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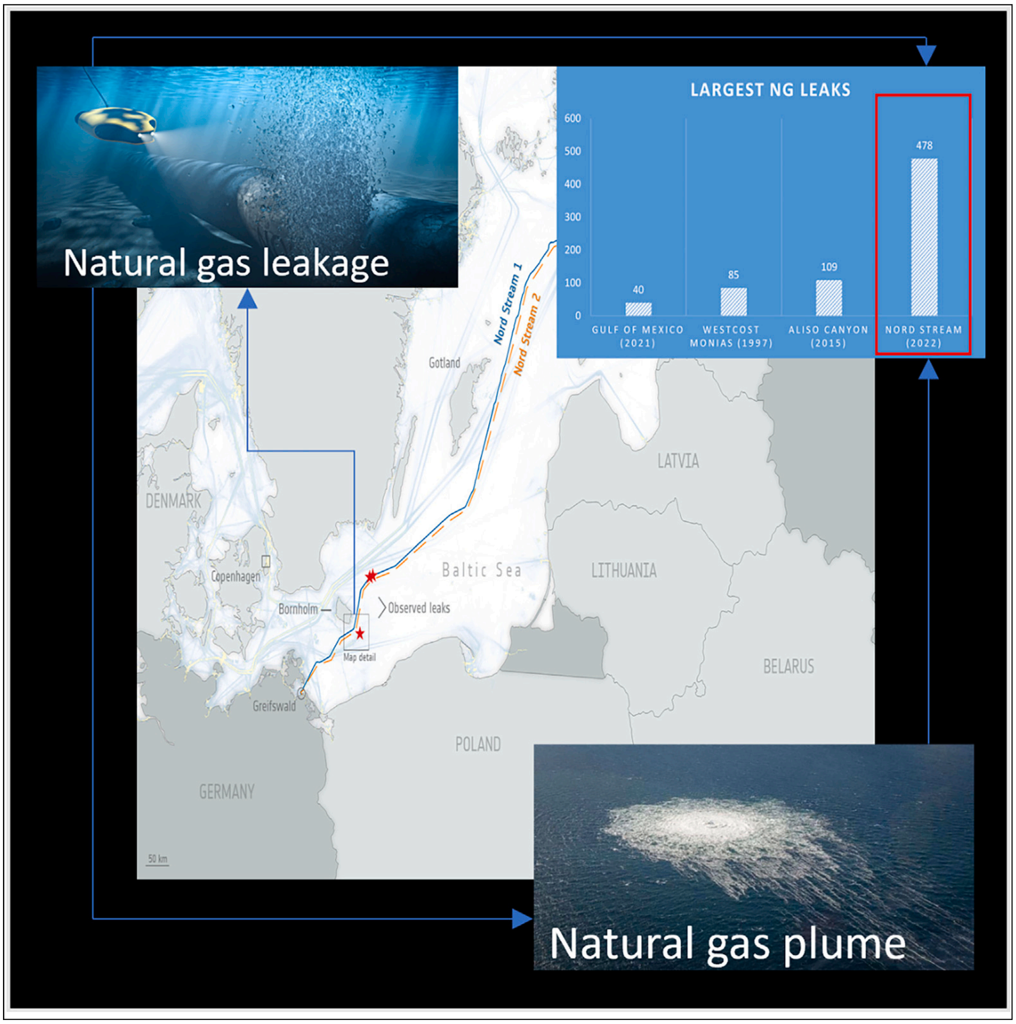

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Highlights

Nord Stream gas leaks released about 478,000 tonnes of methane into the atmosphere

The incident constitutes the largest single methane gas source in recent memory

The amount of gas and duration of the episode concur with other estimates

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World's largest natural gas leak from nord stream pipeline estimated at 478,000 tonnes

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SUMMARY

Methane is a potent heat trapping gas believed to account for 30% of the observed global warming to-date. At a capacity of 110 bcm/year, the Nord Stream (NS) pipeline corridor measuring 1,153mm in internal diameter and stretching 1,224km from Russia to Germany is the biggest in the world. The explosions that NS sustained in September, 2022, in the Baltic Sea, have unleashed the largest single methane gas source in recent memory. Over the course of 7 days, our transient multiphase pipeline model has estimated that the gas leaks from 3 lines pumped 478,000 tonnes of methane into the atmosphere. A range of pipeline shut-in pressures as a function of leakage time deduced an envelope of gas volume that matched the timeline of observed outflows. Interestingly, the methane gas that escaped from the damaged threads amounted to the CO_2 equivalent emitted by concrete sufficient to build about 27 Burj Khalifa towers.

