Date: **20 February 2023**

Draft Working Paper: **Estimate of total methane emissions from the Nord Stream gas leak incident**

On 26 September 2022, several leaks in the Nord Stream twin pipeline system (NS1 and NS2), which connects Russian gas supply with the EU, resulted in natural gas contained in the pipelines escaping into the Baltic Sea. Satellite images provided evidence of massive bubbling at the sea surface lasting until 1 October 2022. Considering almost all the gas in the pipeline is methane (CH_4), a potent greenhouse gas, several research groups focused on using a diversity of data sources to estimate CH_4 emissions from this event throughout the following month.

This working paper briefly summarizes the reported estimates, and puts those into a broader context, including an estimate of a plausible range of the total CH_4 emissions from this incident, which we quantified as 75–230 kt CH_4 (1 kt = 1,000 metric tons) as outlined below including a comparison with other observed large CH_4 releases. An in-depth scientific evaluation of the accuracy of the reported emission estimates from each research group as well as addressing several caveats of our initial synthesis estimate is beyond the scope of this analysis and will be completed later in 2023. In parallel, several research groups are updating their initial estimates, which is not accounted for here as these updates are not yet publicly available. All research groups listed here have had an opportunity to review this working paper, and their comments have been addressed according to the scope of this analysis.

Figure 1 provides a brief comparison of the reported CH_4 emission rates over the periods for which the measurements/analyses are valid. There are five sources of data that we have utilized (see additional details in the Annex):

- **Tower measurements**: Data gathered and postprocessed after applying various atmospheric data integration (“inversion”) methods, largely within the Integrated Carbon Observation System (ICOS) tower network[1] across the Baltic Sea (see Annex for details), from beginning of the event until the CH_4 signal was too weak for detection.
- **Satellite-based estimates**: Snapshot measurements from Sentinel-2B and the Canadian GHGSat (commercial) spaceborne instruments[2].
- **Aerial measurements:** A single day of two measurement flights by the German Aerospace Agency, Institute of Atmospheric Physics (DLR) and Technische Universität of Braunschweig (TUBS), commissioned by IMEO, that found methane emissions four days after the leak was declared closed by the Danish Energy Agency.
- **Engineering calculations**: Estimates of the volume of gas in the pipeline based on pipeline dimensions and conditions by 26 September and making the assumption that all gas escaped into the atmosphere (see Annex for details).

Note that *total emissions* from the incident are calculated as the sum of *emission rates* multiplied by the number of hours over which a measurement/estimate is valid to ensure the entire period of the emissions is included, not duplicated. As such, a total emission estimate cannot be reasonably calculated for each of the measurement approaches singularly, but rather have to be combined.

Emission rates across all estimate types span three orders of magnitude (approximately 50–4200 t CH_4/hr). Engineering estimates alone (solid lines) vary by a factor of 2.5. Tower-based estimates (dotted lines) vary by an order of magnitude. Reported empirically-based emission rates (i.e., tower, satellite, and aerial measurements) valid for the early days of the incident are notably higher than towards the end of the event, as would be expected. Specifically, average tower-based emission rates decline with increasing time horizon, and snapshot estimates towards the end of the incident were the smallest recorded, as anticipated. The pattern among the data sets is expected as the emission rates would be expected to fall as the pressure in the pipe fell.

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[1] The network consists of 39 tall tower and mountain measurement stations in 14 European countries measuring greenhouse gas concentrations and other parameters to study regional emission sources and sinks.

[2] Additionally, the Planet, Landsat-8, Sentinel-2, and Sentinel-1 satellites acquired images of the up to 0.7 km in diameter methane bubbles at the sea surface, but these were not used to quantify CH_4 emissions.

