Technology Assessment

Methane Detection, Quantification, and Inspection Technologies for the LDAR Programme

Under EU Regulation 2024/1787

Prepared for

Gas Networks Ireland

Prepared by

SurveyLabs Ireland

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Changelog

v1.0	Feb 2026	Initial release of the report.
V2.0	April 2026	Added S3.5 Compliance Decision Framework) and S5.5 (Satellite-Based Detection); regulatory status updated for H1 2026 developments; consistency and editorial corrections.

Contents

Table of Figures

Table of Tables

Abbreviation	Definition
3DGS	3D Gaussian Splatting
3LPE	Three-Layer Polyethylene
AGI	Above Ground Installation
ASME	American Society of Mechanical Engineers
ATEX	Atmosphères Explosibles (EU Directive 2014/34/EU for equipment in explosive atmospheres)
BSI	Back-Side Illuminated (sensor architecture)
BVLOS	Beyond Visual Line of Sight
CEN	European Committee for Standardization (Comité Européen de Normalisation)
CH_4	Methane
CMOS	Complementary Metal-Oxide-Semiconductor
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CRDS	Cavity Ring-Down Spectroscopy
CRU	Commission for Regulation of Utilities
DAS	Distributed Acoustic Sensing
DEM	Digital Elevation Model
DIAL	Differential Absorption LiDAR
DNV	Det Norske Veritas
DRI	District Regulating Installation
DSM	Digital Surface Model
DSO	Distribution System Operator
DTM	Digital Terrain Model
DTS	Distributed Temperature Sensing
EGIG	European Gas Pipeline Incident Data Group
EPA	Environmental Protection Agency (Ireland unless otherwise specified; US EPA where stated)
ESG	Environmental, Social, and Governance
EU	European Union
FBE	Fusion-Bonded Epoxy
FID	Flame Ionisation Detector / Detection

Abbreviation	Definition
FMCW	Frequency-Modulated Continuous-Wave
GCP	Ground Control Point
GERG	Groupe Européen de Recherches Gazières (European Gas Research Group)
GIS	Geographic Information System
GML	Gas Mapping LiDAR
GNI	Gas Networks Ireland
GPS	Global Positioning System
GSD	Ground Sample Distance
GWP	Global Warming Potential
IAA	Irish Aviation Authority
IGEM	Institution of Gas Engineers and Managers
InSb	Indium Antimonide
IPCC	Intergovernmental Panel on Climate Change
I.S.	Irish Standard
ITM	Irish Transverse Mercator
LDAR	Leak Detection and Repair
LEL	Lower Explosive Limit
LiDAR	Light Detection and Ranging
LLM	Large Language Model
LNG	Liquefied Natural Gas
MARCOGAZ	Technical Association of the European Natural Gas Industry
MEMS	Micro-Electro-Mechanical Systems
METEC	Methane Emissions Technology Evaluation Center
MIR	Mid-Infrared
ML	Machine Learning
MOS	Metal Oxide Semiconductor
MVS	Multi-View Stereo
NDIR	Non-Dispersive Infrared
NeRF	Neural Radiance Fields
NIR	Near-Infrared
NSPS	New Source Performance Standards (US)

Abbreviation	**Definition**
OGI	Optical Gas Imaging
OGMP	Oil and Gas Methane Partnership
OTM	Other Test Method (US EPA designation)
OTDR	Optical Time-Domain Reflectometry
Pd	Probability of Detection
PE	Polyethylene
PHMSA	Pipeline and Hazardous Materials Safety Administration (US)
PID	Photoionisation Detector
QA	Quality Assurance
QC	Quality Control
QOGI	Quantitative Optical Gas Imaging
RGB	Red, Green, Blue (visible-light imaging)
RMLD	Remote Methane Leak Detector
ROW	Right of Way
RTK	Real-Time Kinematic (GNSS positioning)
SAM	Segment Anything Model
SfM	Structure-from-Motion
SLB	Schlumberger
SnO_2	Tin Dioxide
TDLAS	Tunable Diode Laser Absorption Spectroscopy
TIN	Triangulated Irregular Network
TRL	Technology Readiness Level
TSO	Transmission System Operator
UAV	Unmanned Aerial Vehicle
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UV	Ultraviolet
VMC	Visual Meteorological Conditions
YOLO	You Only Look Once (object detection architecture)

Units of Measurement

Unit	Definition
g/hr	grams per hour
kg/hr	kilograms per hour
ppm	parts per million (volumetric concentration)
ppb	parts per billion (volumetric concentration)
ppm·m	parts per million–metre (path-integrated concentration)
µm	micrometre (10^{-6} m)

EXECUTIVE SUMMARY

Under EU Regulation 2024/1787, Gas Networks Ireland must implement a mandatory leak detection and repair (LDAR) programme, quantify source-level methane emissions, submit annual reports to authorities, and phase out routine venting and flaring. This report evaluates the detection, quantification, and inspection technologies available to support the programme, identifying current and future state-of-the-art systems capable of meeting these increasingly rigorous obligations.

The central finding is that GNI's existing survey approach, walking surveys with handheld TDLAS and FID instruments at accessible point assets, vehicle-mounted CRDS surveys on the distribution network, and manned helicopter flights for transmission corridor surveillance, provides a sound and defensible foundation. The technologies currently deployed are the most mature available (TRL 9), carry the strongest regulatory precedent, and satisfy the Regulation's Article 14 detection thresholds at accessible locations. No wholesale change of approach is required. The programme enhancements identified by this assessment are targeted additions that extend compliance coverage to areas the current approach does not fully reach, and that build the measurement-based dataset needed for Article 12 emissions reporting.

GNI already incurs substantial expenditure on aerial surveillance of the transmission corridor under I.S. 328:2021. Mounting a gimballed open-path TDLAS sensor and a high-resolution RGB camera onto these existing flights would extract additional operational value from that expenditure, delivering supplementary methane screening for significant emission sources and systematic corridor documentation for encroachment monitoring and condition assessment alongside pipeline surveillance compliance. At I.S. 328 surveillance altitudes of 500 feet (150 metres), helicopter-mounted TDLAS does not achieve the detection sensitivity required for Article 14 Type 1 (17 g/hr) or Type 2 (500ppm) compliance but provides a prioritisation layer that directs subsequent ground-based and drone compliance surveys to the locations most likely to require attention. This avoids creating a parallel flight programme solely for screening purposes and extracts value from flying hours already being incurred.

For the approximately 1,100 AGIs, DRIs, and regulating stations that make up the bulk of GNI's survey workload, walking FID and closed path TDLAS remain the right tools. These are accessible, component-dense sites where handheld instruments are proven and where GNI's existing workforce capability is strongest. The near-term enhancement at these locations is not a change in detection method but a change in what happens after a leak is found: confirmed detections should now be quantified within the repair window, through high-flow sampling at significant leaks and measurement-informed emission factors built from representative sampling for the remainder, to produce the emission rate data that Article 12 requires.

At compressor stations and CNG units, where the Regulation imposes the highest survey frequencies and where both detection and quantification are needed in a single visit, Quantitative Optical Gas Imaging offers a practical solution, providing simultaneous Article 14 detection and Article 12 quantification from one instrument.

For the parts of the network that cannot be reached by walking or vehicle survey, river crossings, bridge-mounted pipelines, elevated infrastructure, UAV-mounted TDLAS addresses a genuine access gap. Previous surveys using the UAV mounted TDLAS platform provides direct operational evidence of this capability in the Irish context. The same UAV deployments can incorporate photogrammetric structural inspection, delivering dual-purpose sorties that address both methane detection and the structural condition assessment requirements of I.S. 328:2021. This is particularly valuable at bridge crossings, where conventional inspection has repeatedly been unable to fully assess the most degradation-prone elements due to access constraints.

Beyond site-specific access, drone mounted open path TDLAS represents the most viable aerial pathway to Article 14 Type 1 and Type 2 compliance for the transmission corridor. Operating at 25–50 metres altitude, drone TDLAS achieves detection sensitivity at both regulatory thresholds (17 g/hr for Type 1 and 500 ppm for Type 2), a capability that cannot be matched by helicopter-mounted systems at I.S. 328 surveillance altitudes. As BVLOS regulatory approvals progress under the EU U-space framework, drone TDLAS is positioned to transition from site-specific deployment to recognised compliance survey method for transmission pipeline corridors, with emerging quantification workflows also offering a potential Article 12 pathway.

On the distribution network, vehicle mounted CRDS provides the primary survey pass for network wide LDAR coverage, consistent with the compliance methodology now deployed by over 50 European DSOs, including Italgas, Cadent, and Netz Niederösterreich, in response to EU Regulation 2024/1787. Coverage rates an order of magnitude faster than walking surveys enable systematic coverage across more than 12,000 km of predominantly urban and suburban pipeline within the survey frequencies the Regulation requires. Ground-based confirmation at flagged locations provides component-level localisation and repair initiation. The ethane co-measurement capability of CRDS platforms discriminates thermogenic pipeline methane from biogenic agricultural sources, a significant operational advantage across GNI's predominantly rural distribution network.

The report also assesses several emerging technologies. LiDAR cameras, aerial gas mapping LiDAR, and distributed fibre optic sensing all present credible pathways toward reduced cost and improved coverage in the medium term. However, none is at the maturity or regulatory acceptance level needed for primary compliance reliance today. They should be tracked through pilot deployments and industry engagement, with the programme designed to accommodate technology substitution as these systems mature.

Several areas are highlighted for attention. The methodology for site level reconciliation on linear transmission assets, a requirement taking effect in February 2027, has no established precedent at the scale of GNI's network, and early engagement with regulators may be advisable. The Commission implementing act specifying approved detection techniques had not been adopted at the time of writing; programmes built on FID, TDLAS, and OGI are unlikely to require material revision when it is, but the position should be reviewed once published. Published detection performance data is drawn predominantly from North American and continental European environments, and Irish maritime conditions may affect performance differently; a controlled release programme at representative GNI assets would provide locally relevant validation. Additionally, LDAR data management infrastructure, integrating survey data from multiple methods into a systematic annual emissions inventory, requires resolution regardless of which delivery model is chosen for the survey programme itself.

GNI's compliance pathway rests on a combination of mature, precedent-backed technologies already largely in use, supplemented by targeted enhancements, helicopter sensor integration for corridor screening and documentation, drone TDLAS for transmission corridor Article 14 compliance, systematic high-flow sampling, QOGI at high-priority facilities, and UAV access to hard-to-reach sections, that extend the programme to meet the full scope of the Regulation's requirements.

PART I: INTRODUCTION AND CONTEXT

1. Background

EU Regulation 2024/1787, adopted on 13 June 2024 [1], establishes binding requirements for methane emissions monitoring, reporting, and reduction across the European energy sector. For gas transmission and distribution operators, the Regulation introduces mandatory leak detection and repair (LDAR) programmes under Article 14, source-level emissions quantification and reporting under Article 12, and progressive restrictions on routine venting and flaring under Articles 15 and 16. These obligations apply to Gas Networks Ireland (GNI) as the operator of Ireland's national gas transmission and distribution networks.

This report provides a technology assessment of the detection, quantification, and inspection technologies available to support GNI's LDAR programme. The assessment covers methane detection technologies across all deployment platforms (handheld, vehicle-mounted, UAV, and aircraft), leak rate quantification methods for Article 12 reporting, and visual and structural inspection technologies relevant to pipeline integrity and dual-purpose survey deployment.

The objective is to evaluate each technology against the specific requirements of the Regulation, the characteristics of GNI's network, and the practical constraints of the Irish operating environment, and to establish which technologies and technology combinations satisfy the full scope of Article 14 and Article 12 obligations across each asset category. The focus of this assessment is on programme enhancement and review of the technologies relevant to the progressively more demanding obligations now in effect, in particular measurement-based reporting, and site level reconciliation.

1.1 Methodology

Published manufacturer specifications and technical documentation for each detection, quantification, and inspection technology were reviewed against the detection thresholds, quantification requirements, and survey frequencies established in EU Regulation 2024/1787 and its Annex I.

Peer-reviewed field validation studies, including controlled release programmes conducted at the Methane Emissions Technology Evaluation Center (METEC) and comparable facilities [2], were used to assess real-world detection probability and quantification accuracy under operational conditions. Key studies are cited throughout the report. GNI data, including the asset data, survey frequency requirements by asset category, and field data from the UAV survey provided additional basis for assessing technology applicability in the Irish context [3].

The regulatory framework analysis draws on the text of EU Regulation 2024/1787, Irish Standards I.S. 328:2021 [4] and I.S. 329 [5], the CRU Gas Safety Framework, EPA greenhouse gas reporting requirements, and international frameworks including OGMP 2.0 [6] and MARCOGAZ [7] guidance.

Supplier engagement informed pricing, availability, and service delivery considerations, though all cost figures presented are indicative and based on publicly available information.

Although no independent controlled release validation programme was conducted as part of this assessment, detection performance data is drawn from published studies conducted predominantly in

North American and continental European environments. The applicability of these data to Irish conditions is discussed in Section 5.12.

2. GNI Infrastructure and LDAR Requirements

2.1 Network Overview (Transmission, Distribution, AGIs)

GNI operates Ireland's natural gas transmission and distribution networks, supplying approximately 720,000 customers through an integrated system of high-pressure transmission pipelines, pressure reduction and metering installations, and medium- and low-pressure distribution mains.

The transmission system comprises approximately 1,900 km of protected steel pipeline operating at pressures of 40 to 85 bar, transporting gas from entry points at Inch (Co. Cork) and Gormanston (Co. Meath) to demand centres and the distribution network. The transmission corridor traverses predominantly rural terrain including agricultural land, bogland, river crossings, and road crossings, with extended distances between access points.

Above ground installations include approximately 1,100 AGIs and DRIs (above ground installations and district regulating installations), 10 CNG (compressed natural gas) refuelling units, and approximately 15 valve stations. These facilities concentrate mechanical components valves, flanges, connectors, seals, regulators that represent the primary sources of fugitive emissions at point assets.

The distribution network extends to approximately 12,250 km, comprising approximately 12,160 km of polyethylene (PE) main, 80 km of protected steel, and 7.6 km of non-protected steel across 1,242 individual segments. Distribution mains are predominantly located beneath public roads in urban and suburban environments, operating at pressures from below 75 mbar to 16 bar.

Buried steel pipework at installations comprises approximately 900 locations of non-protected steel at DRIs and approximately 200 locations of protected steel at transmission installations. These assets require survey at the ground-atmosphere interface above buried steel at installation boundaries and entry/exit points. GNI's foreshore and offshore assets include four foreshore pipelines and subsea pipelines in the Irish Sea. These assets present specific access, safety, and instrumentation challenges arising from ATEX requirements, marine working conditions, and limited access windows due to tidal and weather constraints.

2.2 Survey Requirements

The network is subject to routine surveillance and inspection under I.S. 328:2021 (transmission) and I.S. 329 (distribution), including manned helicopter flights for pipeline corridor surveillance under I.S. 328:2021 Section 15.5. These existing activities represent both an established operational capability and, in the case of helicopter surveillance, a recurring expenditure from which supplementary screening value may be derived.

EU Regulation 2024/1787 Annex I specifies minimum survey frequencies for Type 1 and Type 2 LDAR surveys, varying by asset category and material type. The following summarises the survey obligations applicable to GNI's asset base, based on GNI's asset register and the Regulation's frequency requirements. CNG units and regulating/metering stations require Type 1 surveys every 4 months and Type 2 surveys every 8 months (CNG units) or every 8 months (regulating/metering stations). These are the highest-frequency survey obligations in the programme and apply across approximately 1,100 AGI and DRI locations and 10 CNG units.

Valve stations (approximately 15 locations, TBC) require Type 1 surveys every 9 months and Type 2 surveys every 18 months. The modest site count allows these to be incorporated into AGI survey routes. Buried non-protected steel at DRIs (approximately 900 locations) requires Type 1 surveys every 9 months and Type 2 surveys every 18 months. Buried protected steel at transmission installations (approximately 200 locations) requires Type 1 surveys every 15 months and Type 2 surveys every 30 months.

Transmission pipelines (approximately 1,900 km of protected steel) require Type 1 surveys every 24 months and Type 2 surveys every 36 months. The linear extent of the corridor and limited ground access make this the most challenging survey task in terms of coverage methodology. Distribution networks require Type 2 surveys every 24 months for non-protected steel (7.6 km across 1,242 segments) and every 36 months for PE (12,160 km) and protected steel (80 km across 2,192 segments).

Foreshore pipelines require Type 1 surveys every 12 months for components above sea level and every 24 months for components below sea level, with Type 2 surveys every 24 months for above-sea-level components. Subsea pipelines require Type 1 surveys every 24 months. Components below the seabed are subject to a 36-month Type 1 frequency. Upon detection of a leak at or above the applicable threshold (500 ppm or 1 g/hr for Type 2; 7,000 ppm or 17 g/hr for Type 1), repair must be attempted within 5 working days and completed within 30 calendar days.

These survey frequencies define the operational scale of the LDAR programme and, combined with Article 12 quantification and reporting obligations, determine the technology requirements assessed in the remainder of this report.

PART II: REGULATORY AND COMPLIANCE LANDSCAPE

3. EU Methane Regulation 2024/1787

3.1 Overview and Scope

Regulation (EU) 2024/1787 of the European Parliament and of the Council, adopted on 13 June 2024, represents the first comprehensive EU legislative framework specifically targeting methane emissions in the energy sector. The Regulation entered into force on 4 August 2024 and establishes binding rules for the accurate measurement, monitoring, reporting, and verification of methane emissions, as well as measures for their reduction through leak detection and repair (LDAR) programmes and restrictions on venting and flaring.

The Regulation forms a critical component of the European Green Deal and the EU Methane Strategy, responding to the scientific consensus that methane is the second most significant greenhouse gas contributing to climate change. With a global warming potential approximately 80 times greater than carbon dioxide over a 20-year period, methane reduction represents one of the most effective short-term climate mitigation strategies available.

Scope of Application: The Regulation applies to methane emissions from the following activities within the EU:

- Crude oil and natural gas exploration, production, gathering, and processing.
- Natural gas transmission, distribution, and underground storage.
- LNG terminals and regasification facilities.
- Coal mining and post-mining activities.
- Methane emissions associated with crude oil, natural gas, and coal placed on the EU market, including imports from third countries.

For Gas Networks Ireland, as the operator of Ireland's natural gas transmission and distribution networks, the Regulation applies directly to all transmission pipelines, distribution networks, above ground installations (AGIs), compressor stations, CNG units, valve stations, metering and regulating stations, and associated infrastructure.

Key Definitions: The Regulation introduces several key definitions relevant to LDAR activities.

Table 1: Key Definitions Relevant to LDAR Activities

Term	Definition
Operator	Any natural or legal person who operates or controls a site, or to whom decisive economic power over the technical functioning of the site has been delegated
Site	A location where one or more activities covered by the Regulation are carried out, including all equipment and infrastructure
Component	Any individual piece of equipment that could potentially be a source of methane emissions
LDAR Survey	A survey to identify and detect sources of methane leaks and to repair or replace the components from which such leaks originate
Methane Emissions	Direct emissions from any component, whether from venting, incomplete combustion from flaring, or leaks

3.2 Type 1 and Type 2 LDAR Requirements

This establishes a tiered approach to leak detection and repair, distinguishing between Type 1 and Type 2 LDAR surveys based on detection sensitivity and survey frequency. This risk-based approach recognises that different survey intensities are appropriate for different asset types and operational contexts.

Type 1 LDAR Surveys: Type 1 LDAR surveys are designed to identify larger, more significant leaks that contribute disproportionately to total emissions. These surveys are conducted more frequently but with a higher detection threshold. Key parameters for Type 1 surveys include:

- Detection threshold: Components emitting ≥7,000 ppm or ≥17 grams per hour of methane at standard temperature and pressure.
- Suitable technologies: Optical Gas Imaging (OGI) cameras, acoustic leak imaging, handheld detectors (FID, TDLAS-closed-path, TDLAS-open-path), or equivalent methods. The higher threshold (7,000 ppm) means most detection technologies qualify for Type 1 surveys.

- Survey frequency: Varies by asset type, ranging from quarterly to annually depending on risk classification.

Type 2 LDAR Surveys: Type 2 LDAR surveys employ more sensitive detection equipment to identify smaller leaks that, while individually less significant, can collectively represent a substantial portion of total emissions. These surveys are conducted less frequently due to the greater resource requirements. Key parameters for Type 2 surveys include:

- Detection threshold: Components emitting ≥500 ppm or ≥1 gram per hour of methane at standard temperature and pressure.
- Suitable technologies: High-sensitivity instruments including TDLAS-closed-path, TDLAS-open-path sensors, flame ionisation detectors (FID), or equivalent methods meeting the detection threshold requirements.
- Survey frequency: Varies by asset type, typically ranging from every 8 months to every 36 months.

The thresholds are expressed as alternatives: detection at ≥500 ppm OR measurement at ≥1 g/hr triggers the repair obligation. Operators may use either pathway, concentration detection or emission rate measurement, to satisfy Article 14 requirements. This distinction is significant for technology selection: instruments capable of detecting at 500 ppm (handheld FID, TDLAS-closed-path, TDLAS-open-path, UAV sensors) satisfy the LDAR survey requirement without requiring quantification capability.

Survey Frequency Requirements: The Regulation specifies minimum survey frequencies in Annex I, which vary based on asset type, risk profile, and whether the survey is Type 1 or Type 2. The following table summarises the key frequency requirements applicable to gas transmission and distribution operations.

Table 2: Summary of Required LDAR Survey Frequencies by Asset Category

Asset Type	Type 1 LDAR Frequency	Type 2 LDAR Frequency
CNG units / compressors	Every 4 months	Every 8 months
Regulating and metering stations	Every 4 months	Every 8 months
Valve stations	Every 9 months	Every 18 months
Transmission pipelines	Every 24 months	Every 36 months
Distribution networks (PE)	As per risk assessment	Every 36 months
Distribution networks (steel)	As per risk assessment	Every 24 months
Offshore (above sea level)	Every 12 months	Every 24 months

Operators may substitute a Type 2 survey for a scheduled Type 1 survey, as Type 2 surveys inherently meet or exceed the detection requirements of Type 1 surveys. This flexibility allows operators to optimise their survey programmes while maintaining or exceeding compliance requirements.

Equipment and Methodology Requirements: Article 14(6) of the Regulation requires that LDAR surveys be carried out with detection devices capable of identifying leaks at the specified thresholds. The European Commission is mandated to adopt an implementing act by 5 August 2025 specifying minimum detection limits, techniques, and thresholds based on best available technologies.

Until the adoption of this implementing act, operators are required to use the best available technologies and detection techniques, in compliance with manufacturer specifications for operation and maintenance. This transitional provision ensures that LDAR programmes can proceed while detailed technical standards are being developed.

Advanced Detection Technologies: Article 14(4) permits operators to use advanced detection technologies as part of their LDAR programmes, provided that such technologies can demonstrate equivalent or superior detection capabilities. This provision explicitly accommodates emerging technologies such as:

- UAV-mounted methane sensors (TDLAS-closed-path, TDLAS-open-path).
- Mobile vehicle-based detection systems (now widely deployed by European DSOs for distribution network screening).
- Continuous monitoring systems with fixed sensors.
- Satellite-based methane detection (for screening and prioritisation).
- Aircraft-based survey methods (possible for screening).

The use of advanced technologies must be approved by the competent authority and must demonstrate that they can achieve equivalent detection performance to the methods specified in the Regulation.

3.3 Compliance Obligations Under Articles 12 and 14

LDAR Survey Requirements (Article 14): LDAR surveys under Article 14 are designed to identify leaks and trigger repair actions. The compliance requirement is met when a leak is detected at or above the applicable threshold:

Table 3: Repair Trigger Thresholds for Type 1 and Type 2 LDAR Surveys

Survey Type	Repair Trigger
Type 1	≥7,000 ppm OR ≥17 g/hr
Type 2	≥500 ppm OR ≥1 g/hr

Detection at the ppm threshold is sufficient to trigger the repair obligation. Quantification in g/hr is an alternative compliance pathway but is not mandatory for LDAR purposes. Technologies capable of detecting methane at concentrations below 500 ppm, including handheld (TDLAS-closed-path, TDLAS-open-path), FID instruments, and appropriately deployed UAV sensors, satisfy Article 14 Type 2 requirements through the concentration pathway.

Repair Obligations and Timelines: When a leak is identified at or above the applicable threshold (500 ppm / 1 g/hr for Type 2, 7,000 ppm / 17 g/hr for Type 1), operators must initiate repair activities according to strict timelines:

- First repair attempt: Within 5 working days of leak detection.
- Final repair completion: Within 30 calendar days of leak detection.
- Post-repair verification: Confirmation that the repair has been effective must be documented.
- Documentation: All leaks, repair attempts, and outcomes must be recorded and retained.

Where safety considerations or technical constraints prevent repair within the specified timelines, operators must document the justification and implement interim mitigation measures. The competent authority may grant extensions in documented cases where repair during normal operations would pose unacceptable safety risks.

Emissions Quantification and Reporting (Article 12): Separate from LDAR survey obligations, Article 12 establishes mandatory requirements for emissions quantification and annual reporting. Unlike the detection focused LDAR surveys, emissions reporting requires measurement or estimation of emission rates in mass units (g/hr, kg/hr, or tonnes/year).

Source-Level Quantification:

Operators must quantify methane emissions at the source level for all identified emission sources within their operations. Quantification shall be based on direct measurements or measurement-informed emission factors, with the use of generic emission factors permitted only during the initial transition period. Source-level data must be reported in a disaggregated form, distinguishing between emission source types such as venting, flaring, fugitive leaks, and combustion.