INTRODUCTION

Nord Stream (NS) consists of four offshore export lines which cross the Baltic Sea and, until recently, used to source Russian natural gas to Germany. At a capacity of 110 billion cubic meters per year, the NS1 and NS2 pipeline system exhibiting an internal diameter of 1,153mm and stretching some 1,224 km is the largest in the world,[1] as shown in Table 1. Bypassing Ukraine, the gas corridor's NS1 and NS2 twin pipelines were laid to supply.

Europe with abundant and inexpensive natural gas. More specifically, NS had the potential to meet about 25% of the European Union (EU) future energy needs.[2] Serving European customers, NS was transporting gas directly to countries and customers where demand is vibrant, such as, Germany, Netherlands, Belgium, France, and the Czech Republic. At a price tag of $25 bn, the NS constitutes one of Europe's biggest energy projects.[3]

A notice issued by the Geological Survey of Denmark, on the 26th of September, 2022, which alluded to three submarine explosions that occurred at three distinct locations helped pinpoint the time and location of the three NS1 and NS2 leaks.[4] More specifically, the first blast tied to NS2 was registered at 02:03a.m. Central European Summer Time (CEST) while the second and third events, linked to NS1, were recorded at 07:03p.m. CEST time.[4,5] Subsequently, the Danish Airforce identified the geographical location of the NS2 leak, which affected line A, as being southeast of the Bornholm Island. Shortly after the last two blasts, the Swedish authorities traced two sea-surface gas plumes in lines A and B, of the NS1 pipeline system, transcending the Danish-Swedish Exclusive Economic Zones (EEZs). Media reports stated that the ruptures on the NS natural gas pipelines have led to what was likely the biggest single release of methane into the atmosphere ever recorded. According to the Danish Energy Agency's preliminary estimates the amount of methane from the damaged pipelines was equivalent to about 0.1% of the annual global methane emissions.[6] Images released by the Swedish Coast Guard revealed a large ring of methane bubbles at the sea surface emanating from a submarine pipeline leak.

Methane gas is estimated to be responsible for approximately 30% of global warming. It is also widely accepted that methane is 25 times more potent as a heat trapping gas than carbon dioxide (CO_2) over a 100-year time horizon. Even though CO_2 has a longer-lasting effect, methane sets the pace for warming in the near term. For these reasons, over 100 countries have pledged to curb their methane footprint to 30%, by 2030, compared to 2020 levels.[7]

Accurately estimating the quantity of methane that escaped into the atmosphere is essential for appreciating the climate change impact of the incident. Several attempts were made by the Copernicus Atmosphere Monitoring Service (CAMS), the Laboratoire des Sciences du Climat et de l'Environnement (LSCE), and the Norwegian Institute for Air Research (NILU) to calculate the amount of methane that reached the atmosphere from NS. Input data pertaining to methane concentrations derived from satellite observations and land measuring stations. Considerable variability in methane levels underlined the complexity behind the efforts to deduce the amount of methane from NS1 and NS2 in the context of a restricted number of accurate observations.