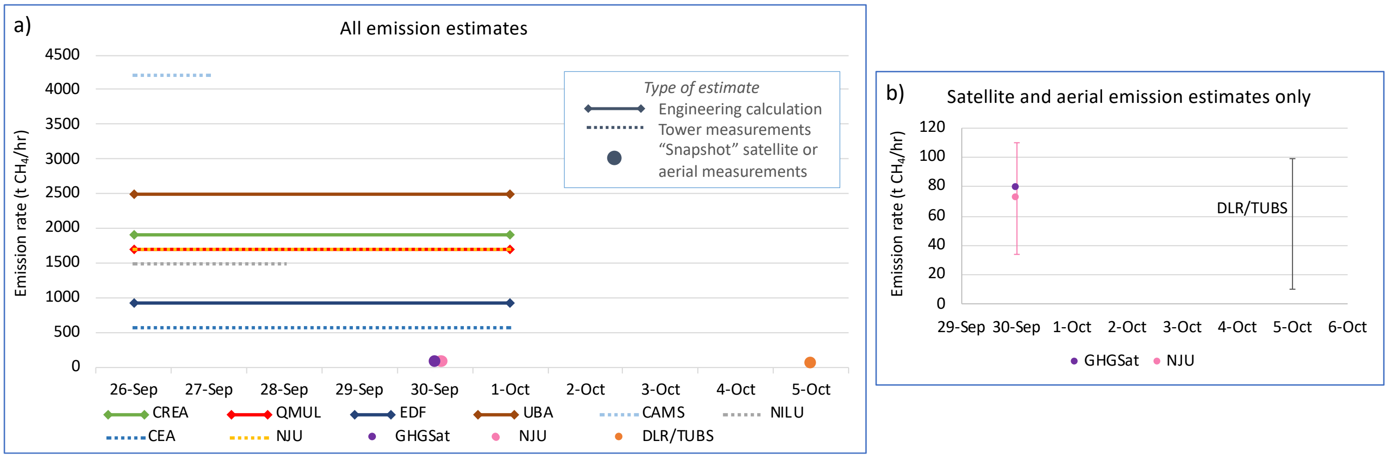

Figure 1. Reported CH_4 emission rates from different research groups and categorized by estimation method, plotted over the periods for which the measurements/analyses were reported valid. Panel a) summarizes all estimates (details and data sources as indicated in the Annex below). Panel b) presents the satellite and aerial emission estimates separately. See text and Annex for institution acronyms and detailed data. Note that each estimate (except for snapshots) is a temporal average over the reported periods, which ignores the exponential decay of the emissions over time. This simplification will be addressed in a future version of this working paper (see below).

Satellite estimates are smaller than any of the tower or engineering estimates. This suggests that satellite quantifications account for only the largest isolated plume(s), but not the full aerial extent of the emissions. The aerial estimate appears to confirm this hypothesis. The aerial estimate is based on in-situ measurements that were taken four days after visual bubbling largely subsided and five days after the satellite estimates, i.e., after emissions from a large, centralized plume must have declined substantially. Nevertheless, the aerial estimate accounts for a substantially larger spatial extent of the elevated CH_4 concentrations in the atmosphere (100s of km^2) compared to the satellite measurements. The aerial estimate thus integrates the locally detectable CH_4 signal over large areas, likely from the outgassing of saturated CH_4 in the surface water. Both factors – the temporal offset between the satellite and aerial estimates and the difference in spatial coverage – appear to offset each other, leading to similar snapshot emission rate estimates.

Considering the above characteristics of each emission *rate* estimate, the plausible range of *total* CH_4 emissions from the Nord Stream incident is 75–230 kt CH_4. We have not yet modeled the emission decline rate, and in this initial emission estimate we use best judgment to estimate emissions over time using all of the available data. The Copernicus Atmosphere Monitoring Service (CAMS) estimate is only valid for the first two days, and thus not representative for the average emission rate of the full incident. The German Environment Agency (UBA) engineering estimate appears biased high considering that it is (i) about 70% greater than the Norwegian Institute for Air Research (NILU) tower estimate for the first three (highest emitting) days and (ii) about 40% greater than the tower/satellite integrated estimate for the same period. This suggests a plausible range for the *average* emission rate (for the full incident) between France's Atomic Energy and Alternative Energies Commission (CEA) tower estimate (580 t CH_4/hr) and the CREA engineering estimate (1,900 t CH_4/hr), which is very close to the Nanjing University (NJU) tower estimate (1,700 t CH_4/hr). Integrating over the period of 26 September – 1 October yields a range of 70–230 kt CH_4. The aerial emission rate estimate from 5 October, extrapolated to the four days from 1 to 5 October, is about 5 kt CH_4. Adding these two time periods yields a plausible range of total emissions of 75–230 kt CH_4.

In summary, the plausible range of 75–230 kt CH_4 still contains substantial uncertainties which require further analysis to reduce. Of particular importance is the questions of microbial CH_4 consumption in the water column as well as CH_4 transport in the Baltic Sea before reaching the sea surface, both of these issues need to be explored further as part of the extended analysis. The present analysis highlights the complementarity of the various monitoring and estimation approaches for quantifying total emissions as well as the need to synthesize them into a coherent total emission estimate including uncertainties.

The plausible range of the average emission *rate* of 580–1,900 t CH_4/hr during 26 September – 1 October is substantially larger than measurements from any other single emission event observed publicly so far. For comparison, the largest "ultra-emitter" onshore plumes measured via satellites range from 0.1–500 t CH_4/hr. The plausible range of *total* emissions of 75–230 kt CH_4 is comparable with the Aliso Canyon gas storage well blowout in 2015 (~100 kt CH_4), but represents less than 0.1% of the global annual anthropogenic CH_4 emissions, and is equivalent to roughly one day of global oil and gas industry CH_4 emissions.

