2023 with two scientists, driving the measurement truck that is equipped with all infrastructure and equipment for the measurements to all four locations. The measurement truck consist of a truck with a trailer, in total with a length of 10 m (Figure 1-1).



Figure 1-1 Image of the measurement truck.

Outline

The experimental procedure, including instrumentation, set-up and quantification method are described in the next chapter. The study area is described in Chapter 3, including the tracer release experiments performed at the sites. Chapter 4 shows the results and discussion, followed by the conclusions in Chapter 5.

2 Experimental procedure

The mobile measurements campaign with tracer release experiments were conducted at the four selected natural gas sites in June 2023. Next to these sites, wellheads were measured at Germigny and Chémery.

All measurement times are recorded in UTC time.

2.1 Mobile plume measurement with the TILDAS laser spectrometer

Instrumentation

Methane sources like oil and gas installations have a complex spatial distribution of the source strength within a confined area. These sources can be evaluated with plume measurement techniques. These techniques evaluate the concentration plume that originates at the source and is transported with the wind. The concentration is measured on a transect perpendicular to the wind direction. Meteorological data (wind speed, wind direction, turbulence) and a Gaussian dispersion model are used to calculate the emission level from the observed concentration pattern. The model has been used to evaluate emissions from landfills in the Netherlands since the 90s (Hensen & Scharff, 2001; Czepiel *et.al.* 1996, Savanne *et.al.* 1997). The same methodology is used here. However, the instruments have improved considerably. The CH₄ concentration is measured with a laser spectrometer, located in a truck with a trailer that drives a transect through the plume downwind of the source. The concentration measurements are performed using a Tunable Infrared Laser Direct Absorption Spectroscopy (TILDAS) instrument. In this campaign, a TILDAS *dual* laser trace gas analyzer (Aerodyne Research, Inc. Billerica, USA) is used, which enables simultaneous measurement of multiple species (CH₄, ethane (C₂H₆), N₂O, carbon monoxide (CO), carbon dioxide (CO₂) and water (H₂O)). This system has a precision of 2.4, 0.1, 0.1, 386.3 and 2.5 ppb for CH₄, C₂H₆, N₂O, CO₂ and CO respectively. In addition, instrument calibrations are conducted at the start and end of each measurement day, with calibration gases measured against WMO certified standards at the Cabauw tall tower in the Netherlands.

Measurement set-up

By releasing a tracer gas with a known emission rate the source strength of a location can be evaluated. It is important that the tracer gas is not emitted by the facility or object of study itself. By assuming that the spatial distribution of the tracer is similar to the gas under study, the actual emission strength can be determined. For this evaluation, no dispersion model is necessary. However, when the point source release of the tracer gas cannot mimic the source distribution (e.g., when the site is large with multiple small sources) a dispersion model is needed. (Hensen, 2012).

To apply the Mobile Tracer Dispersion Method (MTDM), a known source strength of N₂O is released from a gas cylinder located at the site (Figure 2-1 Left). The meteorological data (wind speed, wind direction) are obtained with a 3D sonic anemometer (20Hz sampling frequency), which is placed at a location free of obstacles, in the vicinity of where the measurements are performed (Figure 2-1 Right). To measure the methane plume, the

concentration is measured on a transect perpendicular to the wind direction. The truck is driving at *ca.* 200-1000 meters downwind of the source area to best capture the N₂O tracer and other greenhouse gases. While measuring, the truck driving speed should be relatively low, on average 30 to 50 km/h (if traffic allows). Ambient air is sampled from the top of the truck. A plume-transect takes two to seven minutes, depending on the distance and size of the source; 1Hz sampling frequency is applied to observe detailed concentration patterns on the measurement transect. The position of the truck is obtained using a GPS system. By measuring ethane next to methane, thermogenic sources can be distinguished from biogenic sources, for example an LNG facility and a manure heap.



Figure 2-1 Left: set-up N₂O tracer release; right: 3D sonic anemometer box.

Quantification

With the tracer dispersion methods, emission rates can be determined without the model by using equation (1):

$$Q_{\text{source}} = Q_{\text{tracer}} \cdot \frac{M_{\text{source}}}{M_{\text{tracer}}} \cdot \frac{\int s_{\text{source}}}{\int s_{\text{tracer}}} \quad (1)$$

In this equation, Q_{source} denotes the emission rate of the source gas measured in g/s, Q_{tracer} is the known emission rate of the tracer gas in g/s, M_{source} and M_{tracer} are the molar weight of the target and tracer gas respectively in g/mol, and $\int s_{\text{source}}$ and $\int s_{\text{tracer}}$ are the integrated signals of the source and tracer concentration plumes respectively in ppbv.

When measuring wellheads, no tracer is used. Hence, the emission strength of the wellheads are measured using the Mobile Dispersion Method (MDM). This was done using the Gaussian Dispersion model (Hensen & Scharff, 2001). Specific for the wellheads, an adapted model set-up is made, using the plume height instead of the area under the plume, to simplify the calculations and is less time consuming. The model can be used with or without the tracer data. When a tracer is available the model can be “calibrated” for that location. This is beneficial for sites that are relatively large with multiple source areas that have different distances to the measurement transect. In such case, the measured concentrations in the plume transect are compared with those that follow from the Gaussian dispersion model. The emission strength can be derived from the model set-up in such a way that it is best able to match the observed concentration profile along the measurement transect.

The model needs meteorological data (wind speed and wind direction) which are obtained with a 3D sonic anemometer (20Hz sampling frequency). The anemometer is placed at a location free of obstacles, in the vicinity of where the measurements are performed.

The model also needs dispersion parameters, depending on (1) distance to the source, (2) degree of turbulence of the atmosphere, (3) the roughness length of the surface (flat terrain versus trees or even buildings), and (4) atmospheric stability. Atmospheric stability is indicated by meteorological data (heat flux, wind speed, and cloud cover). For this model, the Pasquill stability classes are used, with seven options: (A) Extremely unstable conditions; (B) Moderately unstable condition; (C) Slightly unstable conditions; (D) Neutral conditions; (E) Slightly stable conditions; (F) Moderately stable conditions; (G) Extremely Stable.

For the quantification calculations, first the model is run for N_2O with the known source strength of N_2O . This, to validate the model settings and calculations as the modelled and observed concentration profile should match. For the unknown CH_4 source a default source strength of 1 g/s is used.

The procedure starts by comparing the released emission rate of the tracer gas to the modelled tracer gas emission rate. Model parameters, such as stability class and roughness length, are tuned in such a way that it aligns with the observations. The resulting difference (correction) is also used to correct the modelled emission rate for CH_4 . For larger sources, such as the natural gas operator site, multiple sources of CH_4 are used to better estimate the total emission rate. The source points are equally distributed around the site (based on the satellite image). When available, known sources can be used for the model calculations. It is possible to estimate the contribution of different emission rates within a source area by using least squares, but that was outside the scope of this project. To differentiate between sources at the site, further study, discussion with operators on expected source locations is needed. Furthermore, it is depended on the meteorological circumstances. Wind speed below 2 m/s makes it difficult, but also the wind direction is a deciding factor. When different sources are in line, it is not possible to separate them.

Methodological requirements

The plume measurement technique has several requirements. The meteorological circumstances and logistics (availability of a measurement transect in a specific wind direction) dictate when measurements can take place (Hensen, 2012). A wind speed lower than 2 m/s is not preferable for measurements because the gas will not be transported in a well-defined direction. The uncertainty in an emission estimate will in these cases increase significantly. For complex or large facilities, when the tracer is placed at a particular location within the facility, other parts of that facility, not in the vicinity of the tracer might experience different dispersion effects (for example due to large obstacles). This effect decreases when the distance between source and measurement transect increases. The atmospheric dispersion model can help to provide a correction for a non-ideal tracer source distribution on the site.

Uncertainty

First, instrument noise, drift of the laser and uncertainty in the background, causing an instrumental uncertainty in the CH_4 and N_2O concentration measurements of about 1 to 5%. Second changes in wind direction (on a timescale of 5 to 10 min) are the main cause for variation in the set of emission estimates (Fredenslund *et.al.*, 2019). Third, the emission from the facilities is not constant over time. Fourth, the concentration in the atmosphere downwind (i.e., the background) of the site changes due to differences in meteorological parameters (wind speed, wind direction, temperature, inversion layer height, air pressure, cloud density/sunshine etc.). This measurement method gives an emission level for the whole location on the day of measurements. All mentioned uncertainties are included in the final reported emission rates, as an average +/- standard error from the selected plume measurements.

Based on experience of multiple mobile measurements onshore, it is demonstrated that multiple transects downwind of a source can reduce the uncertainty of the emission quantification significantly, as the relative error will decrease with an increase of the amount of measured plumes (Hensen *et.al.*, 2018; Hensen *et.al.*, 2019). The reduction following an exponential trend with the number of plumes leading to a lower error. An optimum amount between the reduction of the relative error and the effort to collect more plumes is determined at six plumes (Luetschwager *et.al.*, 2021, 2019, Maazalahi *et.al.*, 2022). However, considering the fact that in this study the focus was on four sites, spread throughout France, more plumes were measured at all sites.

3 Study area

3.1 Germigny sous Coulomb (STORENGY)

Germigny sous Coulomb is an underground gas storage (UGS) site from STORENGY (Figure 3-1). The part in the blue rectangle is in production, the part in the red rectangle is under nitrogen (this part is out of order, not emitting CH_4). Plume measurements from the site were performed on the 13th of June 2023. Measurements of the wellheads were performed on the 14th of June 2023. The site facility map (Figure 3-2) provided by STORENGY shows the schematic overview of the site including ATEX zones.

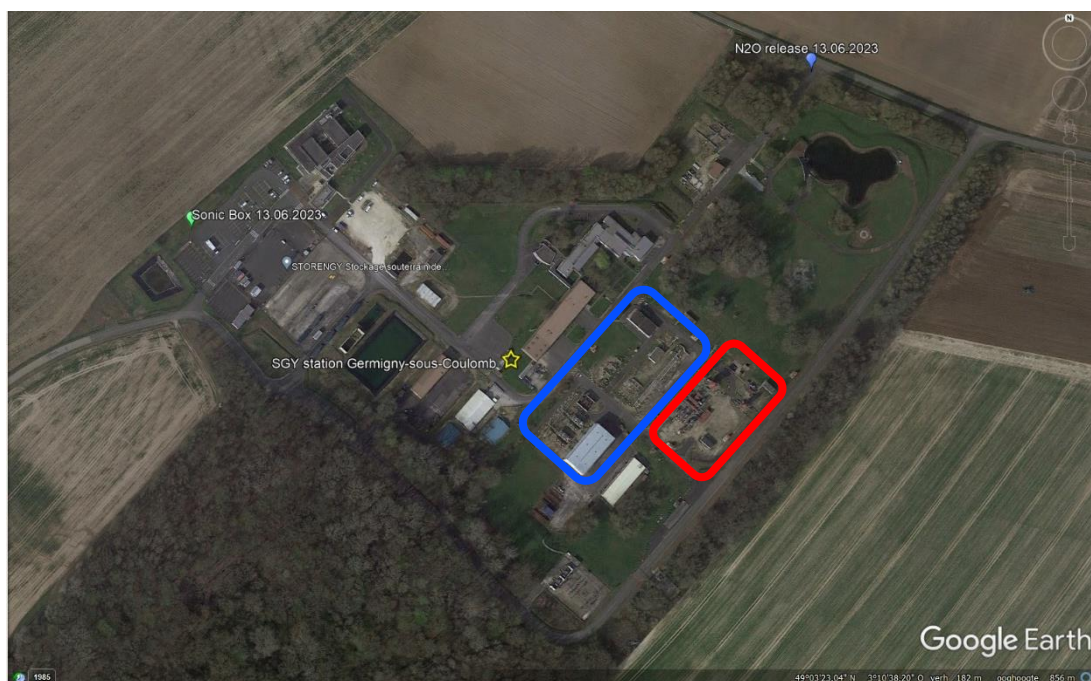


Figure 3-1 Google Earth image of the Germigny site.

Two tracer release cylinders with N_2O (cylinder #17 and cylinder #13) were placed separately on the northeast side of the facility for two different measurement periods.

- Tracer release experiment 1 using N_2O cylinder #17 (between 12:10 – 13:15, measured plumes from #2 to #17, tracer release rate was 0.91 g/s)
- Tracer release experiment 2 using N_2O cylinder #13 (between 14:18 – 14:55, measured plumes from #20 to #28, tracer release rate was 0.94 g/s)

The N_2O tracer release location is shown as blue pin on the top of the image (Figure 3-1). This was the best location given constraints with access in a wind direction of around 60 degrees. The location of the 3D sonic anemometer is shown as green pin on the left side of the image (Figure 3-1).

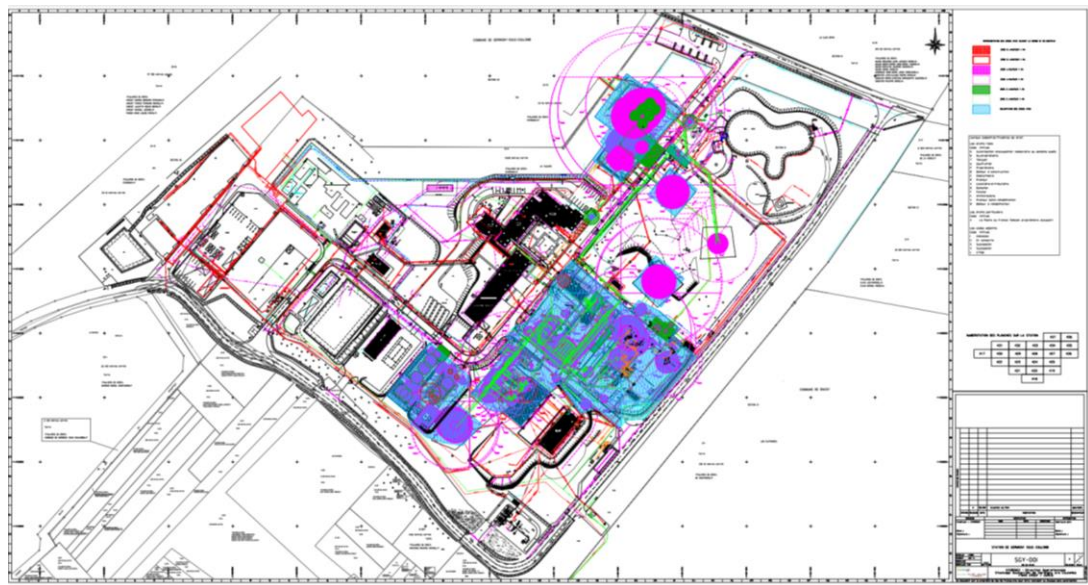


Figure 3-2 Schematic map of the Germigny site including ATEX zones (coloured parts, red is zone 0, pink is zone 2, green is zone 3).

3.1.1 The wellheads

In the surroundings of the Germigny site, multiple wellheads are present. On the second measurement day, only part of the wellheads were measured. Some were passed once or twice only, while others were measured more intensively. At CR14 a tracer was used and CR39 and a manifold platform, PM8 were measured within the same measurement session.