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Table 1. Nord Stream 1 and Nord Stream 2 offshore pipeline particulars

	Nord Stream 1	Nord Stream 2
Pipeline diameter	48 inches (1,153mm, ID[a])	48 inches (1,153mm, ID[a])
Number of lines	2	2
Commissioned	Line A, 8th Nov. 2011; Line B, 8th Oct. 2012.	–
Capacity (bcm/y)	55	55
Natural gas volume (NS1 lines A + B, NS2 line A) (mcm)	800	
Max. seawater depth (m)	180	180
Working pressure (bars)	220	220
Offshore pipeline length (km)	≈1,224	≈1,224
Material	Concrete coated carbon steel	Concrete coated carbon steel
Date and onset of leakage(s) (CEST)	26/09/2022 at 19:03 (Line A and Line B)	26/09/22 at 02:03a.m. (Line A)
Duration of leakage(s)[b]	About 7 days	About 5 days

[a]Internal pipeline diameter.
[b]Based on pressure stabilization.

RESULTS

In light of the sheer dimensions of the offshore NS 1 and NS 2 pipelines which measure 48 inches (1,153 mm internally) in diameter and 1,224 km long, the four lines can hold significant volumes of natural gas (Table 1). A defining factor, which governs the pipelines' inventory gas was their shut-in pressure. In conjunction with the extensive damage that the three pipelines sustained, our flow model indicated that the conduits almost fully emptied their inventory of about 523 kilotonnes of natural gas at the seabed of which 478 kilotonnes of gas reached the atmosphere. Video footage from the NS1 pipeline has revealed widespread destruction to the ruptured pipeline with a missing section deemed to stretch about 50 m.[8] Worth emphasizing that if a pipeline section went missing then gas was liberated from both the upstream and the downstream legs of the line thereby accelerating the discharge rate (Figure 1). Concurrently, seawater started flooding the lines. Both NS1 and NS2 inner pipeline gas pressures of 175 bars and 105 bars, respectively, outweighed the hydrostatic pressure of 9 bars at a seawater depth of 80 m where the damage occurred (Figure S1). A simultaneous efflux of gas out of the conduits progressively led to a drop in the internal gas pressure while allowing an increasingly larger volume of seawater to flood the line. Water ingress in the pipelines was also affected by the seabed bathymetry and topography. Pipeline sections which lay at shallower water depths, compared to the gas leakage sites, acted as bottlenecks to the propagation of gas within a pipeline and its eventual release into the sea. Fluid turbulence triggered by the violently bubbling natural gas from the pipeline in the opposite direction to the seawater influx has also induced a pressure drop to the entrained gas.

The world's largest single methane leak incident

To determine the amount of methane that escaped from NS2, line A, and NS1, lines A and B, into the sea, the developed model proposed here considered different attributes such as a range of gas shut-in pressures, gas inventory, water flooding, and the size of the leaks. Because of the compressible nature of methane, changes in the gas volume due to pressure variations were determined from Peng-Robinson's equation of state.[9] Seawater compressibility was also taken into account even though within the working pressure of the NS pipelines its volume shrinks by a mere 1%.[10] Subject to a parametric investigation, the gas pressure range in the pipeline was progressively lowered from 220 bars to 20 bars, the former of which constitutes the operating pressure of the lines. Gas temperature in the pipelines was considered isothermal, at 4°C,[11] for the course of the gas flow. Even though subsea pipeline isolation valves are instrumental for controlling fluid flow during a pipeline leak event yet risks related to their malfunction constrain their deployment. Presumably, devoid of such block valves, the NS pipelines neither did they contain the amount of gas that escaped from the threads nor water flooding the conduits.

Drawing from various *in situ* observations, the damage to NS1 line A appeared catastrophic as entire sections of the line were destroyed.[8] Aerial video footage has revealed that the gas plume apparently, from NS1 line A, occupied about 1 km in diameter while the smaller one, from NS1, line B, stretched approximately 200 m.[6] Thus, the size of a leak was taken to be the same as the pipeline's internal diameter. Based on our calculations, a maximum of 4% of methane would have dissolved in the water column while the gas emerged from the seabed to the water surface. As far as the amount of methane that the NS1, lines A and B and NS2 line A spewed into the atmosphere, it was determined in the context of a systematic evaluation as a function of the gas leakage duration, as shown in Figure 2. Depending on the gas inlet pressure, the modeling effort was able to deduce the amount of methane released from all three pipelines with respect to the gas seepage, as displayed in Figure S2. Because the details concerning the use of cut-off valves at the NS pipeline system are not publicly available, we have examined various scenarios tied to their use that provide useful information about the gas leak. As illustrated in Figure S3, if the subsea isolation valves were placed at 50 km, 100 km, 200 km, and 300 km from each end of the NS upstream and downstream touch points, the volume of the gas leak would have decreased precipitously. As this was not the case in the actual episode it, therefore, refutes the claim that the pipelines were fitted with shut-down valves, or they have malfunctioned.