Article 12 quantification encompasses all methane emission sources, not solely leaks identified through LDAR surveys. Operators must quantify emissions from venting, flaring, incomplete combustion, and fugitive sources (including background leakage from components not individually identified as leaking). This requires a comprehensive emissions inventory methodology, typically based on component counts and emission factors supplemented by direct measurement at significant sources.

Site level Measurement:

Independent site level measurements must be conducted to validate source-level inventories. These measurements typically involve the use of mobile platforms, such as vehicles, drones, or aircraft, or fixed sensor networks deployed at the site. The results of site level measurements must be reconciled with source-level estimates, and any significant discrepancies identified shall be investigated and clearly explained.

Reporting Obligations: Operators must submit annual reports to competent authorities containing detailed information on methane emissions and LDAR activities. The reporting requirements become progressively more detailed over a four-year transition period:

Table 4: Summary of Methane Reporting Obligations and Deadlines

Reporting Deadline	Requirements
5 August 2025	First annual report with source-level quantification (generic factors acceptable)
5 February 2026	Measurement-based source-level data for operated assets.
5 February 2027	Site level measurements and reconciliation with source-level data
Annually thereafter	Full measurement-based reporting with source-level and site level reconciliation

Annual reports must include the total methane emissions expressed in tonnes of methane and CO_2 equivalent, with emissions disaggregated by source type and asset category. The report should clearly describe the methodologies and emission factors used for quantification, along with a summary of LDAR surveys conducted, including the number of components surveyed and leaks identified. Details of repair and replacement activities undertaken during the reporting period must also be provided, together with a verification statement issued by an accredited third-party verifier.

Relationship Between LDAR and Emissions Reporting: The distinction between Articles 14 and 12 has significant implications for technology selection:

Table 5: LDAR and Emissions Reporting Requirements and Technology Implications

Obligation	Article	**Requirement**	**Technology Implication**
LDAR surveys	14	Detect leaks → trigger repair	ppm detection sufficient (FID, TDLAS-closed-path, TDLAS-open-path, OGI)
Emissions reporting	12	Quantify emissions → annual report	g/hr measurement required (QOGI, high-flow sampling, dispersion modelling)

Common detection approaches such as TDLAS or OGI satisfy Article 14 (detection) but not Article 12 (quantification). QOGI systems can satisfy both obligations simultaneously, detecting leaks for repair while providing quantified emission rates for inventory reporting. This dual capability may justify the higher cost of QOGI systems at facilities where both frequent LDAR surveys and detailed emissions quantification are required.

For operators conducting LDAR surveys with detection-only instruments (handheld FID/TDLAS), a supplementary quantification methodology is required to satisfy Article 12 reporting obligations. Options include:

- High-flow sampling at detected leaks.
- QOGI follow-up surveys.
- Atmospheric dispersion modelling using OTM-33A methodology.
- Application of measurement-informed emission factors.

Venting and Flaring Restrictions: The Regulation introduces significant restrictions on routine venting and flaring, which become fully applicable from 5 February 2026. Routine venting is prohibited except in emergency situations or where flaring is not technically feasible, and routine flaring is likewise prohibited, with flaring permitted only where alternatives such as re-injection or utilisation are not feasible. All flaring activities must use equipment with a destruction and removal efficiency of at least 99%, and any non-routine venting or flaring events must be reported to the competent authorities. Operators are also required to demonstrate that zero-emission alternatives have been considered and are not feasible before venting or flaring is permitted. All venting and flaring events, whether routine or non-routine, must be quantified and included in the annual emissions report under Article 12. Operators must maintain records of volumes vented or flared, duration, and calculated methane emissions.

3.4 Implementation Timeline and Enforcement

Key Implementation Milestones: The Regulation establishes a phased implementation timeline to allow operators to develop the necessary capabilities and infrastructure for compliance:

Table 6: Key Implementation Milestones and Enforcement Deadlines

Date	Milestone
4 August 2024	Regulation enters into force
5 February 2025	Prohibition on routine venting and flaring comes into effect
5 May 2025	LDAR programme submission deadline for existing sites
5 August 2025	First Type 2 LDAR survey must be completed for all existing sites; First annual

	emissions report due; Commission implementing act on detection methods due
5 February 2026	Venting and flaring restrictions fully applicable; Methane transparency database operational
5 February 2027	Source-level and site level measurement reconciliation required
5 August 2028	Methane intensity reporting for importers commences
5 August 2029	Commission assessment on maximum methane intensity values
August 2030	Imports must meet methane performance standards

By 5 May 2025, operators of existing sites must submit a comprehensive LDAR programme to the competent authorities, while for new sites the programme must be submitted within six months from the start of operations. The LDAR programme must provide a detailed description of all planned LDAR survey activities, including specific timelines for Type 1 and Type 2 surveys by asset category, the technologies and methodologies to be employed, and the procedures for leak repair and verification. It must also set out data management and record-keeping arrangements, quality assurance and quality control protocols, and requirements for personnel competency and training. Competent authorities may require operators to amend their LDAR programmes to ensure compliance with the Regulation, and any changes to the programme must be submitted to the authorities as soon as possible.

Enforcement and Penalties: Member States are required to establish effective, proportionate, and dissuasive penalties for non-compliance with the Regulation, with specific penalty levels determined at national level. The Regulation requires Member States to establish effective, proportionate, and dissuasive penalties. These significant financial and regulatory consequences underscore the importance of establishing robust LDAR programmes and maintaining continuous compliance, as non-compliance may also lead to reputational damage and increased stakeholder scrutiny, particularly in the context of growing environmental, social, and governance (ESG) expectations within the energy sector.

Certification and Training Requirements: Article 14(16) requires Member States to ensure that certification, accreditation, or equivalent qualification schemes are available for LDAR service providers and for operator personnel conducting LDAR surveys. This requirement reflects the technical complexity of LDAR activities and the importance of ensuring survey quality and reliability.

Operators should ensure that personnel involved in LDAR activities receive appropriate training and hold relevant certifications. This may include manufacturer-specific training for detection equipment, as well as broader competency certification for LDAR methodologies.

3.5 Detection Versus Quantification

The Regulation imposes two separate obligations that require different measurement capabilities, and the distinction determines which instrument is required for which task. This subsection consolidates that distinction into a single operational reference.

When detection alone is sufficient: Concentration detection in ppm satisfies every Article 14 LDAR survey obligation. A component found emitting at or above 500 ppm (Type 2) or 7,000 ppm (Type 1) triggers the repair obligation directly: first repair attempt within 5 working days, completion within 30 calendar days. No emission rate measurement is required at any point for the repair obligation itself. Instruments capable of reliable detection at the applicable ppm threshold, handheld FID, closed-path

TDLAS, and appropriately deployed UAV sensors, are therefore fully sufficient for the conduct of Type 1 and Type 2 surveys.

When flow measurement is required: Quantification in mass units (g/hr or tonnes/year) is required in exactly four circumstances:

- The Article 12 annual emissions inventory, which from 5 February 2026 must be based on measurement-based source-level data for operated assets — this obligation is now in force;
- Optionally, as the alternative repair-trigger pathway under Article 14 (≥17 g/hr Type 1, ≥1 g/hr Type 2), where an operator elects to demonstrate the threshold by rate rather than concentration;
- Quantification of venting and flaring events for reporting under Article 16;
- Site-level measurement and reconciliation campaigns under Article 12(3), applicable from 5 February 2027.

Because repair must be attempted within 5 working days of detection and completed within 30 days, quantification of a detected leak must be carried out within the repair window: once a component is repaired, the emission source no longer exists and the opportunity to capture the Article 12 data point is lost. The operational field sequence is therefore detect, quantify, then repair, with quantification scheduled as part of the repair mobilisation rather than as a separate subsequent activity.

Article 12 permits source-level quantification by direct measurement or by specific (measurement-informed) emission factors derived from source-level quantification or sampling. Direct high-flow measurement of every individual detection is therefore not mandated: a structured programme that directly measures significant leaks and builds GNI-specific emission factors by component class from representative sampling satisfies the obligation, with direct measurement of all detections remaining a best-practice option where field logistics allow. The quantification approaches recommended throughout this report should be read in that light.

4. Irish and International Standards

4.1 I.S. 328:2021 and I.S. 329 Requirements

Irish Standard I.S. 328:2021 (Gas Transmission Pipelines) and I.S. 329 (Gas Distribution Pipelines) establish the national framework for the design, construction, operation, and maintenance of gas infrastructure in Ireland. While predating EU Regulation 2024/1787, these standards include requirements for surveillance, inspection, and leakage surveys that align with and complement the new EU requirements.

I.S. 328:2021 Gas Transmission Pipelines: I.S. 328:2021 provides comprehensive requirements for gas transmission pipelines and is the primary technical standard governing Gas Networks Ireland's transmission network. The standard includes specific requirements for pipeline surveillance and inspection in Section 15 (Operation and Maintenance).

Section 15.5 Pipeline Surveillance

Section 15.5 of I.S. 328:2021 requires that the route of pipelines be kept under surveillance to ensure system security is not at risk. Key surveillance requirements include:

- Regular liaison with landowners, occupiers, and tenants through whose land pipelines pass.

- Aerial surveys at frequencies determined by risk assessment (or every 2 weeks in Type R and S areas where risk data is unavailable).
- Ground patrols to inspect exposed crossings, river crossings, and installations.
- Reporting of all encroachments and potential third-party interference.
- Monitoring for evidence of ground movement, subsidence, and changing water courses.

Section 15.5.2.4 Leakage Survey

I.S. 328:2021 specifically addresses leakage surveys in Section 15.5.2.4. Leakage surveys are required in the following circumstances:

- Where proximity requirements have been infringed.
- Where the pipeline has sustained damage.
- Where buried fittings are present on the pipeline system.
- Where temporary repair clamps or sleeves are fitted to the pipeline.

The frequency of leakage surveys is determined by risk assessment in accordance with Section 15.2.4. Where risk data is unavailable, leakage surveys must be carried out every 3 months in both Type R (rural) and Type S (suburban) areas. Any leakage detected must be immediately reported to grid control.

Section 15.6 Pipeline Inspection

Section 15.6 establishes requirements for various inspection activities including:

- Cathodic protection system maintenance and monitoring.
- External coatings inspection, with Close Interval Potential Surveys at intervals not exceeding 10 years.
- Sleeve maintenance inspections (six-monthly where nitrogen-filled annulus is present)
- Underwater crossings inspection (initially at intervals not exceeding 2 years, and not exceeding 5 years thereafter).
- Pipeline wall condition monitoring through intelligent pigging (on-line inspection) at intervals determined by risk assessment, or not exceeding 10 years where risk data is insufficient.

Risk-Based Approach

Section 15.2.4 of I.S. 328:2021 establishes a risk-based framework for determining surveillance, inspection, and maintenance frequencies. This framework requires consideration of factors such as the age and standard of pipeline construction, the history of surveillance, inspection, and maintenance activities, and the results of cathodic protection monitoring. It also takes into account evidence of ground movement or external interference, prevailing ground conditions and operating temperature history, the density of population surrounding the pipeline, and any proximity infringements. This risk-based approach aligns well with EU Regulation 2024/1787, which similarly permits adjustments to inspection and survey frequencies based on demonstrated risk profiles and historical performance data.

I.S. 329 Gas Distribution Pipelines

I.S. 329 applies to gas distribution systems operating at pressures up to 16 bar and covers Gas Networks Ireland's extensive distribution network of over 12,000 km of polyethylene and steel pipelines. The standard includes requirements for:

- Periodic leakage surveys of distribution mains and services.
- Condition assessment of metallic pipelines, particularly non-protected steel.
- Monitoring of pressure regulating equipment at district regulating installations (DRIs).
- Documentation and record-keeping of all inspection and survey activities.

The specific survey frequencies and methodologies in I.S. 329 complement the EU Regulation requirements, with the higher detection sensitivity required by EU Type 2 surveys representing an enhancement to existing practice rather than a fundamental change in approach.

Alignment of Irish Standards with EU Regulation

The following table summarises the alignment between I.S. 328:2021 / I.S. 329 requirements and EU Regulation 2024/1787:

Table 7: Alignment of LDAR and Methane Management Requirements Between Irish Standards and EU Regulation

Requirement Area	Irish Standards (I.S. 328/329)	EU Regulation 2024/1787
Leakage Surveys	Required; frequency by risk assessment or per Table 9	Type 1 and Type 2 surveys with specified frequencies and detection thresholds
Detection Threshold	Not specified numerically	≥500 ppm (Type 2) and ≥7,000 ppm (Type 1)
Repair Timelines	Immediate reporting; repair as soon as possible	First attempt within 5 days; completion within 30 days
Documentation	Required for all surveys and repairs	Comprehensive reporting to competent authorities
Emissions Quantification	Not explicitly required	Mandatory Article 12 requires source-level and site level quantification in g/hr or tonnes CH_4; separate from LDAR detection

4.2 CRU and EPA Obligations

Commission for Regulation of Utilities (CRU): The Commission for Regulation of Utilities (CRU) is Ireland's independent energy regulator with responsibility for the safety regulation of natural gas supply, transmission, distribution, storage, and use. The CRU exercises its functions under the Gas Safety Framework, which includes the safety case regime for gas network operators.

Gas Safety Framework Requirements

Under the Gas Safety Framework, Gas Networks Ireland is required to maintain an approved safety case that demonstrates how safety risks associated with its operations are identified, assessed, and managed. Key obligations include:

- Maintenance of a comprehensive safety case approved by the CRU.
- Quarterly safety performance reporting to the CRU.
- Incident reporting for all natural gas incidents, including leaks and releases.
- Implementation of safety management systems covering all aspects of network operation.
- Participation in the CRU's audit and inspection programme.

The CRU has enforcement powers where undertakings are found to be non-compliant with their safety cases, including the power to require improvement plans and to serve improvement and prohibition notices.

Relevance to LDAR

While the CRU's safety framework has traditionally focused on public safety and operational integrity rather than environmental emissions, the implementation of EU Regulation 2024/1787 creates an intersection between safety and environmental compliance. LDAR programmes contribute to both objectives by identifying and remediating leaks that pose safety risks while simultaneously reducing methane emissions.

Gas Networks Ireland should ensure that its LDAR programme is integrated with its overall safety case and that LDAR activities are reflected in safety performance reporting where relevant (for example, leaks identified during LDAR surveys that pose safety concerns).

Environmental Protection Agency (EPA): The Environmental Protection Agency (EPA) is Ireland's designated competent authority for greenhouse gas emissions inventory compilation and reporting. The EPA compiles Ireland's national greenhouse gas emission inventory annually for submission to the European Commission and the United Nations Framework Convention on Climate Change (UNFCCC).

Greenhouse *Gas* Reporting Framework

Ireland's greenhouse gas inventory includes methane emissions from the energy sector, categorised as fugitive emissions arising from fuel handling and distribution. The Environmental Protection Agency (EPA) reports methane emissions using methodologies and emission factors established by the Intergovernmental Panel on Climate Change (IPCC) [10]. The EPA's greenhouse gas reporting framework requires the annual submission of a national inventory covering all greenhouse gases, including methane, with a sectoral breakdown that explicitly includes fugitive emissions from natural gas transmission and distribution. Emissions are quantified using IPCC emission factors, with scope to apply country-specific factors where supported by measurement data, and are reported both in mass units (tonnes of CH_4) and as CO_2 equivalents using global warming potentials. This reporting framework also underpins compliance monitoring against Ireland's obligations under the EU Effort Sharing Regulation.

Climate Action Plan Alignment

Ireland's Climate Action Plan sets a target of 51% reduction in greenhouse gas emissions by 2030 compared to 2018 levels [11]. The gas transmission and distribution sector contribute to national emissions through fugitive methane releases, and improved LDAR programmes represent a direct mechanism for emissions reduction in this sector.

The implementation of EU Regulation 2024/1787 aligns with national climate policy by requiring measurement-based quantification of methane emissions, which will improve the accuracy of national inventory data and enable better tracking of emissions reduction progress.

4.3 International Best Practice (EPA, OGMP 2.0, MARCOGAZ)

US EPA Methods: The United States Environmental Protection Agency (US EPA) has developed several methods and protocols for methane leak detection and quantification that are widely referenced in international practice:

EPA Method 21

Method 21 is the traditional reference method for equipment leak detection using portable analysers [8]. Key characteristics include:

- Component-by-component screening using portable hydrocarbon analysers (typically FID or PID).
- Measurement of concentration at potential leak interfaces.
- Definition of leak thresholds (typically 500 ppm or 10,000 ppm depending on regulation).
- Established calibration and quality assurance procedures.
- Widely accepted as a reference method for regulatory compliance.

Method 21 satisfies LDAR detection requirements (Article 14) but does not provide the quantified emission rates required for Article 12 reporting. Operators using Method 21 for LDAR must supplement with quantification methods (high-flow sampling, QOGI, or dispersion modelling) to meet emissions reporting obligations.

OTM-33A (Other Test Method 33A)

OTM-33A is a mobile measurement method that enables emission rate quantification from point sources using downwind concentration measurements and atmospheric dispersion modelling [9]. The method is particularly useful for:

- Quantification of emission rates from identified leak sources.
- Site level emissions assessment using mobile platforms.
- Validation of source-level inventory data.
- Supporting regulatory compliance demonstrations.

OTM-33A principles underpin many of the mobile survey methods now being deployed for LDAR, including vehicle-mounted and UAV-based approaches.

Oil and Gas Methane Partnership 2.0 (OGMP 2.0)

The Oil and Gas Methane Partnership 2.0 (OGMP 2.0) is the flagship voluntary reporting framework of the United Nations Environment Programme (UNEP). It represents the most comprehensive, measurement-based international framework for methane emissions reporting in the oil and gas sector.

Reporting Levels

OGMP 2.0 defines five progressive levels of reporting quality, as outlined below:

- Level 1: Asset- or country-level consolidated emission estimates based on industry average emission factors.

- Level 2: Emissions categorised by source type, such as venting, fugitive emissions, and flaring, using generic emission factors.
- Level 3: Reporting by detailed source type using generic emission factors.
- Level 4: Reporting by detailed source type using company-specific, measurement-informed emission factors.
- Level 5: Site level measurements that are reconciled with source-level emission estimates.

Gold Standard Pathway

The OGMP 2.0 Gold Standard requires companies to achieve Level 4/5 reporting for operated assets within three years of joining and for non-operated assets within five years. Achieving Gold Standard demonstrates:

- Comprehensive measurement-based emissions quantification.
- Reconciliation between bottom-up (source-level) and top-down (site level) measurements.
- Commitment to continuous improvement and emissions reduction
- Transparent reporting to stakeholders.

Alignment with EU Regulation

EU Regulation 2024/1787 explicitly references OGMP 2.0, stating that until EU-specific standards are adopted, operators may use the latest OGMP 2.0 technical guidance documents for measurement and quantification purposes. This provides a clear pathway for operators to develop compliant measurement programmes while EU implementing acts are being developed.

MARCOGAZ: MARCOGAZ is the Technical Association of the European Natural Gas Industry, representing gas infrastructure operators including transmission system operators (TSOs) and distribution system operators (DSOs). MARCOGAZ has developed methodology and guidance for methane emissions assessment specifically applicable to gas transmission and distribution operations.

Key MARCOGAZ Contributions

MARCOGAZ publications relevant to LDAR and methane emissions include:

- Assessment of Methane Emissions for Gas Transmission and Distribution System Operators, providing standardised methodology for emissions quantification.
- Emission factors specific to European gas transmission and distribution infrastructure
- Guidance on measurement techniques and data collection.
- Surveys of methane emissions from European transmission networks, providing benchmarking data.
- Input to European standardisation efforts (CEN/TC 234).

The MARCOGAZ methodology has been submitted to the European Committee for Standardization (CEN) for use as a technical reference in preparing European standards on methane emissions quantification. Gas Networks Ireland should consider alignment with MARCOGAZ methodologies to ensure consistency with emerging European standards.

UK IGEM Standards: The Institution of Gas Engineers and Managers (IGEM) in the United Kingdom has developed standards and recommendations that are often referenced alongside Irish standards due to similarities in gas infrastructure and operating conditions. Key references include:

- IGEM/TD/1 Steel pipelines and associated installations for high pressure gas transmission.
- IGEM/TD/3 Steel and PE pipelines for gas distribution.
- IGEM/SR/23 Venting of natural gas.
- IGEM/SR/25 Hazardous area classification of natural gas installations.

While I.S. 328:2021 and I.S. 329 are the primary references for Irish operations, IGEM standards provide useful supplementary guidance, particularly for risk assessment methodologies and quantitative risk analysis.

Summary: Regulatory Framework Integration: Gas Networks Ireland operates within a multi-layered regulatory framework that includes:

- EU Regulation 2024/1787 providing binding requirements for LDAR surveys, emissions quantification, and reporting.
- Irish Standards (I.S. 328:2021, I.S. 329) establishing technical requirements for pipeline surveillance and inspection.
- CRU Gas Safety Framework requiring safety case compliance and incident reporting.
- EPA Greenhouse Gas Reporting contributing to national emissions inventory.
- International best practice (OGMP 2.0, MARCOGAZ) providing guidance on measurement methodologies and benchmarking.

A successful LDAR programme must satisfy the requirements of all applicable frameworks while avoiding duplication of effort. The programme design presented in subsequent sections of this report addresses this integration challenge by identifying technologies and methodologies that can efficiently serve multiple compliance objectives.

PART III: TECHNOLOGY OVERVIEW

5. Methane Detection Technologies

This section provides a comprehensive review of methane detection technologies applicable to leak detection and repair (LDAR) programmes within gas transmission and distribution networks. The technologies are presented in order of operational prevalence, beginning with handheld instruments commonly used for walking surveys and progressing through vehicle-mounted, aerial, optical imaging, and distributed sensing systems. Each technology is assessed against the detection and quantification requirements established under EU Regulation 2024/1787, with particular attention to their applicability for Gas Networks Ireland (GNI) operations across transmission pipelines, Above Ground Installations (AGIs), and distribution networks.

5.1 Overview of Detection Methods

The Methane Absorption Spectrum: Methane (CH_4) exhibits characteristic absorption features in the infrared region of the electromagnetic spectrum, providing the physical basis for most optical detection technologies. The molecule absorbs infrared radiation at specific wavelengths due to vibrational and rotational transitions, with the most significant absorption bands occurring in the near-infrared (NIR) and mid-infrared (MIR) regions.

The primary absorption bands relevant to detection instrumentation include the fundamental C-H stretching mode at approximately 3.3μm, the combination band at 2.3μm, and the overtone band at 1.65μm. The 3.3μm band provides the strongest absorption and is exploited by mid-infrared detectors including optical gas imaging cameras and some NDIR sensors. The weaker 1.65μm band, whilst offering lower sensitivity, benefits from compatibility with telecommunications-grade optical components and is utilised by tunable diode laser absorption spectroscopy (TDLAS) systems, cavity ring-down spectroscopy (CRDS), and some distributed fibre optic sensing technologies.

The selection of operating wavelength involves trade-offs between absorption strength, atmospheric interference, component availability, and cost. Mid-infrared systems typically achieve lower detection limits but require specialised optical materials and cooling systems, whereas near-infrared systems can leverage mature telecommunications technology at reduced cost.

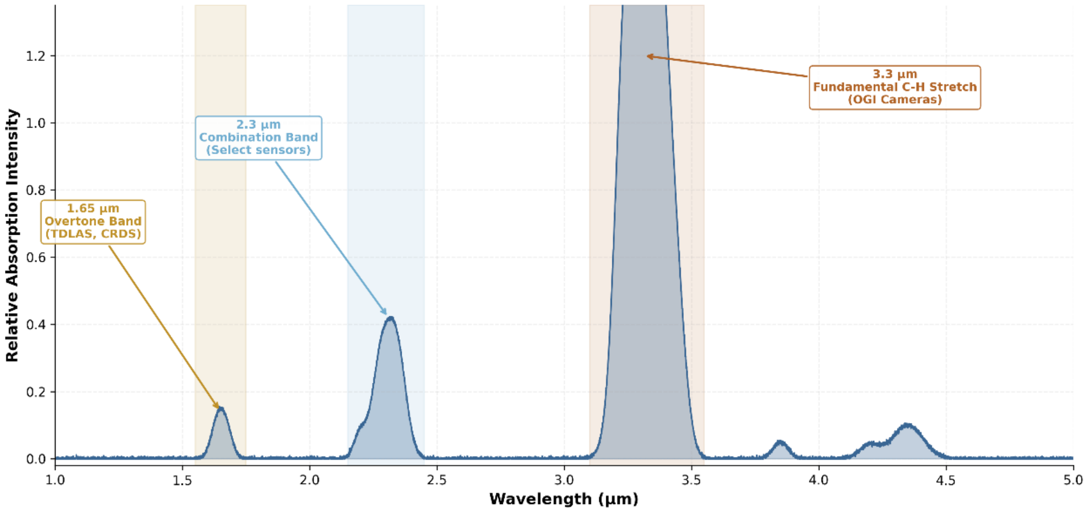

Figure 1 Methane infrared absorption spectrum showing principal absorption bands at 1.65μm (TDLAS, CRDS), 2.3μm (combination band), and 3.3μm (OGI cameras).

Classification of Detection Technologies

Methane detection technologies may be classified according to their underlying measurement principle, deployment platform, or measurement output. For the purposes of LDAR programme design, a classification based on measurement principle provides the most useful framework for understanding technology capabilities and limitations.