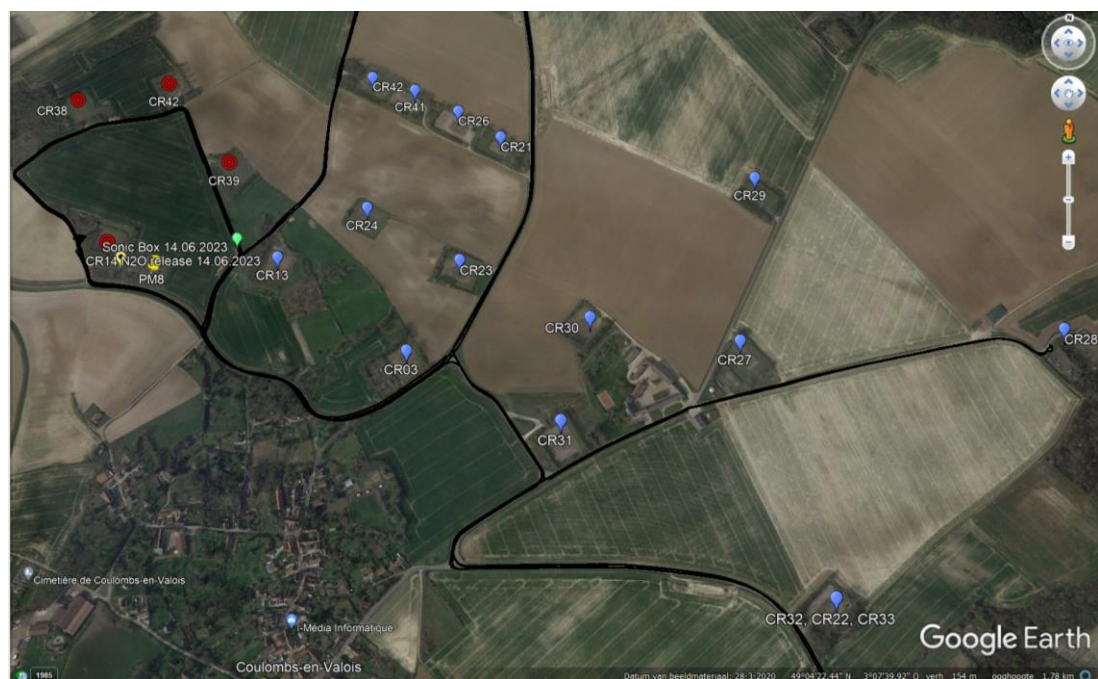


Figure 3-3 Google Earth image of the wellheads (red is priority, blue is other wellheads) related to Germigny site. The track is shown by the black line.

PM8 is a distribution station next to CR14. The 3D sonic anemometer is shown with a green pin in the image (Figure 3-3). The N_2O tracer release location is shown a yellow pin in the image (Figure 3-3).

- Trace release experiment 1 using N_2O cylinder #11 (between 08:08 – 09:24, measured plumes from #3 to #18, tracer release rate is 0.083 g/s)

Furthermore a gas location near CR35 was measured more intensively with tube measurements, by walking back and forth as the measurement truck could not drive there. This location is not further analyzed to determine an emission rate, as there was not enough time and budget within the project.

3.2 Montoir de Bretagne (ELENGY)

Montoir de Bretagne is an LNG terminal from ELENGY (Figure 3-4). Plume measurements from the site were performed at the 16th of June 2023. The site facility map (Figure 3-5) provided by ELENGY shows the schematic overview of the site.



Figure 3-4 Google Earth image of the Montoir de Bretagne site.

Two tracer release cylinders of N_2O (cylinder #16 and cylinder #18) were placed separately on the northeast and southwest side of the facility for two different measurement periods:

- Trace release experiment 1 using N_2O cylinder #16 (between 09:15 to 09:55, measured plumes from #2 to #4, tracer release rate was 0.75 g/s)
- Tracer release experiment 2 using N_2O cylinder #18 (between 11:53 to 13:20, measured plumes from #5 to #19, tracer release rate was 1.07 g/s)

The N_2O tracer release location is shown with blue pins, in the morning on the right side next to the 3D sonic anemometer, shown with a green pin and in the afternoon on the left side of the image (Figure 3-4).

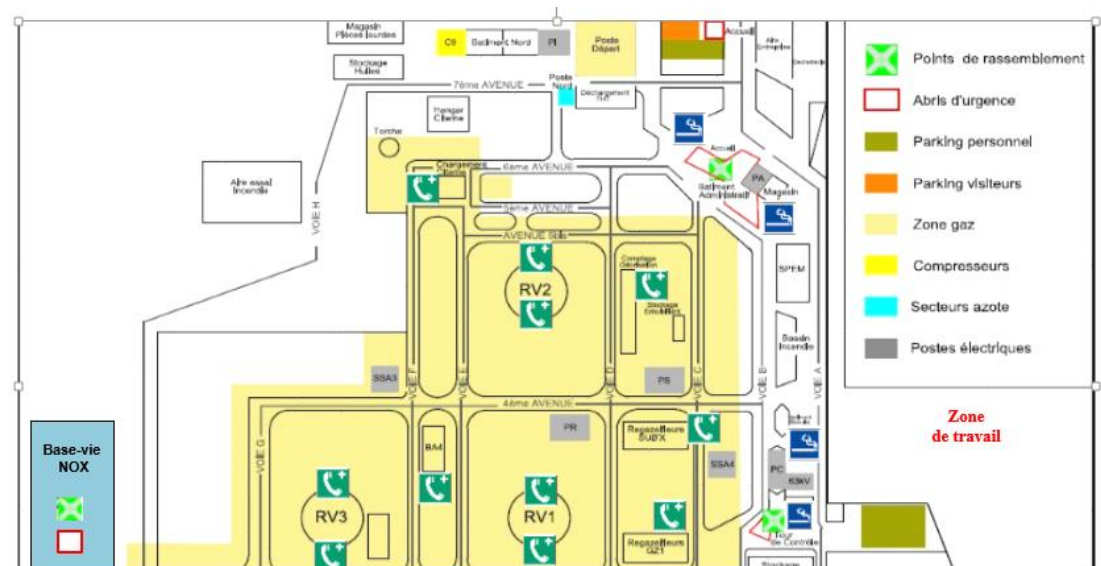


Figure 3-5 Schematic map of the Montoir site.

3.3 Prinquiau (GRTgaz)

Prinquiau is an interconnection site terminal from GRTgaz (Figure 3-6). Plume measurements from the site were performed on the 17th of June 2023. The site facility map (Figure 3-7) provided by GRTgaz, shows the schematic overview of the site.



Figure 3-6 Google Earth image of the Prinquiau site.

One tracer release cylinder (cylinder #15) was used. The 3D sonic anemometer was standing next to the tracer, so no extra pin is placed in the image (Figure 3-6). The N₂O tracer release location is shown with the blue pin, in the middle of the image on the south side of the site (Figure 3-6).

- Trace release experiment 1 using N₂O cylinder #15 (between 07:22 to 09:05, measured plumes from #2 to #39, tracer release rate was 0.09 g/s)

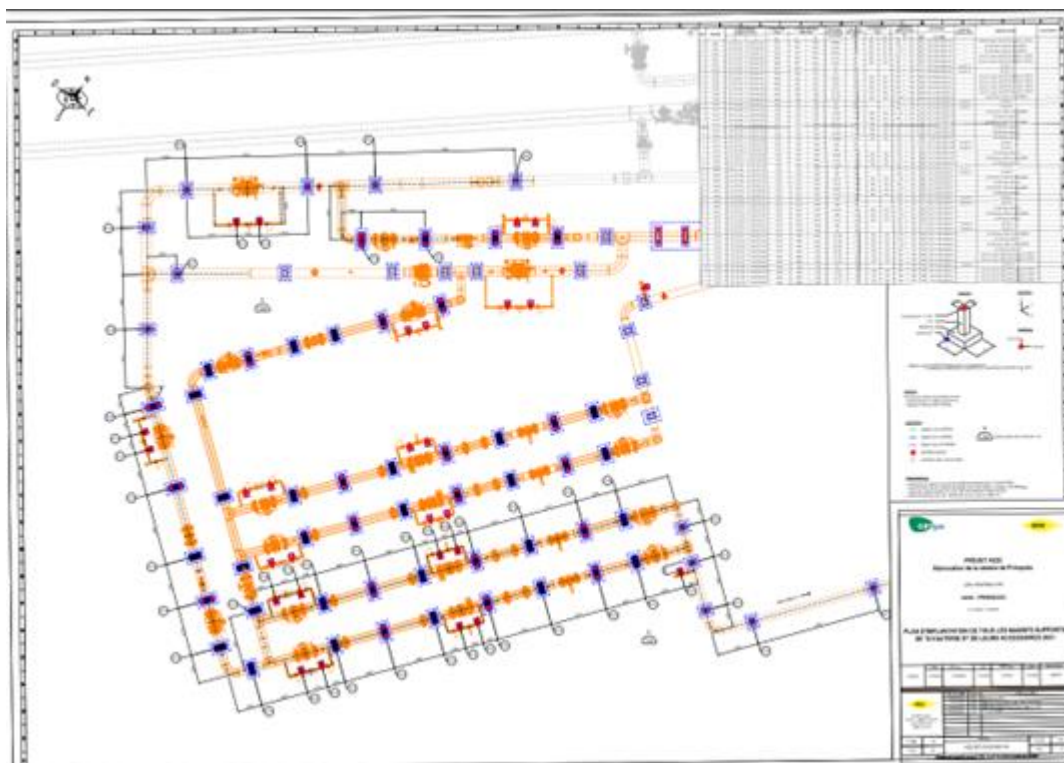


Figure 3-7 Schematic map of the Prinquiau site.

3.4 Chémery (STORENGY)

Chémery is an underground gas storage (UGS) site from STORENGY (Figure 3-8). Plume measurements from the site were performed on the 20th of June 2023. Measurements of the wellheads were performed on the 19th of June 2023. The site facility map (Figure 3-9) provided by STORENGY) shows the schematic overview of the site including functioning zones in orange and under maintenance zones in green.



Figure 3-8 Google Earth image of the Chémery site, including wellheads located at the site.

Three tracer release cylinders (cylinder #11, cylinder #15 and cylinder #10) were placed separately on the southwest side of the facility for three different measurement periods:

- Tracer release experiment 1 using N₂O cylinder #11 (between 08:35 to 09:45, measured plumes from #4 to #22, tracer release rate was 0.94 g/s)
- Tracer release experiment 2 using N₂O cylinder #15 (between 13:10 to 14:05, measured plumes from #25 to #34, tracer release rate was 1.20 g/s)
- Tracer release experiment 3 using N₂O cylinder #10 (between 14:05 to 14:35, measured plumes from #35 to #44, tracer release rate was 1.20 g/s)

The N₂O tracer release location is shown as a blue pin in the middle of the left side of the image (Figure 3-8). The 3D sonic anemometer is shown as a green pin in the middle of the right side of the image (Figure 3-8).

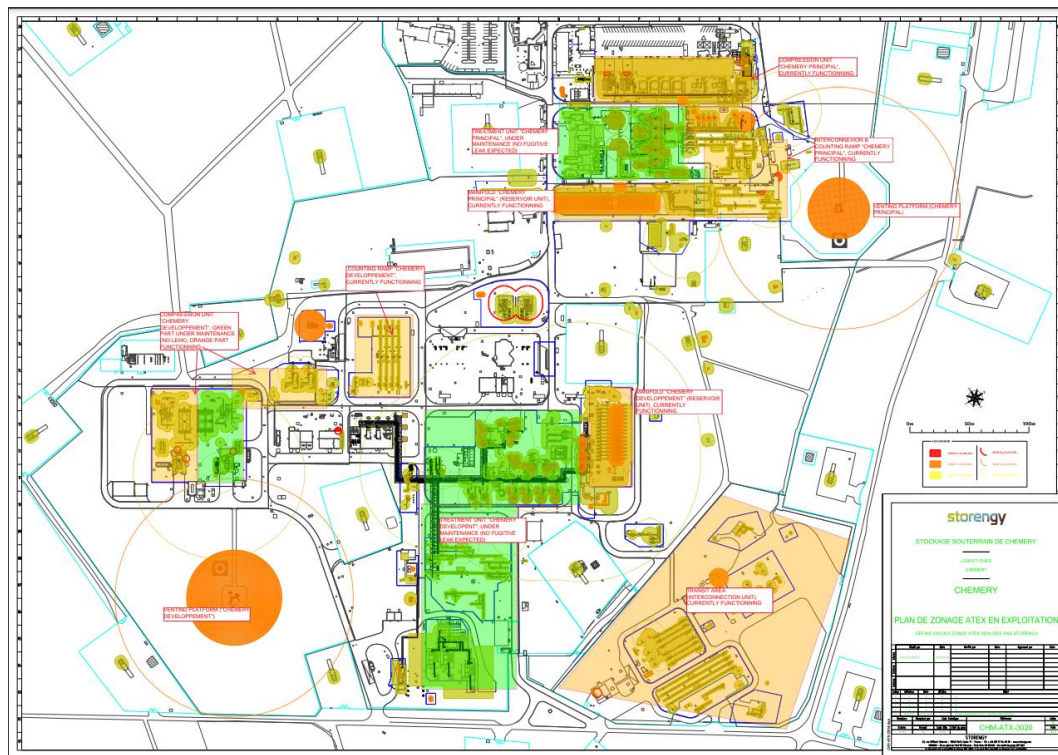


Figure 3-9 Schematic map of the Chémery site.

3.4.1 The wellheads

Multiple wellheads were present in the surroundings of the Chémery site. On the second measurement day (20th of June 2023), part of the wellheads were measured. It was not possible to measure all wellheads because of time limitations in combination with unstable wind .

The potential CH₄ emissions wellheads present at the Chémery site were included in the total emission estimates of the site, as it was not possible to separate them from the site emissions with the used mobile measurement method and existing wind direction.

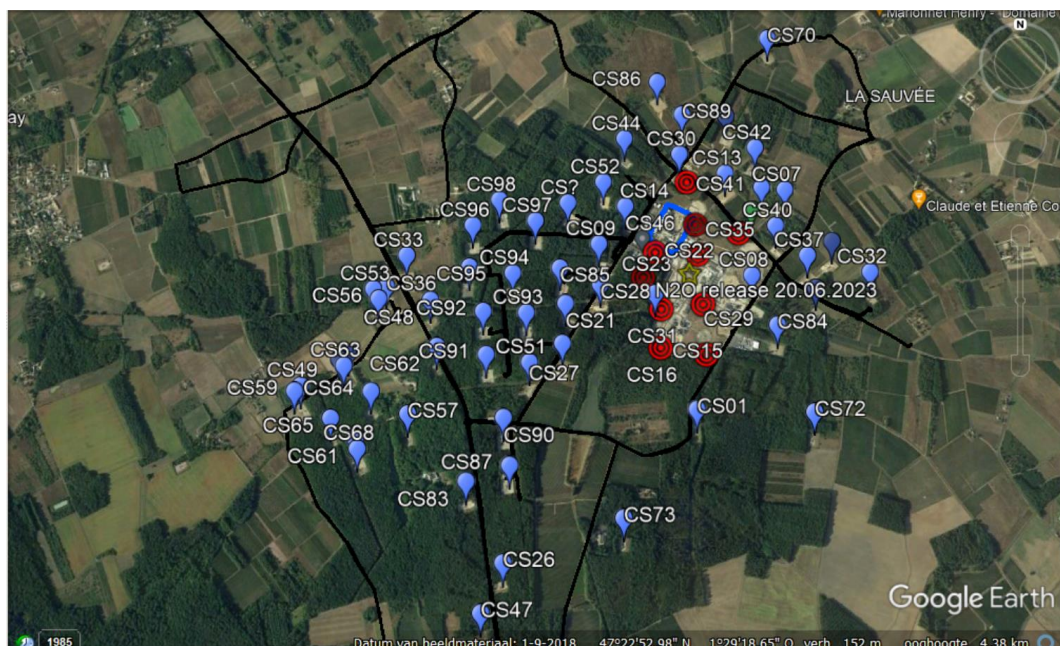


Figure 3-10 Google Earth image of the wellheads (red pins) related to Chémery site. The track is shown by the black line.

4 Results and discussion

4.1 The Germigny sous Coulomb site

The meteorological conditions were sufficient for conduction mobile measurements on the 13th of June 2023. During the day, the northeast (about 60 degrees) wind direction was stable. The average wind speed throughout the measurement day was 3.5 m/s. The measurements took place at a public road around the site (Figure 4-1). With wind coming from northeast, plumes were measured on the south side of the facility. Next to the site, there was a manure heap (light blue dot in Figure 4-1), which was also emitting CH_4 . However, the manure heap did not emit C_2H_6 , thus it was possible to distinguish it from the site emissions (Figure 4-2 and Figure 4-3).

The plume measurements show an overall CH_4 emission of 17 +/- 1.6 kg/h based on an average of 28 plumes, using stability class B (moderately unstable weather conditions) for the first tracer release experiment (cylinder #17) and stability class C (slightly unstable conditions) for the second tracer release experiment (cylinder #13). Uncertainty is based on the standard error of the measured plumes.



Figure 4-1 Overview of track (in blue) around the site, the sources (in red) and the tracer location (cylinder #17 and #13 in yellow) used for the model runs. The light blue dot represents a manure heap. The orange arrow represent the wind direction.