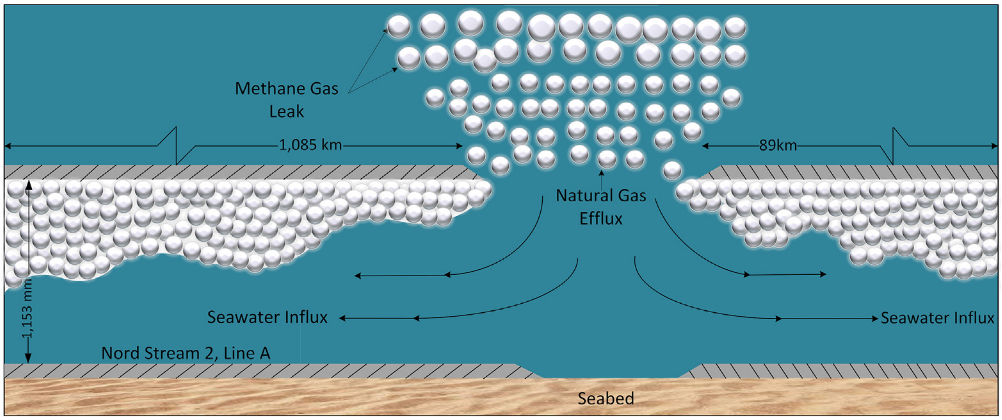

Figure 1. Rendering of a breached cross-section of the Nord Stream 2 pipeline displaying the concurrent leakage of gas out of the pipeline and the line seawater flooding during the early stages of the leak Drawing not to scale

Collectively, the spills from the three Nord Stream damaged pipelines pumped into the atmosphere 478,000 tonnes of methane gas. Overall, the twin leaks from NS1 lines A and B discharged about 388,000 tonnes of methane at the seabed, at a shut-in pressure of 175 bars, during 7 days. Over 5 days, NS2 line A, at a shut-in pressure of 105 bars, released 110,000 tonnes of methane at the seafloor. Internal pressure in all 3 pipelines stabilized as soon as the inner pipeline pressure matched the ambient seabed water pressure of about 9 bars. Water hold-up in the pipelines did not appear to fundamentally influence the gas efflux from the conduits.

Comparative size of methane leaks

Shortly after the news about the pipeline bursts spread at the end of September, 2022, many teams of scientists rushed to estimate the outflow of natural gas from the damaged pipelines with figures displaying considerable variability from 36,000 tonnes[12] to 500,000 tonnes.[13] Notably, some of the methane gas leak volume estimates were deduced from crude approximations which were announced through press releases,[14] interviews with experts[13] while others factored in atmospheric or satellite observations[15,16] and onshore measurements.[12]

CAMS calculated that, during the first two days of the gas leak, the pipelines discharged 175,000 tonnes or 60% of their entrained methane (Table 2). Methane concentration was obtained from a transport and dispersion model, which took into account a constant gas source strength.[15] Model validation involved comparing simulated methane levels with atmospheric dry-air methane molar fraction measured at various observation stations operated by the Integrated Carbon Observation System (ICOS). According to CAMS, determining the concentration of methane in the atmosphere by Sentinel 5P, Sentinel 2 and Sentinel 3 satellites over the sea is a challenging task mainly owing to the reduced light reflectance compared to land masses. Compounding visibility, dense clouds over the area during the first two days of the incident impaired the satellites' remote-sensing capabilities. As a result, the main observations made available during the first two days of the natural gas discharge originated from four ICOS sites. These simulations utilized emission rates of 1,500 and 2,700 tonnes of methane per hour for the NS1 and NS2 pipelines, respectively.