Annex: Data sources and references

Category	Group	Period valid for emission estimate	Emission Rate[a] (Tonnes/hour)	Total emission (Tonnes)[a]	Publication date	Notes	Reference
Tower measurement flux estimate	Copernicus Atmosphere Monitoring Service (CAMS)	NS2: 26 Sep 2022 00:00 to 28 Sep 2022 00:00 UTC NS1: 26 Sep 2022 18:00 to 28 Sep 2022 00:00 UTC	NS2: 2,700 (Duration 48 h) NS1: 1,500 (Duration 30 h)	175,000[b]	17 Oct 2022	Model simulations based on an estimated sourced strength compared to the atmospheric methane dry-air molar fraction measured by three ICOS stations in Sweden (Norunda, Hyltemossa) and Norway (Birkenes)	Atmosphere Monitoring Service
	Norwegian Institute for Air Research (NILU)	26 - 28 Sep 2022	1,500 (780 – 2,200)[c]	110,000[b] (56,000 - 160,000)	12 Oct 2022	Modeling using ICOS (Norunda, Hyltemossa, Birkenes, Utö-Baltic Sea) and NILU (Kjeller, Norway) observations, and initial pressure of gas in the pipelines	nilu.com
	France's Atomic Energy and Alternative Energies Commission (CEA)	Entire event	580[c]	70,000	5 Oct 2022	Calculation based on data from ICOS monitoring stations across Europe (sites not specified)	phys.org
	International Institute for Earth System Science of Nanjing University (NJU)	Entire event	Total: 1,700[c] (1,400 - 2,000)	Total leakage (M1): 220,000 (190,000-250,000)	26 Oct 2022	Inversion using ICOS data (Norunda, Hyltemossa, Birkenes, Utö-Baltic Sea)	sciencedirect.com
		26-27 Sep 2022	M1: 3,300 (2,800 - 3,800) M2: 2,500 (1,600 - 3,300)	Model 1: 160,000 (140,000-180,000) Model 2: 120,000 (80,000-160,000)			
Satellite measurement flux estimate	International Institute for Earth System Science of Nanjing University (NJU)	30 Sep 2022	72 (34-110) (Nord Stream 2)	(8,400[c])	26 Oct 2022	Inversion based on the Sentinel-2B observations	sciencedirect.com
	GHGSat	30 Sep 2022 10:28 to 12:56 UTC	79 (Nord Stream 2)	(9,500[c])	5 Oct 2022	Satellite observations	ghgsat.com
Aerial measurement flux estimate	German Aerospace Center (DLR), Technische Universität Braunschweig (TUBS)	5 Oct 2022	55 (10-99)[d] (preliminary)	6,600 (1,200 - 12,000)[c] (preliminary)	Unpublished	In-situ measurements from the HELiPOD sonde attached to a helicopter via a sling to evade potential helicopter rotor wash; two more flights occurred on 16/17 Nov with much lower CH_4 enhancements than on 5 Oct, analysis pending	Unpublished
Ship measurement flux estimate	Leibniz Institute for Baltic Sea Research Warnemünde (IOW)	To be determined	Data analysis not yet completed	Data analysis not yet completed	Unpublished	Regular measurements of methane concentrations in the surface waters through a ship-of-opportunity programme affiliated with ICOS	Unpublished
Engineering calculation flux estimate	Centre for Research on Energy and Clean Air (CREA)	Entire event	1,900 (1,500 – 2,200)[c]	230,000 (180,000 - 270,000)	29 Sep 2022	Method not reported	sciencealert.com
	Queen Mary University (QMUL)	Entire event	1,700[c]	200,000	4 Oct 2022	Calculation based on pipeline gas volume capacity	energyconnects.com
	Environmental Defense Fund (EDF)	Entire event	920[c] (Nord Stream 2)	120,000	30 Sep 2022	Calculation made based on pipe's dimensions and water temperature	nature.com twitter.com
	German Environment Agency (UBA)	Entire event	2,500[c]	300,000	28 Sep 2022	Calculation based on estimates of the filling level and volume of both pipelines	umweltbundesamt.de

Notes:

[a] All values rounded to two significant digits

[b] Estimation made for period listed in third column

[c] Calculations assume a period of 5 days for illustration purposes only, starting on September 26 and ending on October 1, when the leakage at the pipeline had reportedly ceased (Danish Energy Agency)

[d] Preliminary results reported to IMEO are "in the order of tens of metric tons per hour"