Landfill Methane Emission Measurements 2022 - 2023

TNO Public ⟩ TNO 2023 R11711
27 February 2024

Energy & Materials Transition
www.tno.nl
+31 88 866 50 65
info@tno.nl

TNO 2023 R11711 – 27 February 2024

Landfill Methane Emission Measurements 2022 - 2023

Author(s)	Velzeboer I., Zhang J., Van de Bulk W.C.M., Hensen A.
Classification report	TNO Public
Title	TNO Public
Report text	TNO Public
Number of pages	38 (excl. front and back cover)
Number of appendices	0
Sponsor	Afvalzorg NV
Project name	Afvalzorg
Project number	060.52913

Contents

1 Introduction

Methane emissions from landfills form an important part of the Dutch non-CO_2 greenhouse gas emissions. Afvalzorg operates a number of landfill sites in North Holland and Flevoland. In 1997, ECN and Afvalzorg carried out the first joint research to quantify methane emissions at the Nauerna landfill, with the mobile measurement techniques and the atmospheric dispersion modeling approach and several campaigns were carried out after that until 2009. Many operators now extract gas from the waste material in landfills. And the prediction of the amount of produced gas is based on gas generation models. The main reason to commission new measurements to quantify the total emissions at three operational landfills is find out why the gas production models and actual gas extraction levels do not always match. Measurements were carried out at Nauerna (NAU; Assendelft), Zeeasterweg (ZEE; Lelystad), and Wieringermeer (WIE; Midddenmeer).

The laser spectrometers used for the new experiments are significantly better compared with the one's used in the previous campaigns (1997-2010). This means we can detect things now that we were unable to see before. This makes the set of measurement presented here extra relevant. The report contains the field measurement campaigns' results at three Dutch landfills in autumn 2022. To distinguish landfill emissions from those of adjacent sources like natural gas distribution stations and agricultural fields, concentrations of other atmospheric gases (CO, CO_2, and C_2H_6) were measured simultaneously to the concentrations of CH_4 and N_2O at 1-Hz intervals using a laser spectrometer in a mobile truck driving downwind of each landfill. Emission estimates were obtained both using a Gaussian dispersion model and with the Mobile Tracer Dispersion Method (MTDM). The emission levels of CH_4 (and N_2O if it is above the detection limit) were determined. The study demonstrates that landfill emissions can be distinguished from other sources in close proximity, thereby contributing to a better understanding of non-CO_2 greenhouse gases emitted from landfills and enabling better landfill emission inventories in the Netherlands.

To fully evaluate the recovery system function under different seasons in various landfills, the measurement will be performed in fall 2022 and spring 2023 and compare it to the previous results generated in the 1990's.

2 Experimental procedure

Three mobile campaigns with tracer release experiments were conducted at the three landfills in September and October 2022. In the following year, 2023, the same landfills were measured again in May (NAU), July (ZEE) and August (WIE) respectively to better evaluate their seasonal CH_4 emission patterns. All listed measurement time in the report is in UTC time (equals local time – 2 hours).

2.1 Mobile plume measurement with the TILDAS laser spectrometer

The plume measurement method was already used in the nineties to evaluate emissions from the Nauerna (Hensen & Scharff, 2001) and other landfill locations (Czepiel et al. 1996, Savanne et al. 1997). The methodology we use now is still the same, the instruments however have improved significantly. During the measurement campaign, the CH_4 concentration was measured with a laser spectrometer, located in a truck that drives a transect through the plume downwind of the landfill. The concentration measurements were performed using Tunable Infrared Laser Direct Absorption Spectroscopy (TILDAS). In these three campaigns, a TILDAS *dual* laser trace gas analyzer (Aerodyne Research, Inc. Billerica, USA) was used, which enables the simultaneous measurement of multiple species (CH_4, C_2H_6, N_2O, CO, CO_2, H_2O). This system has a precision of 2.4, 0.1, 0.1, 386.3 and 2.5 ppb for CH_4, C_2H_6, N_2O, CO_2 and CO respectively. In addition, instrument calibrations were conducted at the start and end of the measurement campaigns, with calibration gases measured against WMO certified standards at the Cabauw tall tower. Ambient air is sampled from the top of the truck. A plume-transect takes 2-7 minutes, depending on the distance and size of the source; 1Hz sampling frequency was applied to observe detailed concentration patterns on the measurement transect. The position of the truck was obtained using a GPS system. The measured concentrations in the plume transect are compared with the output of the Gaussian plume model described below (Hensen, 2012).

When measuring, the truck driving speed is relatively low, on average at 50 km/h (if possible on a provincial road). The mobile truck's driving path was selected depending on the actual wind direction on the measurement day and source area location. Depending on the site the truck was driving on a road located at *ca.* 200-1000 meters downwind of the source area to best capture the N_2O tracer and other greenhouse gases.

The emission strength of the landfill is equal to the source strength needed in the model to get an agreement between the integral of the concentration along the measurement transect for the modelled and the measured plume. The meteorological data (wind speed, wind direction) used by the model were obtained with a 3D sonic anemometer (20Hz sampling frequency), which was placed on top of the landfill soil landfill at a location free of obstacles.

To apply the mobile tracer dispersion method (MTDM), N_2O was released from a gas cylinder located at the landfill. The uncertainty in the N_2O and CH_4 concentration measurements is 1-5% due to instrument noise, drift of the laser and uncertainty in the background concentration level. The changes in wind direction and speed (on a timescale of 5-10 minutes) are the main cause for variation within the set of emission estimates. Furthermore the emission of the landfill site is not constant in time. Apart from this the concentration in the atmosphere downwind of the landfill changes due to differences in meteorological parameters (windspeed, 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. This was determined with the Gaussian Dispersion model (Hensen & Scharff, 2001).

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

$$Emission\ (source) = Emission\ (tracer\ \ ) \cdot \frac{Concentration\ (plume\ source)}{Concentration\ (plume\ tracer)} \quad (1)$$

Here, $Emission\ (source)$ refers to the source emission (unit in g/s); $Emission\ (tracer\ \ )$ is the total emission from the tracer N_2O in each releasing period (unit in g/s); $Concentration\ (plume\ source)$ refers to the total area of the plume (integral) after removing background value (unit in ppb); $Concentration\ (plume\ tracer)$ refers to the measured plume from the landfill area where the tracer experiment was conducted, after removing background value (unit in ppb). This was done using the Gaussian Dispersion model (Hensen & Scharff, 2001)

The uncertainties of the reported emission rates, are presented as an average +/- standard error from the selected plume measurements. Here, the standard deviation is divided by the square root of the measured plumes.

3 Study areas

3.1 The Nauerna site (NAU)

The Nauerna landfill in Assendelft is located at the north side of the Noordzeekanaal (Figure 1). This location also hosts the company's head office. The landfill opened in 1985 and landfilling operation ended in April 2022, but the site is still a source of CH_4. The total surface is 75 hectares, of which 60 hectares are now phase-wise turned into a recreation park. The remainder 15 hectares is an industrial site, where Afvalzorg and other companies are located.

The waste landfilled at Nauerna has a high inorganic content as the main waste stream, including asbestos, contaminated soil and sludges. In recent years the landfill gas extraction system has been improved and intensified with the drilling of new vertical wells and the construction of horizontal landfill gas extraction fields. Construction is expected to be finished in 2024. Afvalzorg has also his own wastewater treatment plant (WWTP).

Methane generation prediction using the Afvalzorg Multiphase Model shows an average production of 235 kgCH_4/h in 2022 and 212 kgCH_4/h in 2023 (up to November 1th). In 2022, the 3-day average recovery prior to the measurements was 52 kgCH_4/h. In 2023, the 3-day average recovery prior to the measurements was 162 kgCH_4/h.

The landfill gas that is recovered is either flared in one of two flares or utilized in boilers. The resulting hot water is used to heat and cool the offices on site and is transported to a nearby greenhouse gas complex. In addition, a leachate treatment facility is present, operated by Afvalzorg.

Figure 1 Google Earth image of the Nauerna site including the tracer release locations (yellow pins for 2022, blue pins for 2023). The yellow circle shows the landfill part, the orange triangle shows the part with the other companies on the site, the blue square represents the WWTP.

Specific for the first measurement day (27 October 2022), the landfill gas installation was switched off at the time of the measurements, making this measurement not representative for comparison. On the second measurement day (26 May 2023) the installation was operational, to be representative measurement.

Two N_2O tracer release experiments were conducted at the landfill area during the mobile measurements on October 27, 2022. Tracer release cylinders (cylinder #8 and cylinder #7) were placed separately on the landfill in two different measurement periods and locations. One was released in the morning, and the other one was released in the afternoon, respectively (see Google Earth image in Figure 1). Two different locations were chosen to test the differences in dispersion caused by the chosen locations.

- Episode 1: Trace release experiment Nr.1 using N_2O cylinder #8 (between 08:30 – 10:00, measured plumes from #1 to #13, tracer release rate is 0.41 g/s)
- Episode 2: Tracer release experiment Nr. 2 using N_2O cylinder #7 (between 10:45 – 12:15, measured plumes from #14 to #30, tracer release rate is 0.58 g/s)

On 26th May 2023, the Nauerna landfill was measured again using two tracer releases. The first tracer release was located at the same spot as it was last year, in the middle of the landfill. The 2nd tracer release was placed in the southern edge of the landfill. The detailed release rates and time periods were:

- Episode 1: Trace release experiment Nr.1 using N_2O cylinder #9 (between 09:22 – 10:32, measured plumes from #3 to #26, tracer release rate was 0.41 g/s)
- Episode 2: Tracer release experiment Nr.2 using N_2O cylinder #12 (between 12:11 – 12:57, measured plumes from #27 to #40, tracer release rate was 0.78 g/s)

3.2 The Zeeasterweg site (ZEE)

The Zeeasterweg landfill is located near Lelystad in the Flevopolder (Figure 2). The site opened in 1980 and was operated between 1980 – 1984 and 1993 – 1995. In 1996, Afvalzorg acquired this site and the landfilling started again since 2005 until now. The main waste streams are asbestos, soil recycling residue and shredder waste, with small amounts of other waste types as well.

When Afvalzorg acquired the location, several waste compartments were present. All but one have been reconstructed up to modern standards. This does mean that older waste has been picked up, mixed and aerated, introducing a challenge in the modelling of the methane generation of this waste.

Landfill gas extraction systems are present on four out of five compartments that are or have been operational. Two of the compartments have a layer of immobilised incinerator bottom ash aggregate (IBAA) on top, which improves the landfill gas recovery in addition to providing extra surface for recycling or storage activities. The landfill gas recovery systems consists of a mix of vertical wells and horizontal fields. The recovery landfill gas is flared in a 2.5 MW flare which has the option to utilisation using a heat exchanger on the flare pipe. This heat is used to warm up leachate before entering the leachate treatment facility.

Methane generation prediction using the Afvalzorg Multiphase Model shows an average production of 103 kgCH_4/h in 2022 and 131 kgCH_4/h in 2023 (up to November 1th). The 3-day average recovery prior to the measurements of 63 m^3 kgCH_4/h. In 2023, the 3-day average recovery prior to the measurements was 78 kgCH_4/h.

On the site two other companies are present: HVC with a municipal recycling facility and Orgaword (part of Renewi) with a compositing facility. Furthermore, a wastewater treatment plant (WWTP) and a leachate treatment plant are also present, operated by Afvalzorg. This means that there are several sources of CH_4 and N_2O expected at the site.

Figure 2 Google Earth image of the Zeeasterweg site including the tracer release location (same location for 2022 and 2023). The purple area indicates the active landfill part while the yellow square activities started only in 2023 (not covered yet), the red square indicates Orgaworld, the orange square indicates HVC, the blue square represents the WWTP.

Two N_2O tracer release experiments were conducted at the landfill area during the mobile measurements on October 7, 2022. Release cylinders (cylinder #8 and cylinder #2) were placed at the same location on the landfill in two different measurement periods: one was given a lower release rate in the morning (to minizine N_2O emission during the measurement as much as possible) and the second one was given a higher release rate in the afternoon (for easier distinction of the release plume from the background concentrations)(see Google Earth image in Figure 2).