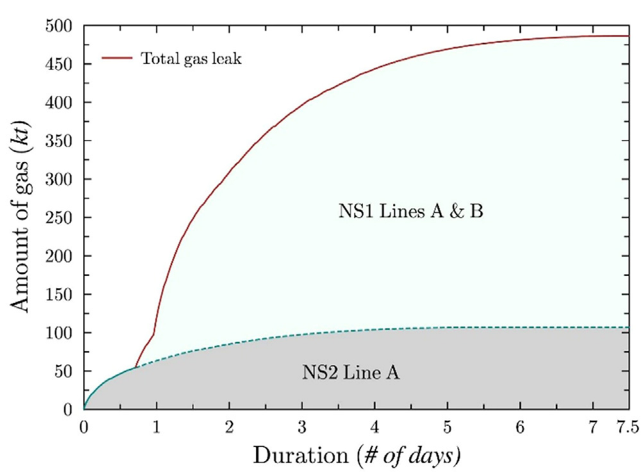

Figure 2. Aggregate leakage of natural gas, in kilotonnes (kt), from the Nord Stream 1 and 2 pipelines as a function of time, in days

Table 2. Overview of different methane leakage estimates

Method	Source	Measurement approach	Duration (days)	CH_4 leakage (tonnes)
Multi-phase pipeline modeling (This study)	Marine & Carbon Lab	A multi-phase pipeline model estimated the amount of leaked methane at the point of rupture.	7	478,000
Satellite and ground measurements	CAMS/ICOS	Combination of satellite and ground methane remote measurements tied to gas.[15]	2	175,000
Atmospheric remote sensing (offshore stations)	LSCE	Ground based spectrometers use sunlight and its attenuation to estimate methane concentration.[19]	5	70,000
Atmospheric remote sensing (offshore stations)	NILU	Ground based spectrometers use sunlight and its attenuation to estimate methane concentration.[11]	7	36,000 – 155,000
Satellite remote sensing	GHGSAT	Satellite methane remote measurements tied to 3 gas plumes.[16]	Hourly	22,920 kg/h, 79,000 kg/h
Satellite & atmospheric remote sensing	Nanjing University	Inversion algorithms & meteorological reanalysis dataset supplemented by satellite and atmospheric remote sensing to calculate the total methane mass that leaked to the atmosphere.[17]	6	220,000 ± 30,000
–	Danish Energy Agency	Danish agency estimated that the escaped methane was equivalent to 0.1% of the annual emission of methane.[14]	–	370,000–500,000
–	PBS News	Reported amount of CH_4 was 5× the size of gas released from Aliso Canyon underground gas storage leak— largest terrestrial release of gas in US history.[13]	–	500,000

Jia et al.[17] based their methane leak estimations on surface *in situ* observations using two inversion methods and two meteorological reanalysis datasets, supplemented with satellite observations. Similar to CAMS, the Jia et al.[17] investigation utilized ICOS methane concentrations from 4 sites, namely, Norunda and Hyltemossa in Sweden, Birkenes in Norway, and Uto in Finland. CAMS estimated that 175,000 tonnes of methane were released in two days, however, Jia et al.[17] calculations allude to 159,000 ± 21,000 tonnes and 119,000 ± 39,000 tonnes during the same period. Meanwhile, the CAM study emphasized the necessity for future research to address issues related to satellite observations, particularly in avoiding potential artifacts stemming from the presence of bubbles. Recognizing the inherent limitations and uncertainties, the CAMS team put the gas release mass to 220,000 ± 30,000 tonnes.