Table 8: Classification of Methane Detection Technologies by Measurement Principle

Category	Principle	Representative Technologies
Optical Absorption	Attenuation of light at methane-specific wavelengths	TDLAS-open-path, TDLAS-closed-path, CRDS, OGI, LiDAR
Flame Ionisation	Ionisation of hydrocarbons in hydrogen flame	FID (portable and fixed)
Catalytic/Thermal	Heat release from catalytic oxidation	Pellistor sensors, catalytic bead
Electrochemical	Electrochemical reaction generating current	MOS sensors, MEMS devices

Distributed Sensing	Fibre optic measurement of temperature or acoustic signals	DTS, DAS, hybrid systems

Optical absorption methods dominate the LDAR instrumentation landscape due to their specificity for methane, wide dynamic range, and suitability for both point measurement and imaging applications. Flame ionisation detection remains the reference method for regulatory compliance in many jurisdictions but responds to all hydrocarbons rather than methane specifically. Catalytic and electrochemical sensors find application in safety monitoring and screening but generally lack the sensitivity required for fugitive emission detection at regulatory thresholds.

Detection vs Quantification Regulatory Requirements: A critical distinction exists between leak detection (identifying the presence and location of a leak) and leak quantification (measuring the emission rate). EU Regulation 2024/1787 establishes two separate compliance obligations that require different measurement capabilities. LDAR surveys are designed to identify leaks and trigger repair actions. The repair obligation is triggered when a component is found emitting at or above the applicable threshold:

Table 9: Overview of Regulatory Thresholds for Type 1 and Type 2 LDAR Surveys

Survey Type	Concentration Threshold	Emission Rate Threshold	Implication
Type 1 LDAR	≥7,000 ppm	OR ≥17 g/hr	Either threshold triggers repair
Type 2 LDAR	≥500 ppm	OR ≥1 g/hr	Either threshold triggers repair

The thresholds are expressed as alternatives: detection at ≥500 ppm OR measurement at ≥1 g/hr triggers the Type 2 repair obligation. Concentration measurement alone is sufficient for Article 14 compliance.

Separate from LDAR surveys, Article 12 requires quantification of emissions in mass units (g/hr or tonnes/year) for annual reporting. Technologies that satisfy Article 14 detection requirements may not provide the quantification capability required for Article 12. The relationship between these obligations and technology selection is summarised in Table 5 (Section 3.3).

5.2 Point Sensor Technologies

Handheld and portable detectors represent the most widely deployed instrumentation for LDAR surveys within the gas transmission and distribution industry. These instruments enable technicians to conduct walking surveys along pipeline routes, around AGIs, and at customer installations, providing real-time detection of methane concentrations at individual components and potential leak locations. The principal technologies employed in portable instruments include non-dispersive infrared (NDIR) sensors, flame ionisation detectors (FID), and tunable diode laser absorption spectroscopy (TDLAS).

Non-Dispersive Infrared (NDIR) Sensors: Non-dispersive infrared sensors measure methane concentration by detecting the attenuation of broadband infrared radiation, typically at the 3.3μm absorption band. Optical filters select measurement and reference wavelength bands, with the difference in transmitted intensity providing a concentration reading. NDIR instruments are robust, relatively low-cost, and widely used for safety monitoring and leak detection.

However, NDIR technology has lower sensitivity and accuracy compared to closed-path TDLAS. Detection limits are typically 1-10 ppm (versus ~1 ppm for TDLAS), and the broadband measurement approach introduces cross-sensitivity to water vapour and carbon dioxide. For precision LDAR applications requiring reliable detection at regulatory thresholds, closed-path TDLAS offers superior performance.

Flame Ionisation Detection (FID): Flame ionisation detection operates by introducing the sample gas into a hydrogen-air flame, where hydrocarbon compounds undergo ionisation. The resulting ions are collected by electrodes, generating a current proportional to the carbon content of the sample. FID provides exceptional sensitivity, with detection limits typically below 1 ppm and linear response over several orders of magnitude.

FID remains the reference method for many regulatory frameworks, including US EPA Method 21 for equipment leak detection. The technology offers advantages of high sensitivity, fast response (typically less than one second), and immunity to water vapour interference. The linear response enables accurate measurement across a wide concentration range from sub-ppm levels to percentage concentrations.

The principal limitation of FID for LDAR applications is its response to all hydrocarbons, not methane specifically. In environments where other volatile organic compounds may be present, FID readings represent total hydrocarbon concentration rather than methane alone. Additionally, FID instruments require hydrogen fuel supply (typically from small cylinders), regular flame ignition maintenance, and more frequent calibration than optical methods.

Portable FID instruments commonly deployed for LDAR surveys include the Thermo Scientific TVA-2020, Heath Consultants Detecto-Pak series, and Ion Science Tiger models. These instruments typically offer detection limits of 0.5 to 1 ppm with sampling rates suitable for walking surveys at component level.

Tunable Diode Laser Absorption Spectroscopy (TDLAS): Tunable Diode Laser Absorption Spectroscopy (TDLAS): Tunable diode laser absorption spectroscopy employs a narrow-linewidth semiconductor laser whose emission wavelength is rapidly modulated across a methane absorption line, typically in the 1.65μm near-infrared band. By measuring the differential absorption as the laser wavelength sweeps through the absorption feature, TDLAS achieves high selectivity for methane and rejection of interfering species. TDLAS instruments may operate in either closed-path (extractive) or open-path configurations. Closed-path instruments draw sample gas through a measurement cell and report concentration in ppm. Open-path instruments transmit the laser beam through ambient air and report path-integrated concentration in ppm·m (the product of concentration and path length). Some open-path instruments employ backscatter detection, reflecting the laser beam from surfaces at varying distances to enable standoff measurement. These configurations can be deployed on handheld or UAV platforms, resulting in five principal system types relevant to LDAR applications:

Handheld closed-path TDLAS instruments draw air into a measurement cell at or near the device inlet, reporting concentration in ppm. The operator must position the instrument within or immediately adjacent to the plume to detect elevated concentrations. This configuration is suited to component-level inspection where direct access is available. Detection at regulatory thresholds (500 ppm for Type 2, 7,000 ppm for Type 1) is reliable when the sensor is positioned within 1-2 metres of the source.

Handheld open-path TDLAS instruments transmit the laser beam toward a target surface and measure the path-integrated concentration along the beam in ppm·m. The measurement covers the full path from instrument to target wherever the device is pointed. This enables standoff detection from distances of several metres to tens of metres, allowing rapid screening of elevated or difficult-to-access components without requiring the operator to approach closely. Representative instruments include the Pergam Laser Methane range (mini, backpack, and vehicle-mounted variants), Heath Consultants RMLD (Remote Methane Leak Detector), and Crowcon LaserMethane. These instruments are widely used for pipeline route surveys, above ground facility inspection, and rapid screening of distribution networks.

UAV-mounted closed-path TDLAS systems employ the same extractive measurement principle as handheld closed-path instruments, with air drawn into a measurement cell aboard the aircraft. Concentration is reported in ppm at the aircraft's location. To detect emissions, the UAV must fly close to the source, typically within 2-5 metres. The Soarability Sniffer4D is a representative system, offering 1 ppm resolution with real-time data visualisation and mapping. This configuration is particularly effective for inspecting elevated or inaccessible infrastructure such as pipe bridges, river crossings, and above ground installations where close-proximity flight is feasible.

UAV-mounted open-path TDLAS (nadir configuration) systems transmit the laser beam downward from the aircraft to the ground surface, measuring the path-integrated methane column in ppm·m between the UAV and the surface. This configuration enables detection of emissions from buried pipelines and area sources without requiring the aircraft to fly through the plume. The measurement integrates all methane along the vertical path, which can complicate interpretation when emissions occur at varying heights. The Soarability MetScan and Pergam DragonFly are representative nadir-configured systems.

UAV-mounted open-path TDLAS (gimbal configuration) represents a further development where the laser sensor is integrated with a stabilised gimbal mount, allowing the beam to be directed at varying angles during flight. This enables the sensor to scan across a wider area whilst the aircraft is in motion, significantly improving spatial coverage compared to fixed nadir configurations. The gimbal-mounted approach also allows the beam to be oriented to intersect plumes more effectively under varying wind conditions, and can target specific components or areas of interest during flight. This configuration is emerging in commercial systems and offers advantages for rapid area screening and complex facility surveys.

Portable TDLAS instruments offer detection limits typically at 1 ppm or below with excellent methane specificity and rapid response. The technology is particularly suited to standoff detection where direct access to the measurement point is difficult or hazardous. Open-path TDLAS can survey extended areas more rapidly than point-sampling methods, whilst closed-path systems provide direct concentration readings against regulatory thresholds.

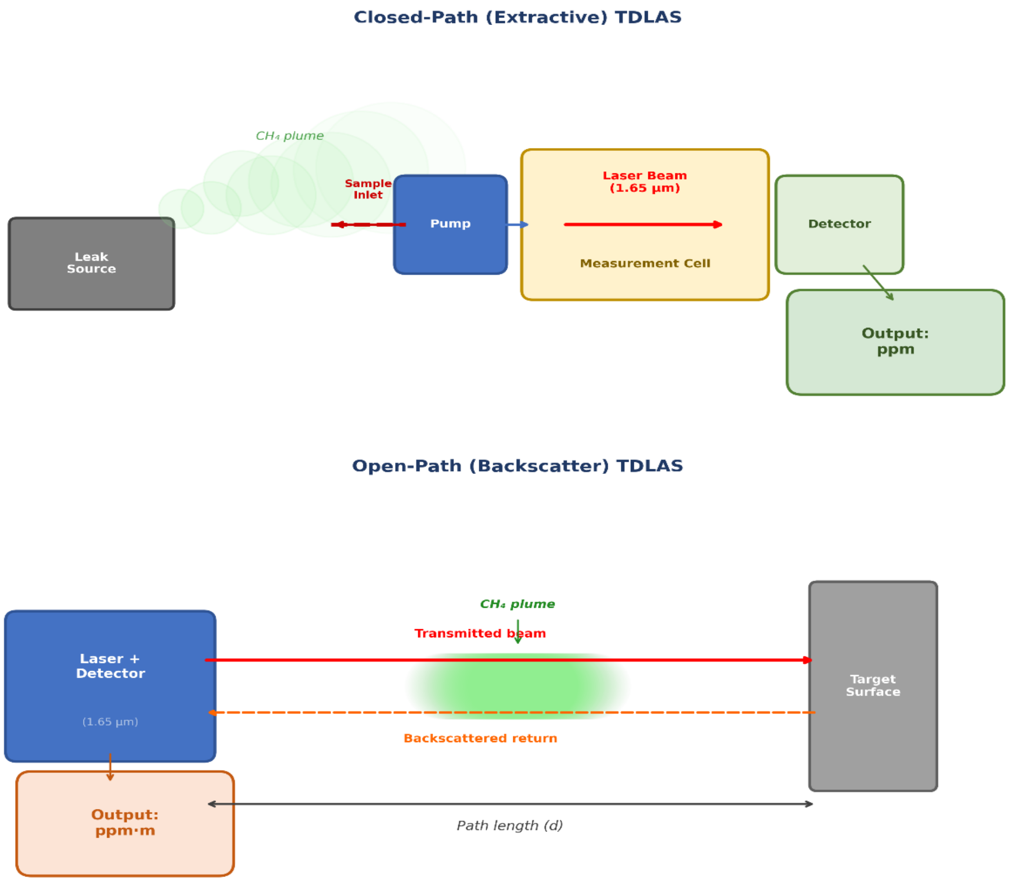

Figure 2 TDLAS measurement configurations, closed-path (extractive, ppm output) and open-path (backscatter, ppm·m output).

Metal Oxide Semiconductor (MOS) and Catalytic Sensors: Metal oxide semiconductor sensors detect combustible gases through changes in electrical conductivity when target gases adsorb onto a heated metal oxide surface (typically tin dioxide, SnO_2). Catalytic sensors (pellistors) detect combustible gases through the heat released when gas oxidises on a catalytic surface, measured as a resistance change in a Wheatstone bridge circuit.

Both technologies are widely deployed in fixed gas detection systems and lower-cost portable instruments for safety monitoring applications. They offer advantages of low cost, simple electronics, and proven reliability. However, their detection limits (typically tens to hundreds of ppm), lack of gas specificity, and susceptibility to poisoning by contaminants limit their applicability for LDAR surveys targeting the concentration thresholds specified in EU Regulation 2024/1787. This limitation should extend to catalytic & semiconductor handheld instruments widely deployed across EU utility fleets for safety response and escape location: because the lower explosive limit of methane is 5% by volume (50,000 ppm), the Type 2 threshold of 500 ppm corresponds to just 1% LEL, the very bottom of a catalytic instrument's measurement range and within the typical accuracy band of such sensors.

MOS and catalytic sensors find appropriate application in safety monitoring, LEL detection, and initial screening where cost constraints preclude deployment of more sensitive instrumentation. They should not be relied upon as primary detection technology for Type 1 or Type 2 LDAR surveys but may complement optical methods for personnel safety during survey operations. Existing fleet instruments of these classes should be retained for their safety and operational roles, with Type 1 and Type 2 survey duty assigned to methane-specific (TDLAS) or reference-method (FID) instruments.

5.3 Optical Gas Imaging (OGI)

Optical gas imaging enables visualisation of methane emissions as apparent plumes superimposed on thermal imagery of the inspected scene. OGI cameras have become the predominant technology for LDAR surveys at oil and gas production facilities and increasingly at transmission and distribution infrastructure. The technology offers significant advantages for rapid survey of complex facilities with numerous potential emission sources.

Operating Principles: OGI cameras operate in the mid-infrared region, exploiting the strong methane absorption band at 3.2 to 3.4μm. The cameras employ cooled indium antimonide (InSb) focal plane arrays operating at cryogenic temperatures (typically 70-80 K), achieved through integrated Stirling cycle coolers. A narrow bandpass filter selects the spectral region encompassing the methane absorption feature, rendering methane-containing plumes visible against the thermal background.

The physical principle relies on differential absorption between methane-laden air and the thermal background. When methane absorbs infrared radiation from a warmer background, it appears as a dark plume against that background; conversely, methane absorbing radiation from a cooler background and re-emitting at its own temperature may appear brighter. This thermal contrast enables visualisation of gas plumes that would be invisible to conventional thermal or visible-light cameras.

Figure 3 OGI thermal image showing methane plume visualisation at a gas facility [27].

Detection sensitivity depends on multiple factors including gas concentration and plume thickness (the concentration-path length product), thermal contrast between the plume and background, atmospheric conditions (wind disperses plumes; humidity affects transmission), and camera performance characteristics. Published minimum detection limits for OGI cameras are typically expressed as mass flow rates under specified conditions (e.g., 0.5 to 6 g/hr methane equivalent for various leak configurations), but real-world detection depends heavily on survey conditions.

Detection Capabilities and Limitations: OGI provides rapid qualitative detection of methane emissions, enabling surveyors to scan large areas and numerous components quickly. A trained operator can survey a facility far more rapidly than would be possible with point-sampling instruments, making OGI particularly efficient for facilities with many potential emission points. The visual nature of the output aids in identifying the specific leaking component and communicating findings to maintenance personnel.

Standard OGI provides detection and localisation but not quantification. The camera image shows the presence of a plume but does not directly indicate the emission rate. While experienced operators may make rough estimates based on plume appearance, these are subjective and cannot confirm that the leak exceeds the 500ppm or 1 g/hr threshold required for Type 2 compliance. This limitation has driven development of quantitative OGI methods discussed in the following section.

Additional limitations include dependence on adequate thermal contrast (challenging in isothermal conditions), wind effects (high winds disperse plumes below detection threshold; no wind allows plumes to accumulate reducing source localisation), and operator training requirements. OGI surveys are most effective during favourable meteorological windows, typically early morning or late afternoon when thermal gradients are pronounced.

Quantitative OGI (QOGI) for Type 2 Compliance: Quantitative optical gas imaging addresses the fundamental limitation of standard OGI by combining plume visualisation with algorithms that estimate emission rates. The FLIR QL320 system exemplifies this approach, integrating OGI camera imagery with Gaussian plume dispersion modelling to derive emission rate estimates from observed plume characteristics.

The QOGI methodology requires input of meteorological data (wind speed, atmospheric stability class) and geometric parameters (distance to source, camera angle). The algorithm analyses the plume image to estimate the concentration-thickness product along multiple lines of sight, then applies dispersion model inversion to estimate the source emission rate. Results are expressed in g/hr, directly comparable to the Type 2 threshold of 1 g/hr specified in EU Regulation 2024/1787.

QOGI enables OGI cameras to serve as both detection and quantification instruments, potentially streamlining Type 2 LDAR surveys by eliminating the need for separate quantification procedures at each detected leak. However, quantification accuracy depends on the validity of the dispersion model assumptions, accuracy of meteorological inputs, and operator skill in applying the methodology. Controlled studies report uncertainties of approximately a factor of two under favourable conditions, which may be acceptable for compliance determination but requires appropriate quality assurance.

Handheld vs Fixed OGI Systems: OGI cameras are available in handheld configurations for manual surveys and fixed-mount configurations for continuous or scheduled automated monitoring. Handheld cameras such as the FLIR GF320 and GF620 enable operators to survey facilities by walking through and pointing the camera at components of interest. Fixed systems such as the FLIR A8500 series can be installed overlooking process areas, AGIs, or other high-priority locations for automated detection.

Fixed OGI systems offer the potential for continuous monitoring, detecting emissions as they occur rather than only during periodic surveys. This approach aligns with EU Regulation 2024/1787 provisions for continuous monitoring as an alternative to periodic surveys (Article 14(4)). However, fixed system deployment requires substantial capital investment and is typically justified only at high-priority locations with significant emission risk or regulatory focus.

For GNI operations, handheld OGI is likely the most practical deployment mode for the majority of LDAR survey requirements, with potential for fixed installations at major AGIs or CNG units where continuous monitoring provides operational benefits beyond regulatory compliance.

Supplier Comparison (FLIR, Opgal, Sensia): The OGI camera market is dominated by a small number of suppliers offering instruments with broadly comparable detection capabilities but differentiated features and integration options.

Table 10: OGI camera supplier comparison

Manufacturer	Model Range	Key Features	Quantification
FLIR (Teledyne)	GF320, GF620, A8500	Market leader; widest range; QL320 QOGI option	QL320 software integration
Opgal	EyeCGas 2.0	Uncooled option available; lower cost entry point	Limited; primarily detection
Sensia (SLB)	Methane camera	Integrated with Sensia platform; autonomous operation	Proprietary algorithms

FLIR (now part of Teledyne FLIR) dominates the market with the GF-series cameras that have become the de facto standard for OGI surveys globally. The QL320 quantification system provides an integrated path to Type 2 compliance for FLIR camera users. Opgal offers a competitive alternative with the EyeCGas range, including options using uncooled detector technology at reduced cost but lower sensitivity. Sensia (a Schlumberger company) offers cameras integrated with their broader emissions monitoring platform, targeting operators seeking enterprise-scale solutions.

5.4 LiDAR-Based Detection and Quantification

Light Detection and Ranging (LiDAR) technologies adapted for gas sensing offer unique capabilities for simultaneous detection and quantification of methane emissions at ranges from metres to kilometres. Unlike passive OGI which relies on thermal contrast, LiDAR systems actively illuminate the scene and analyse the returned signal, enabling quantitative concentration measurement across extended fields of view.

Principles of Differential Absorption LiDAR: Differential absorption LiDAR (DIAL) exploits the wavelength-dependent absorption of laser light by methane to measure path-integrated concentration. The system transmits laser pulses at two wavelengths: one coinciding with a methane absorption line (on-line) and one adjacent to the absorption feature (off-line). By comparing the backscattered intensity at these wavelengths, the system derives the concentration-path length integral along the beam path.

Backscatter may arise from atmospheric aerosols and molecules (Mie and Rayleigh scattering) for range-resolved measurement, or from hard targets (buildings, ground, vegetation) for integrated path measurement. Scanning the beam across the scene generates a two-dimensional map of concentration-path length product, which can be combined with wind velocity data to estimate emission rates using mass balance or atmospheric inversion methods.

The active illumination of LiDAR systems provides several advantages over passive OGI: independence from thermal background conditions, quantitative concentration measurement, and extended range capability. These advantages come at the cost of increased system complexity, power requirements, and typically higher capital cost.

Gas Mapping LiDAR (Bridger Photonics): Bridger Photonics has developed Gas Mapping LiDAR (GML) technology specifically for aerial methane surveys of oil and gas infrastructure. The system combines a frequency-modulated continuous-wave (FMCW) LiDAR with methane-specific wavelength selection, enabling simultaneous measurement of range and gas concentration from aircraft flying at typical survey altitudes of 100 to 300 metres.

The GML system generates high-resolution concentration maps covering the survey swath beneath the aircraft, with detected emissions automatically flagged for review. The technology has been deployed commercially for basin-scale surveys covering hundreds of thousands of kilometres of pipeline and thousands of production facilities in North American oil and gas operations.

Emission rate quantification is achieved through atmospheric inversion algorithms applied to the concentration map data in conjunction with wind measurements. The methodology has undergone controlled release testing and is accepted by the US EPA as an alternative work practice for OOOOa compliance. Published detection limits are approximately 2 kg/hr for large-area surveys, suitable for identifying significant emitters but not for Type 2 component-level surveys at the 1 g/hr threshold.

For GNI applications, aerial GML surveys could provide efficient screening of the transmission network for significant leaks or third-party damage, complementing rather than replacing ground-based Type 2 surveys. The technology is particularly valuable for rapid assessment of large areas following seismic events, extreme weather, or other situations where network integrity may be compromised.

LiDAR Cameras (QLM, Sensia): LiDAR cameras represent an emerging category of instruments that combine the imaging capability of cameras with active LiDAR illumination for quantitative gas detection. Unlike scanning LiDAR which builds images from sequential beam positions, LiDAR cameras capture the entire field of view simultaneously, enabling real-time visualisation and quantification of methane plumes.

QLM Technology has developed a single-photon LiDAR camera employing a novel detection approach that achieves sensitivity sufficient for component-level leak detection. The system operates at eye-safe power levels, requires no consumables, and provides continuous quantitative imaging of the monitored scene. Emission rates are derived through analysis of the concentration-path length imagery using proprietary algorithms.

Sensia offers a comparable LiDAR camera platform integrated with their emissions management software, targeting automated monitoring applications at fixed installations. Both systems aim to combine the operational benefits of OGI (visual plume identification, rapid facility survey) with inherent quantification capability, addressing the key limitation of passive OGI for Type 2 compliance.

LiDAR cameras are positioned as emerging technology with significant potential, but relatively limited deployment experience compared to established OGI and portable detector methods. Evaluation by GNI could consider pilot deployment at representative facilities to assess real-world performance against Type 2 requirements.

Quantification Capabilities and EPA Acceptance: The quantification capability of LiDAR systems is a key differentiator from detection-only technologies. Both scanning LiDAR (Bridger) and LiDAR cameras (QLM, Sensia) provide direct measurement data from which emission rates can be derived, in contrast to standard OGI which requires supplementary methods for quantification.

The US EPA has accepted Bridger Gas Mapping LiDAR as an alternative means of emission detection under OTM-33A protocols, recognising the scientific basis of the measurement methodology. This regulatory acceptance provides a precedent for similar technologies under other jurisdictions, although specific acceptance under EU Regulation 2024/1787 implementing acts will depend on the technical specifications established by the Commission.

Table 11: LiDAR-based detection system comparison

Technology	Platform	Detection Limit	Quantification	Maturity
Bridger GML	Fixed-wing aircraft	~2 kg/hr	EPA-accepted methodology	Commercial
QLM Technology	Tripod/fixed mount	~0.1 g/hr claimed	Proprietary algorithms	Emerging
Sensia LiDAR	Fixed mount	Not published	Integrated platform	Emerging

5.5 Satellite-Based Detection

Satellite platforms detect methane by measuring the absorption of reflected sunlight in the shortwave infrared region, either across continuous global swaths or through targeted observation of individual facilities. Satellite-derived methane data has attracted significant attention in the context of EU Regulation 2024/1787, and this section assesses its applicability to GNI's LDAR programme, sets out the basis on which it is excluded from the technology selection matrices in this report, and identifies the one respect in which satellite systems nonetheless create an obligation for the programme.

Capability Tiers: Current satellite capability falls into three tiers. Area flux mappers, principally the TROPOMI instrument aboard Sentinel-5P, provide daily global coverage at coarse spatial resolution, with detection limits in the order of tonnes of methane per hour; these systems identify only catastrophic release events and regional emission enhancements. Point-source imagers, including GHGSat, Carbon Mapper's Tanager constellation, and the EnMAP and PRISMA hyperspectral missions, provide targeted observation of individual sites with detection limits of approximately 100 kg/hr under favourable atmospheric and surface conditions. Multispectral land-imaging missions such as Sentinel-2 and Landsat can resolve only very large plumes, typically above 1,000 kg/hr, as an opportunistic by-product of their primary mission. The loss of MethaneSAT in mid-2025, shortly after the commencement of science operations, illustrates that the satellite methane segment remains commercially and technically volatile, and that no single platform should be relied upon for continuity of coverage.

Performance in the Irish Operating Environment: Even the most sensitive point-source imagers operate at detection limits three to five orders of magnitude above the Article 14 Type 2 threshold of 1 g/hr, and well above any emission GNI's network could plausibly produce short of a transmission pipeline rupture. Performance is further constrained in the Irish operating environment. Passive shortwave infrared retrieval requires cloud-free conditions and adequate solar illumination: Ireland's persistent cloud cover substantially reduces the frequency of usable retrievals, low solar elevation angles degrade winter performance at Irish latitudes, and observation over water requires sun-glint geometry available on only a fraction of passes, limiting applicability to foreshore and offshore assets.

Exclusion from Technology Selection: In the single scenario in which satellite detection of a GNI emission is physically plausible, a major transmission pipeline rupture, the capability is redundant: such an event would be identified through SCADA pressure telemetry within minutes, against a satellite revisit cycle measured in days and further degraded by cloud cover. Satellite detection therefore offers no detection scenario on the GNI network in which it is not outperformed by capability already in place. On this basis, satellite-based detection is deliberately excluded from the technology comparison and selection matrices in this report (Tables 12, 20, and 25): no current satellite system approaches either Article 14 detection threshold, none provides the source-level quantification required under Article 12, and inclusion would imply a selection decision where none exists.