- Episode 1: Trace release experiment Nr.1 using N_2O cylinder #8 (between 09:20 – 10:20, measured plumes from #2 to #9, tracer release rate is 0.09 g/s)
- Episode 2: Tracer release experiment Nr. 2 using N_2O cylinder #2 (between 10:41 – 11:52, measured plumes from #10 to #28, tracer release rate is 0.32 g/s)
- Episode 3: pure source emission measurement after tracer release experiments stopped (between 13:00 – 13:15, measured plumes #29 and #30)

On July 6, 2023 the Zeeasterweg landfill was measured again with two tracer releases at the same location as last year. This measurement is not representative for annual emission calculations as in summer there is much more influence of microbial oxidation in the cover soil. The release rate was bit higher than last year to make sure proper separation between tracer signal and N_2O coming from the landfill. Release rates and time periods were:

- Episode 1: Trace release experiment Nr.1 using N_2O cylinder #10 (between 08:07 – 09:07, measured plumes from #2 to #18, tracer release rate is 0.41 g/s)
- Episode 2: Tracer release experiment Nr.2 using N_2O cylinder #11 (between 09:22 – 10:19, measured plumes from #19 to #33, tracer release rate is 0.39 g/s)
- Episode 3: pure landfill source emission measurement after tracer release experiments stopped (between 10:54 – 11:10, measured plumes from # 34 to # 38).

3.3 The Wieringermeer site (WIE)

The landfill site 'Wieringermeer' is located in Middenmeer (Figure 3). The site is shared with two other companies: HVC, a municipal recycling, a transfer facility, and a fermentation- and composting installation; and the other one is Sortiva, which focuses on green composting, transfer of household waste and sorting of plastic waste. Furthermore, Wieringermeer is one of the long-term landfill aeration pilot locations researching on Sustainable Landfill Management (Duurzaam Stortbeheer; iDS).

The landfill covers 36 hectares in two separate parts: the eastern and oldest side, which is closed, and the active western and current active side. The landfill has been in operation since 1985 and since 1997 by Afvalzorg. The main waste streams landfilled are asbestos, contaminated soil, and soil recycling residues. In early years, the main waste streams were commercial wastes, sludge, contaminated soil, and construction and demolition waste.

Landfill gas recovery has already been present in the eastern part since the early 90's. On the western side, the landfill gas extraction system has been renewed and improved in 2021. Both sides are equipped with vertical wells and horizontal fields for optimum landfill gas extraction. Two compartments, 5A and 6, have been separated from the landfill gas extraction system for the research pilot described above. For this pilot project,109 vertical wells are placed and the LFG (landfill gas) over-extraction and injection of air are taken place.

The methane generation has been calculated using the Afvalzorg Multiphase Model. In 2022 the methane generation was calculated to be 31 $kgCH_4/h$ for the eastern side, and 8 $kgCH_4/h$

for the western side. In 2023 (up to November 1th), the methane generation was calculated to be 29 $kgCH_4$/h for the eastern side, and 9 $kgCH_4$/h for the western side. For 2022, the 3-day average methane recovery prior to the measurements was 22 $kgCH_4$/h for the total side (east + west) and 4.9 $kgCH_4$/h for the west side. For 2023, the 3-day average methane recovery prior to the measurements was 24 $kgCH_4$/h for the total side (east + west) and 4.5 $kgCH_4$/h for the west side. Part of the recovered LFG is used to heat the anaerobic digestion process of HVC on-site.

The recovered gas from both the eastern and western sides is flared in two separate flares. The gas of the iDS pilot is oxidized in a biofilter, though plans exist to install a ULC flare in the near future for better CH_4 emission reduction. In addition, Afvalzorg operates a leachate treatment facility on the western side of the location.

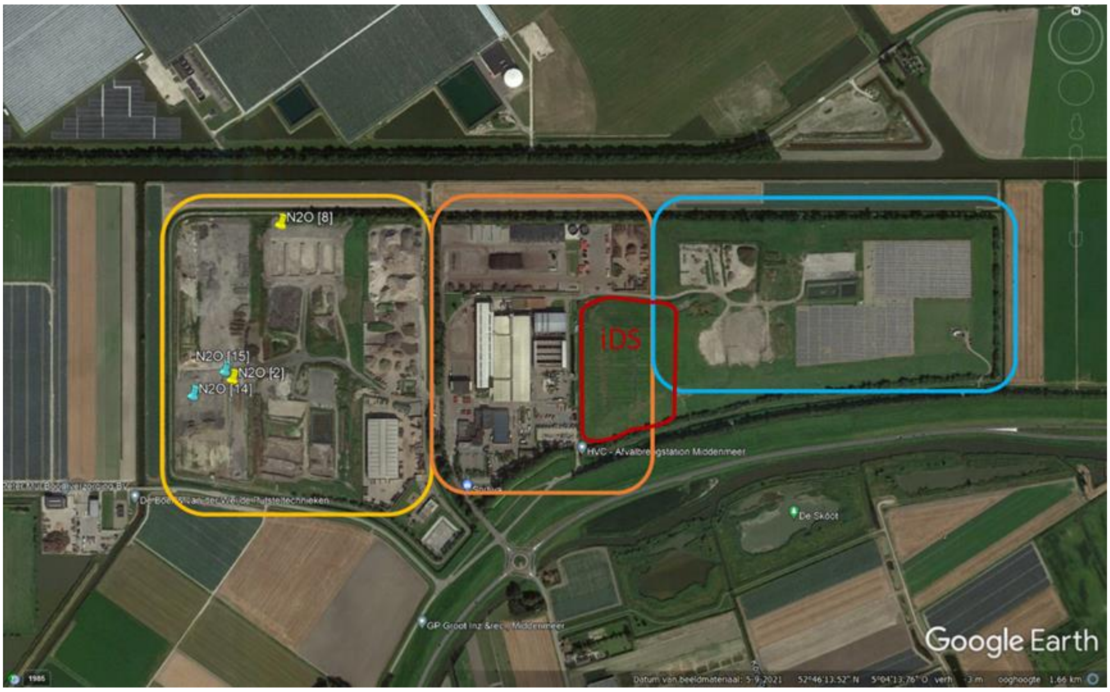


Figure 3 Google Earth image of the Wieringermeer site including the tracer release locations (yellow pins for 2022, blue pins for 2023). The yellow square shows the western still operational part of the landfill, the orange square represents the aera where HVC is active, the blue square shows the no longer operational part of the landfill. The red area indicates the iDS part.

The site is divided in three parts (Figure 3), with their own emission pattern. The eastern, no longer operational part of the landfill (400 m to the east), is partly covered, but could still be a possible source of CH_4 and N_2O. The middle part represents the HVC area, which is a known CH_4 and N_2O source as well. The western part of the site is the operational part of the landfill, which is a stronger CH_4 source.

Two N_2O tracer release experiments were conducted at the landfill area during the mobile measurements on September 30, 2022.The release cylinders (cylinder #2 and cylinder #8) were placed separately on the landfill in two different measurement periods and locations.

One was released in the morning, in the middle of the active western part of the landfill site, to have a good comparison with the dispersion of the emissions from the landfill. The other one was released in the afternoon (see Google Earth image in Figure 3) at the north site of the western landfill, close to a water pumping well. After the tracer release experiments stopped another two transects were measured downwind of the landfill to have an extra check on possible N_2O emissions from the site itself.

- Episode 1: Trace release experiment Nr.1 using N_2O cylinder #2 (between 09:37 – 11:30, measured plumes from #1 to #11, tracer release rate is 0.08 g/s)
- Episode 2: Tracer release experiment Nr. 2 using N_2O cylinder #8 (between 13:07 – 13:56, measured plumes from #12 to #15, tracer release rate is 0.09 g/s)
- Episode 3: pure source emission measurement after tracer release experiments stopped (between 14:15 – 14:30, measured plumes #16 and #17)

On August 11, 2023 the Wieringermeer landfill was measured again with two tracer releases as well. One was at the same location as the 1st tracer release in year 2022 (Figure 3). The other one was placed close to this one instead of close to the driving path for better model results (Figure 3). The release rate was enhanced to be able distinguishing the tracer signal from N_2O coming from the landfill as well. This measurement is not representative for annual emission calculations as in summer there is much more influence of microbial oxidation in the cover soil. The detailed release rates and time periods were:

- Episode 1: Trace release experiment Nr.1 using N_2O cylinder #15 (between 06:27 – 07:48, measured plumes from #2 to #18, tracer release rate is 0.40 g/s)
- Episode 2: Tracer release experiment Nr.2 using N_2O cylinder #14 (between 08:07 – 09:28, measured plumes from #19 to #33, tracer release rate is 0.58 g/s)
- Episode 3: pure landfill source emission measurement after tracer release experiments stopped (between 10:54 – 11:10, measured plumes from # 34 to # 38)

4 Results and discussion

4.1 The Nauerna site (NAU)

4.1.1 NAU 2022 campaign results

The meteorological conditions on October 27, 2022 were optimal for conducting mobile measurements, the wind direction was more or less constant (SSE wind) and the average wind speed was relatively constant at 5 m/s. It was predominantly sunny, temperature was 15^{o}C in the morning and wend up to 18^{o}C around noon. Atmospheric pressure was on average 1019 hPa (Figure 7).

The mobile measurements took place on the road (N246) on north side of the landfill. Wind was south-south-east (SSE), facilitating plume measurements on the N246. The plume measurements show an overall CH_4 emission of 23 +/- 2.1 g /s or 83 +/- 7.7 kg/h, based on an average of 30 plumes, using stability class D (neutral weather conditions) (Table 1).

In total 13 plumes were measured in the morning when the first cylinder with a release rate of 0.41 g/s was places in “the middle” of the landfill site (Figure 1). Using Equation 1, the calculated CH_4 emission was 27 +/- 2.2 g/s or 97 +/- 8.0 kg/h. When using the Gaussian Plume model a CH_4 emission of 29 +/- 2.1 g/s or 104 +/- 7.6 kg/h was estimated.

In the afternoon, 17 plumes were measured when the second cylinder with a release rate of 0.58 g/s was places on the east side of the landfill area (Figure 4). Using Equation 1, the calculated CH_4 emission was 18 +/- 1.5 g/s or 65 +/- 5.3 kg/h. When using the Gaussian Plume model a CH_4 emission of 19 +/- 1.2 g/s or 68 +/- 4.3 kg/h was estimated.

The CH_4 emissions from the landfill were higher in the morning, compared to the afternoon measurements. No significant N_2O plume from the WWTP (wastewater treatment plant) could be distinguished from the low N_2O concentrations (maximum of 2 ppb) during the measurements from the N246. However, during this campaign, before the tracer release started, we observed low-level N_2O (maximum 3 ppb after removing the background) in the middle of the landfill. A few N_2O and CH_4 peaks overlapped, which suggested these two components possibly shared the same sources from the landfill area (possibly water pumping wells or WWTP).

It was beyond the scope of this measurement campaign to measure individual water pumping well emissions.

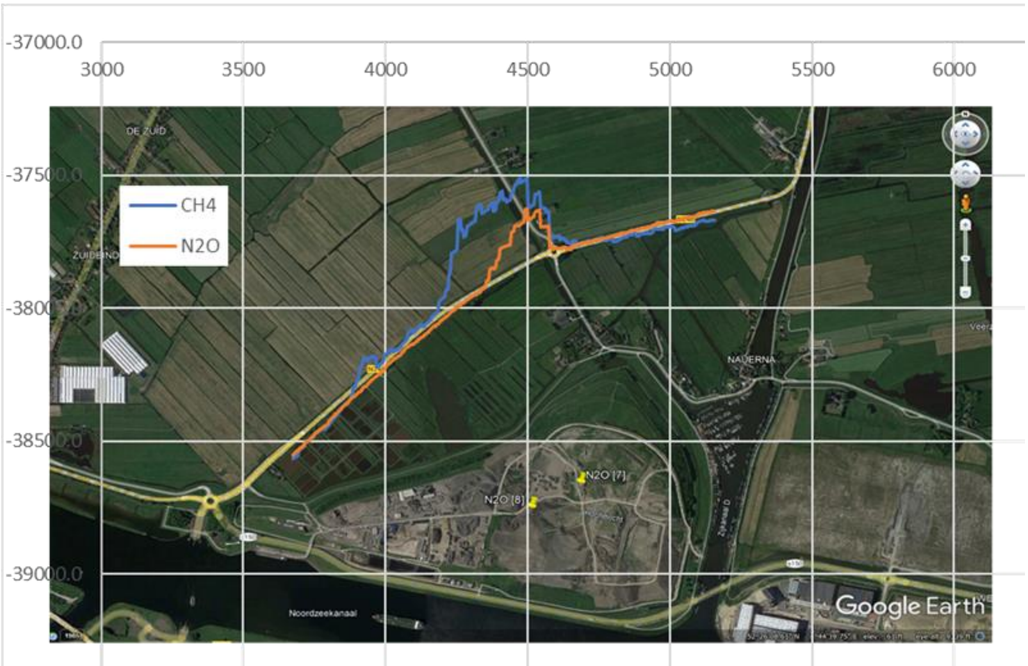


Figure 4 Overview of measured plumes during the second tracer release, showing measured CH_4 (blue) and N_2O (orange) overlapping at certain location of the landfill area.