Other estimates by GHGSAT, on September 30, 2022, refer to a methane flow rate between 22,290 kg/h and 79,000 kg/h. Noteworthy, Sentinel 2 and GHGSAT satellites possess the same spatial resolution of 25m by 25m.[18] LSCE and NILU utilized offshore measurements to deduce the amount of methane that escaped into the atmosphere. Although the LSCE and the NILU applied the same approach, their figures pertaining to the leaked amount of methane are different. LSCE projected that, over five days, the mass of natural gas which dispersed in the air amounted to 70,000 tonnes. In contrast, NILU determined that the mass of released natural gas ranged between 36,000 and 155,000 tonnes, during seven days (Table 2). NILU estimates, which spanned 7 days, match the duration of the gas episode calculated in this study. A press release by the Danish Energy Agency mentions that the amount of released natural gas ranged between 370,000 and 500,000 tonnes, which is equivalent to 0.1% of the world's annual emissions of methane. Finally, PBS News reported that the NS leak was the largest natural gas leak in history. Clearly, the broad range of variability in the estimates of the NS gas leak, which extended from 36,000 to 500,000 tonnes, makes it difficult to pin down the exact magnitude of the gas release. To more accurately determine the amount of gas that escaped from the damaged NS pipelines, herein we present a fluid mechanics pipeline model, which considers the pertinent physics.

Validation of model results

Validation of the dynamic model results was conducted in the context of four parameters: (1) the amount of gas, (2) the duration of the gas leak, (3) the pipeline pressure stabilization, and (4) the comparison between the quasi-analytical and the numerical results (Table 3). CAMS estimates were obtained from a transport and dispersion atmospheric model. During the same 2-day period, the dynamic pipeline model proposed here projected that nearly 63% of the gas stored in the NS1 and NS2 defunct pipelines was discharged into the water. Therefore,

Table 3. Summary of the four pipeline model validation comparisons

Parameter	Entity	This study	Magnitude and source
1) Total amount of gas	NS1 lines A & B and NS2 line A	63% of gas leaked during days 1 & 2	60% of gas leaked during days 1 & 2; CAMS(15)
2 (i)) Duration of gas leak	NS1 lines A & B	7 days	7 days; Nord Stream AG(19)
2 (ii)) Duration of gas leak	NS2 line A	5 days	5 days; Danish Energy Agency(14)
3) Pressure stabilization	NS1 lines A & B and NS2 line B	9 bars	7 bars; Nord Stream AG(19)
4) a)Amount of gas b) Duration of leak	Nord Stream2 line A	≈60% of gas leaked during first 2 days	Computational model (this study)

these findings serve as a cross-verification for both models. In addition, mapping the temporal release of methane from the NS1, line A, and the NS2, lines A and B, the pipelines ceased leaking gas after about 7 and 5 days, correspondingly.[14,19] Thus, our results concur with field observations alluding that NS1, lines A & B, and NS2, line A, stopped gas efflux 7 days and 5 days, respectively, after the pipeline ruptures. Equally important, the pressure drop in the NS1 and 2 pipeline threads stabilized to about 9 bars which almost matches the 7 bars terminal pressure reported by the NS AG operator.[20] Taken together, the preceding findings lend credibility to our calculations that the three pipelines spewed some 478,000 tonnes of methane into the air. A computational model was also used to further scrutinize the validity of the quasi-numerical model results. Developed in the COMSOL multi-physics solver, the model considered the concurrent release of methane and water flooding from a ruptured pipeline section. Almost matching the amount of natural gas and the duration of the gas leaks, as shown in Table 3, this line of validation adds further trustworthiness to the findings presented herein.

DISCUSSION

A closer inspection reveals that the gas flow rate out of the pipelines was more pronounced in the first 48 hours after the pipeline ruptured, during which 63% of the gas left the tubes. This behavior is expected considering the high-pressure difference between the inlet gas and the ambient seawater hydrostatic environment. With a rapidly depleting gas pressure, more seawater entered the pipelines. At its peak volume, the pipeline water hold-up spanned some 12 km upstream and 38 km downstream of the cracked pipeline toward Russia. Perhaps attributed to the particularly mobile nature of methane, the line water hold-up did not seem to precipitously slow-down the gas discharge. In other words, water hold-up in the pipelines did not seem to have acted as a barrier for retaining a considerable methane volume in the lines. Another interesting observation from the pipeline model relates to the mobility of methane in the water. By virtue of being a gas in conjunction with its small solubility in water, almost all gas bubbles that entered the water reached the atmosphere.