Article 30 Super-Emitter Notifications: Satellite systems nonetheless create one obligation and one opportunity for the LDAR programme. Under Article 30 of EU Regulation 2024/1787, super-emitter events detected by third parties, including the United Nations Environment Programme's Methane Alert and Response System (MARS) operated by the International Methane Emissions Observatory, may be notified to the competent authority and forwarded to the operator, triggering a mandatory investigation and response. GNI should therefore establish a documented satellite-notification response procedure, comprising verification against SCADA and operational records, deployment of ground-based or UAV follow-up survey, quantification of any confirmed source, and reporting to the competent authority, regardless of whether GNI ever procures satellite data directly. This is a low-cost programme element that should be in place in advance of any notification being received rather than developed reactively under the Regulation's response timelines. Conversely, the absence of detections over GNI assets in publicly available satellite monitoring provides low-cost negative assurance suitable for inclusion in the annual emissions report narrative. Satellite capability should otherwise be held at watch-brief status, consistent with the treatment of other emerging technologies in this report, with detection limits, constellation coverage, and revisit performance reviewed periodically as the segment matures.

5.6 Distributed Fibre Optic Sensing

Distributed fibre optic sensing technologies enable continuous monitoring along the entire length of a fibre optic cable, providing spatially resolved measurement of temperature or acoustic disturbances. Originally developed for downhole reservoir monitoring and structural health applications, these technologies have been adapted for pipeline leak detection and offer continuous monitoring capabilities complementary to periodic LDAR surveys.

DTS, DAS and Hybrid Systems: Distributed Temperature Sensing (DTS) measures temperature along the fibre by analysing the temperature-dependent Raman backscatter of injected laser pulses. For gas pipeline applications, DTS exploits the Joule-Thomson cooling effect: gas escaping from a pressurised pipeline expands and cools, creating a localised temperature anomaly detectable by the sensing fibre. DTS systems typically achieve spatial resolution of approximately 1 metre over ranges of tens of kilometres, with temperature resolution of 0.1 to 1 °C.

Distributed Acoustic Sensing (DAS) measures acoustic vibrations and strain along the fibre using coherent optical time-domain reflectometry (OTDR) techniques. DAS can detect the acoustic signature of gas flowing through a leak orifice, as well as third-party interference events (excavation, vehicle impact) that may lead to pipeline damage. DAS systems achieve metre-scale spatial resolution with high temporal sampling rates suitable for acoustic analysis.

Hybrid systems combining DTS and DAS leverage the complementary strengths of both technologies, using the same fibre installation to detect both thermal anomalies indicative of leaks and acoustic events indicating third-party activity or incipient failure. Leading suppliers including OptaSense (Luna), Fotech (BP), Silixa, AP Sensing, and Omnisens offer hybrid interrogator platforms capable of simultaneous DTS and DAS measurement.

Technology Maturity and Deployment Considerations: DTS and DAS technologies have achieved commercial maturity through extensive deployment in oil and gas production, LNG facilities, and pipeline monitoring applications. Thousands of kilometres of pipeline worldwide are monitored using distributed fibre sensing, with proven reliability and false alarm management in operational settings.

Deployment requires installation of optical fibre along the pipeline route, either during construction (ideal) or by retrofitting cable alongside existing pipelines. The fibre may be buried alongside the pipeline, installed in existing conduits, or integrated into pipeline coating systems. Interrogator equipment is installed at intervals determined by the fibre attenuation and required spatial resolution, typically every 20 to 50 kilometres.

Emerging developments include fibre coatings sensitised to specific gases through swelling or refractive index changes, and hollow-core fibres enabling direct gas spectroscopy. These approaches remain at research or early commercial stages and face challenges including long-term coating stability, selectivity against interfering gases, and calibration complexity. For near-term GNI deployment, established DTS/DAS hybrid systems represent the most practical distributed sensing option.

Role in Pipeline Monitoring (Complementary to LDAR): DTS/DAS systems do not provide quantified emission rates and therefore do not satisfy Article 12 reporting requirements. Their value lies in continuous surveillance and early warning rather than regulatory compliance measurement. These approaches provide continuous monitoring capability that complements but does not replace periodic LDAR surveys. The technology excels at detecting changes indicating new leaks or third-party interference, providing real-time alerting for rapid response. However, distributed sensing does not provide the component-level inspection required for Type 2 LDAR surveys and cannot quantify emission rates in the manner required for regulatory compliance.

For GNI transmission pipeline monitoring, distributed sensing could provide valuable continuous situational awareness, detecting pipeline damage or significant leaks between periodic LDAR surveys. The technology is particularly suited to high-consequence areas, river crossings, and other locations where early leak detection provides operational or safety benefits beyond regulatory compliance.

Cost-benefit analysis should consider the significant capital investment for fibre installation and interrogator equipment against the value of continuous monitoring, reduced survey frequency potential, and incident prevention. Retrofit installation on the existing GNI transmission network would require substantial civil works; fibre integration should be considered for any new pipeline construction or major rehabilitation projects.

5.7 GNI Network Context and Survey Challenges

The detection technologies described in Sections 5.1 to 5.6 must be evaluated against the specific characteristics of Gas Networks Ireland infrastructure. The key network parameters affecting LDAR survey design are detailed, with reference to the detailed network description provided in Section 2. The objective is to establish the practical framework for technology deployment decisions addressed in subsequent sections.

Network Segments and Pressure Regimes: As described in Section 2.1, the GNI network comprises four principal segments operating at distinct pressure regimes. The transmission system operates at 40 to 85 bar across approximately 1,900 km of steel pipeline. High-pressure distribution networks operate at 7 to 16 bar feeding regional demand centres, whilst medium-pressure (0.075 to 7 bar) and low-pressure (≤0.075 bar) networks serve local and residential consumers across more than 12,000 km of predominantly polyethylene pipeline.

Pressure regime directly influences leak detectability through its effect on emission rate. For a given defect geometry, the mass flow rate of escaping gas scales approximately with the square root of pressure differential, meaning a pinhole defect in a transmission pipeline at 70 bar will produce an emission rate roughly seven times greater than the same defect in a medium-pressure main at 1.5 bar. Methods capable of detecting transmission leaks at standoff distances may therefore lack sensitivity for equivalent defects in low-pressure networks.

The EU Regulation 2024/1787 detection thresholds apply uniformly across all network segments. However, the probability of a given defect exceeding these thresholds varies substantially with operating pressure. Transmission system defects are more likely to produce emissions exceeding detection limits, whilst low-pressure distribution leaks may remain undetectable unless measurement is conducted in close proximity to the source.

Survey Challenges by Asset Type: The transmission network comprises long linear assets traversing predominantly rural terrain with limited road access. Pipeline routes include agricultural land, bogland, river crossings, and road crossings, with extended distances between access points limiting practical coverage by walking surveys. Seasonal access restrictions, the requirement to detect surface emissions from buried assets, and the impracticality of foot-based coverage over hundreds of kilometres favour aerial screening methods for initial detection, with ground-based follow-up at identified anomalies.

Distribution mains are predominantly located beneath public roads in urban and suburban environments. The dense network serving over 720,000 customers presents a different challenge: high component density over extensive geographic areas requiring survey within practical timeframes. Traffic management constraints, interference from biogenic methane sources, and building proximity affecting plume dispersion complicate survey execution. Vehicle-mounted cavity ring-down spectroscopy (CRDS) systems have become a primary survey method for distribution network LDAR among European DSOs, with over 50 operators now deploying Picarro-based platforms covering more than 800,000 km annually. Vehicle surveys are followed by ground-based walking surveys for precise localisation and confirmation at flagged locations.

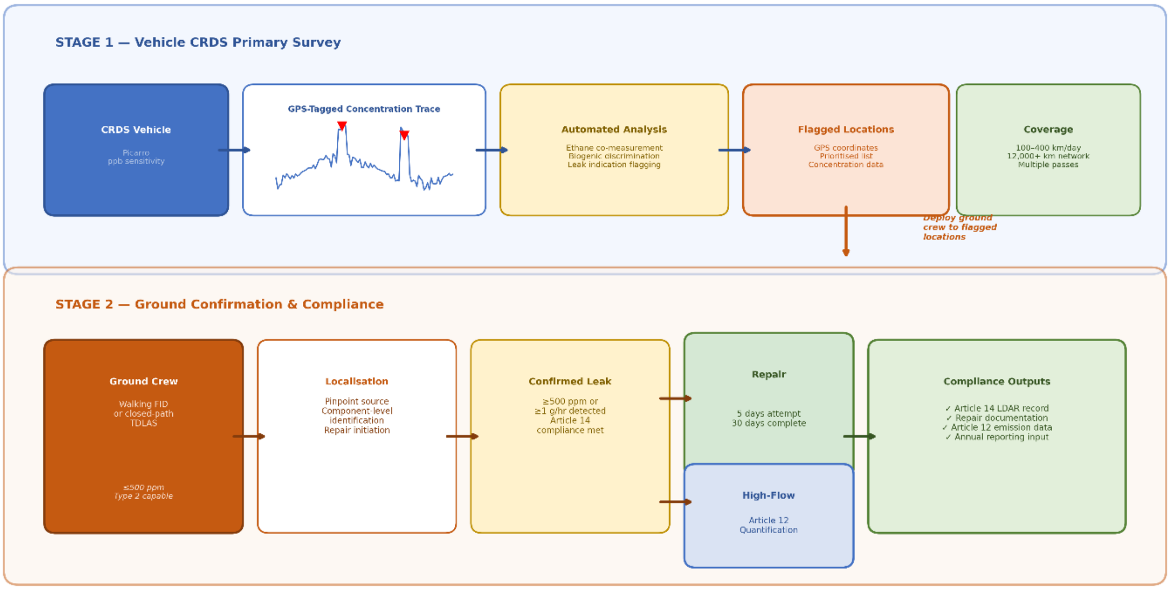

Figure 4 Vehicle CRDS two-stage compliance workflow, mobile survey with GPS-tagged concentration trace followed by ground crew confirmation at flagged locations.

Above Ground Installations include compressor stations, CNG units, pressure reduction installations, district governors, and metering stations. These facilities concentrate mechanical equipment with multiple potential emission sources: valves, flanges, connectors, seals, and vents. High component density requires systematic inspection, Type 2 quantification requirements apply particularly at compressor / CNG units, and confined spaces affect access. AGI surveys require component-level inspection using handheld instruments or OGI with quantification capability, favouring thorough ground-based methods over screening approaches.

Linear vs Point Asset Considerations: A fundamental distinction in LDAR survey design is between linear assets (pipelines) and point assets (AGIs, metering stations). Pipeline surveys must address continuous assets extending over kilometres where leaks may occur at any location. For transmission pipelines, a tiered approach is typically most efficient: screening survey using aircraft or vehicle-mounted sensors for rapid coverage (noting that aircraft screening does not itself satisfy Article 14 Type 1 or Type 2 detection thresholds); confirmation survey using UAV or ground-based methods at flagged locations; and quantification using QOGI, high-flow sampling, or dispersion modelling for confirmed leaks. This tiered methodology balances coverage efficiency against the proximity required for reliable detection and quantification.

Point assets require systematic component-level inspection rather than linear coverage, with protocols specifying inspection of defined component types at defined frequencies. The concentrated nature of point assets enables comprehensive coverage within practical survey durations, and direct quantification methods are practical because each detected leak can be individually assessed.

Pipeline crossings and other inaccessible sections present a hybrid challenge: linear assets that cannot be surveyed by conventional walking methods. These sections require specific methodology, addressed in detail in Section 7, typically involving UAV-based detection capable of achieving close proximity to the pipeline surface. The Parteen Bridge survey conducted by GNI using the Sniffer4D platform demonstrates a practical approach to crossing surveys, achieving detection within regulatory proximity requirements without direct physical access.

Mapping Technologies to LDAR and Article 12 Requirements: The ability of a detection technology to satisfy Type 1, Type 2, or Article 12 requirements depends not only on its measurement principle but also on the distance between the sensor and the emission source. Point sensors measuring concentration in ppm (such as handheld TDLAS, FID, and UAV-mounted TDLAS systems including the Sniffer4D) require close proximity to the source, typically within 2 metres, to ensure the measured concentration accurately represents the leak rather than a diluted ambient plume. For path-integrated instruments reporting in ppm·m (such as open-path TDLAS and LiDAR systems), the detected signal represents the product of concentration and path length; deriving a concentration value therefore requires either a known short path length or application of dispersion algorithms. At close range, ppm·m readings can reliably confirm the Type 1 threshold of 7,000 ppm; confirming the lower Type 2 threshold of 500 ppm typically requires closer proximity still, with specific distance limitations varying by manufacturer and instrument sensitivity. For Article 12 quantification, technologies must derive emission rates in g/hr, which requires either direct measurement (high-flow sampling) or algorithmic conversion from concentration data using dispersion modelling, the accuracy of which is highly dependent on measurement geometry and atmospheric conditions. Operators should consult manufacturer specifications for each instrument to determine the maximum working distance at which Type 1, Type 2, and Article 12 compliance can be demonstrated. The following table summarises the applicability of detection technologies to LDAR and Emission requirements under EU Regulation 2024/1787. Technologies are assessed on their ability to detect leaks at the specified thresholds and, where applicable, their capability to quantify emission rates.

Table 12: Technology Mapping to Article 14 (LDAR) and Article 12 (Reporting) Requirements

Technology	Output	Type 1	Type 2	Article12	Notes
Handheld TDLAS-closed-path	ppm	Yes	Yes	No	Detects well below 500 ppm threshold
Handheld FID	ppm	Yes	Yes	No	Sub-ppm detection; EPA Method 21 reference
Handheld TDLAS-open-path	ppm·m	Yes	Yes	No	~1 ppm detection limit
Vehicle CRDS	ppb	Screening	Screening	No	Area detection; triggers ground follow-up for component-level compliance
UAV TDLAS-open-path	ppm·m	Yes	Possible	In-Trial	Gimbal-mounted; quantification via AIRINS.ai (trial workflow)
UAV TDLAS-closed-path	ppm	Yes	Yes	No	1 ppm resolution; <2m proximity achievable
Standard OGI	Qualitative	Yes	No	No	Qualitative detection; cannot confirm ppm unless close
QOGI	g/hr	Yes	Yes	Yes	Provides g/hr quantification suitable for reporting
Gas Mapping LiDAR	g/hr	Yes	Screening	*Yes	~2 kg/hr detection limit exceeds Type 2 threshold
LiDAR cameras	g/hr	Yes	Yes	Yes	Claimed detection at <1 g/hr
DTS / DAS (fibre optic)	Anomaly detection	Auxiliary	Auxiliary	No	Continuous monitoring; not component-level
High-flow sampling	g/hr	Yes	Yes	Yes	Direct g/hr measurement suitable for reporting

5.8 Deployment Platforms

The detection technologies described in Sections 5.2 to 5.5 may be deployed across a range of platforms, from handheld instruments carried by survey technicians to sensors mounted on aircraft covering hundreds of kilometres per day. Platform selection is driven by the network context and survey challenges outlined in Section 5.7: walking surveys for accessible components and AGIs, vehicle-mounted systems for distribution network screening, UAVs for inaccessible crossings and elevated assets, and aircraft for transmission corridor coverage.

Walking Survey Methods and Current GNI Practice: Walking surveys with handheld detectors represent the established methodology for LDAR inspection within Gas Networks Ireland operations. Technicians traverse pipeline routes, inspect Above Ground Installations, and survey district governor stations using portable TDLAS instruments. This approach enables systematic inspection of all accessible components at defined frequencies aligned with I.S. 328:2021 requirements and operational risk assessments.

Current GNI practice employs portable instruments for leakage surveys at intervals determined by population density classification (Type R, S, T, and C areas), with high-consequence areas surveyed quarterly and rural areas surveyed annually or less frequently. Survey technicians follow prescribed routes, recording instrument readings at specified inspection points and investigating any elevated concentrations to localise and characterise potential leaks.

Walking surveys provide comprehensive coverage of accessible assets and enable direct inspection of individual components. The methodology is well-established, requires minimal specialist equipment, and integrates with existing workforce capabilities. Limitations include the labour-intensive nature of coverage for extensive networks and restricted access to elevated or remote assets. Standard handheld instruments detecting at ≥500 ppm satisfy Article 14 Type 2 requirements; supplementary quantification is required only for Article 12 emissions reporting.

Vehicle-Mounted Sensor Technologies: Vehicle-mounted mobile leak detection systems integrate high-sensitivity gas analysers with GPS positioning and data logging to enable drive-by surveys of gas distribution networks. The vehicle traverses' streets above buried pipelines whilst continuously sampling ambient air and recording concentration measurements synchronised with geographic coordinates. Elevated readings trigger investigation to localise and confirm potential underground leaks.

The most widely deployed vehicle-mounted analyser technology is cavity ring-down spectroscopy (CRDS), exemplified by the Picarro mobile surveyor platform. CRDS achieves parts-per-billion (ppb) sensitivity by measuring the decay time of laser light trapped in a high-finesse optical cavity, providing detection capability far exceeding regulatory thresholds. This sensitivity enables detection of methane plumes from buried leaks dispersed into the atmosphere above street level.

Vehicle-mounted CRDS has moved beyond pilot deployment to become the established distribution LDAR methodology across Europe. Over 50 DSOs now operate Picarro-based mobile surveying platforms, with operators including Italgas (42 vehicles covering 150,000+ km of network, achieving OGMP 2.0 Gold Standard), Cadent (UK's largest distribution network, selected Picarro for network wide deployment in 2025), Netz Niederösterreich (completed 7,500 km of EU Regulation-compliant surveys in 2025), and Netze BW (Germany, operational since 2023 in preparation for EU Methane Regulation compliance). The ethane co-measurement capability of CRDS platforms provides discrimination between thermogenic (pipeline) methane and biogenic methane from agricultural sources   a significant advantage in Ireland's rural landscape where livestock emissions represent a persistent false positive source for methane-only detectors.

Alternative vehicle-mounted technologies include TDLAS systems (Heath Consultants, ABB) offering rapid response and ppm-level sensitivity suitable for leak indication, and emerging systems incorporating multiple sensor modalities. Some operators deploy vehicle-mounted optical gas imaging cameras to provide visual confirmation of emissions from above ground assets encountered during mobile surveys.

Vehicle-based surveying offers dramatic efficiency gains for distribution network coverage. A single vehicle can survey hundreds of kilometres of pipeline route per day compared to a few kilometres achievable by walking surveys. This efficiency enables more frequent survey intervals across the network and supports prioritisation of follow-up investigation resources. Vehicle surveys provide network-level screening rather than component-level inspection; detected concentration enhancements trigger deployment of ground crews with handheld instruments for precise localisation and characterisation. This two-stage workflow, vehicle CRDS screening followed by ground confirmation, is now the accepted Article 14 compliance methodology for distribution networks among European DSOs and regulators, with the vehicle survey constituting the primary detection pass and ground follow-up providing the component-level confirmation required for repair initiation. Detection of elevated concentrations triggers deployment of ground crews with handheld instruments for precise localisation and characterisation.

Vehicle-mounted optical gas imaging systems combine the visualisation capability of thermal infrared cameras with mobile deployment to enable drive-by inspection of above ground assets. The camera, mounted on a stabilised platform, captures thermal imagery of meter installations, service risers, and other visible components as the vehicle passes, with detected plumes flagged for investigation.

This approach addresses a limitation of point-sampling vehicle systems, which detect only diluted plumes reaching the sample inlet and cannot visually identify emission sources. OGI provides direct visualisation of methane releases from above ground components, enabling immediate identification of leaking equipment. Vehicle-based OGI is particularly applicable to surveys of meter sets, service lines, and district regulator stations along urban routes.

Practical deployment requires consideration of camera field of view, vehicle speed, and environmental conditions affecting thermal contrast. Systems typically incorporate image recording for post-survey review and documentation. The technology provides Type 1 detection capability but, as with handheld OGI, does not inherently quantify emission rates.

UAV-Mounted Sensors: Unmanned aerial vehicles equipped with methane sensors provide access to assets that are difficult, dangerous, or impossible to inspect using ground-based methods. River crossings, elevated pipeline sections, offshore approach zones, and congested industrial facilities present challenges for conventional survey methods that UAV deployment can address effectively.

Gas Networks Ireland has completed trials with UAV system, a drone-mounted methane detection system employing TDLAS technology. The Sniffer4D achieves detection limits of approximately 1 ppm with a response time of approximately one second, enabling real-time concentration mapping as the UAV traverses the survey area. The system provides GPS-tagged concentration data that can be visualised as heat maps overlaid on aerial imagery, supporting rapid identification of elevated concentration zones.

Bridge crossing surveys conducted by GNI demonstrated the capability of UAV-based detection for pipeline crossings where direct walking access is impractical. The Sniffer4D platform enabled systematic survey of the crossing with concentration measurements at defined intervals, confirming pipeline integrity without requiring specialist access or traffic management on the bridge.

Alternative UAV sensor platforms include the Pergam DragonFly (TDLAS-based), SeekOps systems (miniaturised analyser technology), and various TDLAS-equipped drones from multiple manufacturers. Platform selection depends on payload capacity, flight endurance, sensor sensitivity, and operational requirements. Regulatory considerations including aviation authority approvals, pilot certification, and operational restrictions in certain airspace categories apply to all UAV deployments.

Beyond access solutions for specific inaccessible assets, drone-mounted open-path TDLAS systems represent the most viable aerial pathway to Article 14 Type 1 and Type 2 compliance for transmission pipeline corridors. Operating at altitudes of 25–50 metres and speeds of 50 km/h, drone TDLAS places the sensor within the detection envelope demonstrated to achieve the 17 g/hr Type 1 threshold in field testing [24], and within the range at which 500 ppm Type 2 detection has been confirmed (Pergam Falcon Plus: 500 ppm at 40 m for above ground, 1,000 ppm at 60 m for underground sources). This performance level cannot be matched by helicopter-mounted systems operating at I.S. 328 surveillance altitudes of 500 feet. Operational constraints, principally flight endurance (30–40 minutes per sortie for multi-rotor platforms), BVLOS regulatory requirements, and the logistical challenge of covering 1,900 km of transmission corridor, currently limit the scalability of drone TDLAS for full-network surveys. However, fixed-wing drone variants (such as the Pergam LMF) offer extended range per sortie, and the EU U-space regulatory framework is progressively enabling BVLOS operations that would substantially improve corridor coverage efficiency. Drone TDLAS is also positioned to support Article 12 emissions quantification in the near term: systems incorporating wind measurement and atmospheric dispersion algorithms (such as the Soarability MetScan with AIRINS.ai) are developing quantification capability that, once validated through controlled release testing, could provide measurement-based emission rate data directly from the survey platform. GNI should monitor the development of drone TDLAS for transmission corridor application as a technology that may transition from site-specific access solution to primary compliance survey method as BVLOS regulation and platform endurance mature.

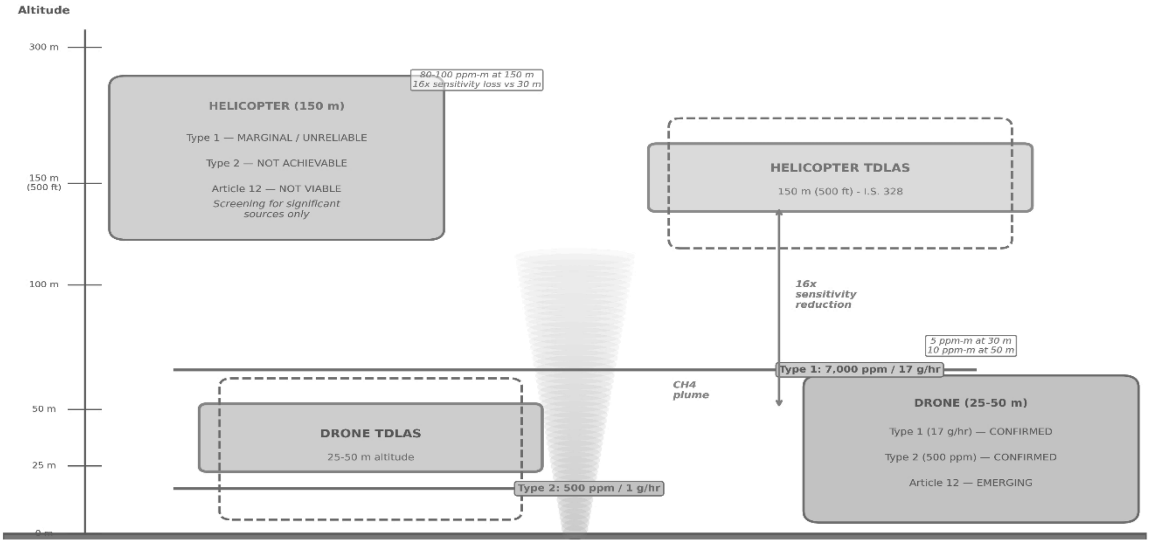

Figure 5 Drone TDLAS (25–50 m) versus helicopter TDLAS (150 m) detection envelopes relative to Article 14 Type 1 and Type 2 thresholds.

Aircraft-Mounted Sensors: Manned aircraft equipped with methane detection systems provide efficient survey capability for long transmission pipeline corridors where ground-based inspection would be prohibitively slow or impractical. Two principal sensor technologies are deployed on aircraft platforms: optical gas imaging (OGI) cameras for thermal visualisation of methane plumes, and gas mapping LiDAR for quantitative concentration measurement.