Table 1 CH_4 Emission estimates from the Nauerna landfill in 2022.

	CH_4 emission using tracer					
plumes	avg	st.err		avg	st.err	
#1-13	27	2.2	g/s	97	8.0	kg/h
#14-30	18	1.5	g/s	65	5.3	kg/h
	CH_4 emission using model					
plumes	avg	st.err		avg	st.err	
#1-13	29	2.1	g/s	104	7.6	kg/h
#14-30	19	1.2	g/s	68	4.3	kg/h
#1-30	23	2.1	g/s	83	7.7	kg/h

4.1.2 NAU 2023 campaign results

The meteorological conditions on May 26, 2023 was suitable for plume model experiment. Both wind speed and wind direction were relatively stable. The prevailing wind direction was northeast (NE) with an average wind speed 5 m/s. It was a sunny day with a temperature of 14ºC in the morning and going up to 16ºC in the afternoon. Atmospheric pressure was on average 1032 hPa (Figure 7). The mobile truck was running on the N202 road, at the south side of the landfill, along the North see channel.

The plume measurements show an overall CH_4 emission of 5.7 +/- 0.5 g /s or 21 +/- 1.7 kg/h, based on an average of 15 plumes, using stability class C for the morning measurements, stability class B for the afternoon measurements (Table 2).

In total 24 plumes were measured in the morning when the first tracer bottle was released at 0.41 g/s in the center of the landfill (Figure 5). After data quality scanning, 9 out of 24 plumes were selected for emission evaluation. Using Equation 1, the calculated CH_4 emission was 5.8 +/- 0.7 g/s or 21 +/- 2.6 kg/h. When using the Gaussian Plume model a CH_4 emission of 5.5 +/- 0.8 g/s or 20 +/- 2.9 kg/h was estimated.

In the afternoon, 14 plumes were measured during the second tracer releasing period with a constant release rate of 0.78 g/s, emitting from the south edge of the landfill (Figure 5). After data quality scanning, 6 out of 14 plumes were selected for emission estimation. Using Equation 1, the calculated CH_4 emission was 7.8 +/- 0.8 g/s or 28 +/- 2.8 kg/h. When using the Gaussian Plume model a CH_4 emission of 5.8 +/- 0.4 g/s or 21 +/- 1.6 kg/h was estimated.

The CH_4 emissions from the landfill were slightly lower in the morning, compared to the afternoon measurements. No significant N_2O peaks from the WWTP were observed during the measurements.

Table 2 CH_4 Emission estimates from the Nauerna landfill in 2023.

	CH_4 emission using tracer					
plumes	avg	st.err		avg	st.err	
#3-26 (n=9)	5.8	0.7	g/s	21	2.6	kg/h
#27-40 (n=6)	7.8	0.8	g/s	28	2.8	kg/h
	CH_4 emission using model					
plumes	avg	st.err		avg	st.err	
#3-26 (n=9)	5.5	0.8	g/s	20	2.9	kg/h
#27-40 (n=6)	5.8	0.4	g/s	21	1.6	kg/h
#3-40 (n=15)	5.7	0.5	g/s	21	1.7	kg/h

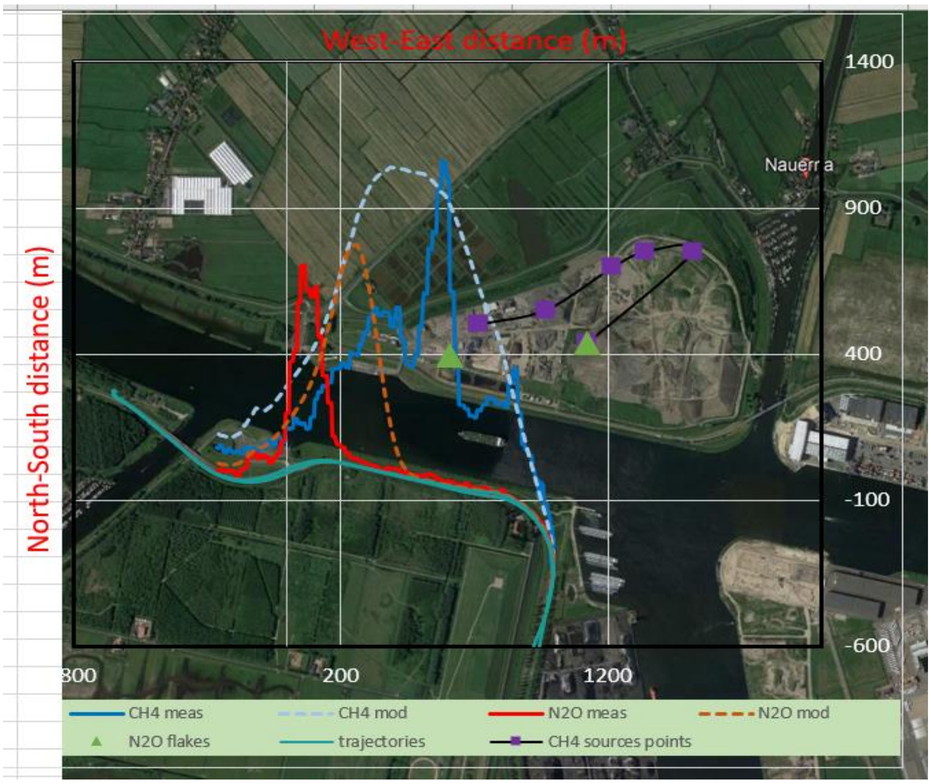


Figure 5 Nauerna landfill May 26, 2023 measurement and modelling results. Landfill area source maps are indicated by the purple squares. The measured and modelled landfill CH_4 concentrations are shown in blue lines; and the measured and modelled N_2O concentrations generated by the 1st tracer (one of the green triangles at the middle of the landfill) are indicated by red and orange lines.

4.1.3 NAU comparison 2022-2023

The CH_4 emission rates from 2022 and 2023 cannot be compared because in 2022 the landfill gas installation was switched off at the time of the measurements, making this measurement not representative for comparison. This is also shown in Figure 6. Interestingly, the modelled emission estimate from the landfill model comes closer to the 2022 measured emission rate than for 2023, while the 2022 emissions are not representative.

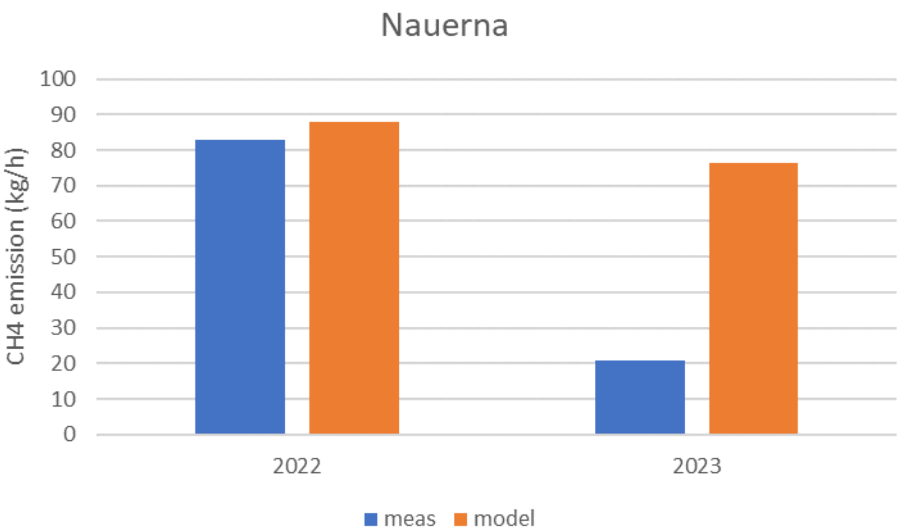


Figure 6 Comparison of the 2022 and 2023 CH_4 emission rates from the mobile measurements (blue) and emission estimates from the Afvalzorg Multiphase Model for Nauerna.

The air pressure, solar radiation and air temperature are plotted in Figure 7

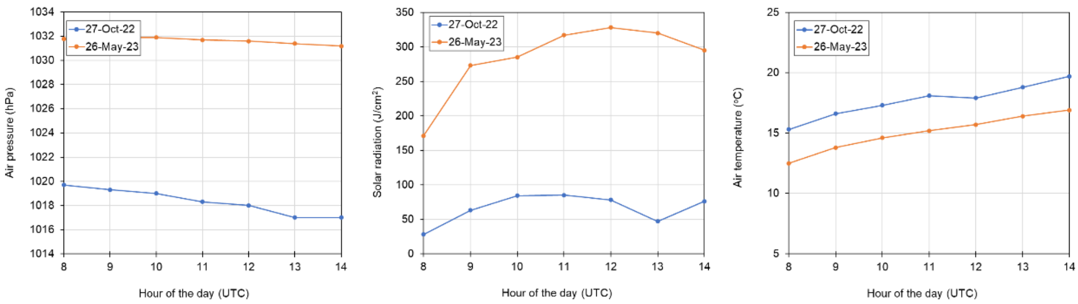


Figure 7 Air pressure, solar radiation and ambient air temperature changes during the measurement periods on 27 October, 2022 (08:30 – 12:15 UTC) and 26 May, 2023 (09:00 – 13:00 UTC) *(Data source: KNMI, Schiphol station)*.

4.2 The Zeeasterweg site (ZEE)

4.2.1 ZEE 2022 campaign results

The meteorological conditions on October 7, 2022 were optimal for conducting mobile measurements, the wind direction was more or less constant (SSW wind) and the average wind speed was relatively constant at 5 m/s. With this wind direction, the plumes from HVC and Orgaworld did not interfere with the measured plumes from the landfill part. The day started sunny, with increasing cloud cover around noon. Temperature was 12^{o}C in the morning and wend up to 16^{o}C at noon. Atmospheric pressure was on average 1022 hPa (Figure 12).

The mobile measurements took place on east side of the landfill (Larserringweg) as well as on N309. Wind was south-south-west (SSW), the plume hit the Larserringweg and was also visible at the N309. The plume measurements show an overall CH_4 emission of 15 +/- 1.7 g/s or 54 +/- 6.1 kg/h, based on an average of 29 plumes, using stability class D (neutral weather conditions)(Table 3).

Two different tracer release experiments were conducted at the same location in this site. In the morning, 5 plumes were measured when the first cylinder with a lower release rate (0.085g/s) was placed (Figure 2). Using Equation 1, the calculated CH_4 emission was 15 +/- 1.0 g/s or 54 +/- 3.5 kg/h. When using the Gaussian Plume model a CH_4 emission of 18 +/- 1.9 g/s or 65 +/- 6.7 kg/h was estimated.

In the afternoon 19 plumes were measured when the second cylinder with a higher release rate (0.324 g/s) was placed at the same position. Using Equation 1, the calculated CH_4 emission was 10 +/- 1.6 g/s or 36 +/- 5.9 kg/h. When using the Gaussian Plume model a CH_4 emission of 13 +/- 2.3 g/s or 47 +/- 8.3 kg/h was estimated.

The CH_4 emissions from the landfill are slightly higher in the morning, but within the range of the standard deviation. N_2O plumes from Orgaworld were visible, but shown as a separate plume, so it did not interfere with the landfill plumes (Figure 8).