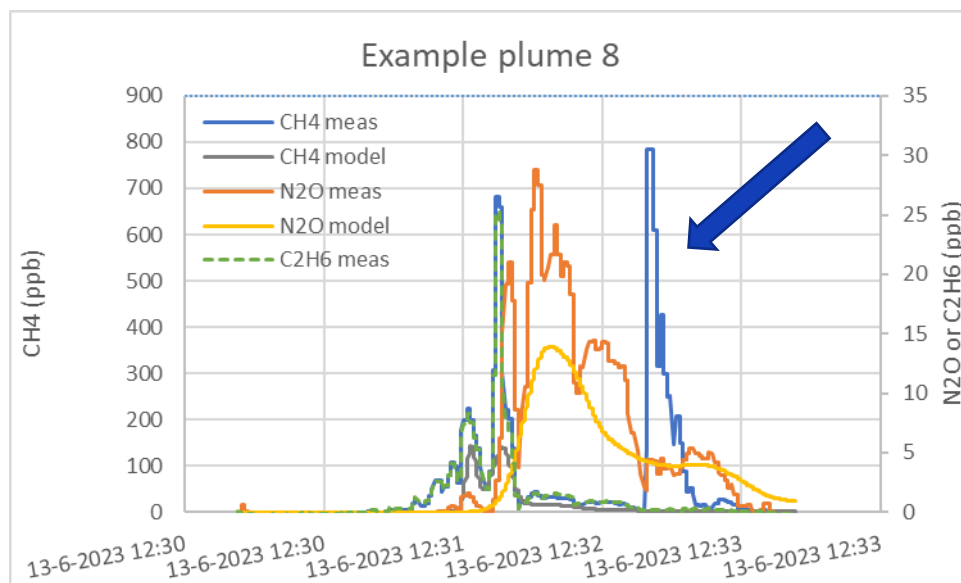


Figure 4-2 Example plume 8 with measured CH_4 , C_2H_6 and N_2O and modelled CH_4 and N_2O concentrations. Blue arrow indicates the manure plume, without C_2H_6 .

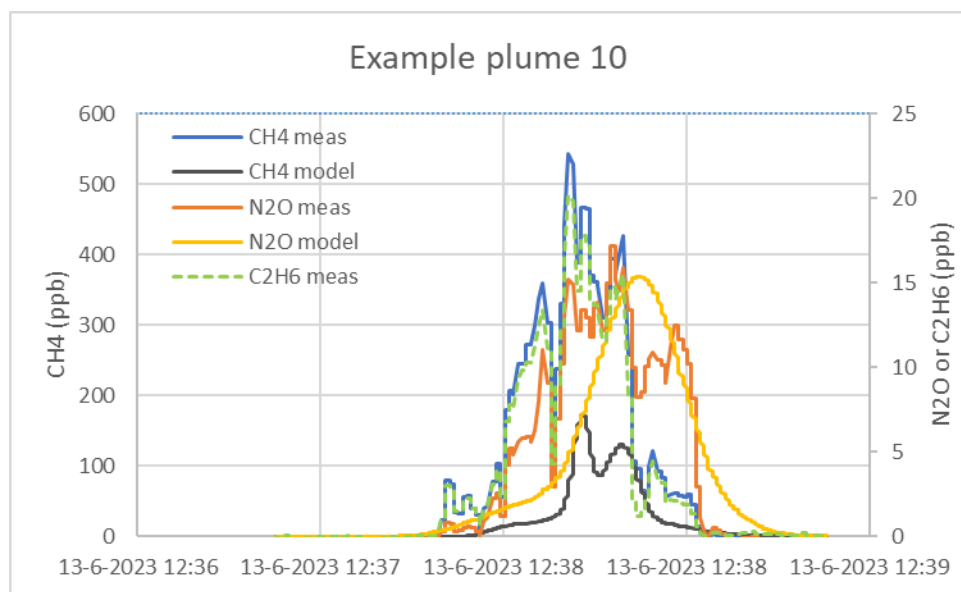


Figure 4-3 Example plume 10 with measured CH_4 , C_2H_6 and N_2O and modelled CH_4 and N_2O concentrations. Here the C_2H_6 and CH_4 concentrations have the same shape, indicating that the emissions are from a thermogenic source.

The plume measurements show a normal distribution for the emissions strength (Figure 4-4). The stable wind speed of 3.5 m/s result in reproducible measurements, but the manure heap did affect the measurements. It was not always possible to separate the plume from manure with that of the site, as the N_2O plume went also over the manure heap. This is also seen in the C_2H_6 : CH_4 ratio (Figure 4-7). When the manure heap plume is present next to the site plume, the ratio is lower. The ratio is on average 3.6% for the site. Including the manure heap, it is on average 2.8%.

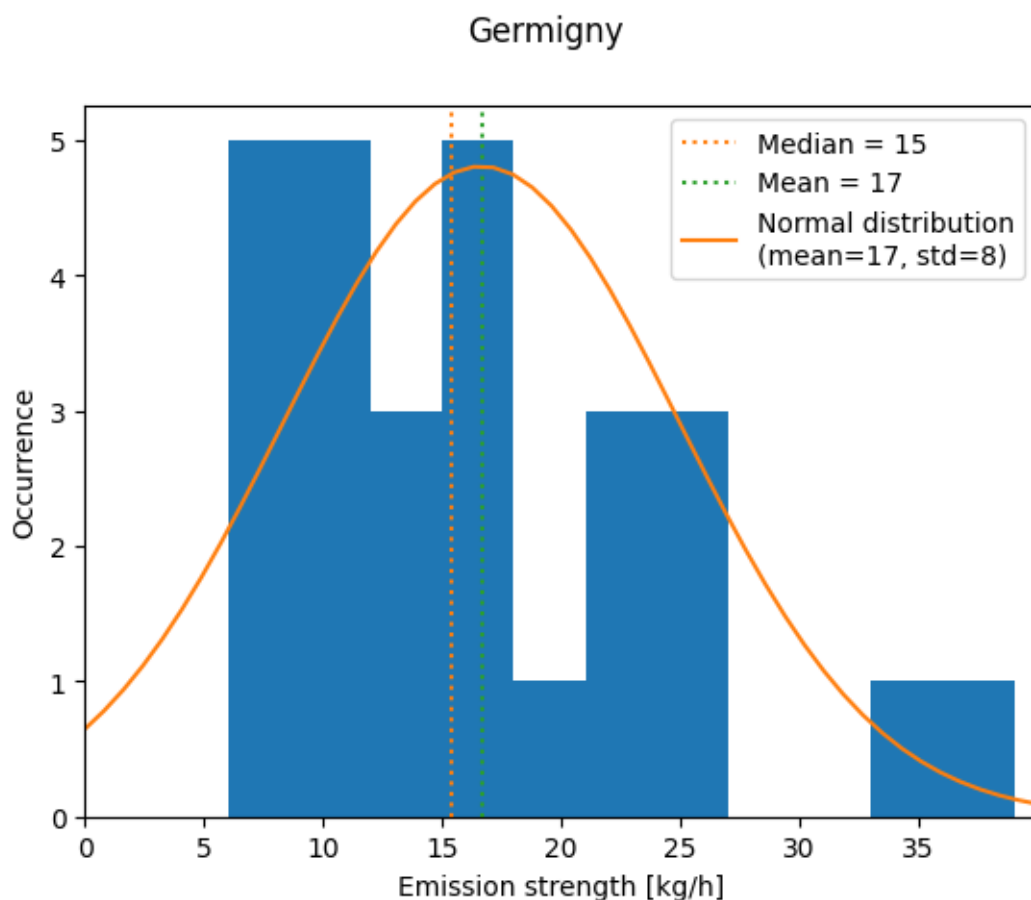


Figure 4-4 Distribution of emission strength (kg/h) from the measured plumes at Germigny-sous-Coulomb.

The emission rate of CH_4 calculated from the model follows the same pattern as the area under the measured plumes (integral) (Figure 4-5). This shows that the model estimates follow the CH_4 concentration measurements, indicating that the parameterisation of the model is sufficient. The C_2H_6 integrated signal follows the CH_4 integrated signal, demonstrating that the source is thermogenic gas (Figure 4-6). The deviation in the $\text{C}_2\text{H}_6:\text{CH}_4$ ratio shows that there is also another source (manure heap) of CH_4 (Figure 4-7), as mentioned above. As also stated above, the plumes where the manure heap could not be extracted from the site emissions, were not taken into account. This clearly demonstrates the added value of the C_2H_6 measurements.

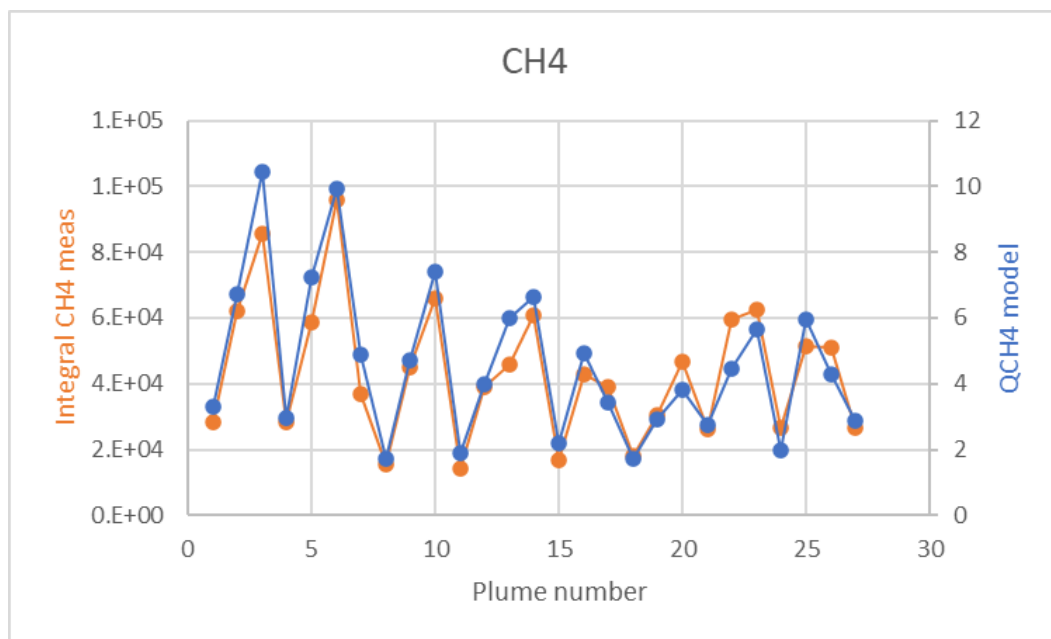


Figure 4-5 Comparison of the measured integrated signal of CH₄ with the modelled emission rate of CH₄ per plume.

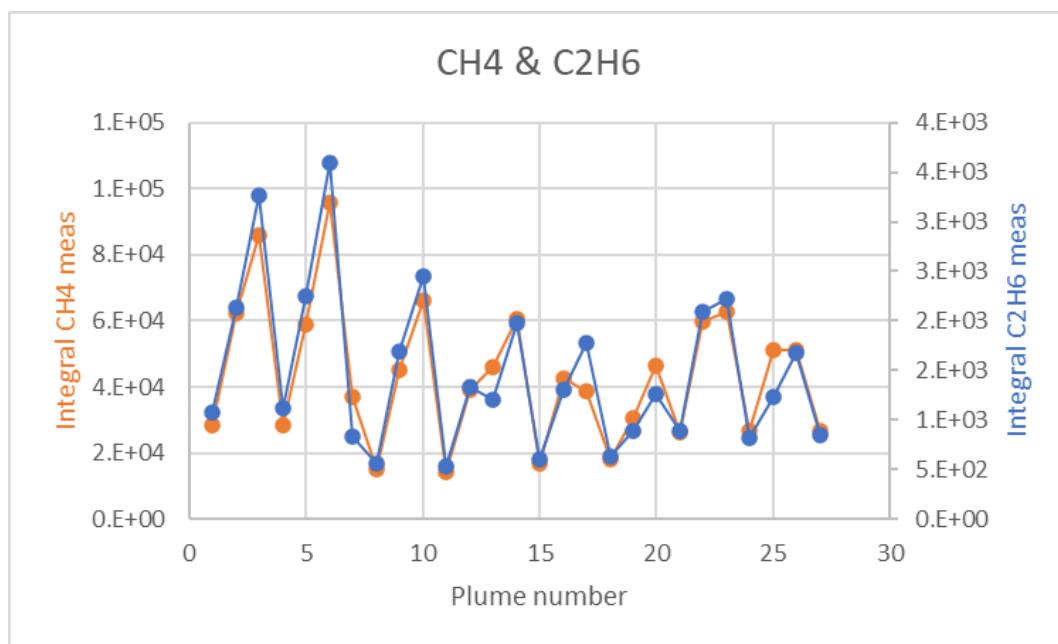


Figure 4-6 Integrated signal from CH₄ and C₂H₆ per plume.

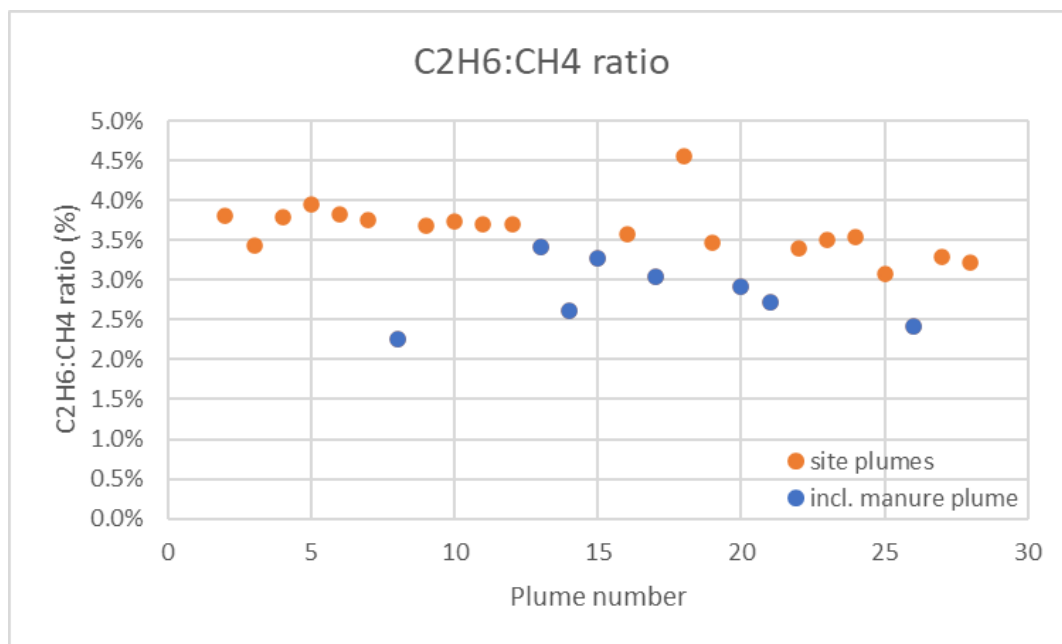


Figure 4-7 C₂H₆:CH₄ ratio per plume.

4.1.1 The wellheads

During the measurements on the 14th of June 2023, the wind speed was very low (< 1m/s), resulting in poor estimates using the Mobile Dispersion Method (MDM) with the Gaussian Plume model. In some cases this low wind speed even caused failures of observing the plume. The low wind speed also causes the wind direction to be less well defined. An overview of the wellhead results is shown in

Table 4-1.

Wellhead CR03 was measured directly south and west five times. Only one plume was observed with a $C_2H_6:CH_4$ ratio 0.3 +/- 0.1%. This ratio is lower than average for LNG. Therefore, it cannot be confirmed with certainty that the plumes originated from the wellhead.

CR13 and CR24 were passed three times (CR13 was passed at approximately 200 meters south). It was not clear if the plumes originated from CR13 or CR24. From two out of three plumes no C_2H_6 was observed. The third plume was too dispersed, resulting in too low concentrations to reliably estimate a source strength.