From the environmental standpoint, the powerful heat trapping capabilities of methane are a major concern especially for climate change. To put things into perspective, the volume of gas that was released from Nord Stream equated to the amount of CO_2 equivalent emitted by concrete sufficient to build about 27 Burj Khalifa towers. Vitally important to mitigate environmental harm from other shut-in pipelines including NS2 intact line B, it is important to keep the inventoried gas pressure to an absolute minimum of about 20 bars.

Conclusion

In this study, we developed a sophisticated multi-phase quasi-numerical pipeline *in situ* model. Primarily, the objective was to devise a robust methodology for accurately deducing the volume of natural gas released from the three ruptured pipelines while factoring the actual conditions surrounding the incident. The results of our analysis demonstrated that 478,000 tonnes of methane had been released into the atmosphere, cementing the NS leakage as the largest of its kind globally. Our approach integrates cutting-edge computational techniques with actual parameters to provide a comprehensive understanding of gas dispersion and release dynamics. By harnessing the capabilities of OLGA,[22] we were able to simulate intricate scenarios, enabling us to make precise estimations regarding the extent of the gas leak. Not only does the model shed light on the magnitude and characteristics of the Nord Stream incident but could also help corroborate other estimates derived from remote sensing and other approaches exhibiting other uncertainties. Gazing at the future, as the effects of climate change become more pronounced there is a pressing need to more accurately account for the various sources and the amount of heat trapping emissions such as methane leaks. Hence, a combination of *in situ* measurements, modeling, aerial, and remote sensing probing techniques are envisioned to prove instrumental in tackling climate change related gases. Besides epitomizing the perils of wars, the Nord Stream pipeline episode has emphasized the need to implement design measures in critical infrastructure facilities intended to mitigate the environmental impacts of future catastrophic failures.

Limitations of the study

Because of the unknown composition of the Russian gas stored in the Nord Stream pipeline system and the fact that natural gas predominantly consists of methane, we assumed that the inventoried gas was made of methane. Another study assumed a methane fraction for the NS pipeline system of 0.965.[17] Seawater and gas temperature considered in the OLGA model were kept constant at 4°C, omitting any potential fluctuations in temperature. Furthermore, the internal diameter of the 3 modeled pipelines was taken uniform throughout the pipeline route, at 1.153 m (48 inches), thus enabling pigging operations. Pipeline internal roughness which governs the pipeline flow characteristics, pressure drop, and operational expenditure was assumed to be 45 microns. Pipeline geometry was also assumed to be circular in the absence of any dents or ovalization. Considering dry natural gas, no gas hydrates were assumed to form during the gas leakage incident.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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  - Data and code availability
- METHOD DETAILS
  - Nord stream 1 and 2 pipeline models

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.108772.

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AUTHOR CONTRIBUTIONS

K.P.: methodology, software, formal analysis, investigation, data curation, writing–original draft. J.S.: conceptualization, methodology, validation, writing–review and editing, visualization. C.H.: conceptualization, methodology, validation, writing–review and editing, supervision.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software & algorithms		
OLGA	Schlumberger	www.software.slb.com/products/olga
Microsoft Visio	Microsoft	www.microsoft.com/en/microsoft-365/visio/flowchart-software/

RESOURCE AVAILABILITY

Lead contact

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Materials availability

This study did not generate new unique reagents.

Data and code availability

Data: No new data were generated.
Code: No codes were generated.
Any additional information is available from the lead contact upon request.