Furthermore, after N_2O tracer release stopped, Figure 9 showed that a low-level N_2O (max. 2 ppb after removing background value) was still detectable from the landfill site. Compared to the CH_4 plumes (max. 1000 ppb after removing background), N_2O plumes show the same patterns, indicating that these two components share the same sources from the landfill. More specified measurements are recommended to estimate the emissions of N_2O from the landfill site, as nitrous oxide is a potent greenhouse gas, with a global warming potential of 265 times that of carbon dioxide within 100 years.

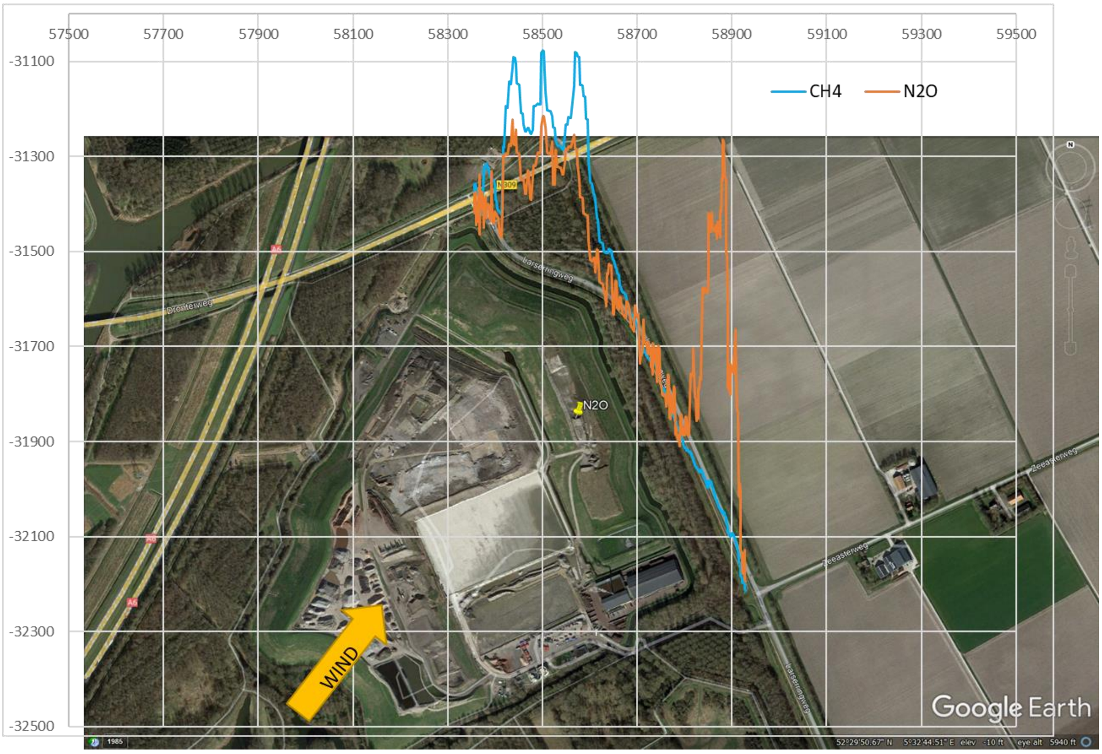


Figure 8 Overview of measured plume #29, showing measured CH_4 (blue) and N_2O (orange), when there was no tracer release. Higher orange N_2O plume on the right is from Orgaworld and not included in the emission calculations.

Table 3 CH_4 Emission estimates from the Zeeasterweg landfill in 2022.

	CH_4 emission using tracer					
plumes	avg	st.err		avg	st.err	
#2-9	15	1.0	g/s	54	3.5	kg/h
#10-28	10	1.6	g/s	36	5.9	kg/h
	CH_4 emission using model					
plumes	avg	st.err		avg	st.err	
#2-9	18	1.9	g/s	65	6.7	kg/h
#10-28	13	2.3	g/s	47	8.3	kg/h
#2-30	15	1.7	g/s	54	6.1	kg/h

4.2.2 ZEE 2023 campaign results

On July 6, 2023, there was a constant southwestern wind direction. The average wind speed was around 3.5 m/s. Is was a sunny day with a temperature of 19°C during the measurements. Atmospheric pressure was on average 1016 hPa (Figure 12). The mobile measurements took place on east side of the landfill (Larserringweg), the plume was shown on the Larserringweg but not visible at the N309. There were more activities on site at the western side of the landfill compared to last year's measurements (Figure 2, yellow square). Therefore, extra sources were added into the source distribution map. In addition, the CH_4 peaks generated from Orgaworld and/or the WWTP of Afvalzorg sometimes interfered with the measured plumes from the landfill part. To test the impact of the interference on the landfill CH_4 emissions, two different approaches were used to determine the landfill CH_4 emission values.

Method 1: The same modelling approach as was used last year and visually decided on the cutting points for the Orgaworld and landfill part.

Method 2: As the Orgaworld peak is much higher, we first modelled Orgaworld using its own source map, and then modelled the whole area (Orgaworld + landfill sources together). The landfill CH_4 emission (Qs_landfill) was estimated by using the whole area CH_4 emission (Qs_total) subtracted the Orgaworld modelled CH_4 emission (Qs_orgaworld).

The two methods generated similar results. For method 1, 24 plumes were selected, and the modelled CH_4 emission of the landfill was 2.1 +/- 0.1 g/s. For method 2, 11 plumes were selected and the modelled CH_4 emission of the landfill was 2.4+/- 0.2 g/s.

Two different tracer release experiments were conducted at the same location on this site. By applying Equation 1, the landfill CH_4 emission was estimated as 0.9 +/- 0.1 g/s (based on two releases and 26 plumes) using the same stability class C (Table 4).

In the morning, when the first cylinder with a release rate of 0.41 g/s was placed, 14 plumes were measured. The calculated CH_4 emission was 0.7 +/- 0.1 g/s or 2.5 +/- 0.2 kg/h, while using the Gaussian Plume model CH_4 emission of 1.8 +/- 0.1 g/s or 6.5 +/- 0.2 kg/h was estimated.

In the afternoon, when the second cylinder with a release rate of 0.39 g/s was placed at the same position, 12 plumes were measured. Using Equation 1, the calculated CH_4 emission was 1.2 +/- 0.1 g/s or 4.3 +/- 0.4 kg/h. When using the Gaussian Plume model a CH_4 emission of 2.4 +/- 0.1 g/s or 8.6 +/- 0.2 kg/h was estimated.

Furthermore, after N_2O tracer release stopped, we measured the background N_2O and CH_4 signals, and noticed N_2O originating from the landfill area at an emission level that is equivalent to 15% of the tracer release level (0.05 gN_2O/s).

Figure 9 and Figure 10 show examples of the measured and modelled results for N_2O and CH_4. The measured and modelled CH_4 concentration are indicated by the light blue solid and red dashed lines respectively; the measured and modelled CH_4 concentrations that originate from Orgaworld are shown as pink solid and a dark-blue dashed lines. It shows that the landfill source emitted CH_4 was small comparing with the Orgaworld emission.

Table 4 CH_4 Emission estimates from the Zeeasterweg landfill in 2023.

	CH_4 emission using tracer					
plumes	avg	st.err		avg	st.err	
#2-18 (n=14)	0.7	0.1	g/s	2.5	0.2	kg/h
#19-33 (n=12)	1.2	0.1	g/s	4.3	0.4	kg/h
	CH_4 emission using model					
plumes	avg	st.err		avg	st.err	
#2-18 (n=13)	1.8	0.1	g/s	6.5	0.2	kg/h
#19-33 (n=11)	2.4	0.1	g/s	8.6	0.2	kg/h
#2-38 (n=24)	2.1	0.02	g/s	7.6	0.1	kg/h

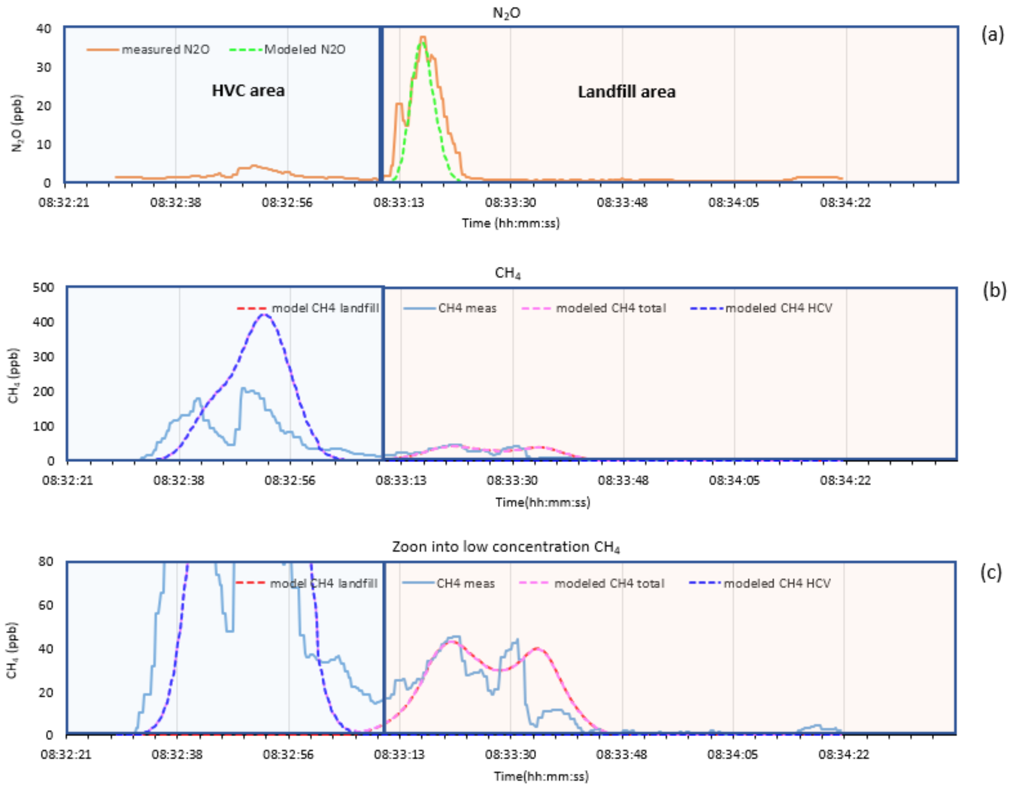


Figure 9. Demonstration of the measured and modeled N_2O and CH_4 within one single plume in Zeeasterweg landfill. (a) measured and modelled N_2O plume during release experiment, (b) measured and modelled CH_4 plume from HVC and landfill area and (c) zoom into modelled landfill CH_4 low concentration in.