Wellhead CR14 is measured over twenty times together with CR39 and PM8 and an N_2O tracer was used (cylinder #11). Plumes originated from PM8. Eight plumes could be used for quantification, resulting in a CH_4 emission of 59 +/- 12 kg/h. For the model a wind speed of 1 m/s was used, wind direction was north to northwest. The $C_2H_6:CH_4$ ratio was 3.5 +/- 0.6%, indicating thermogenic gas as the source of the emissions.

Wellhead CR19 was measured twice approximately 400 m downwind. Only CH_4 plumes were observed. Therefore, it cannot be confirmed that the plumes originated from the wellhead. Plumes from the wellhead could possibly be missed because of the low wind speed and relative large distance of the wellhead to the measurement truck. From these measurements it thus cannot be concluded that there was no emission of CH_4 .

Wellheads CR22, CR32, and CR33 were passed four times approximately 20 m downwind. No CH_4 or C_2H_6 plumes were observed above the detection limit. The emission rate from these wellheads (if exist) are below the limit of detection, indicating no significant emissions from these wellheads.

Wellhead CR27 was crossed twice approximately 20 meters downwind. **No CH_4 or C_2H_6 plumes were observed above the detection limit.**

Wellhead CR28 was passed once approximately 20 m downwind. **No CH_4 or C_2H_6 plumes were observed within a detection limit.** Because of the unstable and low wind speed it cannot be concluded that there was no emission, as the plumes could be missed due to unfavourable wind direction.

Wellhead CR31 was passed five times. **No CH_4 or C_2H_6 plumes were observed above the detection limit.** The emission rate from this wellhead is thus below the limit of detection indicating no significant emissions.

Wellheads CR35 and CR36 were passed once at the west side, but no plumes were observed. Three additional passings were made on the north side, but again no plumes were observed. The emission rate from these wellheads are below the limit of detection, indicating no significant emissions.

Wellheads CR38 and CR42 were passed nineteen times. **No CH_4 or C_2H_6 plumes were observed above the detection limit.** The emission rates from these wellheads are below the limit of detection, indicating no significant emissions.

Table 4-1 Overview of the estimated CH₄ emission rates from the wellheads around the Germigny sous Coulomb area.

Wellhead	Passes	Plumes observed	CH ₄ emission [kg/h]	Remarks
CR03	5	1	- *	C ₂ H ₆ :CH ₄ ratio 0.3 +/- 0.1%
CR13	3	3	- *	C ₂ H ₆ :CH ₄ ratio 0.8 +/- 0.2%
CR24	3	3	- *	C ₂ H ₆ :CH ₄ ratio 0.8 +/- 0.2% Not clear if the plumes are from CR13 or CR24
CR14	20	0	<DL	
PM8	20	8	59 +/- 12**	C ₂ H ₆ :CH ₄ ratio = 3.5 +/- 0.6%
CR39	20	0	<DL	
CR19	2	2	-	***
CR22	4	0	<DL	
CR32	4	0	<DL	
CR33	4	0	<DL	
CR27	2	0	<DL	
CR28	1	0	<DL	****
CR31	5	0	<DL	
CR35	4	0	<DL	
CR36	4	0	<DL	
CR38	19	0	<DL	
CR42	19	0	<DL	

<DL is below the detection limit

* C₂H₆:CH₄ ratio lower than expected from a thermogenic source. Therefore, it cannot be confirmed that the plumes originated from the well.

**Standard error

*** Only CH₄ plumes were observed. Therefore, it cannot be confirmed that the plumes originated from the well.

**** Because of the unstable and low wind speed and direction it cannot be concluded that there was no emission, as the plumes could be missed due to unfavourable wind conditions.

4.2 The Montoir de Bretagne site

The meteorological conditions were sufficient for conduction mobile measurements on the 16th of June 2023. In the morning, the wind shifted from southeast (120 degrees) to southwest (220 degrees). The wind speed increased from 1.5 m/s to 2.5 m/s. The measurements took place at the road around the site. This was not a public road, but it was outside the ATEX zone. With wind coming from southeast to southwest, plumes were measured on the north side of the facility. The left upper red dot represents a potential CH₄ source from a bio-LNG research pilot (Figure 4-8), also emitting CH₄, but no C₂H₆, (Figure 4-9 and Figure 4-10).

The plume measurements show an overall CH₄ emission of 155 +/- 12 kg/h based on an average of 17 plumes, using stability class B (moderately unstable weather conditions). Uncertainty is based on the standard error of the measured plumes.



Figure 4-8 Overview of track (in blue) around the site, the sources (in red) and the tracer locations (cylinder #16 in yellow and cylinder #18 in orange) used for the model runs. The orange arrow represent the wind direction, After shifting.

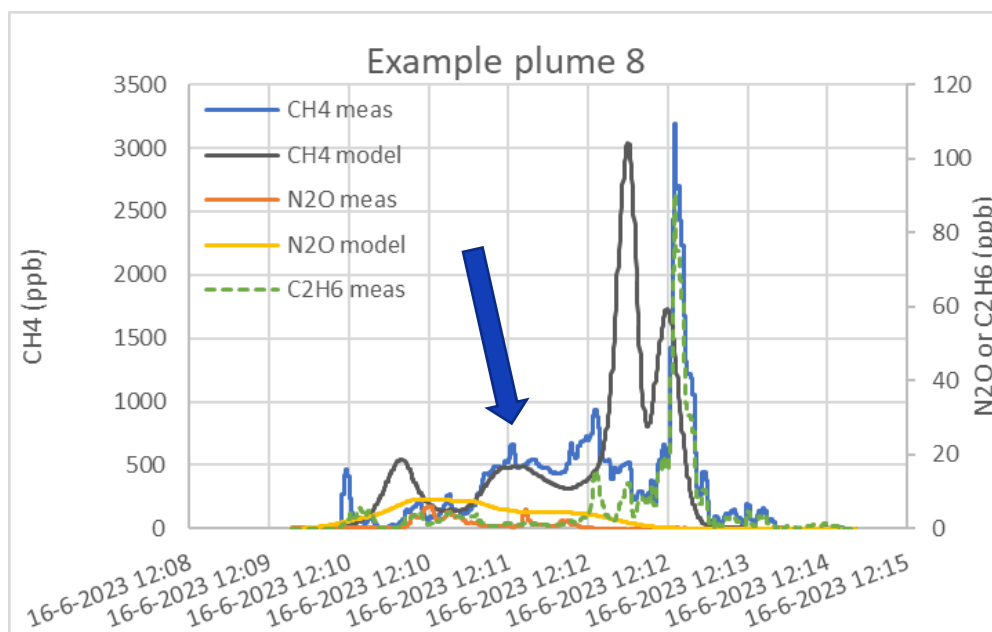


Figure 4-9 Example plume 8 with measured CH₄, C₂H₆ and N₂O and modelled CH₄ and N₂O concentrations. Blue arrow indicates the bio-LNG plume, without C₂H₆.

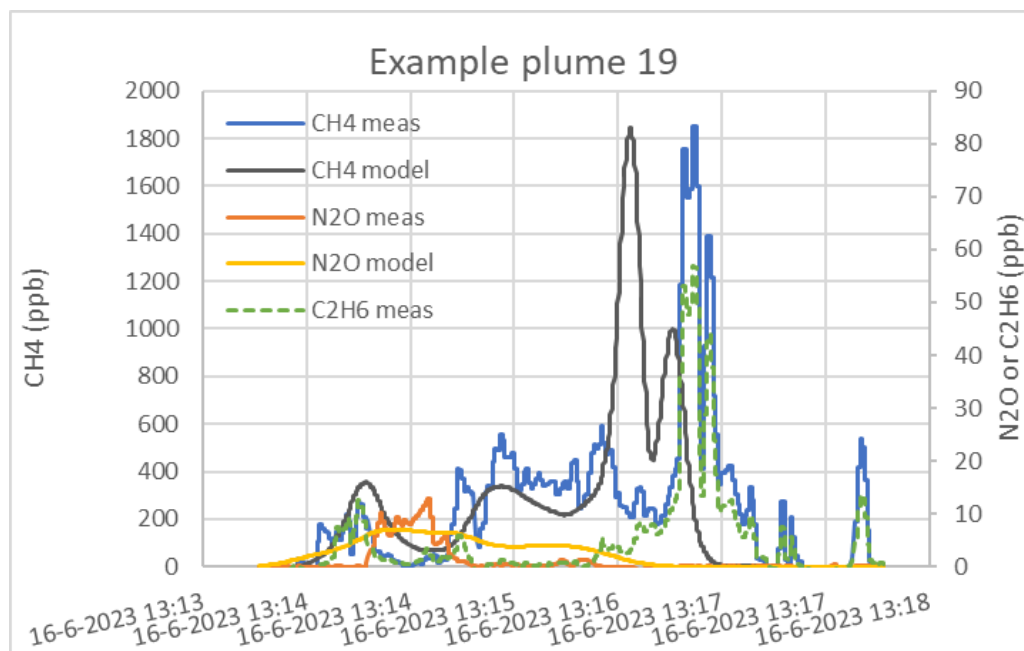


Figure 4-10 Example plume 19 with measured CH_4 , C_2H_6 and N_2O and modelled CH_4 and N_2O concentrations.

The plume measurements show a normal distribution for the emissions strength (Figure 4-11). The wind turned from southeast to southwest during the measurement period, with the wind speed increasing from 1.5 to 2.5 m/s. These changes in meteorological conditions cause more variation in the emission estimate between the plume measurements. The bio-LNG plumes influence the $\text{C}_2\text{H}_6:\text{CH}_4$ ratio (Figure 4-14). When the bio-LNG plume is present next to the other site plumes, the ratio is lower. The ratio of the site is 2.8%. When including the bio-LNG plumes, it is on average 1.9%.

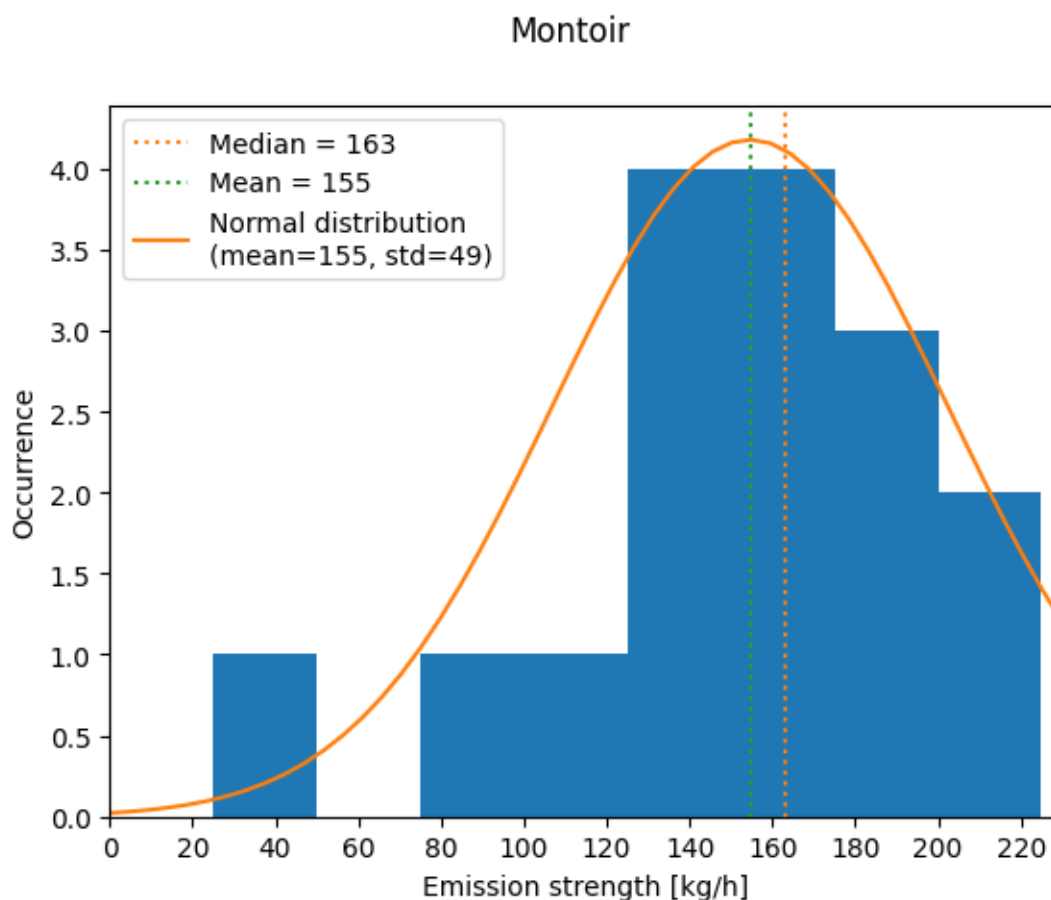


Figure 4-11 Distribution of emission strength (kg/h) from the measured plumes at Montoir de Bretagne.

The emission rate of CH_4 calculated from the model follows the same pattern as the area under (integral) the measured plumes (blue and orange lines; Figure 4-12), but not as agreeable as for Germigny sous Coulomb site. The measurements provide estimates both for the total site (155 ± 12 kg/h) and the bio-LNG source (54 ± 3 kg/h) (yellow and grey lines; Figure 4-12). This result in a site emission rate without the bio-LNG source of 101 ± 9 kg/h. The C_2H_6 integrated signal follows the CH_4 integrated signal, demonstrating thermogenic gas as the source (Figure 4-13), but not always. The deviation in the $\text{C}_2\text{H}_6:\text{CH}_4$ ratio shows that there is also another source (bio-LNG without C_2H_6) of CH_4 (Figure 4-7), as mentioned above. By extracting the bio-LNG source, the $\text{C}_2\text{H}_6:\text{CH}_4$ ratio is more stable and in the range of thermogenic gas (Figure 4-14).

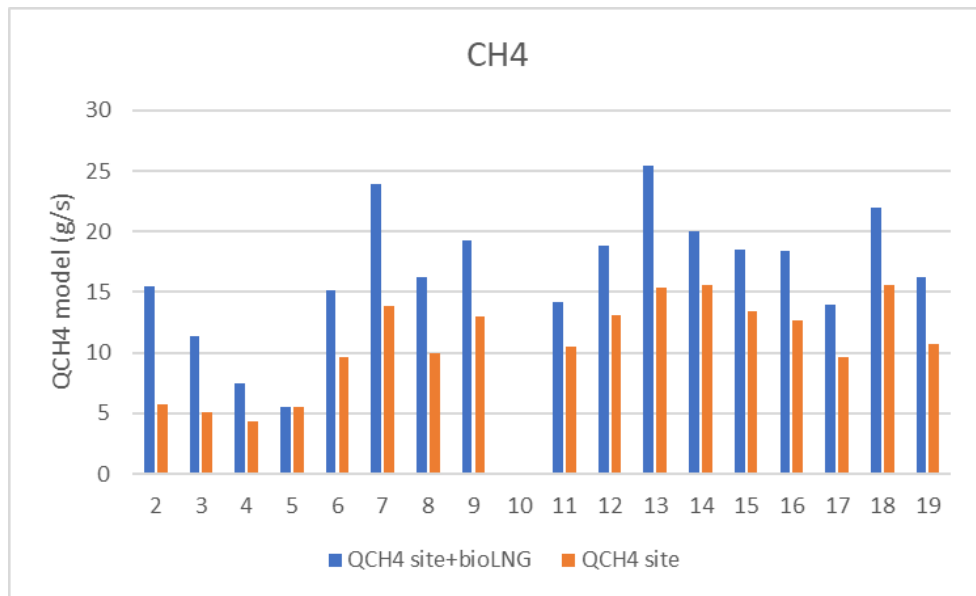


Figure 4-12 Comparison of modelled emission rate of CH₄ per plume. Blue bars include CH₄ from the bio-LNG, orange bars show the site CH₄ excluding the bio-LNG part.