Helicopter and fixed-wing platforms carrying gimbal-stabilised OGI cameras can survey hundreds of kilometres of pipeline route in a single day, identifying methane emissions from above ground installations, exposed pipeline sections, and indicators of third-party damage along the right of way. Aircraft-mounted OGI surveys typically employ mid-wave infrared cameras such as the FLIR GF620 or equivalent, mounted on stabilised gimbals that maintain consistent viewing geometry during flight. Survey altitudes are constrained by aviation regulations to a minimum of 500 feet (150 metres) above ground level for non-congested areas, with typical operational altitudes of 150 to 300 metres depending on terrain and airspace restrictions. The thermal contrast between escaping gas and the background enables detection of significant leaks along visible pipeline sections, with real-time operator review and GPS-tagged recording for post-flight analysis. At regulatory minimum survey altitudes of 500 feet (150 metres), helicopter-mounted OGI detection sensitivity is limited to leaks of approximately 0.28 kg/hr (280 g/hr), substantially above the Type 1 threshold of 17 g/hr [25]. Aircraft OGI therefore provides general screening capability for significant emitters but does not satisfy either Type 1 or Type 2 detection thresholds under Article 14. Its primary value within an LDAR programme is rapid identification of major leaks and third-party damage indicators along transmission corridors, complementing but not replacing survey methods achieving regulatory detection thresholds.

Differential absorption LiDAR systems, exemplified by the Bridger Photonics Gas Mapping LiDAR, provide an alternative approach with quantitative concentration measurement capability. The system transmits laser pulses at methane-absorbing and reference wavelengths, analysing the backscattered signal to generate concentration maps of the survey swath. Unlike passive OGI, LiDAR actively illuminates the scene and can detect methane accumulations above buried pipeline sections where gas has migrated to the surface. Bridger GML operates from fixed-wing aircraft at typical survey altitudes of 150 to 300 metres, covering swaths of approximately 200 metres width with detection limits of approximately 2 kg/hr. Emission rate quantification is achieved through atmospheric inversion algorithms using methodology accepted by the US EPA under OTM-33A protocols. However, the 2 kg/hr detection threshold, whilst suitable for identifying significant emitters across basin-scale surveys, exceeds the Type 2 threshold of 1 g/hr required for component-level compliance.

The primary application for aircraft-mounted sensors within GNI operations is rapid screening of the transmission network for significant emission sources, enabling identification of major leaks across the approximately 1,900 km pipeline system within a matter of days. This screening does not constitute Type 1 or Type 2 LDAR compliance under Article 14 but provides operational value by prioritising locations for subsequent ground-based or UAV survey using methods capable of meeting regulatory detection thresholds.

Applications by Asset Type: The selection between vehicle-mounted and UAV-based mobile detection depends on the asset type, access conditions, and survey objectives. The following table summarises typical deployment scenarios within GNI operations.

Table 13: Mobile detection platform selection by GNI asset category

Asset Category	Recommendation	Article 14	Article 12	Notes
CNG unit / compressors	QOGI + handheld FID	Type 1 + 2	Yes	Integrated detection and quantification
AGIs / DRIs	Handheld TDLAS-closed-path + high-flow sampling	Type 1 + 2	Yes	Quantification at detected leaks
Valve stations	Handheld TDLAS-closed-path + high-flow sampling	Type 1 + 2	Yes	Quantification at detected leaks
River / road crossings	UAV TDLAS for inaccessible locations	Type 1 + 2	Via supplement	Ground quantification at detected leaks
Transmission ROW	Aerial screening (OGI / LiDAR) OR Vehicle CRDS + ground follow-up	Screening	Via follow-up	1st round identifies; ground quantifies
Transmission ROW	UAV open-path TDLAS	Type 1 + 2	In-trial	Speed of acquisition issues.
Distribution (urban)	Vehicle CRDS + walking confirmation	Screening	Via follow-up	Vehicle screening, Walking confirmation
Distribution (rural)	Walking TDLAS	Type 1 + 2	Via supplement	Direct survey where accessible

5.9 Leak Rate Quantification Methods

EU Regulation 2024/1787 specifies Type 2 thresholds as ≥500 ppm OR ≥1 g/hr, either measurement triggers the repair obligation. Consequently, quantification in g/hr is not mandatory for Article 14 LDAR compliance where concentration detection at ≥500 ppm is demonstrated. However, Article 12 requires operators to quantify and report emissions in mass units (g/hr or tonnes/year) for annual reporting. The principal quantification methods available where emission rate data is required for Article 12 compliance or where operators choose the g/hr compliance pathway are discussed. Detection technologies that report concentration (ppm) or path-integrated concentration (ppm·m) must be supplemented by quantification methods to convert these measurements to emission rates. Two principal approaches are employed: direct measurement using capture and flow techniques, and indirect estimation using atmospheric dispersion modelling.

Direct Measurement (High-Flow Sampling): Direct measurement methods capture the emitted gas stream and measure its flow rate to determine the emission rate directly. The most widely used technique is high-flow sampling, where a shroud or enclosure is placed over the leaking component and clean air is drawn through at a measured flow rate. The methane concentration in the exhaust stream is measured, and the product of concentration and flow rate yields the emission rate. Quantification must be scheduled within the Article 14 repair window, since a repaired component no longer provides the emission rate data point required for Article 12 reporting (see Section 3.5).

High-flow sampling provides the most accurate quantification for accessible components and is the reference method against which other approaches are validated. The technique requires direct access to the leak source, appropriate enclosure sizing for the component, and calibrated flow and concentration measurement. Portable high-flow samplers are available from multiple suppliers including Bacharach and Heath Consultants.

Bagging represents a simpler variant where the component is enclosed in a bag or tent and the accumulating gas concentration is measured over time. The emission rate is derived from the rate of concentration increase and the enclosure volume. This approach is practical for small components but becomes unwieldy for larger assemblies.

Limitations of direct measurement include the requirement for physical access, potential interference with ongoing operations, and impracticality for inaccessible or very large emission sources. The methods are best suited to confirmatory measurement at detected leaks rather than as primary survey techniques.

Atmospheric Dispersion Modelling: Atmospheric dispersion modelling estimates emission rates from downwind concentration measurements by applying mathematical models of how released gases disperse in the atmosphere. The approach requires measurement of methane concentration at one or more downwind locations, wind velocity and direction, atmospheric stability classification, and source-receptor geometry. The models invert the dispersion calculation to estimate the source strength that would produce the observed concentration field.

The US EPA Other Test Method 33A (OTM-33A) provides a standardised protocol for emission quantification using Gaussian plume dispersion modelling. The method specifies measurement requirements, dispersion model parameters, and quality assurance criteria for regulatory acceptance. OTM-33A has been widely applied for quantification of fugitive emissions from oil and gas facilities and provides a framework adaptable to transmission and distribution LDAR applications.

Dispersion modelling enables quantification from standoff distances without direct access to the source, making it suitable for inaccessible or hazardous locations. However, accuracy depends on the validity of model assumptions (steady-state conditions, uniform wind field, simple terrain) which may not hold in complex facility environments. Uncertainties are typically larger than for direct measurement, often a factor of two or more under field conditions.

5.10 Atmospheric Dispersion and Detection Reliability

The effectiveness of methane detection technologies in field conditions depends fundamentally on how released gas disperses in the atmosphere between the emission source and the detection instrument. This section examines the physical processes governing plume behaviour, their implications for detection probability, and the operational protocols required to ensure reliable survey results. Understanding these factors is essential for designing LDAR programmes that achieve consistent compliance with EU Regulation 2024/1787 thresholds across varying environmental conditions.

Plume Behaviour and Environmental Factors: When methane escapes from a pressurised pipeline or component, it enters the atmosphere as a buoyant plume that disperses through turbulent mixing with ambient air. The concentration at any point downwind depends one mission rate, distance from source, and atmospheric conditions. Gaussian plume models form the theoretical basis for most quantification methodologies [12] [13].

Key variables affecting dispersion include wind speed, atmospheric stability class (ranging from highly unstable Class A to very stable Class F), and the horizontal and vertical dispersion coefficients which increase with downwind distance. Under unstable conditions, vigorous vertical mixing rapidly dilutes the plume; under stable conditions, the plume remains concentrated but may meander unpredictably [14].

Wind Speed and Direction Effects: Wind is the dominant factor controlling plume transport and dilution. Higher wind speeds reduce concentrations at any fixed measurement point; low wind speeds allow gas to accumulate near the source but complicate localisation as plumes spread in multiple directions. For technologies requiring the sensor to intercept the plume, wind direction determines whether emitted gas reaches the measurement location. A detector positioned upwind of a leak will register no elevated concentration regardless of emission rate. Walking surveys should ideally approach components from the downwind side, and mobile surveys must account for wind direction when interpreting concentration data.

Research by Ravikumar et al. [15] demonstrated that OGI detection probability decreased significantly at wind speeds above 5 m/s. Similarly, Zimmerle et al. [16] found that handheld surveys under high wind conditions missed a greater proportion of controlled releases compared to moderate wind surveys. For GNI operations across Ireland's varied terrain, coastal and exposed areas frequently experience sustained winds exceeding optimal survey conditions, whilst sheltered valleys may exhibit calm conditions with complex flow patterns.

Atmospheric Stability, Temperature and Humidity: Atmospheric stability describes the tendency of vertical air motions to be enhanced (unstable) or suppressed (stable) by buoyancy forces. Stability is primarily determined by the vertical temperature gradient: when temperature decreases rapidly with height (super adiabatic lapse rate), the atmosphere is unstable; when temperature increases with height (inversion), the atmosphere is stable [17] [18].

Table 14: Pasquill–Gifford Stability Classes and Detection Implications

Stability Class	Conditions	Plume Behaviour	Detection Implications
A (Very unstable)	Strong solar heating, light winds	Rapid spreading; looping plume	Fast dilution; short detection window
B-C (Unstable)	Moderate convection	Coning plume; moderate dispersion	Good detection conditions
D (Neutral)	Overcast, moderate winds	Steady dispersion	Consistent detection
E-F (Stable)	Night-time, clear skies, light winds	Limited vertical mixing; fanning plume	Plume may travel far; intermittent detection

The diurnal variation creates predictable windows of optimal survey conditions. Early morning and late afternoon typically offer moderate stability with adequate thermal contrast for OGI whilst avoiding midday dilution [19]. Ambient temperature affects OGI through thermal contrast requirements the Joule-Thomson cooling of expanding gas (approximately 0.5°C per bar) creates the temperature differential that renders plumes visible. When ambient temperatures approach post-expansion gas temperature, detection sensitivity decreases [17]. Temperature also affects TDLAS accuracy, with most instruments incorporating compensation algorithms.

Humidity affects infrared-based detection through water vapour absorption bands overlapping with methane features. High humidity, common in Ireland, may increase measurement noise. CRDS and TDLAS instruments are generally more resistant than broadband NDIR sensors due to their narrow wavelength specificity [18].

Terrain and Obstacles: Local terrain features significantly influence plume behaviour. Buildings, vegetation, and topographic features create turbulent wakes and recirculation zones causing plumes to deviate from idealised behaviour. In complex AGI and urban environments, gas may accumulate in sheltered areas or disperse through unexpected pathways. For buried pipeline surveys, the soil surface channels migrating gas horizontally before emergence. The emergence point may be displaced from the actual defect, particularly in soils with low permeability layers [20]. River crossings, bridge structures, and elevated pipeline sections create additional complexity. Airflow acceleration over water bodies and around structures can rapidly disperse emissions, whilst sheltered zones beneath bridges may accumulate gas.

5.11 Detection Probability and Real-World Performance

Detection probability (Pd) describes the likelihood that a detection technology will successfully identify a leak of specified size under defined conditions. Unlike laboratory detection limits representing minimum measurable concentration under ideal conditions, field detection probability accounts for factors causing leaks to be missed during operational surveys. Detection probability depends on emission rate, distance from source to detector, wind speed, atmospheric stability, instrument sensitivity, operator skill, and survey methodology. Pd approaches 1.0 for large leaks at close range under favourable conditions and approaches 0 for small leaks at distance under adverse conditions.

Empirical studies consistently demonstrate that real-world detection probability falls below laboratory expectations. A comprehensive study by Zimmerle et al. [16] across multiple operators and detection technologies found that even for leaks substantially above regulatory thresholds, detection rates during routine surveys averaged only 40-70% depending on technology and conditions. This "leak through" phenomenon highlights the importance of survey design, repeat coverage, and quality assurance protocols.

Handheld Instruments (FID, TDLAS): Laboratory detection limits of 1–10 ppm for TDLAS and sub-ppm for FID translate to reliable detection below the 500 ppm Type 2 threshold when measured at component level. However, detection probability decreases rapidly with distance from the source. Controlled release studies at METEC have demonstrated that handheld instruments achieve high detection rates (>90%) for larger leaks at close range, but detection probability drops substantially for smaller leaks (1–5 g/hr) even at distances of only a few metres [2]. Closer approach distances and systematic coverage patterns significantly improve detection rates for smaller leaks.

Vehicle-Mounted Systems (CRDS): Vehicle-mounted systems detect diluted plumes at street level above buried infrastructure, fundamentally different from component-level measurement. The concentration reaching the vehicle inlet depends on the emission rate, burial depth, soil permeability, surface cover, and atmospheric dispersion between the soil surface and the sampling height (typically 2-3 metres). Picarro CRDS achieves parts-per-billion sensitivity, but the relevant metric is concentration enhancement that a buried leak produces at vehicle height. Leaks of 1-10 L/min typically produce detectable enhancements of 0.1-1 ppm above ambient [21]. Multiple passes significantly increase cumulative detection probability, Weller et al. [22] demonstrated three passes achieved approximately double the detection rate of single passes.

Optical Gas Imaging: OGI detection probability is uniquely dependent on thermal contrast and operator factors. Unlike concentration-measuring instruments that provide numerical readings, OGI detection relies on visual identification of plume signatures against a variable thermal background. Detection probability therefore includes both the physical visibility of the plume and the probability that the operator correctly identifies it.

Controlled studies at the Methane Emissions Technology Evaluation Center (METEC) found that OGI detection probability for leaks at the 6 g/hr level (below Type 1, above Type 2 threshold) varied from 20% to 80% depending on environmental conditions and operator experience [2]. Training and certification significantly improved detection rates, supporting the EU Regulation 2024/1787 requirement for operator certification.

QOGI systems improve detection probability by providing quantitative feedback, reducing dependence on subjective plume assessment. The QL320 system flags potential leaks based on concentration-path-length thresholds, alerting operators to emissions that might otherwise be overlooked.

UAV-Mounted Sensors: UAV detection platforms combine the advantages of point sensors (direct concentration measurement) with aerial mobility that enables access to otherwise inaccessible locations. Detection probability depends on achieving appropriate proximity to the source whilst maintaining stable flight in potentially turbulent conditions near structures and terrain features.

For point-sampling NDIR sensors, detection probability follows similar principles to handheld instruments: high at close range (<2 metres), decreasing with distance. The UAV's ability to approach elevated or remote assets enables surveys that would otherwise be impractical but requires careful flight planning to ensure adequate coverage.

Open-path TDLAS systems on UAV platforms (such as the Pergam DragonFly or Soarability MetScan) measure ppm·m across the beam path, with detection probability depending on the orientation of the measurement path relative to the plume. Scanning configurations that sweep across the expected plume location increase detection probability compared to fixed-beam orientations.

The Critical Role of Wind Sensors: For both TDLAS point sensors and ppm·m open-path systems, integrated wind measurement significantly enhances detection reliability and enables quantification.

Anemometers on UAV platforms provide real-time data that guides flightpath planning, enables plume tracking, supports concentration-to-emission-rate conversion, and provides QA documentation. The Sniffer4D offers optional wind sensing; MetScan incorporates wind data into its AIRINS.ai quantification workflow.

Systems outputting path-integrated concentration require wind data to convert to emission rates. Wind measurement uncertainty propagates directly to emission rate uncertainty, a 20% wind speed error produces approximately 20% emission rate error. For Article 12 compliance, wind measurement quality assurance is critical [23].

Table 15: False Positive Mechanisms in Methane LDAR Technologies

Technology	False Positive Sources
TDLAS/FID	Biogenic methane; instrument drift; other hydrocarbons (FID)
OGI	Thermal artefacts; steam/water vapour; moving objects
Vehicle CRDS	Biogenic sources; other vehicles; spatial ambiguity
UAV sensors	Biogenic sources; GPS errors; sensor noise

In Ireland's agricultural landscape, biogenic methane presents a significant false positive source. Spatial correlation with known infrastructure provides the primary discrimination method. Multi-pass confirmation protocols reduce false positives by requiring consistent detection across separate occasions.

Operational Implications

Operational Survey Windows and Environmental Constraints: Methane detection performance is highly weather dependent, with survey effectiveness often determined by atmospheric conditions rather than sensor capability. Moderate winds and near-neutral stability are generally optimal, while OGI and QOGI surveys require sufficient thermal contrast and perform poorly under strong solar heating or overcast conditions. Other ground- and UAV-based sensors are less sensitive to thermal effects but are influenced by wind and precipitation, requiring survey planning to account for variable conditions.

Weather Monitoring, QA Protocols, and Go/No-Go Decisions: LDAR programmes require basic weather-based QA procedures to support go/no-go decisions. Wind, temperature, precipitation, and atmospheric stability should be assessed against technology-specific limits and recorded for interpretation, particularly where quantification is required. Atmospheric stability may be estimated using standard classifications, while UAV surveys must also comply with wind, visibility, and temperature constraints to ensure safe and reliable operation.

Instrument Calibration: All instruments require periodic calibration against traceable reference gas standards.EU Regulation 2024/1787 Article 14(6) requires compliance with manufacturer specifications.

Operator Certification: Article 14(16) requires appropriate certifications for LDAR personnel. Industry programmes include ITC OGI certification and manufacturer-specific training.

Survey Documentation: Each survey must document date/time, personnel certifications, instruments and calibration status, weather conditions, coverage confirmation, deviations from procedures, leak indications with GPS coordinates, and follow-up actions.

Blind Quality Control: Periodic controlled release testing provides objective assessment of detection programme effectiveness. Recommended minimum annually or following significant methodology changes.

Table 16: Optimal Environmental Conditions by Detection Technology

Technology	Wind Speed	Stability	Key Constraint
Handheld FID/ TDLAS-closed-path	1-5 m/s	Neutral to slightly unstable	Approach from downwind
Vehicle CRDS	1-5 m/s	Neutral to slightly stable	Multiple passes recommended
Standard OGI	1-4 m/s	Neutral	ΔT >3°C required
QOGI	2-5 m/s	Neutral	Steady wind for quantification
TDLAS-open-path	2-5 m/s	Neutral	Steady wind for quantification
Aircraft LiDAR	3-8 m/s	Neutral to unstable	VMC required

5.12 Controlled Release Validation

Controlled release testing provides empirical validation of detection technology performance under field conditions. By releasing known quantities of methane at representative infrastructure and conducting surveys using operational procedures, controlled releases measure actual detection probability and quantification accuracy metrics that cannot be determined from laboratory specifications alone. The methodology involves:

- Site selection: Representative infrastructure (AGI, pipeline section, distribution network) with controlled access.
- Release system: Calibrated mass flow controllers releasing methane at known rates through simulated leak sources.
- Release rates: Spanning the regulatory thresholds (e.g., 0.5, 1, 2, 5, 10, 17, 50 g/hr for comprehensive assessment).
- Blind testing: Surveyors unaware of release locations and rates.
- Survey execution: Using standard operational procedures.
- Data analysis: Comparison of detected vs. actual releases; quantification accuracy for systems providing emission rate estimates.

The Methane Emissions Technology Evaluation Center (METEC) at Colorado State University has conducted extensive controlled release programmes informing US regulatory development. Similar facilities exist in Europe, including test sites operated by Shell, BP, and research institutions [2]. Controlled release results are typically expressed as detection probability curves showing the relationship between emission rate and probability of detection.

Figure 6 METEC controlled release test facility layout showing calibrated emission points and survey measurement positions [26].

Table 17: Detection Probability as a Function of Emission Rate by Measurement Technology

Emission Rate (g/hr)	Typical Pd (OGI)	Typical Pd (TDLAS Open)	Typical Pd (Vehicle CRDS)	Typical Pd (TDLAS Closed)
0.5	10-20%	30-50%	20-40%	-
1 (Type 2 threshold)	20-40%	50-70%	30-50%	-
5	50-70%	80-90%	50-70%	-
17 (Type 1 threshold)	80-95%	>95%	70-85%	>95% *
50	>95%	>99%	85-95%	>95% *

* Estimated based on instrument sensitivity relative to expected plume concentrations at 2m standoff. Published controlled-release Pd data for closed-path TDLAS at defined distances is not available.

Closed-Path TDLAS (UAV-Mounted): For extractive TDLAS sensors such as the Sniffer4D (1 ppm resolution), detection probability at close range is governed by plume interception geometry rather than instrument sensitivity. At standoff distances of 1–2 metres, the sensor inlet samples air that has undergone minimal atmospheric dilution compared to ground-level vehicle surveys or wide-area aerial screening. Published controlled-release studies [2] [16] evaluated open-path TDLAS instruments outputting ppm·m; directly comparable detection probability curves for closed-path extractive systems at defined standoff distances are not available in the peer-reviewed literature. However, the combination of high instrument sensitivity (1 ppm detection limit versus typical plume centreline concentrations of 10–100+ ppm at 2 metres downwind of a Type 2 threshold leak) and close-proximity operation suggests that detection probability substantially exceeds that of open-path systems operating at equivalent distances.

For UAV survey applications, maintaining a consistent 2-metre standoff from potential emission sources ensures operation within conditions where instrument sensitivity is not the limiting factor. Detection reliability is instead determined by flight path coverage and plume interception factors addressed through systematic survey design rather than instrument specification.

Implications for Survey Design: These data highlight that even at regulatory thresholds, single-pass detection probability for some technologies particularly open-path and standoff methods may be substantially below 100%. Multiple survey passes, complementary technologies, and repeat surveys over time are necessary to achieve high cumulative detection probability across all leak sizes. For GNI programme design, controlled release testing at representative Irish sites would provide locally relevant performance data accounting for typical weather conditions, infrastructure configurations, and soil characteristics affecting buried pipeline surveys.

For technologies providing emission rate quantification (QOGI, LiDAR, high-flow sampling), controlled release testing validates accuracy against known release rates. Results are typically expressed as the ratio of measured to actual emission rate:

Table 18: Quantification Accuracy of Methane Detection Technologies

Technology	Typical Accuracy (Measured/Actual)	Uncertainty Range
High-flow sampling	0.95-1.05	±10%
QOGI (favourable conditions)	0.5-2.0	Factor of 2
LiDAR (mass balance)	0.7-1.5	±50%
Tracer correlation	0.9-1.1	±15%

High-flow sampling provides the most accurate quantification but requires direct access to the leak source. Remote sensing methods (QOGI, LiDAR) exhibit larger uncertainties reflecting the challenges of atmospheric dispersion modelling but remain valuable for inaccessible sources and rapid assessment. For Article 12 reporting, quantification uncertainty should be documented and propagated through emissions inventory calculations. The OGMP 2.0 framework provides guidance on uncertainty estimation and reporting for measurement-based emission quantification [6].

Establishing GNI-Specific Performance Baselines: GNI should consider establishing performance baselines through controlled release testing at representative assets. Recommended approach: Test sites should be selected to include various topology (transmission AGI, distribution DRI, over-water section, buried pipeline section. Controlled release testing at representative GNI assets could provide locally relevant performance data. A programme covering release rates from 0.5 to 50 g/hr across representative asset types, conducted over multiple days to capture a range of Irish weather conditions, would provide detection probability curves and quantification accuracy data specific to GNI's operating environment.

Controlled release testing provides objective evidence supporting technology selection decisions and regulatory compliance demonstration. The cost of testing is typically modest relative to the capital and operational expenditure of detection equipment, and the data generated has enduring value for programme optimisation.

5.13 Data Processing and AI Integration

Modern LDAR programmes generate substantial data volumes from multiple detection platforms. Effective data management ensures detection events are linked to asset records, repair workflows are tracked, and regulatory reporting requirements are met.

Platform-Specific Data Outputs: Detection technologies produce data in varying formats requiring harmonisation for programme-level analysis. Closed-path TDLAS systems (Sniffer4D) output georeferenced concentration time series (ppm with GPS coordinates); open-path systems (MetScan) output path-integrated concentrations (ppm·m) requiring post-processing for quantification. The AIRINS.ai workflow converts MetScan survey data to emission rate estimates, though this remains a developing capability requiring specialist support.

Asset Management Integration: Integration of LDAR data with GNI's asset management systems enables tracking of leak history, repair status, and compliance documentation within enterprise GIS and maintenance platforms. Key requirements include geographic registration of detection events with asset records, workflow management for repair tracking, automated compilation of Article 14 LDAR reports, and analytics identifying component types with elevated leak frequencies.

Quality Assurance documentation: Article 14(6) requires documentation of instrument calibration, operator certification, survey conditions, and detected anomalies. Automated data logging from UAV platforms (flight path, timestamp, concentration, wind conditions) provides the audit trail necessary for regulatory compliance demonstration. Data format and integration requirements are typically specified within detection equipment procurement and LDAR service contracts.

5.14 Technology Comparison Matrix

Summary Comparison Table

The technology selection for specific GNI asset categories is addressed in Table 14, which maps recommended detection methods to Article 14 (LDAR) and Article 12 (reporting) compliance outcomes. The comparison matrix above provides the technical parameters to inform decision making and survey planning across the range of technologies suitable for GNI operations. Satellite-based detection is excluded from these matrices for the reasons set out in Section 5.5; its relevance to the programme is limited to the Article 30 notification response procedure described there.