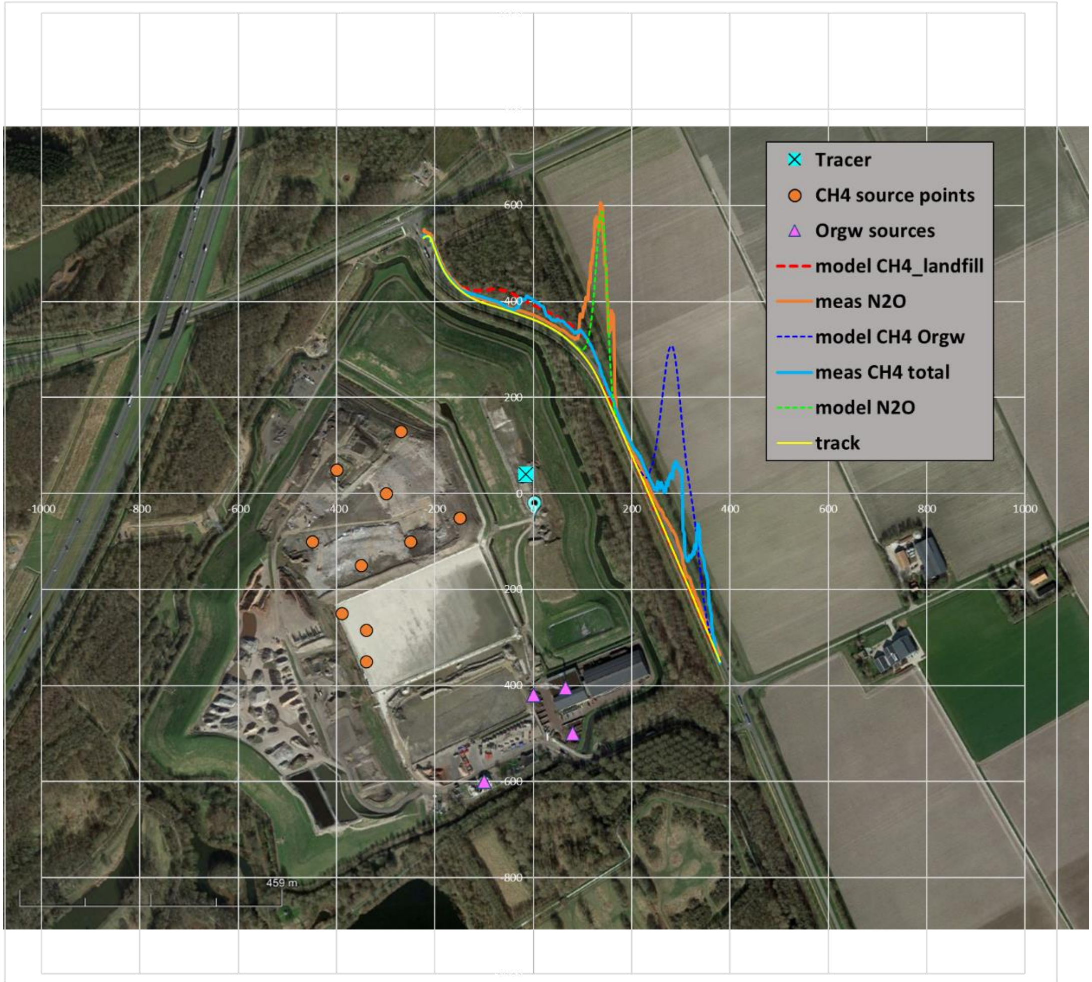


Figure 10 Zeeasterweg site source distribution map for both landfill and Orgaworld and measured and modeled CH_4 concentrations and N_2O are showed in different color lines.

4.2.3 ZEE comparison 2022-2023

The CH_4 emission rates from 2022 and 2023 are not comparable because in 2023 the Zeeasterweg landfill was measured in summer, making this measurement not representative for comparison as also for annual emission calculations. In summer there is much more influence of microbial oxidation in the cover soil. This is also shown in Figure 11. The measured emission rate in 2023 is much lower compared to the 2022 results.

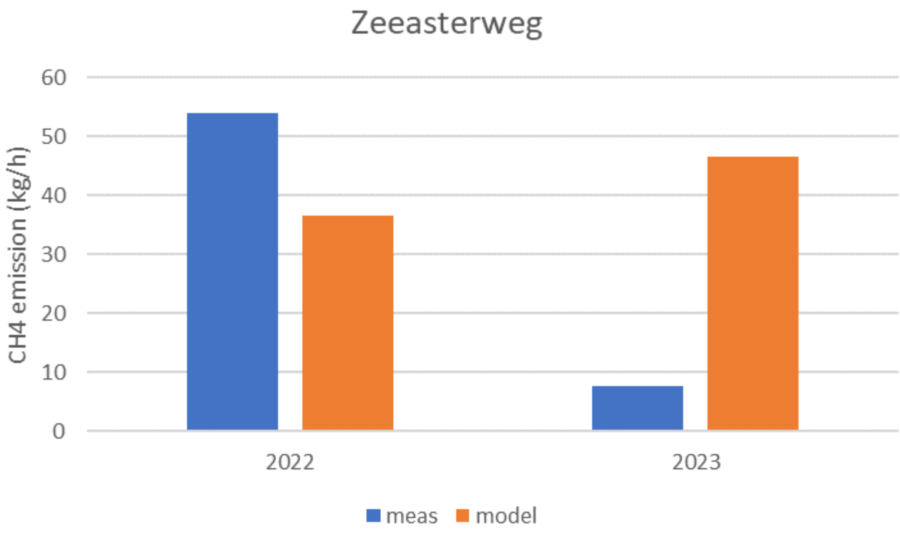


Figure 11 Comparison of the 2022 and 2023 CH_4 emission rates from the mobile measurements (blue) and emission estimates from the Afvalzorg Multiphase Model (orange) for Zeeasterweg.

The air pressure, solar radiation and air temperature are plotted in Figure 12.

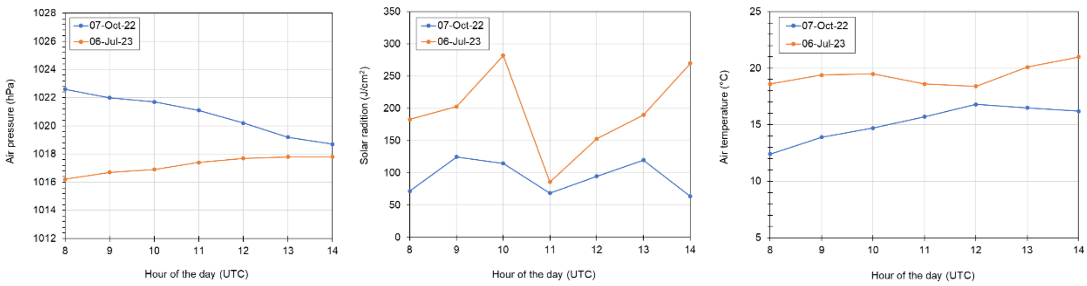


Figure 12 Air pressure, solar radiation and ambient air temperature changes during the measurement periods on 7 October, 2022 (09:00 – 13:15 UTC) and 6 July,2023 (08:00 – 11:10 UTC) *(Data source: KNMI, Lelystad station)*.

4.3 The Wieringermeer site (WIE)

4.3.1 WIE 2022 campaign results

The Wieringermeer site was the first measured site from the three landfills. There were complex adjacent sources also contributing to the measurement signals under the wind condition. Therefore, the data evaluation is more extensive than the other sites.

The mobile measurements took place on a road relatively close to the landfill on the north side. The meteorological conditions were optimal for conducting mobile measurements, the wind direction was more or less constant (SSW wind) and the average wind speed was relatively constant and around 5 m/s. It was a sunny day with a temperature of 16°C and an atmospheric pressure of on average 1009 hPa (Figure 22).

In terms of CH_4, relatively high concentrations were observed downwind of the western landfill and HVC. In terms of N_2O, except for the plumes emitted by the tracer, we also observed N_2O from the western landfill and HVC after tracer release stopped. There was no significant N_2O signal downwind of the eastern landfill. Occasionally, there was an increased CH_4 signal visible, but this needs extra measurements to be able to quantify this.

4.3.1.1 N_2O tracer release experiments and N_2O coming from the landfill

The two tracer release experiments at the western landfill site had similar emission strengths (0.08 g/s and 0.09 g/s) in the morning and afternoon respectively. Figure 13 shows the effect of the stability class used in the model. For the best fit of the measured concentration and modelled concentration, stability class D was used.

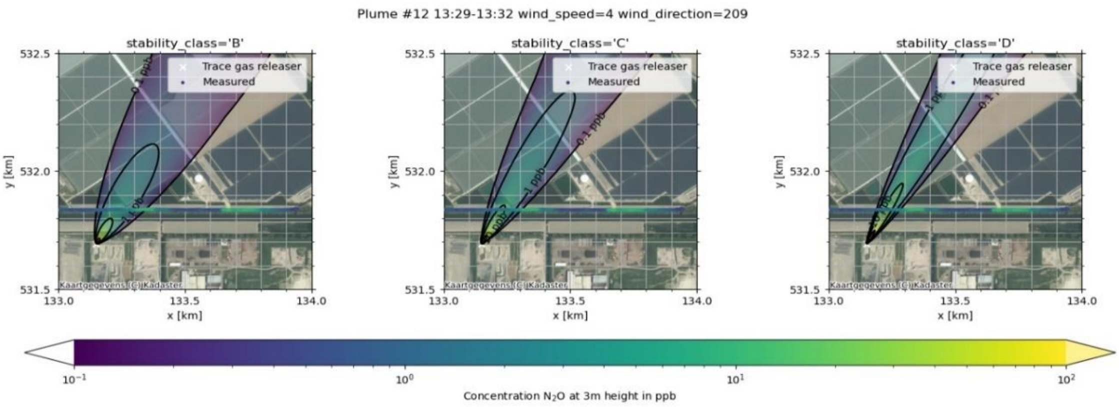


Figure 13 Example of modelled plume dispersion of N_2O with stability classes B, C and D.

After the tracer release experiment stopped, two more plumes (#16, #17) still show N_2O concentrations downwind of the western landfill, at about 2 ppb above N_2O background (Figure 14). The measured N_2O data were compared in the last hour among 3 plumes when wind direction and windspeed were constant: plume #15 with tracer, plume #16, #17 without tracer. The tracer release Equation (1) was applied, and N_2O emitted by the western landfill was estimated between 0.05 and 0.06 g/s, on average 0.06 g/s. Using plume modeling, the modeled N_2O emission of this field was between 0.07 and 0.09 g/s, on average 0.08 g/s, which was almost equal to the tracer release rate. The tracer and the landfill N_2O plumes can be separated by the different plume shape. Multiple water pumping wells or other possible N_2O sources in the landfill generate a wide low peak, while the tracer gas from a single source point generate a narrow sharp peak.

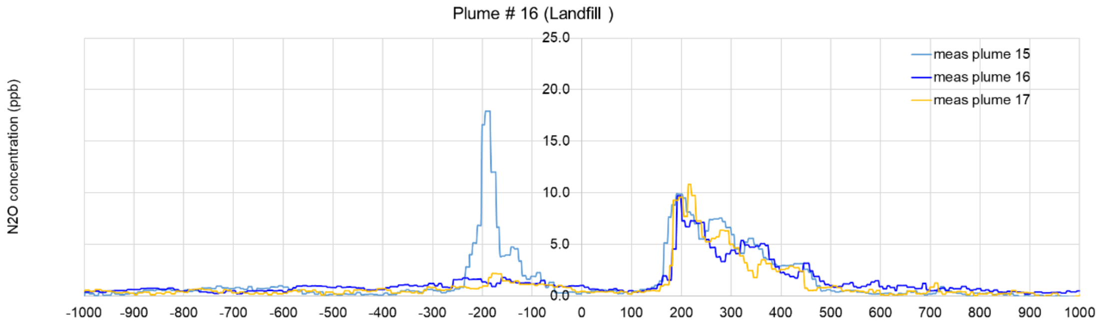


Figure 14 Plume 15, 16 and 17 at the Wieringermeer landfill. Plume 15 is with N_2O release, plume 16 and 17 without N_2O release.

The HVC part in between western and eastern landfills emitted larger amount of CH_4 and N_2O, compared to the two landfills (see Figure 14 and Figure 15). Through the tracer release method, the estimated N_2O emission from the HVC part is about 0.2 ± 0.1 g/s.

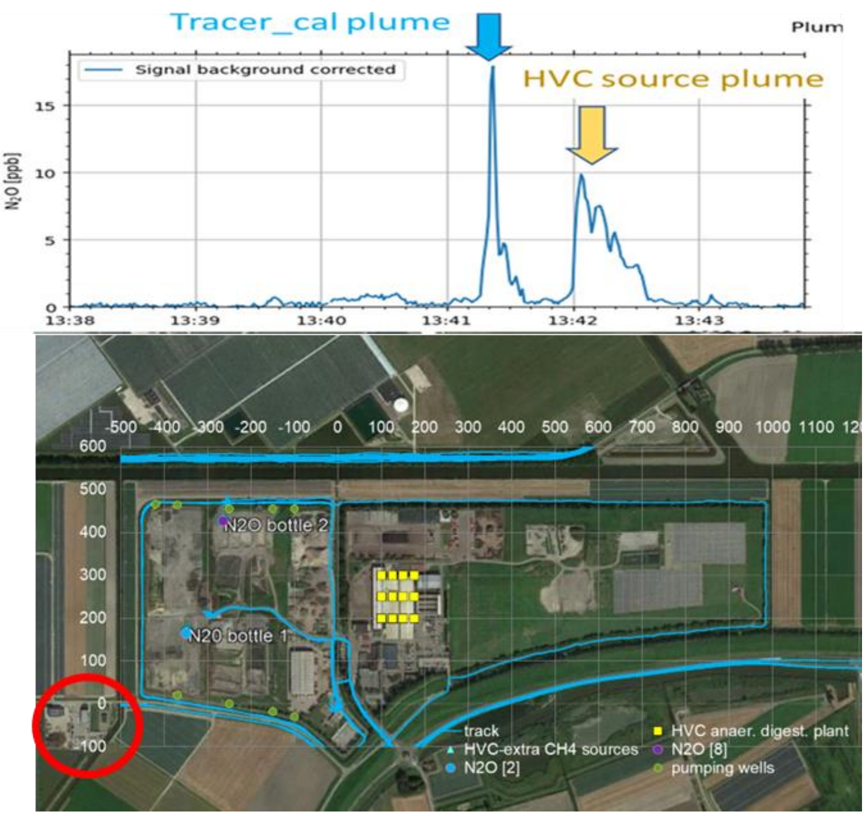


Figure 15 Plumes from the tracer release experiment and the HVC part of the site; Top: N_2O plumes, bottom: Google Earth image with source points (red circle indicate a gas distribution facility).