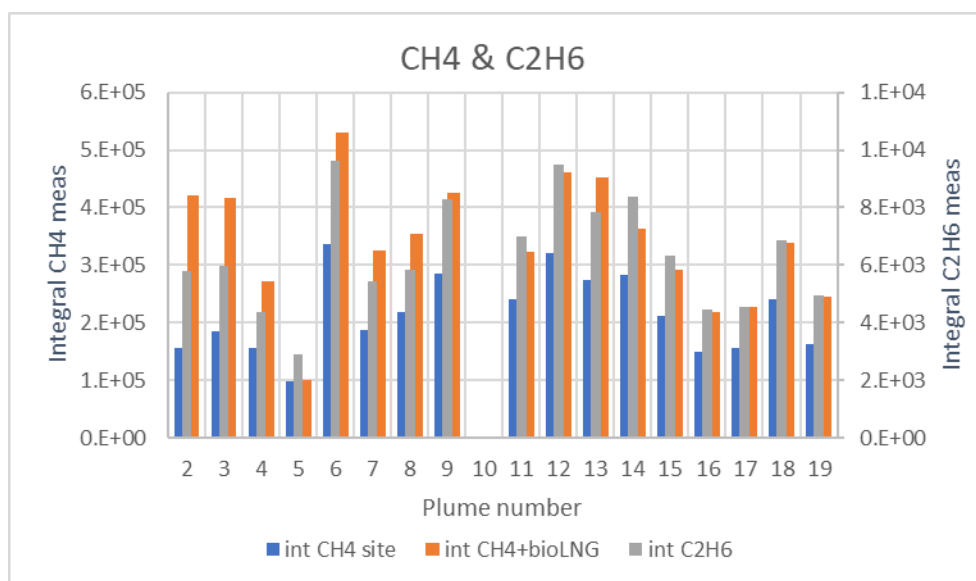


Figure 4-13 Integrated signal from CH₄ and C₂H₆ per plume. Orange bars include CH₄ from the bio-LNG, blue bars show only the site CH₄. Grey dots show C₂H₆.

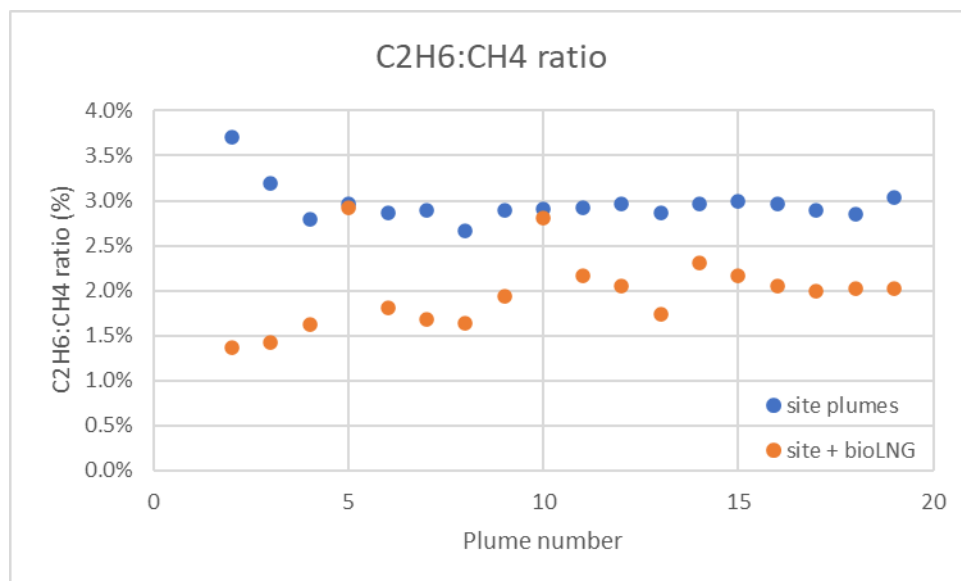


Figure 4-14 C₂H₆:CH₄ ratio per plume. Orange dots include CH₄ from the bio-LNG.

4.3 The Prinquiau site

The meteorological conditions were sufficient for conducting mobile measurements on the 17th of June 2023. This morning, the wind was south to south-east. The wind speed was relatively low around 1.2 m/s. The measurements took place on a public road next to the site. With wind coming from south to southeast, plumes were measured on the north side of the facility. This site had no interfering sources. Figure 4-16 shows an example of plume 7, presenting the measured CH₄, C₂H₆ and N₂O and modelled CH₄ and N₂O concentrations. Because of the relative high N₂O plume, the C₂H₆ plume looks like it is not the same shape as the CH₄ plume, but that is a scaling effect. When only showing the measured CH₄ and C₂H₆ it matches perfectly (Figure 4-17). N₂O was placed quite close to the measurement track, but there was no other option to place the cylinder.

The plume measurements show an overall CH₄ emission of 0.6 +/- 0.1 kg/h based on an average of 34 plumes, using stability class A (extremely unstable weather conditions). Uncertainty is based on the standard error of the measured plumes.



Figure 4-15 Overview of track (in blue) around the site, the sources (in red) and the tracer location (cylinder #15 in yellow) used for the model runs. The orange arrow represent the average wind direction.

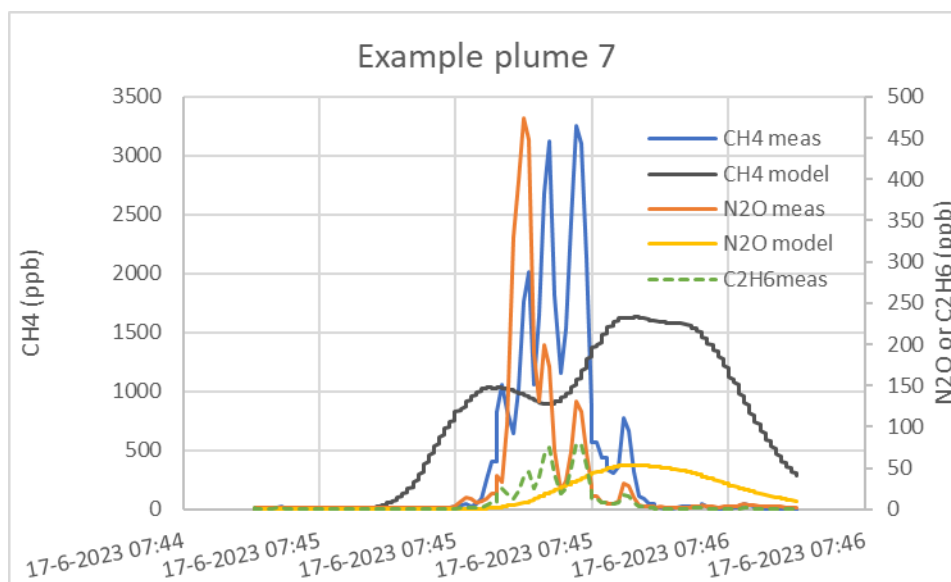


Figure 4-16 Example plume 7 with measured CH_4 , C_2H_6 and N_2O and modelled CH_4 and N_2O concentrations.

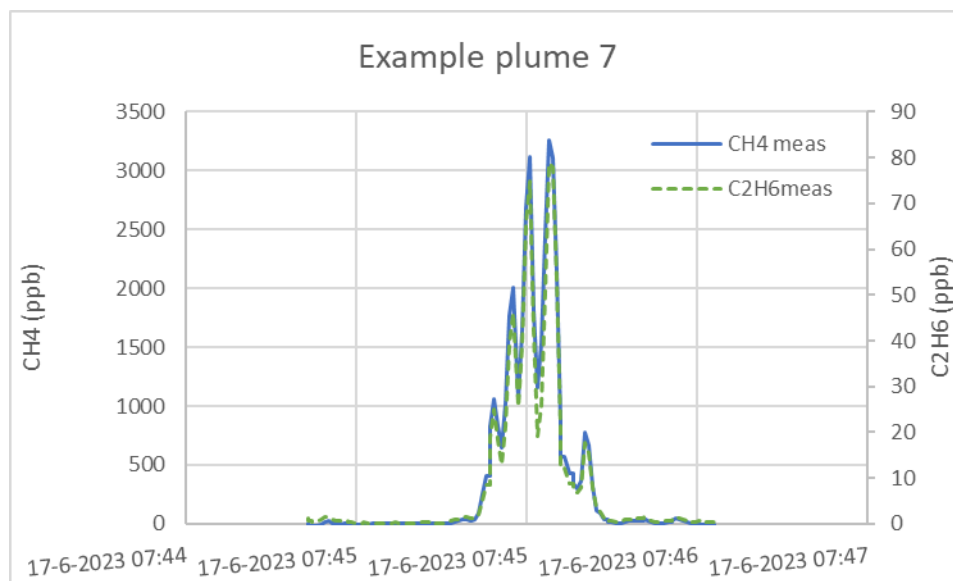


Figure 4-17 Example plume 7 with only measured CH₄ and C₂H₆ concentrations.

The plume measurements show a normal distribution for the emissions strength (Figure 4-18). The wind speed was low around 1.2 m/s and variable, causing also variation in wind direction shifting between 105 and 190 degrees. This variable wind direction also results in more variation in the emission estimates between the plume measurements. The C₂H₆:CH₄ ratio shows also more variation than expected with an average of 2.7 +/- 0.5% (Figure 4-21).

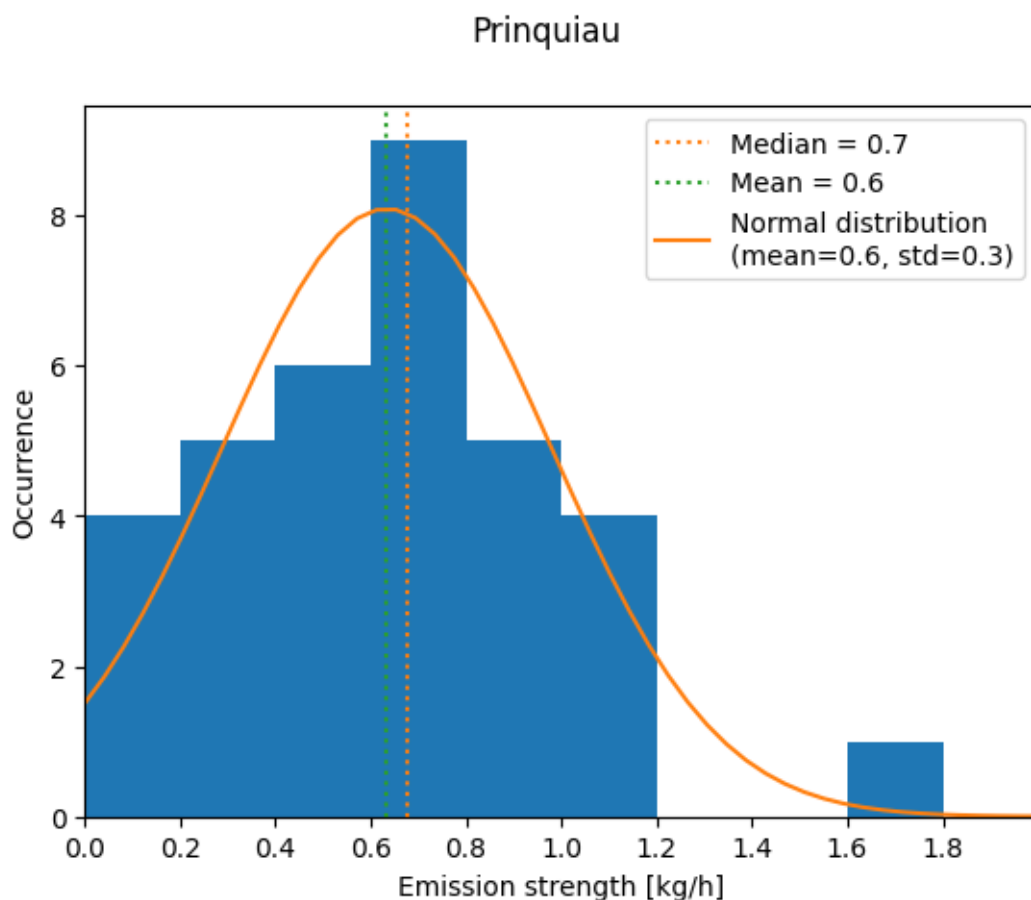


Figure 4-18 Distribution of emission strength (kg/h) from the measured plumes at Prinquiau.

The emission rate of CH_4 calculated from the model follows the same pattern as the area under (integral) from the measured plumes (Figure 4-19). This shows that the model estimates follow the CH_4 concentration measurements, indicating that the parameterisation of the model is sufficient. The C_2H_6 integrated signal follows the CH_4 integrated signal, demonstrating thermogenic gas (Figure 4-20). The spreading of the $\text{C}_2\text{H}_6:\text{CH}_4$ ratio is larger than for example at Montoir de Bretagne. This is probably due to the low wind speed, which result in more variation between the plumes. Furthermore, the distance between the sources and the measurements was relatively small. The plumes are than less well mixed at the measurement location, resulting in more variation between the plumes (Figure 4-21).

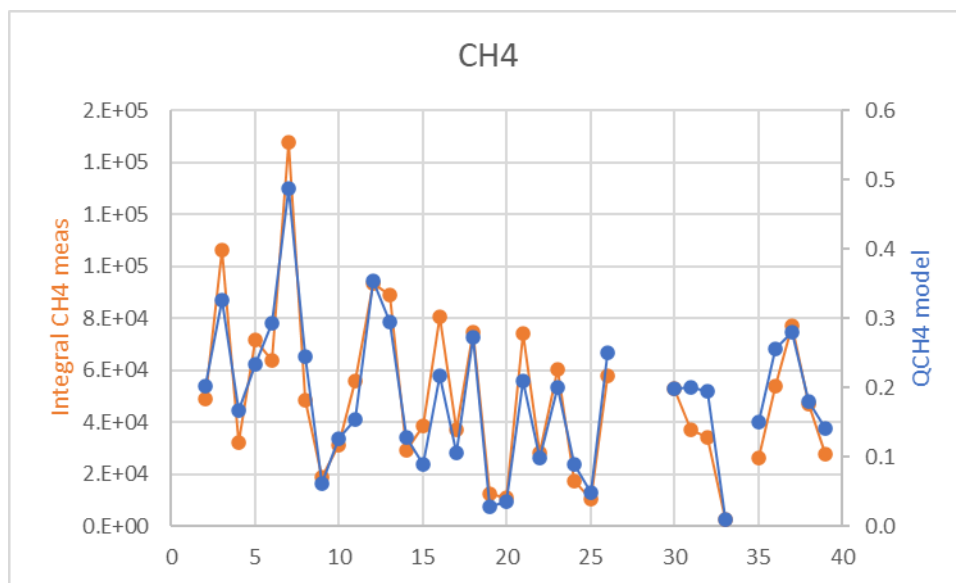


Figure 4-19 Comparison of the measured integrated signal of CH₄ with the modelled emission rate of CH₄ per plume.

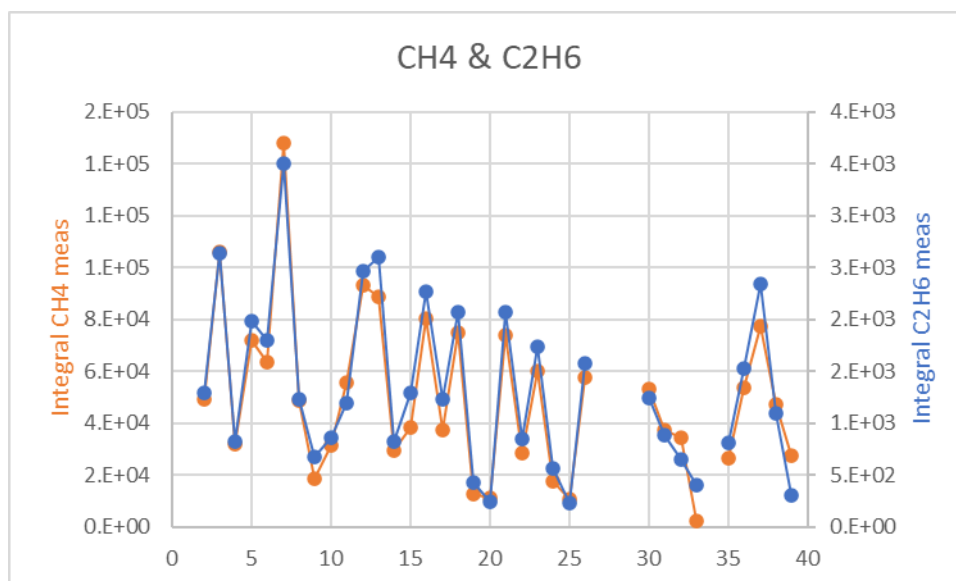
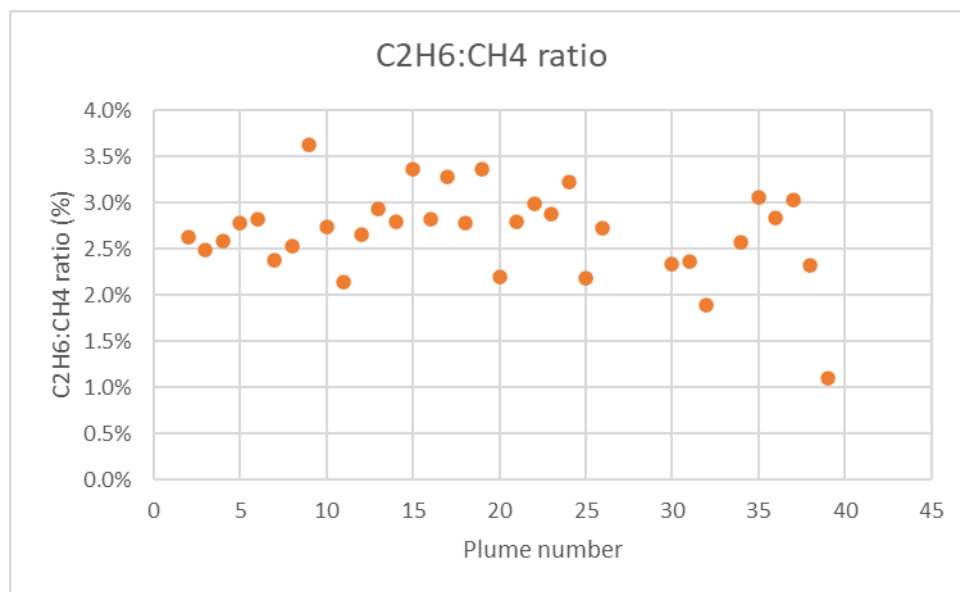


Figure 4-20 Integrated signal from CH₄ and C₂H₆ per plume.