Table 19: Quantification methods by detection technology platform

Detection Technology	Integrated Quantification	Supplementary Options
TDLAS-closed-path /FID	None (concentration only)	High-flow sampling at detected leaks
TDLAS-open-path	None (ppm·m at close range)	High-flow sampling at detected leaks
Vehicle CRDS/TDLAS	None (area screening)	Follow-up ground survey with quantification
UAV TDLAS-open-path	None (concentration only)	Ground-based confirmation and quantification
UAV TDLAS-closed-path	In Development	Ground-based validation recommended
Standard OGI	None (visualisation)	QOGI add-on or high-flow sampling
QOGI (OGI + QL320)	Yes (Gaussian dispersion)	Direct measurement for validation
Bridger GML (aerial)	Yes (Atmospheric inversion)	EPA OTM-33A methodology
LiDAR cameras	Yes (Proprietary algorithms)	Validation against reference methods
High-flow sampling	Yes (Direct mass flow)	Not applicable (reference method)

The following table provides a comparative summary of methane detection technologies across key performance parameters relevant to GNI LDAR programme implementation. Technologies are assessed against detection sensitivity, quantification capability, deployment mode, relative cost, and technology maturity.

Table 20: Technology comparison matrix

Technology	Detection Limit	Quantification	Platform	Relative Cost	Maturity
Handheld TDLAS-closed-path	1-10 ppm	No	Walking	Low	Mature
Handheld FID	<1 ppm	No	Walking	Medium	Mature
Handheld TDLAS	~1 ppm·m	No	Walking/standoff	Medium	Mature
Vehicle CRDS	ppb level	No	Vehicle	High	Mature
UAV TDLAS-open-path	ppm·m	Developing	Aerial (drone)	Medium	Commercial
UAV TDLAS-closed-path	~1 ppm	No	Aerial (drone)	Medium	Commercial
OGI (FLIR GF320)	~0.5-6 g/hr*	No	Handheld	High	Mature
QOGI (OGI+QL320)	~0.5-6 g/hr*	Yes	Handheld	High	Mature
Bridger GML	~2 kg/hr	Yes	Fixed-wing	Very High	Commercial
QLM LiDAR camera	~0.1 g/hr*	Yes	Fixed/tripod	High	Emerging
DTS/DAS	Anomaly	No	Fixed (buried)	Very High	Mature
High-flow sampling	N/A	Yes (direct)	Walking	Low	Mature

*Detection limits for imaging technologies are condition dependent.

PART IV: VISUAL AND STRUCTURAL INSPECTION TECHNOLOGIES

6. Role of Structural Assessment in Pipeline Integrity

Pipeline integrity management has traditionally relied on intelligent pigging (inline inspection), cathodic protection monitoring, and periodic hydrostatic pressure testing. These methods focus on detecting defects that have progressed to measurable wall loss or deformation, but carry significant practical limitations. Intelligent pigging requires purpose-built pig trap facilities, a consistent internal bore free of tight-radius bends, and temporary removal from service. For GNI's transmission network, I.S. 328:2021 Section 15.6 mandates pigging at intervals not exceeding 10 years, with typical campaigns costing €50,000–€150,000 depending on diameter, length, and tool type [28].

Crucially, a substantial proportion of GNI's distribution network, comprising PE mains at pressures of 4 bar or below, is not piggable at all [29]. For these assets, and for above ground crossings and bridge-mounted pipelines where internal inspection provides no information about external condition, visual and structural assessment from external platforms represents the primary integrity assurance approach.

The link between structural condition and leak probability is well established. EGIG and PHMSA failure databases demonstrate that the majority of pipeline failures are preceded by identifiable degradation with external manifestations, with external corrosion, ground movement, third-party interference, and mechanical damage accounting for over 80% of transmission incidents in Western Europe [30] [31]. For GNI, integrating structural assessment with methane detection creates a dual-layer approach: gas sensing identifies active emissions requiring immediate response under EU Regulation 2024/1787, whilst structural assessment identifies conditions that elevate future leak probability, enabling preventive intervention before gas release occurs.

6.1 The Link Between Structural Condition and Leak Risk

The progression from intact pipeline to gas release follows a degradation sequence that, for the principal failure mechanisms affecting gas transmission and distribution infrastructure, involves observable intermediate stages. Understanding this progression enables risk-informed inspection, where structural indicators trigger targeted investigation before emissions commence. Pipeline failure mechanisms can be categorised by their degradation pathway and the nature of observable precursors.

Time-dependent mechanisms progress gradually and produce accumulating evidence over inspection intervals. External corrosion is the archetype: coating degradation exposes steel to the soil environment, pitting initiates at coating holidays, and wall loss progresses until the remaining ligament cannot contain operating pressure. Each stage produces observable indicators coating damage, surface rust, pitting morphology, and ultimately localised distortion or seepage. Stress corrosion cracking follows a similar trajectory with characteristic branching crack patterns visible at the surface under magnification [32]. For bridge crossings carrying steel carrier pipes, atmospheric corrosion of exposed steelwork is a particularly relevant time-dependent mechanism, as the pipe is subject to moisture, temperature cycling, and pollution without the protection of soil burial or cathodic protection systems. Previous bridge crossing examinations have documented this in practice: at various sites i.e. the steel structural members supporting the gas pipeline crossing received a PV/B condition rating (minor fault component not in the condition it should be), with photographic evidence recording significant corrosion on the 8-inch steel carrier pipe, bridge girders, and structural struts [33] [29]. Whilst corrosion progression on unprotected atmospheric steelwork typically follows a power-law relationship with time [34], meaning that the rate of wall loss accelerates if left unaddressed, the degradation at this crossing was identifiable from visual indicators at a stage well before through-wall penetration.

Time-independent mechanisms occur abruptly but are often preceded by observable conditions that elevate probability. Third-party excavation damage is the leading cause of immediate-failure incidents: whilst the damage event itself is unpredictable, indicators of excavation activity near pipeline corridors provide actionable warning. Similarly, ground movement mechanisms (landslides, subsidence, riverbed scouring, bank erosion at bridge abutments) may progress over months or years before imposing sufficient strain to cause failure, with surface deformation observable throughout the progression [35].

Operational mechanisms relate to conditions within the pipeline system that produce external manifestations. Overpressure events may cause permanent deformation visible at above ground sections. Thermal cycling at AGI connections and bridge-to-buried pipe transitions can produce fatigue cracking at stress concentrations, with early stages detectable through close visual inspection. Bracket and support degradation at bridge crossings represents a further operational concern: loss of support integrity imposes unplanned loading on the pipe, potentially initiating fatigue or mechanical damage at bracket interfaces. However, bracket condition, pipe-to-bracket interfaces, and bank-to-bridge transition zones are frequently the most difficult elements to assess using conventional ground-based inspection. At crossings such as Green Street Bridge, the congestion of multiple service pipes, limited overhead clearance, and inaccessibility from below have resulted in bracket coating condition, bracket fixing integrity, flange condition, and pipe-to-structure transitions being recorded as "unknown" across successive inspection cycles [33] [29], meaning that the components most susceptible to operational degradation mechanisms are precisely those receiving the least thorough assessment.

The relationship between structural condition and failure probability has been quantified through reliability analysis of pipeline failure databases, with probabilistic methods enabling estimation of failure probability as a function of observable parameters [36] [37].

For external corrosion, the dominant failure mechanism for buried steel pipelines and steel carrier pipes at bridge crossings, assessment methods such as ASME B31G and DNV-RP-F101 demonstrate that failure pressure decreases progressively with increasing defect depth-to-wall-thickness ratio [38]. Crucially, external manifestations of the corrosion process (coating condition, atmospheric exposure, cathodic protection effectiveness) correlate with underlying wall loss severity, enabling risk assessment from external observation [31].

For ground movement, surface displacement measurements from photogrammetric monitoring provide a quantitative indicator of imposed pipeline strain. Sweeney et al. [35] demonstrated that centimetre-scale displacements detected through repeat survey correlated with strain levels approaching intervention thresholds. At bridge crossings, riverbed scouring, bank erosion, and differential settlement are the primary risks, each explicitly assessed under standard examination protocols, but only partially evaluated where access is constrained by water depth, adjacent services, or traffic.

6.2 Inspection-Detection-Intervention Model and the Case for UAV Deployment

The value of structural assessment depends on the relationship between the rate of degradation progression, the inspection interval, and the intervention response time. For structural assessment to be effective, the inspection interval must be short enough to detect degradation before it progresses from observable precursor to failure, and the intervention response must be rapid enough to implement preventive measures.

For time-dependent mechanisms with progression timescales of years to decades (corrosion, fatigue, ground movement), annual or biennial inspection intervals provide adequate detection probability. For time-independent risks (third-party interference), more frequent surveillance is warranted, particularly in areas of high development activity. GNI's bridge crossing examination programme operates on approximately two-year cycles, which is consistent with this approach. However, the persistent access constraints documented across successive inspection cycles demonstrate that frequency alone does not guarantee completeness: where inspectors require excavation to verify pipe routing, or platform and hoist deployment to examine bracket fixings that are not viewable from any accessible vantage point, the logistical and cost barriers can result in the same items being recorded as "unknown" across multiple inspection periods. This represents a systemic inspection gap rather than an incidental limitation.

UAV-based inspection addresses this gap directly. A drone equipped with high-resolution optical and thermal imaging sensors can access the underside of bridge decks, inspect bracket fixings from multiple angles, document corrosion progression through repeat photogrammetric comparison, and assess bank and abutment condition from vantage points inaccessible to ground-based inspectors all without traffic management, specialist plant hire, or work-over-water risk assessments. Where conventional inspection requires platform or hoist mobilisation to examine elements beneath a bridge deck, a UAV achieves equivalent or superior visual coverage in a fraction of the time, whilst eliminating the working-at-height and work-over-water hazards that complicate conventional access at crossings with significant clearance above river level [39].

When combined with the frequency and cost constraints of intelligent pigging, which at 7–10 year intervals costs €50,000–€150,000 per campaign and is entirely inapplicable to the small-diameter PE distribution mains that constitute the majority of GNI's network, the operational case for UAV-based structural assessment becomes compelling. UAV inspection does not replace intelligent pigging for internal wall-loss assessment on piggable transmission pipelines, but it provides the only practical means of achieving comprehensive external structural assessment at the bridge crossings, river crossings, and elevated sections where degradation mechanisms are most active and conventional access most constrained.

Table 21: Pipeline Integrity Inspection Methods and Coverage Comparison

Method	Frequency	Applicability	Coverage
Intelligent pigging	7–10 years (I.S. 328:2021 S.15.6)	Transmission only (piggable sections)	Internal wall condition – corrosion, geometry, cracking
Conventional bridge inspection (platform/hoist)	2–3 years	Bridge crossings	Partial – access-limited; PV/ grades and "unknown" findings common
UAV structural inspection	Annual or more frequent	All above ground and crossing assets	Comprehensive – multi-angle, repeatable, photogrammetric baseline
Walking leakage survey (I.S. 328:2021 S.15.5.2.4)	Quarterly to annual	All buried pipelines	Gas detection only – no structural condition data

The inspection-detection-intervention model is most effective when multiple complementary methods are deployed in a coordinated programme. Intelligent pigging provides definitive internal condition data for transmission pipelines at multi-year intervals. Walking leakage surveys under I.S. 328:2021 Section 15.5.2.4 detect active emissions requiring immediate LDAR response. UAV-based structural assessment fills the critical gap between these methods by providing high-frequency, comprehensive external condition monitoring at the locations where degradation mechanisms are most active and where conventional access methods have demonstrably failed to achieve complete coverage. The integration of UAV-captured structural data with LDAR methane detection results, correlating, for example, the corrosion state of a bridge crossing's carrier pipe with methane concentrations detected at the transition points, creates the evidence base for the risk-informed, preventive integrity management that both I.S. 328:2021 and EU Regulation 2024/1787 require.

6.3 Structural Indicators of Potential Leaks

Coating Damage and Corrosion: External protective coatings provide the primary barrier against corrosion for buried and above ground steel pipelines. Coating systems employed on GNI infrastructure include fusion-bonded epoxy (FBE), three-layer polyethylene (3LPE), coal tar enamel (on older pipelines), and paint systems on above ground sections. Each system has characteristic degradation modes and associated visual indicators.

Coating Degradation Mechanisms: Mechanical damage from construction, backfill, or soil loading produces coating holidays (areas of bare steel) that initiate corrosion cells. Visual indicators include scratches, gouges, and areas of missing coating at contact points with supports, clamps, or rock fragments. Adhesion loss causes coating to separate from the steel substrate, creating disbondment blisters that may trap moisture and shield the underlying steel from cathodic protection. Visual indicators include blistering, tenting, and areas where coating can be peeled from the surface. Disbondment is particularly significant because it can accelerate corrosion whilst simultaneously preventing the cathodic protection system from reaching the exposed steel [40].

Weathering and UV degradation affect above ground coating systems through chalking, colour fading, and embrittlement. These processes reduce coating barrier properties and eventually expose the substrate. Chemical attack from aggressive soils, particularly those containing sulphates, chlorides, or anaerobic bacteria, can degrade certain coating types from the external surface.

Corrosion Indicators: Once coating protection is compromised, the corrosion process produces a sequence of observable indicators: Early stage: Surface rust staining at coating defects; discolouration of surrounding coating from corrosion product migration; minor pitting visible at close range.
Intermediate stage: Expansion of corroded area beyond original coating defect; development of deeper pitting with visible wall loss; rust pack formation causing further coating disbondment; staining patterns on supports or ground below indicating ongoing corrosion product formation. Advanced stage: Significant wall loss visible as surface depression; lamination and flaking of corroded surfaces; distortion or bulging at areas of severe wall loss approaching failure threshold; in extreme cases, seepage or weeping of gas through porous corrosion deposits before full penetration occurs.

Detection Capabilities: High-resolution RGB imaging from UAV platforms can detect coating defects of 5–10mm dimensions at ground sample distances (GSD) of 1–2 mm, achievable with current camera systems at inspection distances of 2–5 metres. Rust staining patterns are detectable at substantially greater distances due to colour contrast with surrounding surfaces. Thermal imaging supplements visual detection by identifying moisture accumulation beneath disbonded coatings through evaporative cooling signatures and by revealing differential thermal response between intact and degraded coating areas [41]. External visual and thermal inspection cannot directly measure wall thickness or determine subsurface defect depth. Identified coating damage and corrosion indicators warrant further investigation using contact methods (ultrasonic thickness measurement) or detailed assessment against fitness-for-service criteria. The role of visual inspection is to identify locations requiring further assessment rather than to make final integrity determinations.

Ground Movement and Subsidence: Ground movement imposes displacement-controlled loading on buried pipelines that can exceed design strain limits, particularly at transitions between moving and stable ground. The principal ground-movement mechanisms affecting GNI infrastructure include slope instability, where gravitational movements ranging from slow creep to rapid landslides impose axial and lateral loads due to differential soil displacement, particularly in Ireland’s glacial deposits, peat soils, and weathered rock slopes; subsidence, arising from consolidation of compressible soils, dissolution of soluble substrates, or dewatering effects, which creates vertical displacement loading and is especially relevant in areas of made ground, alluvial deposits, and peat; erosion and scour, where watercourse erosion, overland flow, and coastal processes reduce pipeline cover and undermine support, making river crossings particularly vulnerable during flood events and potentially exposing previously buried sections; and frost heave, whereby seasonal ground freezing in Irish upland areas can cause vertical displacement of shallow-buried pipelines, with cumulative ratcheting effects over repeated freeze–thaw cycles.

Surface manifestations of ground movement include: tension cracks in soil aligned perpendicular to the direction of movement; compression ridges or bulging where soil is being compressed; changes in surface topography detectable through comparison of sequential elevation models; tilting of pipeline marker posts, fence posts, or other vertical features; disrupted drainage patterns indicating altered surface gradients; vegetation stress from root zone disturbance; and exposure of previously buried pipeline sections at erosion features [35].

UAV photogrammetry enables detection and quantification of ground movement through comparison of digital elevation models acquired at different times. Vertical accuracy of 2–5cm is routinely achievable with ground control, sufficient to detect movements at the centimetre scale relevant to pipeline strain assessment. Horizontal displacement can be quantified through feature tracking in sequential orthomosaics. The frequency and spatial coverage of UAV survey far exceeds that of traditional ground survey, enabling monitoring of entire pipeline corridors rather than discrete points [42] [43].

Third-Party Interference Signs: Third-party damage to buried pipelines, primarily arising from excavation and development activity, remains one of the most significant threats to pipeline integrity. The European Gas Pipeline Incident Data Group (EGIG) identifies third-party interference as the leading cause of transmission pipeline failures in Europe, accounting for approximately 35% of recorded incidents. Although damage events typically occur suddenly, the conditions that enable third-party interference to develop progressively and generate observable precursor indicators. These include active excavation activity such as earthmoving equipment, open trenches, and spoil heaps within or adjacent to the pipeline easement; encroachment from new structures, roads, agricultural developments, or land-use changes that restrict access and increase the likelihood of inadvertent damage; and damage to or obscuring of pipeline markers, which undermines the effectiveness of “call before you dig” systems and is readily identifiable from aerial imagery. Additional indicators include unauthorised crossings, such as vehicle tracks or informal roadways, which can impose external loads exceeding design limits for shallow-buried or small-diameter pipelines, and unauthorised vegetation clearance within the pipeline corridor, often signalling development activity or changes in land use. Aerial surveillance conducted at regular intervals, typically ranging from monthly to quarterly depending on risk, enables systematic documentation of corridor condition and early identification of these indicators. When combined with automated change detection and machine learning-based feature recognition applied to sequential imagery, such approaches provide an effective means of flagging excavation activity, encroachment, and other interference risks for timely investigation and intervention.

Mechanical Damage: Mechanical damage to above ground pipeline components, joints, fittings, and AGI equipment produces observable deformation, material loss, or displacement from the intended design geometry. Unlike damage to buried pipelines, which generally requires excavation to observe directly, mechanical damage to above ground assets are well suited to visual inspection using UAV platforms. High-resolution imagery enables systematic assessment of damage mechanisms that may compromise structural integrity or increase leak probability.

Mechanical damage indicators include denting and deformation caused by vehicle impacts, falling objects, or construction activity, which result in permanent changes to pipe or component profiles. Such dents are significant because they alter the local stress state and may interact with other defects to reduce failure pressure; high-resolution imaging allows documentation of dent location, dimensions, and geometry for assessment against acceptance criteria defined in standards such as ASME B31.8 and PD 801 [44]. Gouges and scoring represent another common damage mechanism, where material removal from scraping or cutting contact locally reduces wall thickness and introduces stress concentrations, typically visible as linear surface marks with displaced material at the edges. Surface-breaking weld defects, including undercut, porosity, and cracking, may also be visible in high-resolution imagery, particularly at circumferential field welds where access constraints or construction conditions may have affected weld quality. In addition, damage to pipeline support structures such as saddles, pipe shoes, and hangers, arising from corrosion, settlement, or mechanical impact, can alter support conditions and impose secondary stresses on the pipeline.

Joints and fittings, including flanged connections, mechanical couplings, and valves, represent particularly vulnerable locations due to the presence of sealing interfaces, bolted connections, and stress concentrations. Industry data consistently show that fittings account for a disproportionate share of fugitive emissions relative to their population, making them priority targets for both gas detection and structural assessment [45]. Degradation indicators include gasket deterioration resulting from compression set, extrusion, or chemical degradation, which may be observed as gasket material protrusion, uneven flange gaps, or staining patterns indicative of minor seepage. Bolt and stud degradation through corrosion, relaxation, or fatigue reduces gasket clamping force and accelerates seal failure, with visual indicators including corroded fasteners, missing or incomplete nuts, and inconsistent bolt extension. Valve stem leakage may be indicated by staining or corrosion product accumulation around the gland area, while fitting bodies, particularly cast iron and carbon steel components, may exhibit general or localised corrosion; cast iron fittings may additionally suffer graphitisation, where the surface appears intact despite severe loss of structural strength.

The effectiveness of UAV-based detection of mechanical damage depends critically on image resolution and viewing geometry. Ground sampling distances on the order of 1–2 mm are typically required to resolve damage features relevant to pipeline integrity, while oblique imaging from multiple angles improves detection of defects on non-horizontal surfaces. Three-dimensional photogrammetric reconstruction further enables quantitative measurement of dents and deformation directly from imagery, without the need for physical contact [46]. Systematic close-range imaging of joints and fittings at AGI sites, typically capturing multiple views of each connection at sub-millimetre resolution, provides robust documentation supporting both LDAR activities and longer-term structural integrity management [47].

7. Visual and Photogrammetric Inspection Technologies

This section of the report looks at the visual inspection and photogrammetric survey technologies applicable to structural condition assessment of gas transmission and distribution infrastructure. Whereas Section 5 focused on methane detection technologies for identifying active emissions, the technologies described here serve the complementary objective of identifying and quantifying structural degradation that may precede or contribute to future gas release. The integration of high-resolution imaging, three-dimensional reconstruction, and machine-learning-based defect recognition enables a data-driven approach to structural integrity management that significantly extends the capability of conventional visual inspection.

7.1 High-Resolution RGB Imaging

Camera Specifications and Requirements: The effectiveness of visual inspection from UAV platforms is fundamentally determined by the imaging system employed. Camera selection governs spatial resolution, colour fidelity, and the achievable ground sample distance (GSD) at a given inspection range, all of which directly influence the minimum detectable defect size. Three categories of camera are relevant to pipeline infrastructure inspection: integrated UAV cameras, interchangeable-lens survey cameras mounted on UAV gimbals, and full-frame or medium-format mapping cameras designed specifically for photogrammetric workflows.

Integrated UAV cameras, such as the Hasselblad L2D-20c fitted to the DJI Mavic 3 Enterprise series, provide a practical baseline for routine inspection. The Mavic 3E offers a 20-megapixel 4/3-format CMOS sensor with a 12.3 mm equivalent focal length, achieving a GSD of approximately 0.7 mm per pixel at a 3-metre inspection distance. This resolution is sufficient to detect coating damage, surface rust staining, and moderate corrosion at close range, and is well suited to rapid reconnaissance surveys and access-constrained locations where a compact airframe is advantageous. The DJI Mavic 3 Thermal variant adds a 640×512 radiometric thermal sensor alongside the RGB camera, enabling simultaneous capture of visible and thermal imagery for moisture detection beneath coatings and identification of gas-related thermal anomalies. For higher-resolution structural inspection, the DJI Matrice 350 RTK platform supports interchangeable payloads including the Zenmuse P1, a full-frame 45-megapixel camera with interchangeable lenses (24 mm, 35 mm, and 50 mm options). At a 5-metre standoff with the 35 mm lens, the P1 achieves a GSD of approximately 0.5 mm per pixel, enabling detection of fine cracks, pitting morphology, and weld defects at resolutions comparable to close-range manual inspection. The mechanical shutter eliminates rolling-shutter distortion during flight, a significant advantage for photogrammetric accuracy.

Ground-based or tripod-mounted DSLR and mirrorless cameras offer the highest resolution for targeted close-range inspection of accessible assets. The Sony A7R IV, with its 61-megapixel full-frame BSI-CMOS sensor, achieves sub-0.1 mm GSD at inspection distances under 2 metres when paired with a macro or short telephoto lens, enabling documentation of surface-breaking defects at near-microscopic detail. Medium-format systems such as the Phase One iXM-100 (100-megapixel, 43.8×32.9 mm sensor) provide even greater resolution and are employed in high-precision aerial survey applications where sub-centimetre GSD is required over extended areas, though their higher cost and weight typically restrict their use to specialised survey campaigns rather than routine inspection.

Regardless of the camera system employed, lens calibration and distortion correction are essential prerequisites for accurate photogrammetric measurement. All lenses introduce geometric distortions that, if uncorrected, propagate directly into errors in derived measurements and three-dimensional reconstructions. Radial distortion (barrel and pincushion effects) is the dominant error source, particularly for wide-angle lenses commonly used on UAV platforms. Tangential distortion, arising from imperfect lens element alignment, is typically smaller but must also be accounted for. Camera calibration determines the intrinsic parameters of the imaging system: focal length, principal point offset, and distortion coefficients. Calibration may be performed using a pre-surveyed target array (checkerboard pattern) in a controlled environment, or through self-calibration during the photogrammetric bundle adjustment using the survey imagery itself. Self-calibration is the standard approach in aerial photogrammetric workflows and is supported by all major processing platforms. The resulting camera model is applied during image processing to remove distortion effects, ensuring that measurements derived from the corrected imagery are geometrically accurate [48].

Table 22: Camera Systems Applicable to Pipeline Infrastructure Inspection

Camera System	Sensor Format	Resolution	Typical GSD at 5 m	Primary Application
DJI Mavic 3E (Hasselblad L2D-20c)	4/3-format CMOS	20 MP	≈1.5 mm/px	Rapid reconnaissance; confined access
DJI Zenmuse P1	Full-frame (35.9×24 mm)	45 MP	≈0.5 mm/px	High-resolution structural survey
Sony A7R IV	Full-frame BSI-CMOS	61 MP	≈0.4 mm/px	Ground-based close-range inspection
Phase One iXM-100	Medium-format (43.8×32.9 mm)	100 MP	≈0.3 mm/px	Precision aerial mapping campaigns

Image Capture Methodologies: Image capture methodology determines both the quality of individual images and the suitability of the dataset for subsequent photogrammetric processing. Two fundamental capture approaches are employed: nadir (downward-looking) acquisition for area mapping and corridor survey, and oblique acquisition for close-range structural inspection of vertical and under-deck surfaces. For photogrammetric reconstruction, sufficient image overlap is critical. Standard practice for aerial mapping requires a minimum frontal (forward) overlap of 80% and a lateral (side) overlap of 60–70%, ensuring that every point on the ground surface appears in at least five images captured from different perspectives. This redundancy is essential for the feature matching algorithms that underpin Structure-from-Motion processing (described in Section 7.2). For close-range structural inspection of bridge crossings and AGI components, overlap requirements increase to 80–90% in both directions, with images captured from multiple angles around each element of interest.