4.3.1.2 CH_4 emission from the western landfill: extra source contribution correction

Due to the wind direction on the measurement day in 2022, the measured CH_4 concentration downwind of the western landfill was a mixed signal of landfill and an adjacent gas station (Figure 15, red circle). The difference between these two sources is that gas station also emits C_2H_6 while landfill doesn't. In addition, the C_2H_6:CH_4 ratio of the gas installation is a fixed value (3.4%; Figure 16) which were obtained with measurements close to the gas station. Therefore, the extra CH_4 contributed by the gas station can be corrected and removed from the total values. The modeled CH_4 plume #15 from the western landfill is shown in Figure 17 as an example.

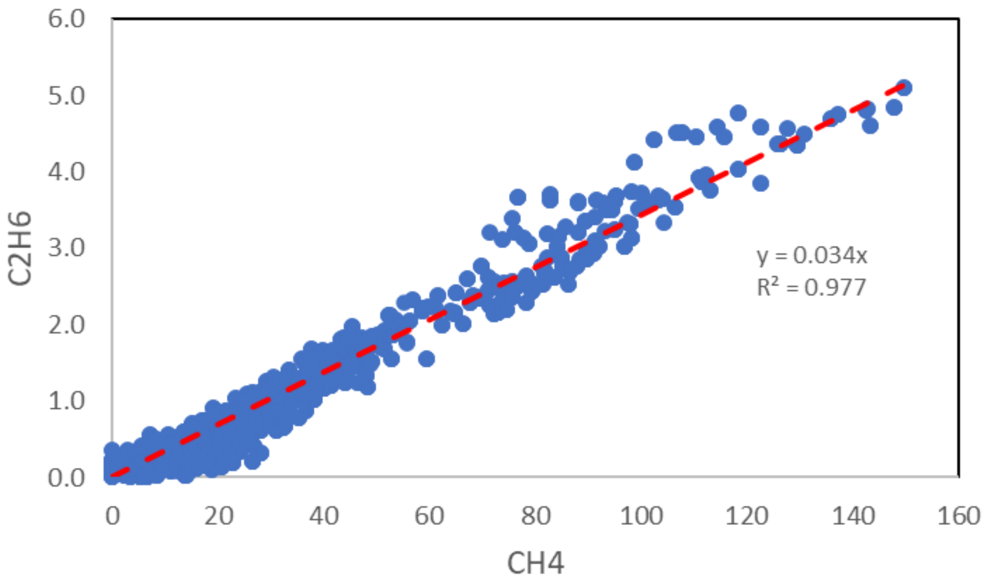


Figure 16 C_2H_6:CH_4 ratio of the gas installation.

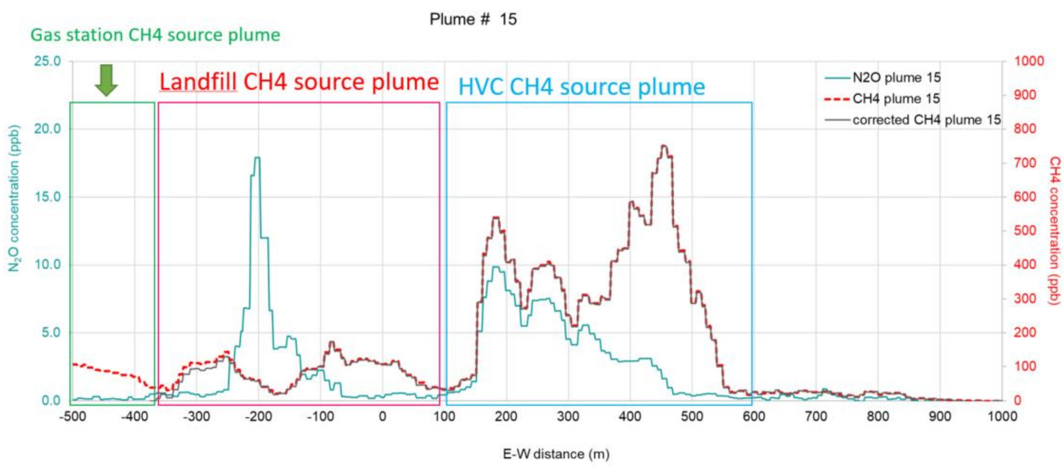


Figure 17 Measured plume 15 after subtraction CH_4 contribution from the adjacent gas installation.

As mentioned above, HVC part located between western and eastern landfills, emitted more CH_4 and N_2O compared to the two parts of the landfill (see Figure 18; HVC in long-dot blue line, landfill in short-dot blue line).

The CH_4 concentrations from the western landfill were higher in the afternoon than in the morning. In addition, measured plume 17 seems to indicate the 'eastern' landfill might also emit certain CH_4, as a third peak observed when the measurement truck drove between 500 m and 600 m at the east-side. This was only shown ones, therefore is was not possible to estimate an emission out of it. The CH_4 emissions determined from the plume measurements represent the western part of the landfill.

The iDS part is just behind the HVC part. Emission from the iDS part is overlapping with the HVC part. With the current southern wind direction and measurement method, it is not possible to separate the plumes and quantify them separately.

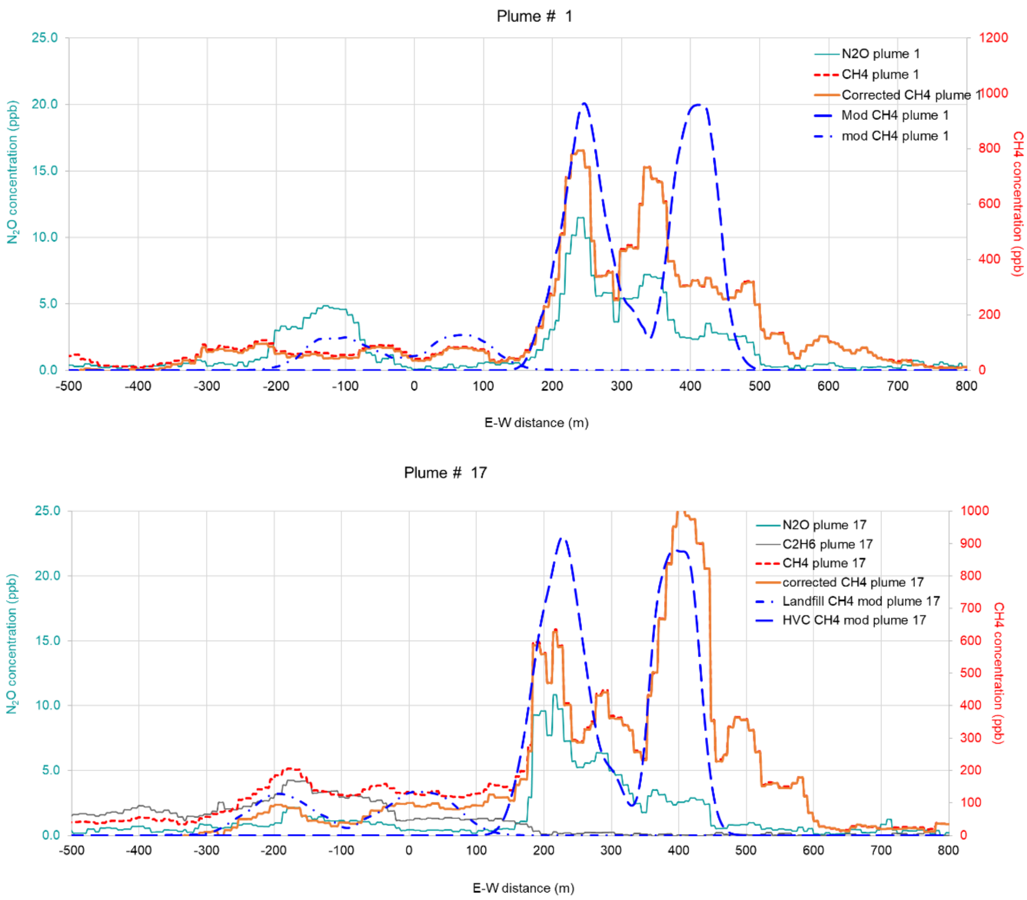


Figure 18 Overview of measured and modelled plumes #1 and #17, showing measured N_2O, C_2H_6, CH_4, CH_4 corrected and modelled CH_4 concentrations. (plume # 1 with N_2O tracer release, #17 without N_2O tracer release)

The overall results for emitted CH_4 from the western landfill are presented in Table 5. It was not possible to quantify the iDS contribution and also the potential emission from the eastern site was not clear to be able to quantity the emission rate.

Table 5 CH_4 emission estimates from Wieringermeer landfill in 2022.

	Western-operational landfill CH_4 emission using tracer					
PLUMES	avg	st.err		avg	st.err	
#1-11	1.9	0.2	g/s	6.8	0.7	kg/h
#12-17	2.1	0.2	g/s	7.6	0.9	kg/h
PLUMES	Western-operational landfill CH_4 emission using model					
#1-11	3.8	0.2	g/s	14	0.7	kg/h
#12-17	4.0	0.4	g/s	14	1.5	kg/h
#1-17	3.9	0.2	g/s	14	0.7	kg/h

4.3.2 WIE 2023 campaign results

The Wieringermeer site was measured last among the three landfills in 2023. Because of the different wind condition, this time there was no influence of the natural gas station. Both tracer cylinders were placed on the west site of the landfill with 5-7 times higher releasing rate than they were last year. Therefore, the increased background concentration of N_2O coming from the landfill was not interfering with the tracer signals.

Still the same is the mobile measurements took place on a road on the north side of the landfill. The wind direction was more or less constant (S to SSE wind) and the average wind speed was relatively constant and around 3.5 m/s. Is was a sunny day with a temperature of 22°C in the morning and going up to 25°C at noon. Atmospheric pressure was on average 1018 hPa (Figure 22).

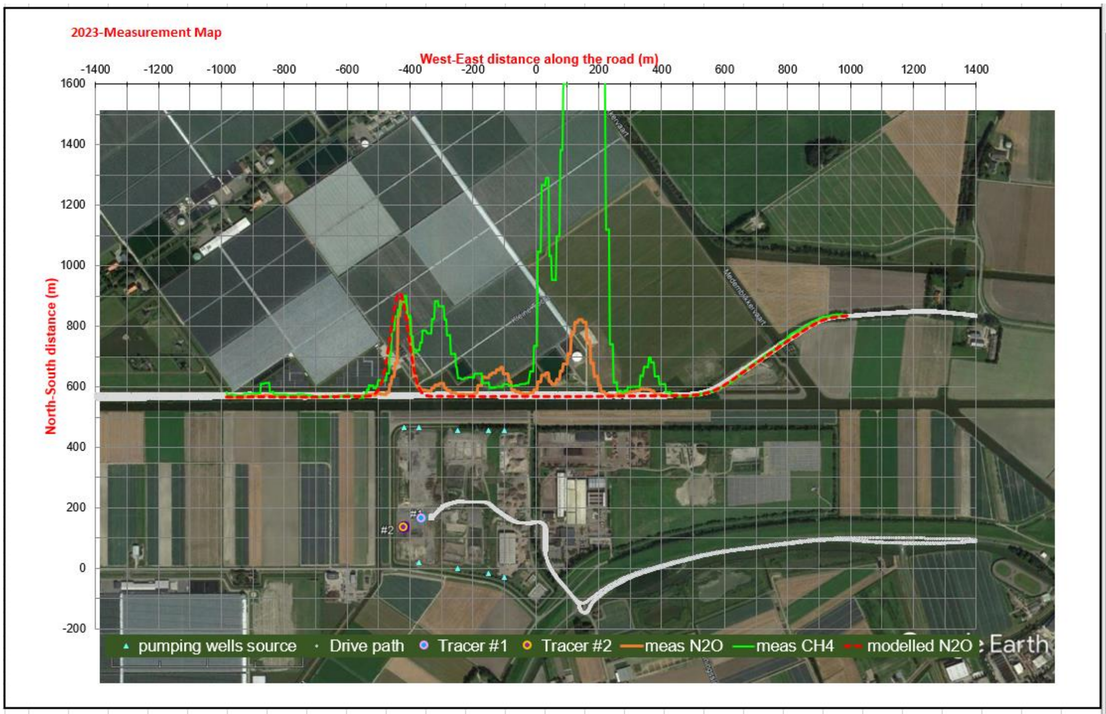
Same as last year, CH_4 concentration was relatively high when the truck was driven downwind of the western landfill and HVC. N_2O concentration was much higher in HVC part comparing it from landfill itself. And there was no significant N_2O signal downwind of the eastern landfill. We did not observe any CH_4 signals from the east landfill this year.