Figure 4-21 C₂H₆:CH₄ ratio per plume.

4.4 The Chémery site

The meteorological conditions were sufficient for conduction mobile measurements on the 20th of June 2023. The wind direction was southwest. The wind speed increased from 1.6 m/s in the morning to 3.8 m/s in the afternoon and dropped at the end of the afternoon to 1.1 m/s. The measurements took place on the road around the site (Figure 4-22). With wind coming from southwest, plumes were measured on the northeast side of the facility. This site had no interfering sources, except for wellheads on and around the site. Figure 4-23 shows an example of plume 9, presenting the measured CH₄, C₂H₆ and N₂O and modelled CH₄ and N₂O concentrations. Note that because of the high CH₄ and C₂H₆ plume, the N₂O plumes and de modelled CH₄ plume are not visible with the used concentrations on the axes. When only showing the lower concentrations, the other plumes become visible (Figure 4-24).

The plume measurements show an overall CH₄ emission of 15E2 +/- 15 kg/h based on an average of 43 plumes, using stability class A (extremely unstable weather conditions) for the first 21 plumes and the last 10 plumes and stability class B (moderately unstable weather conditions) for the 12 plumes in between. Uncertainty is based on the standard error of the measured plumes.

When only using the plumes with stability class B (which have less variability than those with stability class A), an overall CH₄ emission of 98 +/- 8 kg/h is determined. This emission estimate is more reliable to use as the overall emission strength of the site.



Figure 4-22 Overview of track (in blue) around the site, the sources (in red) and the tracer location (cylinder #11, #15 and #10 in orange) used for the model runs.

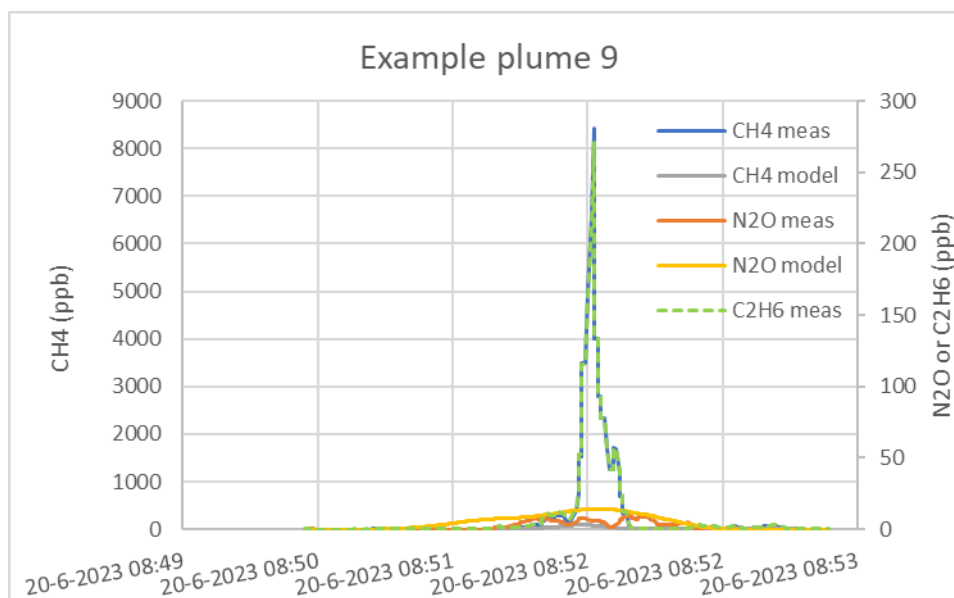


Figure 4-23 Example plume 9 with measured CH_4 , C_2H_6 and N_2O and modelled CH_4 and N_2O concentrations.

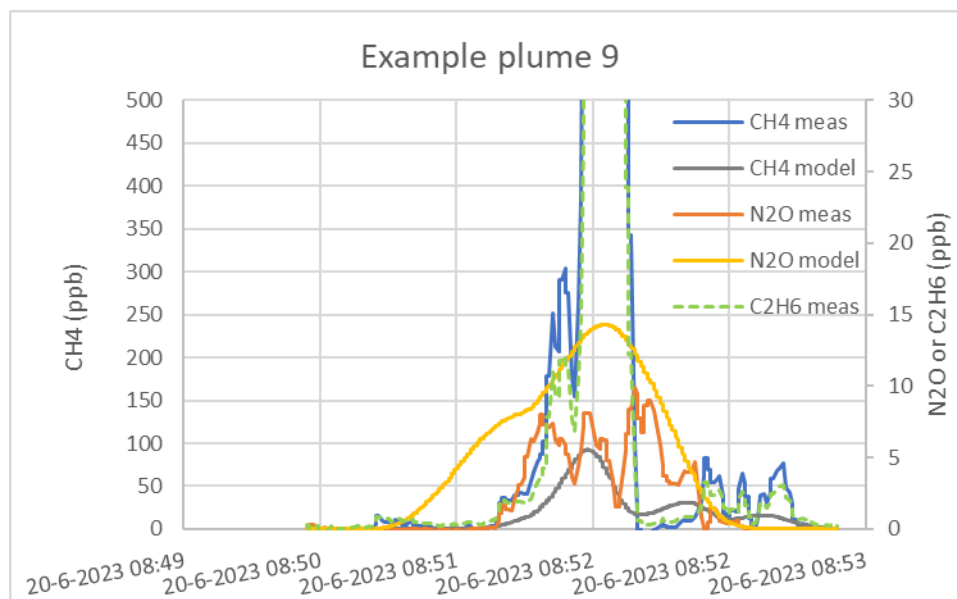


Figure 4-24 Example plume 9 with measured CH_4 , C_2H_6 and N_2O and modelled CH_4 and N_2O concentrations, focussing on the N_2O release.

The plume measurements show a normal distribution for the emissions strength, but is a little skewed because of some outliers with higher emissions (Figure 4-25). The wind speed was low and variable, during the first and last tracer release experiments, resulting in more variation between the plume measurements. During the second tracer release experiment, the wind speed was higher (2.5 m/s), resulting in less variation between the plume measurements. Here also a normal distribution for the emissions strength is shown, with less outliers of the higher emissions (Figure 4-26).

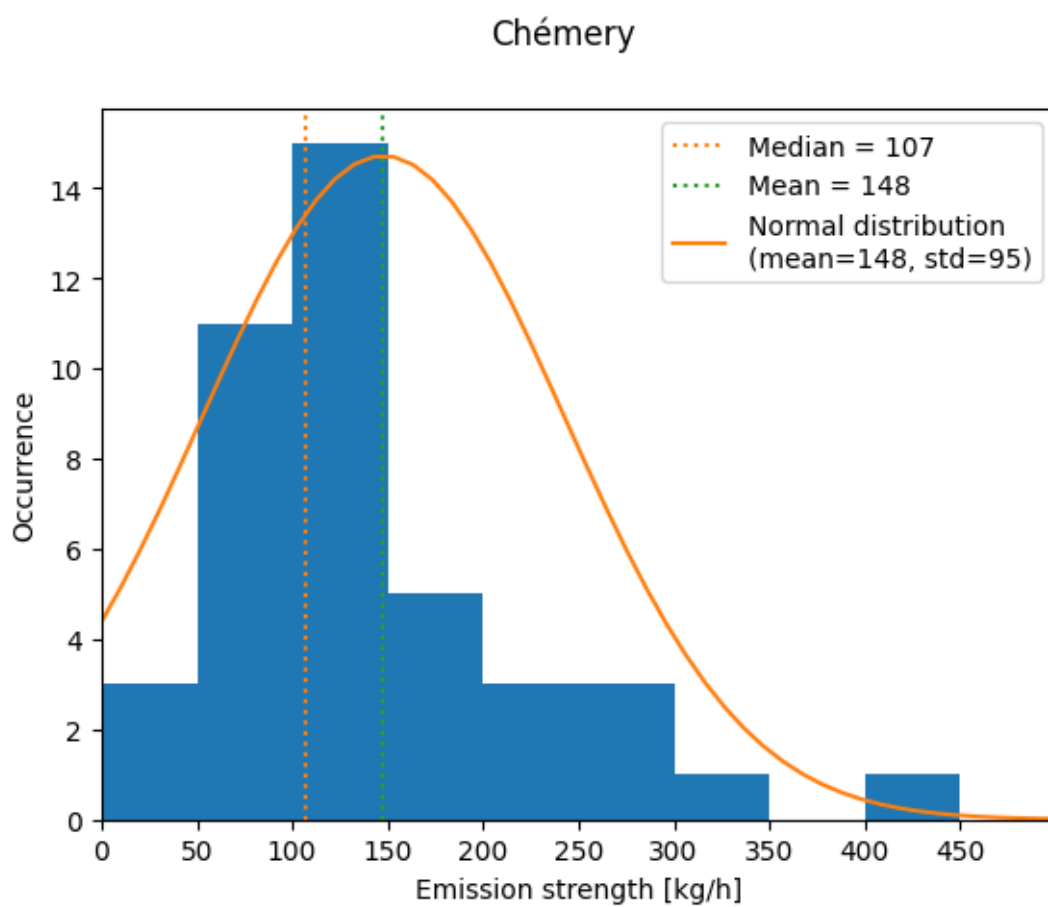


Figure 4-25 Distribution of emission strength (kg/h) from the all twenty-one measured plumes at Chémery.

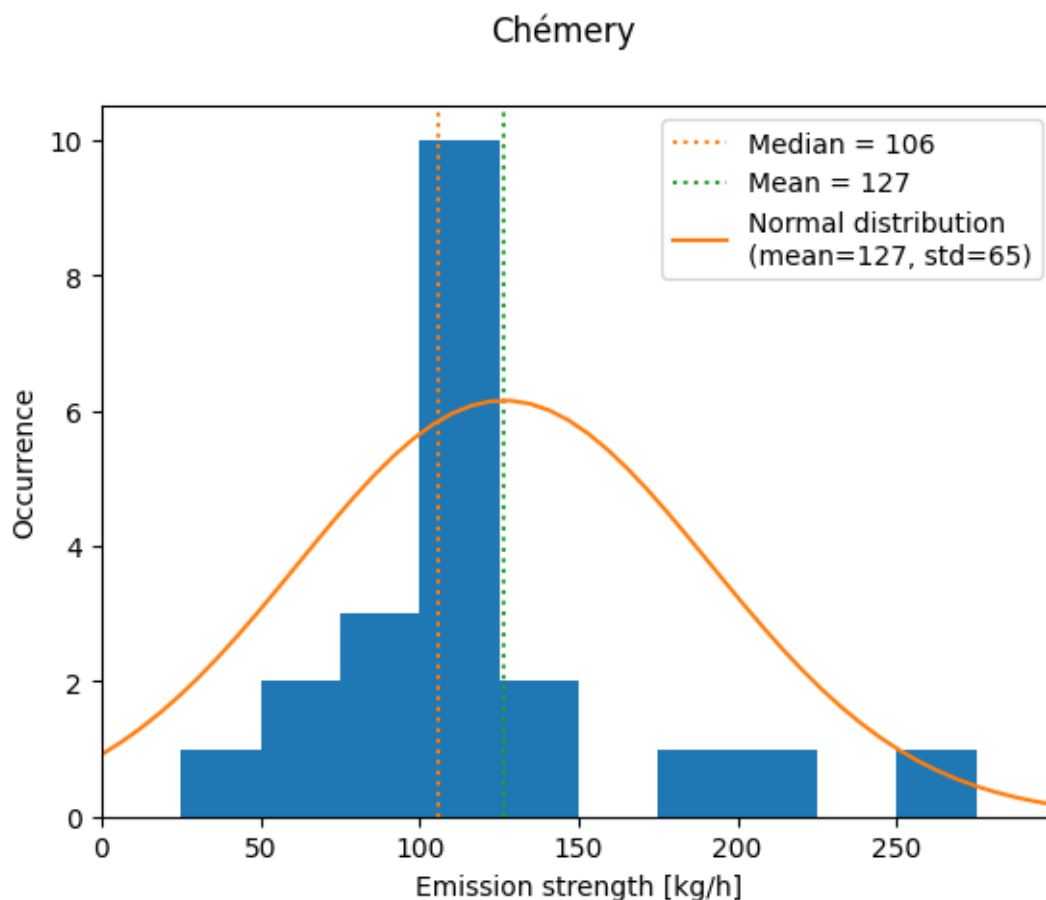


Figure 4-26 Distribution of emission strength (kg/h) from the measured plumes with stability class B at Chémery

The emission rate of CH_4 calculated from the model follows the same pattern as the area under (integral) from the measured plumes (Figure 4-27), except for the middle part. There the wind speed was increasing. It was expected that this should result in a better comparison. This shows that the model estimates not always follow the CH_4 concentration measurements, indicating that the parameterisation of the model is less sufficient for the middle part. The C_2H_6 integrated signal follows the CH_4 integrated signal, demonstrating thermogenic gas as the source (Figure 4-28). The $\text{C}_2\text{H}_6:\text{CH}_4$ ratio shows an increase of the ratio during the day ranging from 3.2 to 4.6% (Figure 4-29). There is not a clear explanation for this.

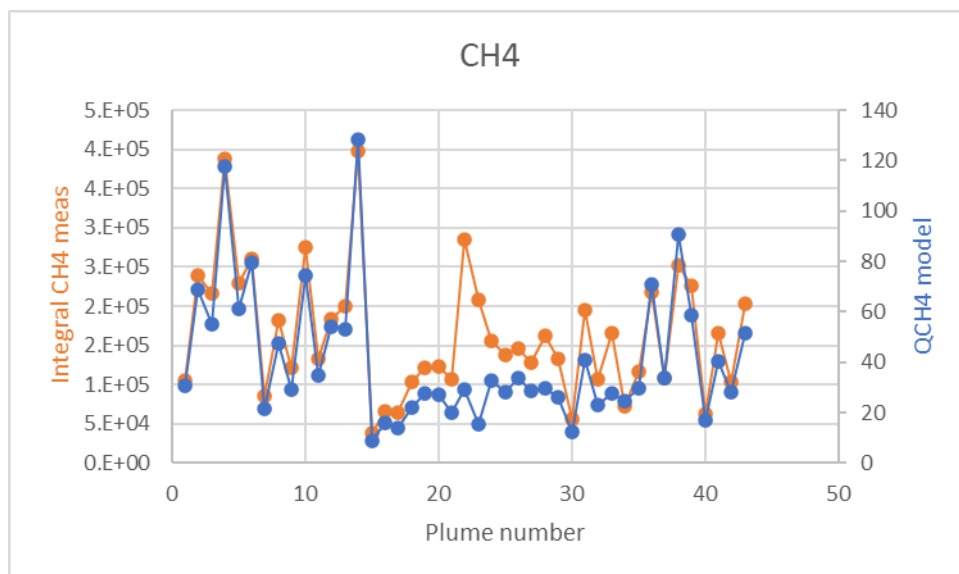


Figure 4-27 Comparison of the measured integrated signal of CH₄ with the modelled emission rate of CH₄ per plume.