METHOD DETAILS

Nord stream 1 and 2 pipeline models

Given that natural gas predominantly consists of methane, it was assumed that the idle gas in the Nord Stream 1 and Nord Stream 2 pipeline threads while shutdown, but still pressurized, consisted of dry methane with specific gravity of 0.55. At the time of the explosions each of the two NS1 branches was demonstrated in this study to contain 302 million standard cubic meters (mscm) of methane at an absolute pressure of 175 bars. Line A of Nord Stream 2 hosted 200 million scm, at a pressure of 105 bars.[8,20] These figures are consistent with the 800 million cubic meters of natural gas that the 3 threads stored, as announced, at the UN, by Gazprom.[21] To enable pipeline pigging, the Nord Stream pipeline system exhibits a uniform internal diameter of 1,153 mm. Owing to the virtually identical characteristics of NS1, lines A and B, and NS2, legs A and B, a dynamic pipeline model was developed stretching 1,224 km. Both pipeline models considered the seawater bathymetry of the Baltic Sea from Russia to Germany in almost two identical routes, as illustrated in Figure S1. Seawater depth along the two paths averaged 63 m while the deepest point the pipelines crossed was 180 m below the sea-level at about half-way between the inlet and the outlet of the pipelines' offshore sections.

Utilizing published data, the length of the NS1, line A, gas leak, Southeast of the Bornholm Island, lied some 140 km from Lubmin, Germany. Similarly, the ruptures inflicted at NS2, line A and line B, resided about 220 km from the same gas delivery point, at Lubmin. Developed in OLGA fluid dynamics suite,[22] the pipeline transient model considers a two-fluid system, that is, the transport of natural gas upstream and downstream of the leaks to the discharge point and the admission of seawater from the same location. Capturing the mechanics of water and natural gas, the multi-phase flow model considered two separate mass transport equations for seawater and gas generalized as:

$$\partial_t m_i + \partial_z (m_i U_i) = \sum_j \Psi_{ji} + G_i \quad \text{(Equation 1)}$$

where U_i the mass field velocity, Ψ_{ij} denotes the rate of mass transfer between the seawater and the natural gas mass systems and G_i constitutes a mass source/sink. Likewise, two momentum balance expressions were considered for the continuous water phase and the modeling of gas liquid droplets, concisely denoted by:

$$\partial_t (m_i U_i) + \partial_z \left(m_i U_i^2\right) = m_i \cdot g \cdot cos(\varphi) + P_i + G_i U_i + \sum_j \left(\Psi_{ji}^{+} U_j - \Psi_{ji}^{-} U_i\right) + \sum_j F_{ji}^{I} \left(U_j - U_i\right) - F_i^{w} U_i \quad \text{(Equation 2)}$$

where φ is the pipe angle, P_i is the pressure force, and Ψ_{ji}^{+} & Ψ_{ji}^{-} refer to the net contribution emanating from mass field i to j and mass field j to i, respectively. Here, F_{ji}^{I} accounts for the frictional forces between the i-th and j-th mass field whereas F_i^{w} is the wall friction. Besides determining the volume of the fluids, the transient model considered the following energy balance equation:

$$\partial_t (m_i E_i) + \partial_z (m_i U_i H_i) = Q_i + \sum_j T_{ij} E_j + S_i \quad \text{(Equation 3)}$$

Term H_i is the field enthalpy, E_i refers to the field energy, Q_i represents the heat flux through the pipe wall, symbol T_{ij} denotes the energy transfer between the fields and, finally, S_i is an enthalpy source/sink.[22] Having imposed appropriate boundary and initial conditions, the preceding equations were linearized and solved with the aid of a sequential solution scheme. Depending on the simulation, a time step between 0.1s to 5s was used to solve the preceding expressions. Supporting the pipeline model constructed in OLGA, the pressure, volume, and temperature (PVT) attributes of methane and water were obtained from Multiflash thermodynamics fluid tool. Utilizing the OLGA High Definition (HD) stratified flow model, it was possible to gain more accurate and detailed insights of the fluid mechanics of the pipeline model. Gas leakage from the Nord Stream pipeline was replicated by a rupture point which in one of the incidents was placed about 1,000 km from the Russian upstream location, with water flowing at a speed of 0.5 m/s. Finally, the seawater column considered the backpressure from the hydrostatic head. Readers interested in the OLGA fluid correlations can consult the software manual.[22]