Two tracer release experiments had similar emission strengths as 0.40 g/s and 0.58 g/s both in the morning in the western landfill site. We noticed that stability changes during the two tracer release period. Hence, in 1st period stability class was D, while the 2nd period the stability class is C.

Table 6 CH_4 emission estimates from Wieringermeer landfill in 2023.

	Western-operational landfill CH_4 emission using tracer					
PLUMES	avg	st.err		avg	st.err	
#1-10 (n=7)	3.8	0.2	g/s	14	0.8	kg/h
#11-20 (n=8)	4.4	0.2	g/s	16	0.8	kg/h
PLUMES	Western-operational landfill CH_4 emission using model					
#1-10 (n=7)	5.7	0.3	g/s	21	1.1	kg/h
#11-20 (n=7)	5.4	0.3	g/s	19	1.1	kg/h
#1-20 (n=15)	5.5	0.2	g/s	20	0.7	kg/h

Figure 19 shows an example of the comparison of the modelled and measured N_2O and CH_4 plumes. Tracer location and CH_4 source maps are also indicated in Figure 19. Please note that N_2O concentrations and CH_4 concentrations have multiplied by a certain ratio to visualize in the same figure, they do not present the actual values. As the wind direction is south, the natural gas station impact no longer an issue.



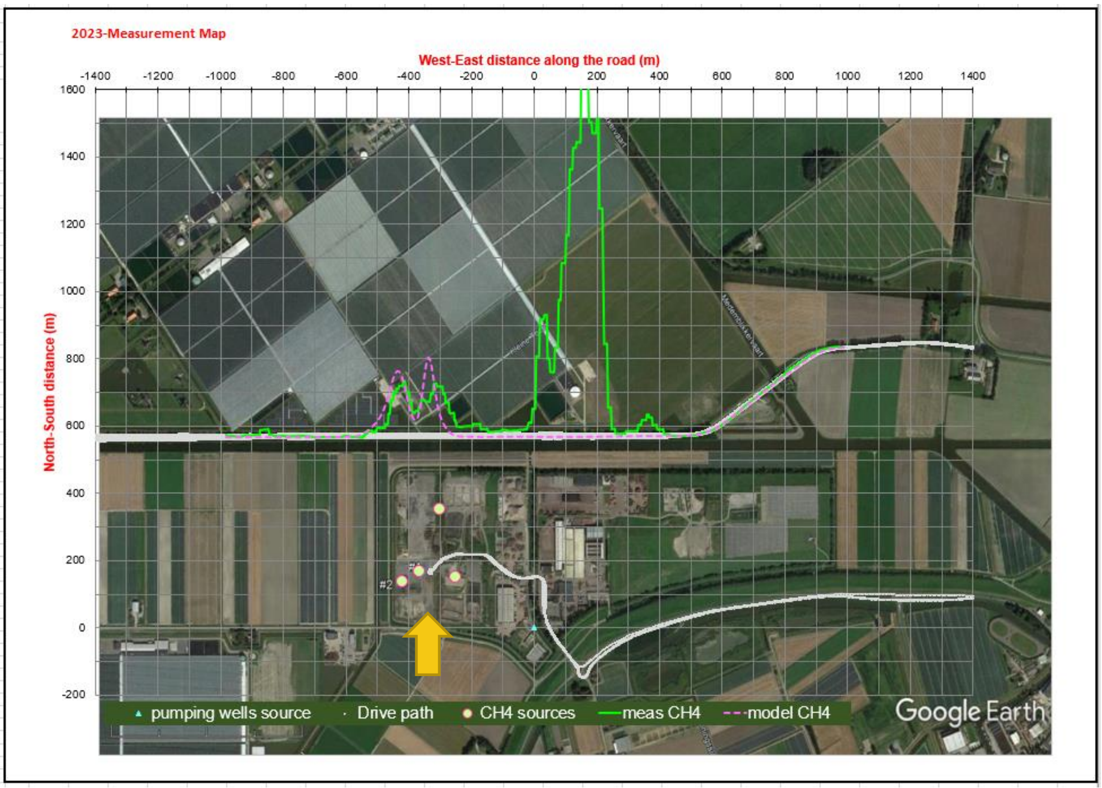


Figure 19 a) one single plume measured and modeled N_2O concentrations. b) the period measured and modeled CH_4 concentration. In this case, the wind direction is south.

4.3.3 WIE comparison 2022-2023

The CH_4 emission rates from 2022 and 2023 are not comparable because in 2023 the Wieringermeer landfill was measured in summer, making this measurement not representative for comparison as also for annual emission calculations. In summer there is more influence of microbial oxidation in the cover soil. Interestingly, the measured emission rate in 2023 is slightly higher compared to the 2022 results. This is the opposite of what was seen for Zeeasterweg (Figure 20). Furthermore, the measured emission rate is quantified from the west part of the landfill, which is much higher than the emission rate from the Afvalzorg Multiphase Model for the west part. The iDS part was impossible to separate from the HVC part from the measured plumes. Remarkable is the relatively high model emissions from the east part, while we did not see clear plumes at the east site. We do not have a clear explanation for the difference between the measured and modelled emission for the west part of the landfill.

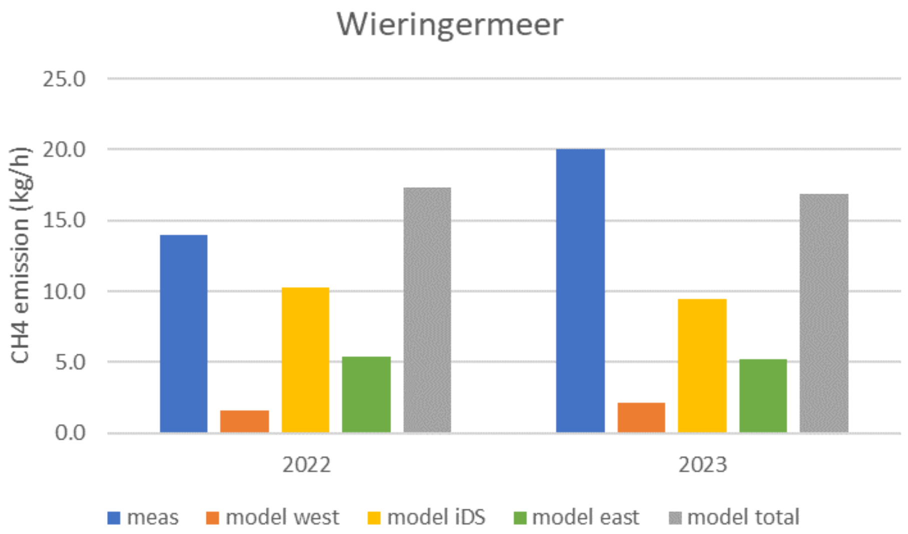


Figure 20 Comparison of the 2022 and 2023 CH_4 emission rates from the mobile measurements (blue) and emission estimates from the Afvalzorg Multiphase Model (orange is west, yellow is iDS, green is east, grey is for total emissions) for Wieringermeer.

The 4 days preceding weather conditions were compared between September 27-30 2022 and August 8-11 2023 (cf. Figure 21 Nearby KNMI station (Berkhout) near Wieringermeer landfill reported hourly air temperature (a) and rainfall amount per hour (b) in the 3 days before each campaign and also during the measurement date in 2022 September 27 till 30 (blue bars) and in 2023 august 08 till 11 (orange bars). The result showed that August 2023 was drier and hotter than September 2022, which is expected to result in lower CH_4 emissions. Multiple studies have found the landfill CH_4 emission was positively correlated with soil layer's moisture. After rainfalls, the soil moisture level increased, which can cause a higher CH_4 emission rate (Zhang et al, 2013). However, the measured results are opposite to the predicted results the Afvalzorg Multiphase Model for the Wieringen site.

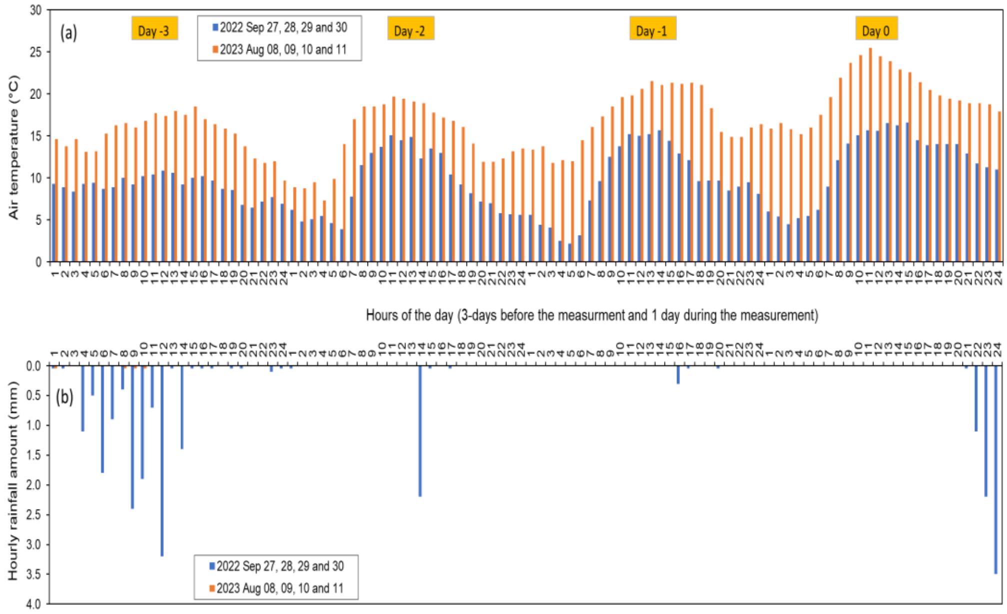


Figure 21 Nearby KNMI station (Berkhout) near Wieringermeer landfill reported hourly air temperature (a) and rainfall amount per hour (b) in the 3 days before each campaign and also during the measurement date in 2022 September 27 till 30 (blue bars) and in 2023 august 08 till 11 (orange bars).