Flight planning for corridor surveys typically employs automated grid patterns generated by mission planning software (DJI Pilot 2, Pix4Dcapture, DroneDeploy, or UgCS), which calculate waypoints, camera trigger intervals, and gimbal angles to achieve the specified overlap at the planned altitude. For structural inspection of discrete assets such as bridge crossings, a combination of automated orbital flights (circling the asset at defined altitudes and radii) and manual close-range manoeuvres is typically employed to ensure comprehensive coverage of all surfaces. Ground control points (GCPs), consisting of surveyed targets with known coordinates in the national reference frame (ITM for Ireland), provide the absolute spatial reference required for georeferenced photogrammetric outputs. A minimum of five well-distributed GCPs is recommended for corridor surveys; for isolated structural inspections where absolute georeferencing is less critical, the RTK positioning of modern UAV platforms (e.g., DJI Matrice 350 RTK) may provide sufficient accuracy without ground control, achieving horizontal accuracies of 1–2 cm and vertical accuracies of 1.5–3 cm at the camera positions [42].

Defect Detection Capabilities: The value of high-resolution imagery extends beyond visual documentation when combined with machine learning and computer vision techniques for automated defect detection. Manual review of hundreds or thousands of inspection images is labour-intensive, subject to operator fatigue, and difficult to standardise. Automated detection addresses these limitations by applying trained algorithms to systematically analyse every image in a survey dataset, flagging regions of interest for expert review.

Object detection architectures from the YOLO (You Only Look Once) family have become the dominant approach for real-time defect identification in infrastructure inspection imagery. YOLO models perform detection and classification in a single forward pass through a convolutional neural network, achieving processing speeds of tens to hundreds of frames per second on modern GPU hardware. Successive iterations, from YOLOv5 through YOLOv8 to the current YOLOv11[49], have progressively improved detection accuracy for small objects, a critical capability when identifying corrosion pitting, hairline cracks, and coating holidays in high-resolution imagery. Training a YOLO model for pipeline defect detection requires an annotated dataset of inspection images with bounding boxes drawn around defect instances, categorised by type (corrosion, coating damage, crack, mechanical damage, vegetation encroachment, and similar classes). Transfer learning from models pre-trained on large general-purpose datasets (COCO, ImageNet) substantially reduces the volume of domain-specific training data required, with usable detection performance typically achievable with 500–1,000 annotated defect instances per class [50].

Where precise delineation of defect boundaries is required, rather than bounding-box detection alone, image segmentation models provide pixel-level classification. The Segment Anything Model 2 (SAM 2), developed by Meta AI, represents a significant advance in this domain. SAM 2 is a foundation model trained on over one billion image masks, enabling zero-shot and few-shot segmentation of objects and features that were not present in its training data [51]. For pipeline inspection applications, SAM 2 can be prompted with a single point click or bounding box on a corrosion patch, crack, or coating defect, and will generate a precise pixel-level mask delineating the defect boundary. This capability is particularly valuable for quantitative assessment: the area of a corrosion patch, the length and width of a crack, or the extent of coating loss can be measured directly from the segmentation mask when combined with the known GSD. SAM 2 can operate interactively (with operator prompts) or in an automated pipeline where YOLO detections provide the initial bounding-box prompts and SAM 2 refines them to precise segmentation masks, creating a two-stage detection-segmentation workflow that combines the speed of YOLO with the precision of SAM 2.

The integration of detection and segmentation outputs with large language models (LLMs) enables automated generation of structured inspection reports. In this workflow, YOLO identifies and classifies defects across the image dataset, SAM 2 segments each detection to provide quantitative measurements, and an LLM synthesises the results into natural-language descriptions following a standardised reporting template. The LLM receives structured data (defect type, location coordinates, measured dimensions, severity classification, comparison with previous survey data) and produces narrative text suitable for inclusion in inspection reports, maintenance work orders, or regulatory submissions. This approach does not replace engineering judgement for integrity assessment but substantially reduces the administrative burden of report preparation and improves consistency across inspection campaigns. Several commercial platforms are beginning to integrate LLM-based reporting into their drone inspection workflows, and GNI should evaluate these capabilities as part of technology selection for structural assessment programmes.

7.2 Photogrammetric Processing and Outputs

Photogrammetry is the science of extracting three-dimensional geometric information from two-dimensional images. In the context of UAV-based infrastructure inspection, photogrammetric processing transforms overlapping image sets into spatially accurate, measurable outputs including orthomosaics, three-dimensional point clouds, textured mesh models, and digital elevation models. The computational foundation for modern photogrammetric processing is Structure-from-Motion

(SfM), a computer vision technique that simultaneously estimates the three-dimensional structure of a scene and the positions and orientations of the cameras that captured it. SfM operates by identifying corresponding features (distinctive points) across multiple overlapping images, then solving the geometric relationships between these correspondences to reconstruct the camera network and sparse three-dimensional point cloud. Multi-view stereo (MVS) algorithms subsequently densify the sparse point cloud by computing depth estimates for every pixel in every image, producing dense point clouds containing millions to billions of three-dimensional points with associated colour information [48] [52].

Several commercial and open-source software platforms implement the SfM-MVS pipeline for photogrammetric processing. Pix4Dmapper and Pix4Dmatic are widely adopted in the surveying and inspection industry, offering automated processing workflows from image import through to deliverable generation, with specific optimisation for UAV-acquired imagery. RealityCapture (Epic Games) provides exceptionally fast processing through GPU-accelerated algorithms and excels at combining laser scan data with photogrammetric point clouds. DJI Terra, bundled with DJI enterprise platforms, offers streamlined processing for DJI-acquired datasets with integration into the DJI ecosystem. Agisoft Metashape is a versatile platform used extensively in academic and professional survey contexts, supporting a wide range of input data types and output formats. On the open-source side, OpenDroneMap provides a free processing pipeline suitable for straightforward mapping tasks, whilst COLMAP offers a research-grade SfM implementation that underpins many academic photogrammetric workflows [52]. The choice of platform depends on processing speed requirements, output format compatibility, and integration with existing GIS and asset management systems.

Orthomosaic Generation: An orthomosaic is a geometrically corrected, seamless composite image assembled from the individual survey photographs. Unlike a simple image mosaic, an orthomosaic has been corrected for lens distortion, camera tilt, and terrain relief, producing a true-to-scale planimetric representation from which distances and areas can be measured directly. Orthomosaics represent the primary two-dimensional (2D) deliverable from photogrammetric survey and serve as the baseline documentation layer for pipeline corridor monitoring, AGI condition recording, and change detection between successive surveys. For pipeline applications, orthomosaics at sub-centimetre GSD enable identification of corridor encroachment, vegetation growth, ground disturbance, and surface indicators of subsidence or ground movement. At AGI sites, high-resolution orthomosaics provide a complete planimetric record of the installation that can be annotated with defect locations, measurement data, and maintenance records within GIS platforms.

3D Model Reconstruction: Three-dimensional reconstruction from photogrammetric data produces two distinct but related outputs: point clouds and mesh models. The dense point cloud, generated by the MVS stage of processing, consists of millions of individually measured three-dimensional points, each with x, y, z coordinates and RGB colour values derived from the source imagery. Point clouds preserve the raw measurement data and are well suited to quantitative analysis, including distance measurement, cross-section extraction, and volumetric calculation. However, point clouds represent a discrete sampling of surfaces and do not define continuous surface geometry.

Mesh reconstruction converts the point cloud into a continuous surface model composed of triangular faces (a triangulated irregular network, or TIN). The resulting mesh defines the geometry, or structure, of the scene. A distinction should be drawn between the structural mesh (the geometric surface) and the textured mesh (the geometric surface with photographic colour information projected onto it). The untextured mesh captures shape, form, and dimensional relationships and is the appropriate representation for geometric measurement, deformation analysis, and structural assessment. The textured mesh adds visual realism by mapping the original image pixels onto the mesh faces, enabling visual identification of surface features (corrosion colour, coating condition, marking text) within the three-dimensional context. Both representations are generated routinely by photogrammetric processing platforms and serve complementary purposes in inspection workflows: the mesh provides the geometric measurement framework, whilst the texture provides the visual condition record.

An emerging alternative to traditional mesh-based three-dimensional representation is 3D Gaussian Splatting (3DGS), a novel rendering technique that represents scenes as collections of three-dimensional Gaussian primitives rather than triangular mesh faces. Each Gaussian is defined by a position, covariance (shape and orientation), opacity, and colour described by spherical harmonics. Introduced by [53], 3DGS achieves photorealistic rendering quality comparable to neural radiance fields (NeRF) but at real-time frame rates, enabling interactive exploration of reconstructed scenes. For infrastructure inspection, 3DGS offers the potential for immersive review of inspection data, allowing engineers to navigate a photorealistic three-dimensional reconstruction of a bridge crossing, AGI, or pipeline section from any viewpoint, identifying features and defects that may not be apparent in conventional 2D imagery or mesh models. The technology is rapidly maturing, with integration into commercial platforms underway, though it currently lacks the geometric precision of mesh-based photogrammetry for quantitative measurement and should be considered a visualisation and review tool that complements rather than replaces conventional photogrammetric outputs.

Figure 7 UAV close-range imagery of Ardnacrusha bridge gas pipeline crossing, Co. Clare, side-view orthomosaic (top) with detail views of pipe supports and fittings at bridge piers (bottom). Source: SurveyLabs Ireland [54]

Digital Elevation Models (DEM): Digital Elevation Models (DEMs) are raster representations of surface elevation derived from the photogrammetric point cloud. Two variants are distinguished: the Digital Surface Model (DSM), which represents the elevation of the highest surface at each grid point (including vegetation, structures, and infrastructure), and the Digital Terrain Model (DTM), which represents the bare ground elevation with above ground features removed through classification and filtering algorithms. For pipeline monitoring, DEMs serve several critical functions. DSMs generated from successive UAV surveys enable quantitative detection of ground surface changes along pipeline corridors, including settlement, heave, erosion, and spoil deposition from construction activity. The vertical accuracy of photogrammetric DEMs, typically 2–5 cm with ground control or RTK positioning, is sufficient to detect the centimetre-scale displacements relevant to pipeline strain assessment. DTMs support pipeline depth-of-cover analysis when combined with as-built pipeline centreline data, identifying locations where erosion or ground disturbance has reduced burial depth below minimum requirements. At river and stream crossings, DEMs of the channel bed and banks (acquired during low-water conditions) document scour depth, bank recession, and changes to channel geometry that may threaten crossing integrity [43].

Table 23: Photogrammetric Output Types and Pipeline Inspection Applications

Output Type	Dimension	Description	Primary Inspection Application
Orthomosaic	2D	Geometrically corrected composite image; true-to-scale planimetric view	Corridor monitoring; visual condition record; change detection
Dense Point Cloud	3D	Millions of measured xyz+RGB points sampling the scene surface	Quantitative measurement; cross-sections; volumetric analysis
Textured Mesh	3D	Triangulated surface with photographic texture mapped onto faces	Visual defect identification in 3D context; stakeholder communication
Structural Mesh	3D	Triangulated surface geometry without texture; captures shape and form	Geometric measurement; deformation analysis; structural assessment
3D Gaussian Splat (3DGS)	3D	Gaussian primitive-based scene representation; real-time photorealistic rendering	Immersive inspection review; interactive navigation of survey data
Digital Surface Model (DSM)	2.5D	Raster grid of highest surface elevation including structures and vegetation	Ground movement detection; corridor surveillance; encroachment monitoring
Digital Terrain Model (DTM)	2.5D	Raster grid of bare ground elevation with above ground features removed	Depth-of-cover analysis; scour assessment; drainage modelling

7.3 Measurement and Dimensional Analysis

Distance and Area Measurements: The georeferenced three-dimensional models produced by photogrammetric processing enable direct extraction of linear distances, areas, and volumes without the requirement for physical contact with the asset. In practice, an engineer can measure the length of a corrosion patch, the diameter of a pipe, the span between support brackets, or the area of coating loss directly within the photogrammetric software environment by selecting points on the textured mesh or point cloud. Measurement accuracy is a function of the GSD, the number of overlapping images contributing to each point, and the quality of the camera calibration and georeferencing. Under typical UAV inspection conditions (GSD of 0.5–2 mm, 80%+ overlap, RTK or GCP georeferencing), measurement accuracies of 1–5 mm are routinely achievable for features visible in the imagery. For area measurements, such as quantifying the extent of corrosion or coating damage identified through YOLO/SAM2 segmentation, the pixel-level segmentation mask is projected onto the three-dimensional model and the enclosed area computed on the mesh surface, accounting for surface curvature. This automated area measurement substantially improves upon the estimation-based approaches typical of manual visual inspection.

Deformation Monitoring: Photogrammetric three-dimensional models provide the reference geometry against which deformation can be detected and quantified. Deformation monitoring compares the current shape of a structure or pipeline section against a baseline (design geometry or a previous survey) to identify dimensional changes indicative of structural loading, settlement, or damage. For pipeline bridge crossings, photogrammetric monitoring can detect vertical deflection (sag), lateral displacement, and rotation of the carrier pipe relative to its supports. These measurements are obtained by comparing point cloud or mesh data from successive surveys, with changes quantified as cloud-to-cloud distances or mesh-to-mesh deviations. Software tools within Pix4D, RealityCapture, and open-source platforms such as CloudCompare enable automated computation of deviation maps, colour-coding the three-dimensional model to highlight areas of change exceeding user-defined thresholds. For GNI bridge crossings where access constraints have historically limited the completeness of conventional inspection, photogrammetric deformation monitoring offers a practical means of quantifying structural movement over time without direct physical access to the asset [42]

Change Detection Over Time: Change detection extends deformation monitoring from structural geometry to the full range of observable surface and environmental conditions along pipeline corridors. By comparing photogrammetric datasets acquired at different times, changes in ground surface elevation, vegetation cover, land use, excavation activity, and infrastructure condition can be systematically identified and quantified. Orthomosaic-based change detection compares planimetric imagery to identify new construction, excavation, vegetation clearance, or encroachment within the pipeline easement. DEM-based change detection quantifies volumetric changes in ground surface, identifying areas of cut, fill, erosion, or settlement. Three-dimensional model comparison identifies structural changes to above ground assets, including progressive corrosion, bracket displacement, or support degradation.

The effectiveness of change detection depends on the consistency of data acquisition across survey epochs. Standardised flight plans, consistent camera settings, similar lighting conditions, and the use of permanent ground control markers all contribute to reducing artefactual differences between datasets and improving the reliability of detected changes. For pipeline corridor monitoring, seasonal effects (vegetation growth, soil moisture variation, shadow angles) introduce variability that must be accounted for in the analysis; acquiring surveys at similar times of year minimises these effects. Machine learning approaches are increasingly applied to automate change detection analysis, training classifiers to distinguish genuine changes of concern (excavation, ground movement, new encroachment) from benign variations (seasonal vegetation, agricultural activity, shadow changes). The combination of repeat UAV survey, photogrammetric processing, and automated change analysis provides a scalable monitoring framework for GNI's pipeline corridors that substantially exceeds the spatial coverage and quantitative capability of periodic walking or aerial visual patrols [43] [46].

PART V: TECHNOLOGY MATURITY AND MARKET LANDSCAPE

8. Technology Readiness and Deployment Maturity

The Technology Readiness Level (TRL) framework is widely used to assess the maturity of technologies from early concept to proven operational deployment. Originally developed by NASA and later adopted by the European Commission for Horizon 2020 and Horizon Europe programmes, the scale ranges from TRL 1 (basic principles observed) to TRL 9 (proven in an operational environment) [55]. It is now the standard maturity metric across sectors including aerospace, energy, and critical infrastructure. For LDAR assessment, generic TRL definitions require contextualisation to the operating conditions of a regulated gas transmission and distribution network. A technology demonstrated at high TRL in upstream oil and gas applications may not achieve the same maturity when deployed across GNI's assets, where access constraints, meteorological exposure, regulatory requirements, and workforce integration differ materially.

TECHNOLOGY READINESS LEVEL (TRL)

DEPLOYMENT	9	ACTUAL SYSTEM PROVEN IN OPERATIONAL ENVIRONMENT
	8	SYSTEM COMPLETE AND QUALIFIED
	7	SYSTEM PROTOTYPE DEMONSTRATION IN OPERATIONAL ENVIRONMENT
DEVELOPMENT	6	TECHNOLOGY DEMONSTRATED IN RELEVANT ENVIRONMENT
	5	TECHNOLOGY VALIDATED IN RELEVANT ENVIRONMENT
	4	TECHNOLOGY VALIDATED IN LAB
RESEARCH	3	EXPERIMENTAL PROOF OF CONCEPT
	2	TECHNOLOGY CONCEPT FORMULATED
	1	BASIC PRINCIPLES OBSERVED

Figure 8 Technology Readiness Level (TRL) scale, from basic principles (TRL 1) to proven operational deployment (TRL 9). Adapted from the European Commission Horizon Europe framework [55]

In addition to TRL, two complementary aspects are considered. First, detection readiness and quantification readiness are assessed separately, as technologies often meet Article 14 detection requirements at a higher maturity than Article 12 quantification. Second, confidence in performance is informed by the extent and relevance of field validation data, as laboratory-derived specifications frequently overstate performance relative to the wind, humidity, and terrain conditions encountered in Irish operations.

8.1 Maturity Assessment by Technology Class

Handheld TDLAS and FID: Rated TRL 9 for detection and Article 14 compliance. These instruments have decades of deployment across gas utilities worldwide, with FID established as the reference method under US EPA Method 21. Multiple manufacturers (Crowcon, Heath, Pergam, Thermo Scientific) supply instruments with well-characterised performance and established calibration protocols. Detection at the 500 ppm Type 2 threshold is routine when the sensor is within 1–2 metres of the source. Neither technology provides Article 12 quantification; both require supplementary high-flow sampling for emissions reporting. Immediately deployable at all accessible GNI point assets.

Handheld Open-Path TDLAS: Similarly rated TRL 9 with extensive deployment across European gas distribution networks. The standoff capability (ppm·m output) enables rapid survey of elevated or difficult-to-access components at distances up to 30 metres under favourable conditions. Satisfies Article 14 detection but does not provide Article 12 quantification.

OGI and Quantitative OGI: Standard OGI (FLIR GF320/GF620, Opgal EyeCGas 2.0) is TRL 9 for qualitative detection, validated through controlled release studies with detection limits of 0.5 to 6 g/hr [16]. Satisfies Type 1 requirements but cannot confirm ppm thresholds for Type 2 without supplementary measurement. QOGI (FLIR QL320) is rated TRL 7–8 for quantification, with uncertainties of approximately a factor of two under favourable conditions. QOGI provides simultaneous Article 14 and Article 12 compliance, making it a strong candidate for compressor stations, CNG units and high-priority AGIs where both obligations apply.

Vehicle-Mounted CRDS: Rated TRL 9 for distribution network LDAR. Picarro CRDS platforms are now the established primary survey method for distribution LDAR compliance across European DSOs, with over 50 operators deploying vehicle CRDS covering more than 800,000 km annually. Operators including Italgas (42 vehicles, 150,000+ km network, OGMP 2.0 Gold Standard), Cadent (UK's largest distribution network, network wide deployment from 2025), and Netz Niederösterreich (7,500 km of EU Regulation 2024/1787-compliant surveys completed in 2025) demonstrate that the vehicle CRDS screening and ground follow-up workflow is accepted as an Article 14 compliance methodology by European DSOs and regulators. The ethane co-measurement capability provides discrimination between thermogenic pipeline methane and biogenic agricultural methane a significant operational advantage in Ireland's rural landscape. For GNI's 12,000 km distribution network, vehicle CRDS represents the most efficient and proven primary survey method, with ground-based walking confirmation at flagged locations completing the compliance workflow.

UAV-Mounted TDLAS: Closed-path systems (Soarability Sniffer4D) are rated TRL 8, supported by GNI's Parteen Bridge crossing survey as direct operational evidence in the Irish context. The 1 ppm detection limit and sub-2-metre proximity capability enables reliable detection at both Type 1 and Type 2 thresholds. Open-path/gimbal-configured systems (Pergam DragonFly, Soarability MetScan) are rated TRL 7–8 for detection and TRL 5 for quantification. Gimbal configurations offer improved spatial coverage over nadir-only systems, with quantification workflows through platforms such as AIRINS.ai representing an active development pathway toward Article 12 compliance.

Beyond site-specific access solutions, drone mounted TDLAS represents a viable aerial pathway to Article 14 Type 1 and Type 2 compliance for transmission pipeline corridors. Operating at 25–50 metres altitude and 50 km/h, drone TDLAS places the sensor within the detection envelope demonstrated to achieve 17 g/hr (Type 1) in field testing, and within the range at which 500 ppm (Type 2) detection has been confirmed by laboratory testing of the Pergam Falcon Plus system. This performance level cannot be matched by helicopter-mounted systems operating at I.S. 328 surveillance altitudes. Drone TDLAS with integrated wind measurement and dispersion algorithms is also positioned to support Article 12 quantification in the near term, pending controlled release validation. The principal constraints on scalability flight endurance, BVLOS regulatory approval, and corridor logistics are operational rather than technical, and are progressively being addressed through fixed-wing drone variants and the EU U-space framework.

LiDAR Cameras: QLM Technology and Sensia systems are rated TRL 5–6 with published detection claims below 1 g/hr. The active illumination and inherent quantification capability represent significant advantages over passive OGI, but the technology is pre-commercial with limited gas TSO deployment. Fixed-mount pilot deployment at CNG units represents the appropriate initial evaluation pathway.

Aerial Gas Mapping LiDAR (Bridger Photonics): Rated TRL 8–9 in the North American context with US EPA acceptance as an alternative work practice. The 2 kg/hr detection threshold limits application to screening and Type 1 rather than Type 2 compliance. European gas TSO deployment is rated TRL 6–7, requiring establishment of a service arrangement and validation under Irish conditions. Represents a future pathway for efficient transmission corridor screening.

DTS/DAS: Rated TRL 8–9 for pipeline surveillance with thousands of kilometres deployed globally, but TRL 4–5 for LDAR-specific applications. Does not provide component-level detection or emission rate quantification. Continuous monitoring value is complementary to periodic surveys. Most relevant for new construction where fibre can be installed during pipeline works rather than retrofit.

Photogrammetric and ML-Based Inspection: Rated TRL 6–8, reflecting a split maturity profile. The underlying technologies are individually mature, SfM photogrammetry, YOLO, SAM 2, and high-resolution UAV cameras are all at TRL 9 for their respective domains. Their integrated application to pipeline defect detection is less established but advancing rapidly, with growing published datasets for pipeline-specific defect classes and demonstrated capability in infrastructure inspection contexts. Highly promising for dual-purpose UAV sorties combining leak detection with structural condition assessment.

Table 24: Technology Readiness Assessment for GNI LDAR Deployment

Technology Class	Detection TRL	Quantification TRL	Art. 14 Ready	Art. 12 Ready	Deployment Status
Handheld TDLAS (closed-path)	9	N/A	Yes	No	Operational
Handheld FID	9	N/A	Yes	No	Operational
Handheld TDLAS (open-path)	9	N/A	Yes	No	Operational
Vehicle CRDS	9	N/A	Screening	No	Operational
Standard OGI	9	N/A	Type 1	No	Operational
QOGI (FLIR QL320)	8	7–8	Yes	Yes	Early operational
UAV TDLAS (closed-path)	8	N/A	Yes	No	Demonstrated
UAV TDLAS (open-path/gimbal)	8	5	Screening	In trial	Emerging
LiDAR cameras (QLM/Sensia)	5–6	5–6	Potential	Potential	Pre-commercial
Aerial GML (Bridger)	8–9	7–8	Screening	Yes	Commercial (America)
DTS/DAS	8–9	N/A	Auxiliary	No	Operational (surveillance)
Photogrammetric/ML	6–8	N/A	N/A	N/A	Emerging

8.2 Regulatory Acceptance and Evidentiary Status

Technology maturity alone does not determine suitability for a compliance programme. GNI must also demonstrate that its chosen technologies are accepted, or defensibly acceptable, under the regulatory framework. This subsection maps each technology against existing regulatory precedent and addresses the implementing act gap under EU Regulation 2024/1787.

Established Regulatory Precedent: Several technologies benefit from formal regulatory acceptance in other jurisdictions. US EPA Method 21 establishes FID and equivalent portable analysers as the reference method for equipment leak detection, directly relevant to Article 14 Type 2 surveys at the 500 ppm threshold. OTM-33A provides an accepted framework for mobile emission rate quantification relevant to Article 12 site level reconciliation. Bridger Photonics GML has received US EPA acceptance as an alternative work practice under NSPS OOOOa, establishing precedent for aerial LiDAR-based detection. The OGMP 2.0 Framework (UNEP, 2022) provides a voluntary reporting hierarchy aligning with Article 12's progression from generic emission factors to measurement-based quantification; operators at Level 4 or 5 are already producing Article 12-compatible data. MARCOGAZ guidelines complement the EU Regulation with technical guidance on leakage survey methodology and emission factor development for European gas TSOs [7].

The Implementing Act Gap: Article 14(6) mandates the Commission to adopt an implementing act by 5 August 2025 specifying minimum detection limits, techniques, and survey methodologies based on best available technologies. Until published, operators must use "best available technologies" without a definitive approved list. Technologies with established regulatory precedent (FID under EPA Method 21, OGI under EPA OOOOa) are highly likely to appear in the approved list. Technologies without such precedent face greater uncertainty.