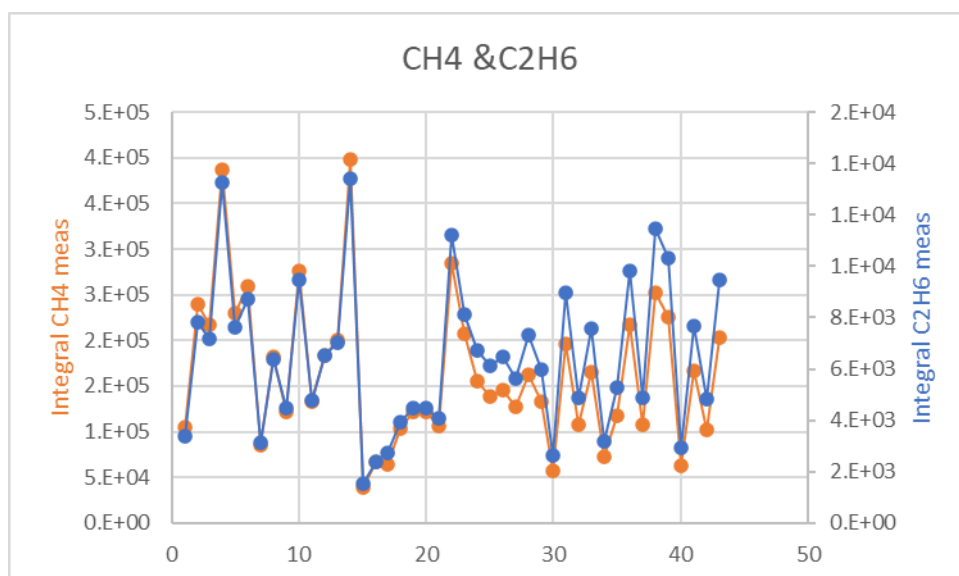
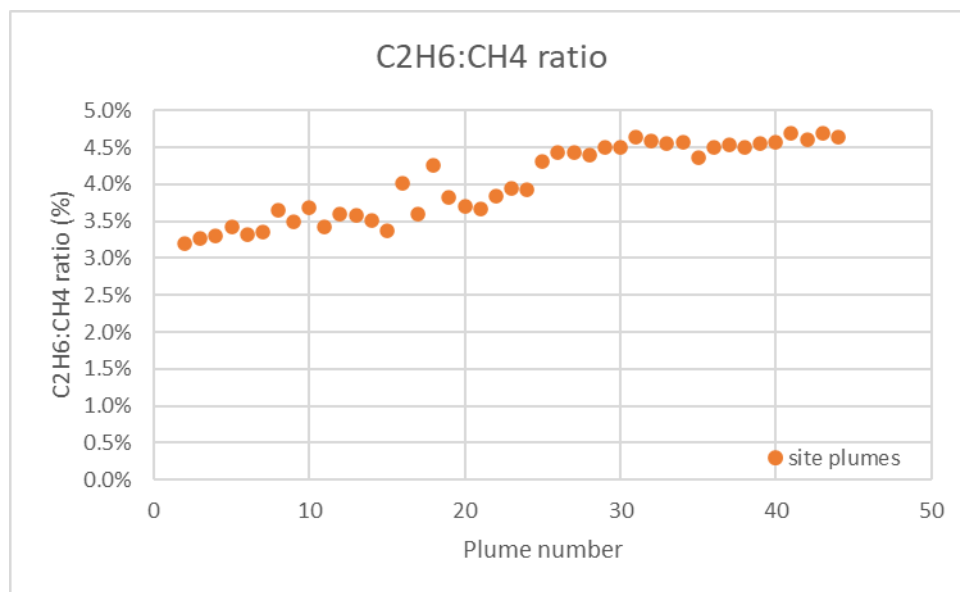


Figure 4-28 Integrated signal from CH₄ and C₂H₆ per plume.

Figure 4-29 C₂H₆:CH₄ ratio per plume.

4.4.1 The wellheads

Wellhead CS01 was passed three times within 50 m. Eastern wind was needed to measure the plumes originating from this wellhead. Two times wind conditions were unfavourable. One time, the wind conditions were favourable, with a peak height of 60 ppb. It was not possible to calculate an emission rate with a variable wind direction and a wind speed below 1 m/s. When running the model with a wind speed of 1 m/s, using stability class A, this will result in an emission estimate of 40 kg/h. From this measurement it can only be stated that there is natural gas coming from the wellhead.

Wellheads CS07 and CS41 are close to each other, separated by 114 meters. These two wellheads were passed from two directions, allowing detection of plume by western and northern winds. The wellheads were passed two times from the east, but no plumes were observed. The wellheads were passed eight times from the south. Three plumes were observed, but it is unclear from which of the two wellheads they originated. The peak height of CH₄ ranged from 40 to 260 ppb. The apparent wind direction calculated from the azimuth between the wellhead and the peak plume suggest that CS41 is more likely. Furthermore, all three times a bimodal distribution was identified, suggesting that the plumes originate from two distinct sources. Possible mixing of the upwind wellheads (CS42, CS88) occurred. It was not possible to calculate an emission rate with a variable wind direction and a wind speed below 1 m/s. When running the model with a wind speed of 1 m/s, using stability class A, this will result in an emission estimate of 240 kg/h, assuming that the plumes are from the wellhead from wellhead CS07 and 120 kg/h if the plumes are from wellhead CS41. From this measurement it can only be stated that there is natural gas coming from one of both wellheads.

Wellhead CS09 was passed six times within 50 meters. Two times a clear plume was observed with concentrations of 40 to 80 ppb. It was not possible to calculate an emission rate with a variable wind direction and a wind speed below 1 m/s. When running the model with a wind

speed of 1 m/s, using stability class A, this will result in an emission estimate of 36 +/- 6 kg/h. From this measurement it can only be stated that there is natural gas coming from the wellhead.

Wellhead CS40 was passed directly (within 40 meters) from all directions, except north. At five out of eight times that the wellhead was passed, plumes were identified with concentrations between 40 and 100 ppb. Because of the variable wind direction and wind speed below 1 m/s, the model was run with a wind speed of 1 m/s, using stability class A, resulting in an emission estimate of 20 +/- 2 kg/h. From this measurement it can only be stated that there is natural gas coming from the wellhead.

Wellhead CS13 was passed six times within 50 meters. None of these times a plume was observed. The emission rate from this wellhead is thus below the limit of detection, indicating no significant emissions.

Wellhead CS14 was passed two times within 50 m. A couple of difficulties arose when assessing the emission strength of this wellhead. First, there is a complex terrain around this wellhead. Directly south of it, a forest is present. This forest will alter wind directions in the direct vicinity. Second, the processing site is relatively close to the road. It means that with the varying wind, the results can be influenced. Third, other wellheads are directly upwind of it, most notably CS44, CS46 and CS52. The two observed plumes had a concentration of 350 and 20 ppb. It was not possible to calculate an emission rate with a variable wind direction and a wind speed below 1 m/s. When running the model with a wind speed of 1 m/s, using stability class A, this will result in an emission estimate of 1800 kg/h for the plume with a peak height of 350 ppb and 800 kg/h for the plume with a peak height of 20 ppb. These are unrealistic emission estimates. From this measurement it can only be stated that there is natural gas coming from the wellhead.

Wellhead CS21 has been passed five times at a distance of approximately 30 meters. Because wellhead CS85 is in close proximity and the variable wind conditions, it is not completely certain that observed plumes relate to wellhead CS21 or CS85. However, sometimes two plumes were observed, suggesting the attribution of plumes to the wellhead. Furthermore, the direct vicinity of wellhead CS28 to the road where the measurements were done, may cause some overestimations. At three out of five times that the wellhead was passed, plumes were identified with concentration of 25 to 300 ppb. It was not possible to calculate an emission rate with a variable wind direction and a wind speed below 1 m/s. When running the model with a wind speed of 1 m/s, using stability class A, this will result in an emission estimate for CS21 of 470 kg/h for the plume with a peak height of 300 ppb and 23 +/- 4 kg/h for the plumes with peak heights of 25 to 50 ppb. For CS85 an emission estimate of 400 kg/h for the plume with a peak height of 160 ppb and 50 +/- 15 kg/h for the plumes with peak heights of 25 to 70 ppb. These are unrealistic emission estimates. From this measurement it can only be stated that there is natural gas coming from the wellhead.

At wellheads CS37 and CS39 no plumes were found. They were passed four times. At wellhead CS32 a small plume was found, but it was not clear that it originated from CS32. Also at wellhead CS47, no plumes were seen, although the area was passed four times. The emission rates from these wellheads were thus below the limit of detection, indicating no significant emissions.

Wellhead CS51 was passed seven times. Only three times a clear plume structure was observed. Their CH₄ concentration levels were between 30 and 50 ppb. It was not possible to calculate an emission rate with a variable wind direction and a wind speed below 1 m/s.

Wellhead CS52 was passed several times. On multiple occasions clear plumes were identified. Concentrations up to 200 and 6.6 ppb of CH_4 and C_2H_6 , respectively, were found. Hence, the ratio is 3.3%, suggesting that the plume originates from a wellhead. It was not possible to calculate an emission rate with a variable wind direction and a wind speed below 1 m/s. When running the model with a wind speed of 1 m/s, using stability class A, this will result in an emission estimate of 350 kg/h. This is an unrealistic emission estimate. From this measurement it can only be stated that there is natural gas coming from the wellhead.

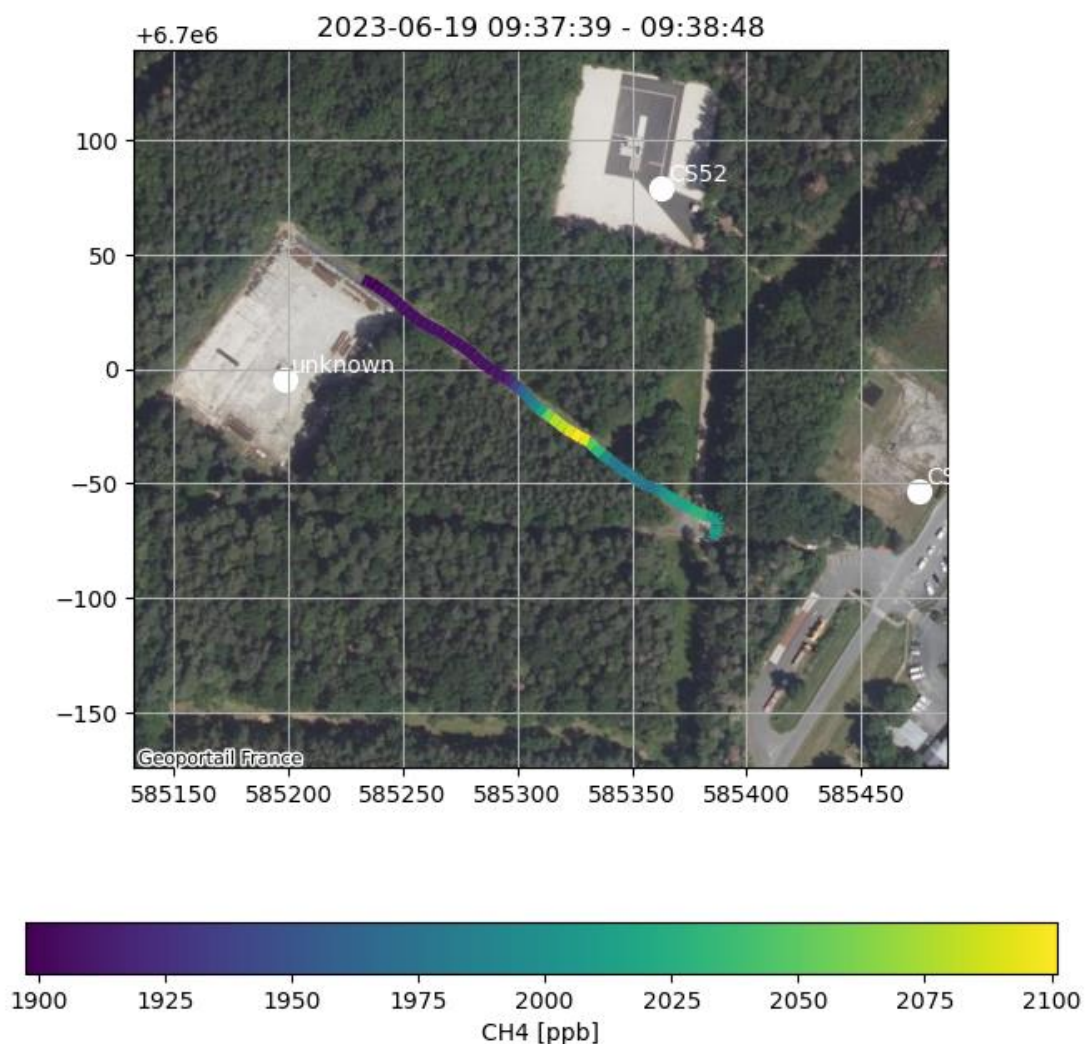


Figure 4-30. Example of measured plume at CS52.

Wellhead CS70 was passed two times in the southern and two times in the north-eastern direction. None of these times a plume was observed, indicating no significant emissions.

Wellhead CS83 was passed four times. At three passes, two plumes were observed in the direct vicinity of each other. At the last pass, no plumes were detected. The plume concentrations were rather low, the highest peak was 2 ppb of CH_4 . It was not possible to calculate an emission rate with a variable wind direction and a wind speed below 1 m/s. From this observation, it can be said that the emission rate is below the detection limit.

At wellheads CS86 and CS89 no plumes were found. They were passed two and four times respectively, indicating no significant emissions.

Wellheads CS87 and CS90 show complex plumes. Four passes were performed. In the first two passes, a build-up of CH_4 and C_2H_6 was observed, with a $\text{C}_2\text{H}_6:\text{CH}_4$ ratio of 3.0%. Three distinct plumes could be identified (see Figure 4-31). In the afternoon, only two plumes were observed. In all cases, a CH_4 concentration increase of at most 40 ppb and C_2H_6 concentration increase of at most 1.2 ppb were observed. Because of the unstable wind conditions and the complex plumes, it was not possible to calculate an emission estimate for these wellheads. It cannot be guaranteed that there is no emission from these wellheads, as CH_4 enhancements were shown.