The air pressure, solar radiation and air temperature are plotted in

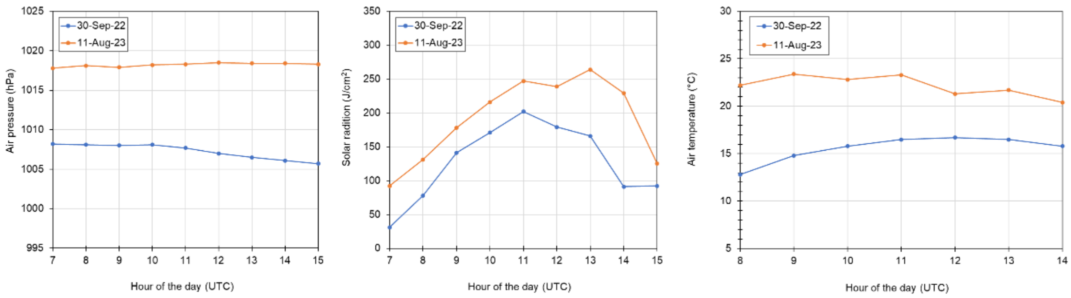


Figure 22 Air pressure, solar radiation and ambient air temperature changes during the measurement periods on 30 September, 2022 (09:30 – 14:30 UTC) and 11 Augustus,2023 (06:30 – 11:30 UTC) *(Data source: KNMI, De Kooy station. The air pressure data is missing at Berkhoud station).*

5 Conclusion and outlook

5.1 Landfill CH_4 emissions from 2022 and 2023

Methane emission measurements at the three landfills: Nauerna, Zeeasterweg and Wieringermeer operated by Afvalzorg were performed in September/October 2022 and May to August 2023. The emission estimates based on the measurement days are presented in this report (see Table 7).

In every measurement session the emission was calculated using two methods. With the tracer ratio method that relies on the assumption that the dilution of gas emitted into the atmosphere for both the tracer and the landfill area is the same. The second method is using the gaussian plume model which takes into account dispersion parameters, like that different parts of the landfill have not the same distance to the measurement transect.

Table 7 Overview of the results of the three landfills CH_4 emissions using dynamic modelling approach in six campaigns days of 2022 and 2023.

	CH_4 emission per landfill					
Site	avg	st.err		avg	st.err	
Nauerna 2022	23	2.1	g/s	83	7.7	kg/h
Nauerna 2023	5.7	0.5	g/s	21	1.7	kg/h
Zeeaster 2022	15	1.7	g/s	54	6.1	kg/h
Zeeaster 2023	2.1	0.02	g/s	7.6	0.1	kg/h
Wieringen 2022	3.9	0.2	g/s	14	0.7	kg/h
Wieringen 2023	5.5	0.2	g/s	20	0.7	kg/h

In autumn 2022, the Nauerna landfill had an overall emission based on the model results at 83 +/- 7.7 kg/h CH_4. The N_2O release experiments indicate a higher emission strength in the morning compared to the early afternoon measurements. Furthermore, the emission at the Nauerna site in 2023 was much lower with 21 +/- 6.1 kg/h CH_4. This is most probably related to the fact that the gas recovery system was not in operation on the measurement day in 2022, but it was active in 2023.

At the Zeeasterweg site, CH_4 emission was also higher in 2022 comparing with 2023. In autumn 2022, the modeled emission was 54 +/- 6.1 kg/h, while in summer 2023 the emission level was dropped to 7.6+/- 0.1 kg/h. The emission estimates in 2022 showed a much larger spread in the data as reflected its large uncertainty with a coefficient of variation (CV) as ±60%, whereas CV was only ±5% for the 2023 result, which was much more certain.

In general, the emissions in the morning were higher than in the afternoon, and the autumn was higher than summer. A higher top soil temperature could result in more oxidation of CH_4 (*(Börjesson and Svensson, 1996, Zhang et al, 2013),* which could reduce the CH_4 emission. However, this is not the overall reasoning to explain such significant methane reduction in both Nauerna site (relative 75% CH_4 reduction, main reason was the turnoff of the gas recovery system in 2022) and Zeeasterweg site (relative 86% CH_4 reduction) between autumn 2022 and summer 2023. As was mentioned above, for the Zeeasterwerg, the measurements in summer 2023 are expected to be deviating from the autumn measurements in 2022, because in summer there is much more influence of microbial oxidation in the cover soil.

At the Wieringermeer site, the emission measurements show an emission of 14 +/- 0.7 kg/h CH_4 in 2022 and 20 +/- 0.7 kg/h CH_4 in 2023, which were very similar. For the evaluation, the Wieringermeer location was the most challenging site of the 2022 campaign, as the source strength of the N_2O release that was used, was a bit low compared to the N_2O emission from the HVC part of the site and because the western landfill part emitted N_2O as well. Besides that, also a gas installation upwind of the landfill site emitted CH_4, which had to be subtracted from the measured CH_4 concentrations. In addition, the HVC part emitted 3-4 times more CH_4 and N_2O compared to the landfill site itself. From the 2022 campaign, it was not possible to separate the HVC plume from eastern non-operational landfill area. Therefore, it was not possible to estimate the potential CH_4 emission from the eastern non-operational landfill area.

In the summer 2023 campaign, extra measurements were conducted between HVC and the eastern landfill area to distinguish the source contributions, but there were no visible emission signals from the old landfill part seen. By increasing the N_2O tracer release in 2023, the tracer plume could be separated from the N_2O emissions coming from the landfill. Because of the different wind conditions, the landfill plumes and the natural gas station plumes did not overlap this time.

At the Wieringermeer site, the CH_4 emissions was slightly higher in 2023 compared to 2022. This finding is opposite to other two locations. Also for Wieringermeer, the measurements in 2023 were done in summer (July), so not representative because in summer there is much more influence of microbial oxidation in the cover soil. It was expected that it result in lower emissions in 2023, just as seen for the Zeeasterweg site.

5.2 Measured landfill CH_4 emissions compared to landfill production model results

When comparing the measured CH_4 emissions to the production and recovery levels provided by Afvalzorg (Table 8), the Nauerna sum of recovered and emitted CH_4 in 2022 is close to the estimate of the production model, but for 2023 the measured emissions were much lower (Figure 23). For the Zeeasterweg the emissions are above the expected level for 2022, but below the expected level for 2023 (Figure 23). At Wieringermeer the emissions are below the expected level, both for 2022 and 2023 (Figure 23). The observed emissions at the iDS and east side seemed to be very low. In the afternoon we might have observed a certain amount of methane originating from the iDS site but it is difficult to separate that emission from the HVC composting plant emissions in 2022. Also in 2023, no clear plumes were observed.

Table 8 CH_4 production, recovery and emission estimates for three landfills in $kgCH_4/h$ in 2022 and 2023.

	Production model[1]	Recovery[2]	Emission (meas)[3]	Recovery/ Prod.	Emission/ Prod.	Oxidised or uncertain
NAU						
2022	235	52	83	22%	35%	43%
2023[4]	212	162	21	76%	10%	14%
ZEE						
2022	103	63	54	61%	52%	-14%
2023	131	78	7.6	60%	6%	35%
WIE west						
2022	8.2	4.4	14	54%	171%	-124%
2023	8.8	6.4	20	73%	227%	-200%

[1]Production in $kgCH_4/h$
[2]Recovery is given as a 3-day average prior to the measurement campaign in $kgCH_4/h$
[3]Emission (meas) is emission rate determined with mobile plume measurements in $kgCH_4/h$
[4]2023 number are until November 1th

Figure 23 Nauerna, Zeeasterweg and Wieringen landfills production model results from 2022 and 2023, together with the mobile plume measurement determined CH_4 emissions in kg/h.

5.3 Measured Nauerna CH_4 emissions compared to the Dutch national emission inventory data

From the historic perspective, the Nauerna site has a set of valuable long-term measurement based CH_4 emission data. The comparison data from 2022 and 2023 combined with the "historical" Nauerna data is shown in Figure 24. The different symbols in the figure denote different measurement methods. DPM (dynamic plume model) is the mobile tracer dispersion method that is used for the study in this report and in the study of Stroeken et.al. (a master student at Utrecht University) with whom we collaborated in the context of the EU MEMO program. The SPM measurements were static plume measurements using a gaussian plume model-triggered gasbag sampling system. The MBM measurements were mass balance emission measurements performed by Oonk et.al. from TNO. The Nauerna CH_4 emission reduction trend proven by various measurements in various years was in line with the temporal pattern being reported by the national CH_4 emission inventory from landfills (displayed on the right axis).

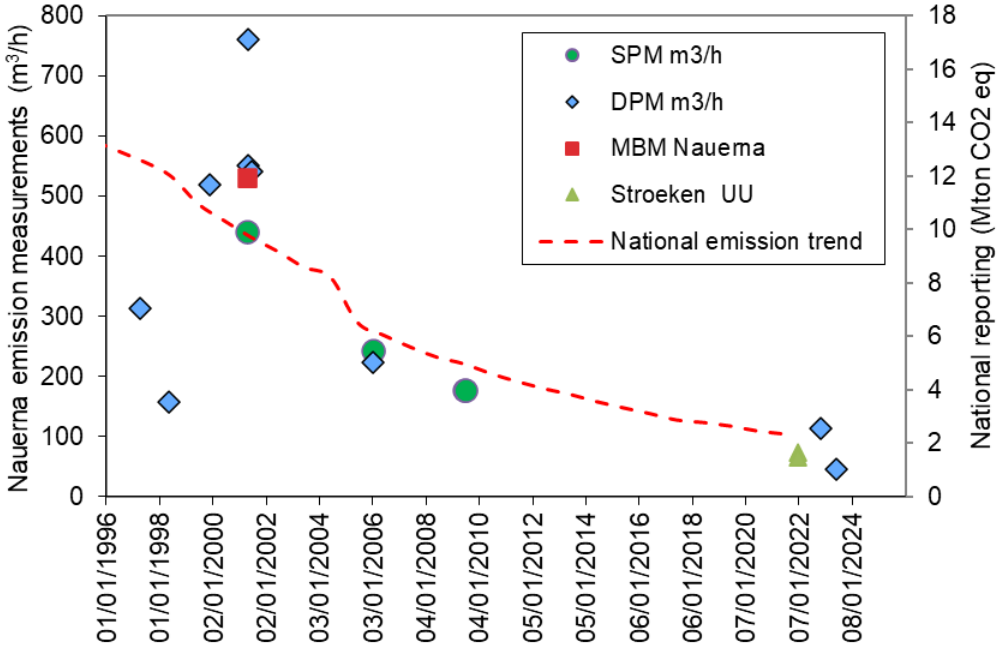


Figure 24 Historical trend of the Nauerna landfill estimated emissions by different methods. SPM is stationary plume modelling, DPM is dynamic plume modelling, MBM is mass balance method, Stroeken UU is also a dynamic modelling. The red dashed line is representing the Dutch national emission inventory data in the last two decades.

5.4 Recommendations

To follow up this research, new measurements should be performed on all three landfills in spring 2024. In such a way, that the result should be more comparable to the emission estimates with the Afvalzorg Multiphase Model, as the emission measurements in spring and autumn are representative for comparison. Besides the mobile CH_4 emission measurements, the measurements should have an extra focus on N_2O emissions. By reducing the CH_4 emissions, the possible N_2O emissions coming from the landfill sites, becomes more important to further meet the GHG mitigation target within the EU. CH_4 is a 28 times stronger greenhouse gas compared to CO_2, but N_2O is 265 times stronger greenhouse gas compared to CO_2. This makes the contribution of N_2O more relevant to the total greenhouse gas emissions of the landfills.

6 References

Börjesson, G., Svensson, B.H., 1997. Seasonal and diuruial methan emssios from a landfill and their regulation by methane oxidation, *Waste Management & Research*, Volume 15, Issue 1, Pages 33-54, https://doi.org/10.1006/wmre.1996.0063.

Czepiel, P.M., Mosher, B., Harriss, C., 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.***1 01**, 16711-16719

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

K. Kissas, A. Ibrom, P. Kjeldsen, C. Scheutz, 2022. Methane emission dynamics from a Danish landfill: The effect of changes in barometric pressure, *Waste Management,* 138, 234-242. https://doi.org/10.1016/j.wasman.2021.11.043.

Oonk, J., Boom, A., 1995. Landfill gas formation, recovery and emissions. NOVEM Programme Energy Generation from Waste and Biomass (EWAB), TNO report R95-203, Apeldoorn, Netherlands.

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.

Stroeken, 2022. Attribution and quantification of CH4 emissions in the Port of Amsterdam. MSc thesis, University of Utrecht. 52 pages.

Zhang, H., Yan, X., Cai, Z., Zhang, Y., 2013. Effect of rainfall on the diurnal variations of CH4, CO2, and N2O fluxes from a municipal solid waste landfill, *Science of The Total Environment*, Volume 442, Pages 73-76. https://doi.org/10.1016/j.scitotenv.2012.10.041.

Energy & Materials Transition

Westerduinweg 3
1755 LE Petten
www.tno.nl

innovation
for life