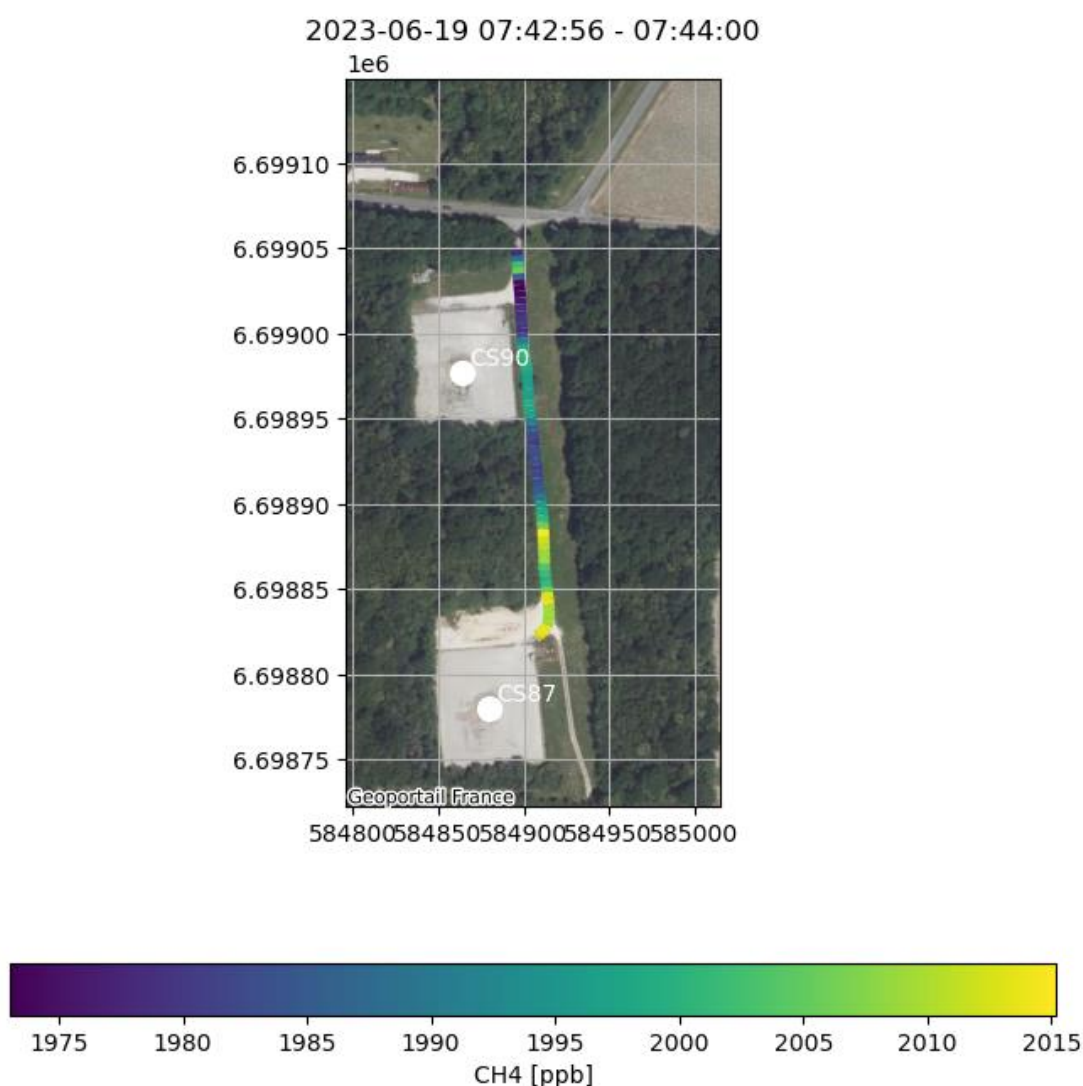


Figure 4-31 Example of CH_4 plumes next to wellheads CS90 and CS87.

Wellheads CS91, CS92, and CS93 are located in the direct vicinity of each other and covered well within the forest. In Figure 4-32 we present an image showing where plumes were observed. The wellheads were passed ten times, at CS92 four plumes were observed with CH_4

concentrations between 15 and 85 ppb. At CS93 three plumes were observed with CH₄ concentrations between 15 and 100 ppb. At CS91 no plumes were observed, resulting in an emission rate below the limit of detection, but it is difficult to distinguish between CS91, CS92 and CS93, because of the low wind speed and the forest area. It was not possible to calculate an emission rate with a variable wind direction and a wind speed below 1 m/s. When running the model with a wind speed of 1 m/s, using stability class A, this will result in an emission estimate of 35 +/- 12 kg/h for CS92 and 70 +/- 25 kg/h for CS93. From this measurement is can only be stated that there is natural gas coming from the wellheads.



Figure 4-32 Image of the wellheads and where the plumes were observed. The orange small dots indicate the tracks driven by the measurement truck at 2023-06-19 (each dot represent the position of the vehicle for a specific second). The red large dots indicate the locations where a clear plume was observed.

At wellheads CS94 and CS95 no plumes were observed. For wellhead CS94 the wind was from an unfavourable wind direction. Therefore, it cannot be guaranteed that there is no emission. For wellhead CS95 no plumes were observed, which should be detected with the given wind direction, indicating no significant emissions.

Wellhead CS96, CS97, and CS98 were passed four times. Multiple plumes were observed. It was not possible to estimate a reliable emission strength, since from the shape of the peak a build-up of CH₄ occurred between the trees. Also, elevated levels of N₂O were observed, suggesting that there may be other origins of the CH₄ gas or originated from the measurement truck. In general, the found ratio C₂H₆:CH₄ was rather low (<3%). These data do not guarantee that there is no emission, but it was not possible to calculate an emission rate with a variable wind direction and a wind speed below 1 m/s.

Table 4-2 Overview of wellhead results from the Chemery aera, using wind speed of 1 m/s and stability class A as model input for the CH₄ emission estimation.

Wellhead	Passes	Plumes Observed	CH ₄ concentration (ppb) ¹	CH ₄ emission estimate [kg/h]	Remarks
CS01	3	1	60	40	C ₂ H ₆ :CH ₄ ratio 3.6%
CS07	10	3	40 - 260	240 ²	C ₂ H ₆ :CH ₄ ratio 4.3%
CS41	10	3	40 - 260	120 ²	C ₂ H ₆ :CH ₄ ratio 4.3%
CS09	6	2	40 - 80	36 +/- 6	C ₂ H ₆ :CH ₄ ratio 3.1%
CS40	8	5	40 - 100	20 +/- 2	C ₂ H ₆ :CH ₄ ratio 4.1%
CS13	6	0		<DL	-
CS14	2	2	20 - 300	800-2800 ³	C ₂ H ₆ :CH ₄ ratio 3.1%
CS21	5	3	25 - 50	23 +/- 4 ⁴	C ₂ H ₆ :CH ₄ ratio 3.4%
CS85	5	3	25 - 70	50 +/- 15 ⁴	C ₂ H ₆ :CH ₄ ratio 3.2%
CS32	4	0		<DL	-
CS37	4	0		<DL	-
CS39	4	0		<DL	-
CS47	4	0		<DL	-
CS51	7	3	30 - 50	ND	C ₂ H ₆ :CH ₄ ratio 3.7%
CS52	5	1	200	350	C ₂ H ₆ :CH ₄ ratio 3.3%
CS70	2	0	-	<DL	-
CS83	4	3		<DL	-
CS86	2	0	-	<DL	-
CS89	4	0	-	<DL	-
CS87	4	4	40	<DL	C ₂ H ₆ :CH ₄ ratio 3.0%
CS90	4	4	40	<DL	C ₂ H ₆ :CH ₄ ratio 3.0%
CS91 ⁵	10	10	-	<DL	-
CS92 ⁵	10	4	15 - 85	35 +/- 12	C ₂ H ₆ :CH ₄ ratio 3.5%
CS93 ⁵	10	3	15 - 100	70 +/- 25	C ₂ H ₆ :CH ₄ ratio 3.2%
CS94	2	0	-	<DL	Not right wind direction
CS95	2	0	-	<DL	No plumes detected
CS96 ⁶	4	4		ND ⁷	C ₂ H ₆ :CH ₄ ratio <3%
CS97 ⁶	4	4		ND	C ₂ H ₆ :CH ₄ ratio <3%
CS98 ⁶	4	4		ND	C ₂ H ₆ :CH ₄ ratio <3%

¹ maximum height of the measured plume; if multiple plumes, than the lowest and highest concentration is noted.

² Not clear if the emissions are from CS07 or CS41, furthermore, wellheads CS42 and CS88 further upwind, could also add to the total emission.

³ Complex terrain, very close to processing site, upwind wellheads, CS44, CS46 and CS52

⁴ CS21 and CS85 are close to each other, so difficult to separate and CS28 is also close and may cause so overestimation.

⁵ Difficult to distinguish between CS91, CS92 and CS93, because of the low wind speed and the forest area.

⁶ Plumes have relative low C₂H₆:CH₄ ratio, indicating other sources of CH₄. Unable to calculate emission rates because build-up of the peaks.

⁷ ND is not determined

5 Conclusions and outlook

Emission measurements from the four sites Germigny-sous-Coulomb, Montoir de Bretagne, Prinquiau and Chémery were performed in June 2023. The emission estimates based on the measurement days were presented in this report. An overview of the results is given in Table 5-1.

The Germigny-sous-Coulomb site has an overall CH₄ emission estimate of 17 +/- 1.6 kg/h. The manure heap next to the site made it challenging to do the emission calculations. The wellhead measurements were also difficult because of the very low and variable wind, resulting in poor estimates.

The Montoir de Bretagne site has an overall CH₄ emission of 155 +/- 12 kg/h. This is including the bio-LNG source at the site (54 +/- 3 kg/h).

The Prinquiau site has an overall CH₄ emission of 0.6 +/- 0.1 kg/h.

The Chémery site has an overall CH₄ emission of 98 +/- 8 kg/h. Interestingly the C₂H₆:CH₄ ratio shows an increase during the day. From the measurements, there is no explanation for this.

Germigny sous Coulomb was good to measure with the given wind direction and wind speed. The manure heap made it challenging to make emission estimates. Montoir de Bretagne was also good to measure, but was more difficult than Germigny sour Coulomb. This was because of another source without C₂H₆ which was coming from bio-LNG and the lower wind speed (around 2.5 m/s) and shift of wind direction. Prinquiau was easier to measure because the site was smaller than the other sites, but the low wind speed (around 1.2 m/s) made it more difficult. The south to south-east wind direction made it possible to measure, other wind directions makes it harder to quantify. The Chémery site was also good to measure, but the low wind speed at the beginning and end of the day resulted in higher uncertainty in the CH₄ estimate. Besides that, the wellhead at the site and close to the site, made it hard to separate from the site itself. Overall, the selected sites were diverse, but all suitable for the measurements.

The measurements of the wellheads are under appropriate circumstances good to measure. The extra time reserved for the sites was now used to measure wellheads, but because of the low and variable wind, quantification was challenging. Where plumes were detected, the plume model was used with a wind speed of 1 m/s and stability class A as model input to give an emission estimate. However, due to unfavorable conditions, the uncertainty of these estimates is relatively high. In some cases, it was possible to verify that the emissions were below the limit of detection. More time for the measurements of the wellheads under more stable meteorological circumstances (stable wind direction with a wind speed > 2 m/s) is recommended.

Table 5-1 Overview of the emissions rates of the four sites.

Site	# plumes	Emission (kg/h)	C ₂ H ₆ :CH ₄ ratio
Germigny	28	17 +/- 1.6	3.6%

Montoir	17	155 +/- 12	1.9% (3.0%*)
Prinquiau	34	0.6 +/- 0.1	2.7%
Chémery	43 (12)	98 +/- 8	3.2-4.6%

*excluding the bio-LNG

Table 5-2 Overview of the emission estimates of the wellhead at Germigny sous Coulomb.

Wellhead	# plumes	Emission (kg/h)	C ₂ H ₆ :CH ₄ ratio
CR03	1	-	0.3
CR13	3	-	0.8
CR24	3	-	0.8
CR14	0	< LOD	-
CR19	2	ND	-
CR27	0	< LOD	-
CR28	0	< LOD	-
CR31	0	< LOD	-
CR32	0	< LOD	-
CR22	0	< LOD	-
CR33	0	< LOD	-
CR38	0	< LOD	-
CR42	0	< LOD	-
CR39	0	< LOD	-
PM8	8	59 +/- 12	3.5%

*LOD = Limit of Detection

Table 5-3 Overview of the emission estimates of the wellhead at Chémery.

Wellhead	# plumes	Emission (kg/h)	C ₂ H ₆ :CH ₄ ratio
CS01	1	40	3.6%
CS07	3	240 ¹	4.3%
CS41	3	120 ¹	4.3%
CS09	2	36 +/- 6	3.1%
CS40	5	20 +/- 2	4.1%
CS13	0	<DL	-
CS14	2	800-2800 ²	3.1%
CS21	3	23 +/- 4 ³	3.4%
CS85	3	50 +/- 15 ³	3.2%
CS32	0	<DL	-
CS37	0	<DL	-
CS38	0	<DL	-
CS47	0	<DL	-

CS51	3	ND	3.7%
CS52	1	350	3.3%
CS70	0	<DL	-
CS83	3	<DL	-
CS86	0	<DL	-
CS89	0	<DL	-
CS87	4	<DL	3.0%
CS90	4	<DL	3.0%
CS91 ⁴	10	<DL	-
CS92 ⁴	4	35 +/- 12	3.5%
CS93 ⁴	3	70 +/- 25	3.2%
CS94	0	<DL	
CS95	0	<DL	
CS96 ⁵	4	ND	<3%
CS97 ⁵	4	ND	<3%
CS98 ⁵	4	ND	<3%

¹ Not clear if the emissions are from CS07 or CS41, furthermore, wellheads CS42 and CS88 further upwind, could also add to the total emission.

² Complex terrain, very close to processing site, upwind wellheads, CS44, CS46 and CS52

³ CS21 and CS85 are close to each other, so difficult to separate and CS28 is also close and may cause so overestimation.

⁴ Difficult to distinguish between CS91, CS92 and CS93, because of the low wind speed and the forest area.

⁵ Plumes have relative low C₂H₆:CH₄ ratio, indicating other sources of CH₄. Unable to calculate emission rates because build-up of the peaks.

To have a better understanding of the emission strength over the year, a second measurement campaign is recommended. When different activities occur at the site throughout the year, it is recommended to have measurements during the different activities. For better emission estimates of the wellhead, more time, more and stable wind and one or two tracer release experiments per day are recommended.

For future methane emission reduction and measurement regulation, more research and innovation of the current approach is needed to speed up the measurement and data analyses and reduce the costs. With this approach, the emission quantification can be standardized to compare emission estimated for different sources.

References

Czepiel, P. M., Mosher, B. J., Harriss, C. J., Shorter, J. H., McManus, J. B., Kolb, C. E., Allewine, E. and Lamb, B. K., 1996. Landfill methane emissions measured by enclosure and atmospheric tracer methods, *J. Geophys Res.* **101**, 16711-16719

Fredenslund, A.M., Rees-White, T.C., Beaven, R.P., Delre, A., Finlayson, A., Helmore, J., Allen, G., Scheutz, C., 2019. Validation and error assessment of the mobile tracer gas dispersion method for measurement of fugitive emissions from area sources. *Waste Management*, **83**: 68-78

Hensen, A. and Scharff, H., 2001. Methane emission estimates from landfills obtained with dynamic plume measurements. *Water Air Soil Pollut.* **1** 455-64 (Focus)

Hensen, A., 2012. Methods for observation and quantification of trace gas emissions from diffuse sources. *PhD Thesis* VU Amsterdam

Hensen, A., Velzeboer, I., Dinther, D. van, Bulk, W.C.M. van den, Frumau, K.F.A., 2018. Berekening van methaanemissies van een geselecteerd aantal actieve gaswinningslocaties voor Staatstoezicht op de Mijnen. TNO 2019 R10332, TNO Petten.

Hensen, A., Velzeboer, I., Frumau, K.F.A., Bulk, W.C.M. van den, Dinther, D. van, 2019. Methane emission measurements of offshore oil and gas platforms. TNO report R10895, TNO Petten.

Lopez, C., Fabre, J., 2021. Overall quantification of a site's methane emissions – State of the art on “Top Down” methodologies. RICE.PACG_GERG

Luetschwager, E., von Fischer, J. C., Weller, Z. D., Characterizing detection probabilities of advanced mobile leak surveys: Implications for sampling effort and leak size estimation in natural gas distribution systems. *Elementa: Science of the Anthropocene*, **9** (1): 00143. <https://doi.org/10.1525/elementa.2020.00143>, 2021.

Maazallahi, H., Delre, A., Scheutz, C., Fredenslund, A. M., Schwietzke, S., Denier van der Gon, H., and Röckmann, T.: Intercomparison of detection and quantification methods for methane emissions from the natural gas distribution network in Hamburg, Germany, *Atmos. Meas. Tech. Discuss.* [preprint], <https://doi.org/10.5194/amt-2022-134>, in review, 2022.

Savanne D., Arnaud A., Beneito A., Berne P., Burkhalter R., Cellier P., Gonze M.A., Laville P., Levy F., Milward R., Pokryszka Z., Sabroux J.C., Tauziede C., Tregoures A., 1997. Comparison of different methods for measuring landfill methane emissions. Sardinia '97 *Sixth International Landfill Symposium*. **Vol. IV**: 81-85.

Energy & Materials Transition

Westerduinweg 3
1755 LE Petten
www.tno.nl