Table 25: Regulatory Acceptance and Evidentiary Status by Detection Technology

Technology	Regulatory Precedent	EU Reg. 2024/1787 Status	Risk Level
FID (handheld)	EPA Method 21 reference method	Very likely to be approved in implementing act	Low
TDLAS closed-path	Equivalent to EPA Method 21	Very likely to be approved	Low
TDLAS open-path	Widely deployed; no formal method	Likely to be approved; methodology TBC	Low–Medium
OGI (FLIR/Opgal)	EPA OOOOa approved alternative	Likely to be approved for Type 1	Low
QOGI (QL320)	Limited formal precedent	Status depends on implementing act detail	Medium
Vehicle CRDS	Formal method; operational.	Accepted for screening	Low
UAV TDLAS	No full regulatory method	Article 14(4) provides pathway	Medium
LiDAR cameras	No regulatory precedent	Status uncertain	Medium–High
Aerial GML (Bridger)	EPA alternative work practice	Possible for screening; not for Type 2	Medium
DTS/DAS	No LDAR-specific precedent	Not directly applicable to LDAR compliance	N/A
High-flow sampling	EPA-accepted quantification method	Very likely for Article 12 quantification	Low

9. Supplier and Service Landscape

The LDAR equipment market is structured around technology categories, with a small number of established manufacturers dominating each segment. Supplier consolidation has occurred through acquisition (Teledyne's acquisition of FLIR, Baker Hughes's Panametrics division) whilst new entrants continue to emerge in UAV and LiDAR segments. The following assessment covers the principal suppliers for each technology class relevant to GNI.

Flame Ionisation and Closed-Path TDLAS: The handheld detection market is mature with multiple established suppliers. Thermo Scientific (TVA-2020) and Ion Science (Tiger series) supply portable FID instruments with detection limits below 1 ppm, established calibration infrastructure, and UK/European service networks. For closed-path TDLAS, Crowcon Detection Instruments (Gasman/XGard series, LaserMethane), Heath Consultants (Detecto-Pak, RMLD), and Pergam Technical Services (Laser Methane series) provide instruments widely deployed across European gas utilities. Pergam maintains a particularly strong European presence through direct relationships with gas TSOs including Gasunie, Flúxys, and National Grid. Crowcon, as a UK-based manufacturer, offers proximity advantages for after-sales support, calibration, and training relevant to Irish operations.

Optical Gas Imaging: The OGI camera market is dominated by Teledyne FLIR, whose GF-series cameras (GF320 for methane, GF620 for larger hydrocarbons) have become the de facto industry standard. The FLIR QL320 QOGI integration provides the only commercially established pathway to quantified OGI measurement, a critical capability for simultaneous Article 14 and Article 12 compliance. Opgal Optronic Industries offers the EyeCGas 2.0 as a competitive alternative, including uncooled detector variants at lower cost but reduced sensitivity. Sensia (a Schlumberger/SLB company) provides OGI cameras integrated with their emissions management software platform, targeting operators seeking enterprise-scale monitoring solutions. For GNI, FLIR GF320 with QL320 represents the lowest-risk OGI procurement given market dominance, QOGI capability, and the broadest base of operational experience and third-party validation data [56].

UAV Platforms and Payloads: The UAV methane detection segment is characterised by rapid development and a fragmented supplier landscape. Soarability (Sniffer4D closed-path TDLAS) has established an operational track record including GNI's Parteen Bridge survey, providing direct precedent for continued use. SeekOps offers miniaturised analyser payloads with sub-ppm sensitivity for integration with third-party UAV platforms. Pergam's DragonFly provides open-path TDLAS in a nadir-configured UAV payload. DJI supplies the dominant UAV airframe platforms (Matrice 350 RTK, Mavic 3 Enterprise) upon which most third-party sensor payloads are integrated, and offers the Zenmuse L2 LiDAR and H30T thermal/RGB payloads for structural inspection applications. The UAV segment is evolving rapidly, with new entrants and capability improvements expected annually.

Vehicle-Mounted Analysers: Picarro dominates the vehicle-mounted CRDS market with its mobile surveyor platform. European deployment has accelerated significantly under EU Regulation 2024/1787, with over 50 DSOs now operating Picarro-based platforms and network coverage exceeding 800,000 km annually. Italgas, Europe's largest DSO, operates a fleet of 42 Picarro vehicles supplemented by 117 backpack units across its 150,000+ km network. The system's ppb-level sensitivity and established data analytics pipeline provide proven capability for network wide screening. ABB offers vehicle-mounted laser-based analysers as an alternative, with TDLAS technology providing ppm-level sensitivity suitable for leak indication. Heath Consultants provides integrated vehicle survey solutions combining multiple sensor types with GPS data logging and reporting software.

LiDAR and Advanced Detection: Bridger Photonics supplies Gas Mapping LiDAR for aerial surveys, operating commercially from its Montana (USA) base with a fleet of instrumented aircraft. European deployment would require either a Bridger service contract or licensing arrangement, as no equivalent European provider currently exists. QLM Technology (UK-based) offers single-photon LiDAR cameras for fixed-mount gas detection, representing the most promising emerging technology for continuous quantitative monitoring at point assets. Sensia's LiDAR camera platform targets similar applications through integration with SLB's broader emissions management offering.

Distributed Fibre Optic Sensing: The DTS/DAS market includes OptaSense (Luna Innovations), Silixa, Fotech (bp subsidiary), AP Sensing, and Omnisens, all offering interrogator platforms with established deployment in pipeline monitoring. OptaSense and Silixa have the broadest deployment base in European pipeline applications, with Silixa offering an advantage in combined DTS/DAS interrogation from a single unit. These suppliers serve the pipeline surveillance market rather than the LDAR market specifically; engagement would be relevant if GNI pursues continuous monitoring for new pipeline construction or major rehabilitation.

9.1 Integrated LDAR Service Providers

Beyond equipment procurement, GNI may engage service providers offering turnkey LDAR survey delivery. This model shifts the operational burden from GNI to the service provider, who supplies equipment, trained personnel, survey execution, data processing, and compliance reporting as an integrated service. The LDAR service market in Europe is less mature than in North America, where specialist providers such as Montrose Environmental Group, Leak Surveys Inc., and numerous regional firms offer established survey programmes to oil and gas operators.

In the European gas TSO context, LDAR services are typically provided through one of three models. First, specialist environmental consultancies with gas sector experience offer survey design, execution, and reporting services, often deploying client-owned or rented equipment with consultant-trained operators. Second, equipment manufacturers (particularly Pergam, FLIR, and Crowcon) offer survey services alongside equipment sales, leveraging their product expertise and training infrastructure. Third, UAV service providers offer aerial inspection services that combine methane detection with visual and structural survey, relevant to the crossing and corridor inspection requirements discussed in Sections 5 and 7.

The helicopter surveillance programme represents a specific service category. GNI's existing aerial surveillance under I.S. 328:2021 Section 15.5 is delivered through a contracted helicopter operator. The dual-payload opportunity described in Section 10, mounting gimballed TDLAS and RGB camera systems on these existing flights, provides supplementary screening value for the transmission corridor, though at I.S. 328 surveillance altitudes this does not satisfy Article 14 Type 1 or Type 2 detection thresholds. The service requirement encompasses methane detection payloads with the surveillance mission, processing TDLAS data to produce georeferenced detection maps, and delivering RGB corridor imagery for encroachment monitoring and photogrammetric analysis. This is a specialist service requirement that may be met through the existing helicopter contractor adding sensor capability, or through a separate sensor and data processing subcontract.

For Article 12 quantification, service providers offering high-flow sampling, QOGI survey, or mobile measurement campaigns are required. These services tend to be more specialised than general LDAR survey provision, requiring specific equipment and expertise in emissions quantification methodology.

9.2 Emerging and Continuous Monitoring Providers

Fixed OGI Systems: Teledyne FLIR's A8500 series and Opgal's fixed-mount cameras provide automated OGI monitoring for installation at compressor stations, CNG units, AGIs, or other facilities where continuous surveillance is justified by emission risk or regulatory focus. These systems operate autonomously, capturing imagery at scheduled intervals or continuously, with automated plume detection algorithms flagging potential emissions for review. Deployment requires significant capital investment per installation and is typically justified only at the highest-priority facilities.

LiDAR Camera Systems: QLM Technology's LiDAR camera is positioned as a fixed-mount continuous monitoring solution providing quantitative methane detection. The system's claimed detection sensitivity below 1 g/hr, if validated under field conditions, would enable continuous Type 2 compliance monitoring. The UK location of QLM provides proximity advantages for engagement, pilot deployment, and ongoing support. Sensia's LiDAR camera offering targets similar applications through the SLB ecosystem, with integration into broader emissions management platforms.

9.3 Procurement Considerations and Supply Chain Risk

Calibration and Service Infrastructure: Ongoing LDAR programme operation requires access to calibration facilities, spare parts, and technical support. For handheld instruments, UK-based manufacturers (Crowcon) and distributors offer the shortest turnaround for calibration and repair. FLIR OGI camera servicing typically requires return to Teledyne FLIR facilities in Sweden or the United States, with turnaround times of several weeks. GNI should consider procuring backup instruments for critical equipment categories to avoid survey programme disruption during maintenance periods.

Training and Certification: Article 14(16) requires certification or equivalent qualification for LDAR personnel. Equipment suppliers (FLIR, Pergam, Crowcon) offer manufacturer-specific training programmes, typically 2 to 5 days in duration. Broader LDAR methodology certification (equivalent to BVAA or similar industry schemes) may need to be sourced through specialist training providers. The availability of training in Ireland or the UK, rather than requiring travel to continental Europe or North America, is a practical consideration for workforce development. Training requirements and certification pathways form part of LDAR programme design, with personnel competency documented in advance of the implementing act publication.

ATEX and Hazardous Area Requirements: Equipment deployed in hazardous areas (compressor stations, CNG units, enclosed valve chambers) must meet ATEX directive requirements for the applicable zone classification. Handheld FID and TDLAS instruments are generally available in ATEX-certified variants, though certification may limit functionality or increase cost. OGI cameras including the FLIR GF320 are available with ATEX certification. UAV operations in ATEX zones require specific risk assessment and may be restricted. Procurement specifications for equipment intended for deployment at classified locations would need to include ATEX requirements.

10. Operational Cost Drivers and Delivery Model Analysis

The cost of an LDAR survey programme is driven by distinct factors depending on the survey method employed. Understanding these cost drivers enables comparison between survey approaches on a like-for-like basis and supports procurement strategy.

Walking Surveys (Handheld FID/TDLAS): Walking surveys are labour-intensive with a cost structure dominated by personnel time. The primary cost drivers are surveyor daily rates (including travel, subsistence, and overhead for remote locations), survey coverage rate (typically 50 to 200 components per day at AGIs, or 2 to 5 km of pipeline route per day depending on terrain and access), calibration gas and consumables (FID hydrogen supply, calibration standards), and data recording and reporting time. Equipment capital cost is relatively modest: handheld TDLAS instruments range from €5,000 to €25,000 depending on specification, with FID instruments at similar price points. Equipment depreciation is a minor component of total survey cost over a multi-year programme. The dominant cost factor is the number of person-days required to achieve the survey frequencies specified in Annex I of the Regulation across GNI’s full asset base.

Vehicle-Mounted Surveys (CRDS): Vehicle surveys have higher capital costs but dramatically better coverage rates. A Picarro mobile surveyor system represents a capital investment typically in the range of €150,000 to €300,000 for the analyser, vehicle integration, and data processing software. Operating costs include vehicle running costs, operator time (one to two personnel), and data analysis. Coverage rates of 100 to 400 km per day make vehicle surveys highly cost-effective for distribution network screening where pipeline routes follow public roads. The cost per kilometre of network surveyed is typically an order of magnitude lower than walking surveys. Vehicle CRDS surveys constitute the primary detection pass within a two-stage compliance workflow; ground-based walking confirmation at flagged locations provides the component-level localisation required for repair initiation and adds additional cost that must be included in the total programme estimate. This two-stage methodology is now the accepted Article 14 compliance approach for distribution networks among European DSOs.

OGI and QOGI Surveys: OGI survey costs are driven by equipment capital cost (FLIR GF320: approximately €80,000 to €120,000; QL320 QOGI addition: approximately €15,000 to €25,000), trained operator requirements (OGI requires specialist training and practice to achieve reliable detection), and survey speed at facilities (typically faster than walking FID/TDLAS for large facilities with many components, but slower for linear assets). QOGI adds meteorological measurement requirements (portable weather station) and additional data processing time for quantification. Where GNI opts to outsource OGI surveys, daily service rates for an OGI survey team (operator plus equipment) are typically in the range of €1,500 to €3,000 per day depending on provider and location.

UAV Surveys: UAV survey costs include equipment (airframe, sensor payload, ground control station: €15,000 to €80,000 depending on platform and sensor), pilot certification and training, aviation authority approvals and operational permits, and mobilisation to survey locations. UAV surveys for pipeline crossings and hard-to-reach sections are typically costed per mobilisation rather than per kilometre, reflecting the site-specific nature of each survey. A single crossing inspection including mobilisation, flight, data processing, and reporting may cost €2,000 to €5,000 depending on complexity and location. For routine structural and methane inspection of crossings, annual survey programmes covering multiple sites on a planned schedule achieve better unit economics through efficient route planning.

Helicopter Surveys (Dual-Payload): The helicopter survey cost structure is unique because GNI already incurs substantial expenditure on aerial surveillance under I.S. 328:2021. The marginal cost of adding TDLAS and RGB payloads to existing surveillance flights is significantly lower than the full cost of a standalone aerial methane detection programme. Cost drivers for the incremental capability include sensor procurement or lease (gimballed TDLAS system, high-resolution RGB camera: equipment cost varies significantly by specification), integration with the helicopter platform (mount engineering, power supply, data links), data processing and reporting (converting raw TDLAS and

RGB data into actionable outputs), and additional flight time if sensor requirements extend sortie duration beyond the surveillance baseline. The key cost argument is that the surveillance flights already cover the transmission corridor at the required frequency; adding sensors extracts additional operational and screening value from an existing expenditure. The incremental cost of methane screening capability and corridor imaging is a fraction of the cost that would be incurred to establish these capabilities as standalone programmes. However, it must be recognised that helicopter mounted TDLAS operating at I.S. 328 surveillance altitudes of 500 feet (150 metres) does not achieve the detection sensitivity required for Article 14 Type 1 (17 g/hr) or Type 2 (1 g/hr) compliance. At these altitudes, TDLAS sensitivity is limited to detecting substantially larger leaks. The helicopter dual-payload therefore provides rapid screening for significant emission sources and corridor condition documentation, but does not constitute Article 14 LDAR compliance. The incremental cost of methane detection and corridor imaging is a fraction of the cost that would be incurred to establish these capabilities as standalone programmes.

High-Flow Sampling (Article 12 Quantification): High-flow sampling equipment (Bacharach Hi Flow Sampler or equivalent) represents a moderate capital cost (€8,000 to €15,000) with operating costs driven by personnel time and calibration. High-flow sampling is conducted at confirmed leak locations identified through LDAR surveys, so the volume of sampling is proportional to the number of detected leaks rather than the number of components surveyed. This makes the cost variable and dependent on network condition. For a well-maintained network with low leak rates, high-flow sampling costs may be modest; for ageing infrastructure with higher leak incidence, costs scale accordingly.

Table 26: Cost Structure Summary by LDAR Survey Method

Survey Method	Capital Cost	Primary Cost Driver	Coverage Rate	Compliance Output
Walking FID/TDLAS	Low (€5–25k)	Personnel time	50–200 components/day	Art. 14 Type 1 + 2
Vehicle CRDS	High (€150–300k)	Equipment capital	100–400 km/day	Screening only
OGI (handheld)	High (€80–120k)	Equipment + operator	Facility per day	Art. 14 Type 1
QOGI	High (€95–145k)	Equipment + operator	Facility per day	Art. 14 + Art. 12
UAV TDLAS	Moderate (€15–80k)	Mobilisation	Per site	Art. 14 Type 1 + 2
Helicopter (dual)	Incremental	Sensor integration	Corridor per sortie	Art. 14 Type 1 + screening
High-flow sampling	Low (€8–15k)	Personnel time	Per detected leak	Art. 12 quantification

*Capital cost figures are indicative estimates based on publicly available pricing and supplier engagement;

10.1 Delivery Model Comparison

In-House Delivery: GNI procures equipment, trains personnel, and executes surveys using internal resources. This provides maximum operational control and builds internal expertise but requires developing competency across multiple technology types (handheld, OGI, UAV, vehicle-mounted), managing equipment lifecycle and calibration, and ensuring sufficient staffing to meet survey frequencies across the full asset base. The principal risk is specialist capability concentrated in a small team, creating vulnerability to staff turnover. The principal advantage is full control over scheduling, quality, and integration with existing maintenance programmes. Article 14(16) certification requirements apply equally to in-house and outsourced personnel.

Outsourced Delivery: GNI contracts specialist service providers to deliver the survey programme under framework agreements specifying frequencies, coverage, reporting, and quality standards. This converts capital to operating expenditure, avoids recruiting specialist staff, and leverages provider experience across multiple clients. Pricing is typically structured per survey day, per facility, or per kilometre. The model transfers operational risk (equipment failure, staff availability, technology refresh) to the provider but introduces dependency on supplier performance. GNI must maintain sufficient internal expertise to oversee, audit, and validate outsourced work. The helicopter surveillance programme already operates under this model, providing an established precedent.

Hybrid Delivery: A hybrid model deploys internal resources for routine activities and engages specialists for specific technology requirements. For GNI, this would likely comprise in-house walking surveys at AGIs and distribution networks using GNI-owned handheld FID/TDLAS, outsourced helicopter surveillance with integrated TDLAS and RGB payloads, outsourced OGI/QOGI at CNG units where specialist equipment justifies service procurement, and outsourced UAV surveys for crossings and structural assessment requiring specialist certification. These balances cost against capability, keeps high-volume activities in-house, and provides natural redundancy. The hybrid approach is the most common model among European gas TSOs implementing LDAR programmes.

10.2 Scalability and Network Coverage Implications

Scale of the Survey Task: GNI's network comprises approximately 1,900 km of transmission pipeline, 12,000 km of distribution network, approximately 1,200 AGIs (including CNG units, stations, pressure reduction stations, metering stations, valve stations, and district governors), and offshore and foreshore assets. The survey frequencies in Table 2 (Section 3.2) require compressor stations / CNG units to be surveyed quarterly (Type 1) and annually (Type 2), regulating and metering stations every 4 months (Type 1) and annually (Type 2), valve stations every 6 months (Type 1) and every 18 months (Type 2), and transmission pipelines every 6 months (Type 1 for above ground) and every 24–36 months (Type 2). Distribution networks require survey as per risk assessment, with Type 2 surveys every 24 months for steel and 36 months for PE.

Transmission Corridor Coverage: The existing helicopter surveillance programme already covers the transmission corridor at intervals determined by I.S. 328:2021. Adding gimballed TDLAS and high-resolution RGB payloads to these flights provides supplementary screening for significant emission sources and systematic corridor condition documentation at incremental rather than standalone cost. For Article 14 Type 1 and Type 2 compliance on the transmission corridor, drone-mounted TDLAS operating at 25–50 metres altitude represents the most viable aerial pathway, with demonstrated detection capability at both thresholds. The operational challenge of covering 1,900 km by drone is addressed through phased survey programmes prioritising higher-risk sections, fixed-wing drone variants for extended range, and the progressive enabling of BVLOS operations under the EU U-space framework. Type 2 compliance additionally requires targeted ground or UAV follow-up at flagged locations and high-risk sections (crossings, older steel, known ground movement areas)."

AGI and Point Asset Coverage: The approximately 1,200 AGIs represent the highest survey volume in terms of survey events per year. Assuming an average of 2 to 4 hours per AGI for a Type 2 survey (varying with facility size and component count), and allowing for travel time between locations, a single two-person survey team could complete approximately 2 to 3 AGI surveys per day. At this rate, covering 1,200 AGIs once per year for Type 2 requires approximately 200 to 300 person-days, equivalent to one full-time team operating year-round with allowance for travel, weather, and administrative days. Type 1 surveys at higher frequency (quarterly or every 4 months for some asset categories) add to this volume. The total survey workload for point assets is estimated at approximately 600 to 900 person-days per year, manageable with a dedicated in-house team of 3 to 4 trained surveyors supplemented by outsourced support during peak periods.

Distribution Network Coverage: The 12,000 km distribution network presents the largest coverage challenge in absolute terms. Vehicle-mounted CRDS survey offers the most efficient and proven approach, now established as the primary Article 14 compliance methodology for distribution networks across European DSOs, with coverage rates of 100 to 400 km per day enabling complete network screening within approximately 30 to 120 survey days depending on urban density, traffic conditions, and repeat coverage of flagged areas. This is within the capacity of a single dedicated vehicle operating year-round. Ground-based confirmation surveys at flagged locations add variable workload proportional to the number of indications, which depends on network condition and the screening threshold applied.

Data Management and Reporting: The survey programme generates substantial data volumes requiring systematic management. Handheld survey records, QOGI quantification data, helicopter TDLAS and RGB datasets, UAV flight data, high-flow sampling results, and associated metadata must be stored, processed, and reported to the competent authority in the annual emissions report required under Article 12. Data storage costs are driven primarily by the helicopter and UAV imagery: a full corridor RGB dataset at sub-centimetre resolution generates tens of terabytes per campaign, whilst TDLAS detection data and handheld survey records are comparatively modest in volume. Cloud-based storage for the full data portfolio is estimated at low thousands of euros per year, a negligible fraction of total programme cost. The more significant cost consideration is the data processing and reporting pipeline: converting raw survey data into compliance documentation, maintaining the emissions inventory, and producing the annual report with third-party verification. This function requires either dedicated internal analytical capability or contracted data management services, and is a consideration regardless of the survey delivery model chosen.

Dual-Purpose Flights and Cost Efficiency: The operational integration of methane detection with existing infrastructure monitoring activities represents the principal cost efficiency opportunity. The helicopter dual-payload concept delivers three operational functions from a single flight programme: I.S. 328:2021 Section 15.5 pipeline surveillance, supplementary methane screening for significant emission sources along the transmission corridor (noting this does not satisfy Article 14 Type 1 or Type 2 detection thresholds), and corridor condition documentation through systematic high-resolution RGB capture for encroachment detection, third-party activity monitoring, and ground condition assessment. Similarly, UAV surveys at crossings and inaccessible sections can integrate methane detection (closed-path TDLAS) with structural inspection (photogrammetric survey and ML-based defect detection as described in Section 7), delivering both LDAR compliance and structural condition data from a single mobilisation. These dual-purpose deployments reduce the per-function cost of each activity and should be reflected in programme planning and procurement specifications.

Future Cost Reduction Pathways: Several technology developments are likely to reduce LDAR programme costs over the medium term, though they should not be relied upon for near-term compliance planning. Beyond visual line of sight (BVLOS) UAV operations represent the most significant near-term development for GNI's LDAR programme. As regulatory approvals progress through the Irish Aviation Authority and the EU U-space framework, BVLOS operations will enable drone TDLAS to transition from site-specific access solutions to primary compliance survey method for transmission corridor Type 1 and Type 2 surveys the only aerial technology demonstrated to meet both thresholds. Fixed-wing UAVs operating BVLOS with TDLAS payloads could provide the transmission corridor coverage currently achievable only by helicopter, at substantially lower cost and with detection sensitivity sufficient for Article 14 compliance. GNI should actively engage with IAA on BVLOS pathway development and consider early-stage trials of fixed-wing drone TDLAS over representative corridor sections. Fixed-wing UAVs operating BVLOS with TDLAS and RGB payloads could provide a lower-cost alternative to helicopter corridor surveys for the data collection mission, though they do not replicate the immediate response and deterrence function of manned helicopter surveillance.

LiDAR cameras, if validated at the claimed detection sensitivity, would enable continuous monitoring at high-priority facilities, potentially reducing or eliminating the need for periodic OGI/QOGI surveys at those locations. Aerial GML surveys using Bridger Photonics or future European providers could deliver efficient transmission corridor screening if detection sensitivity improves or if the technology is accepted for Type 1 compliance by the implementing act. Advances in distributed fibre optic sensing may eventually provide continuous leak detection along new pipeline installations. These technologies should be tracked through pilot deployments and industry engagement, with the LDAR programme designed to accommodate technology substitution as maturity and regulatory acceptance develop.

PART VI: SWOT ANALYSIS

11. SWOT Analysis

11.1 Detection and Quantification Technologies

Handheld FID and TDLAS (Closed-Path and Open-Path)

Strengths	Weaknesses
• TRL 9, highest maturity of any LDAR technology • Proven regulatory acceptance (EPA Method 21 for FID) • Reliable detection well below 500 ppm Type 2 threshold • Multiple suppliers; no single-source dependency • Low capital cost; immediate deployability at all GNI point assets • Open-path variants enable standoff survey of elevated components	• No Article 12 quantification capability; supplementary method required • Labour-intensive, coverage limited by walking speed and access • Impractical for surveying full transmission corridor (1,900 km) • FID responds to all hydrocarbons, not methane-specific • Operator-dependent, detection quality varies with technique and fatigue • Open-path ppm·m output requires interpretation for Type 2 threshold confirmation
Opportunities	**Threats**
• Foundation of a hybrid programme, high-volume, low-risk baseline capability • Measurement-informed emission factors improve Article 12 accuracy over time • Integration with digital data capture and automated reporting platforms	• If implementing act mandates quantification at point of detection, supplementary cost increases • Workforce availability and retention of trained LDAR surveyors in Irish market • Survey frequency requirements may exceed available person-days without scaling

Optical Gas Imaging (OGI) and Quantitative OGI (QOGI)

Strengths	Weaknesses
• Rapid visual detection across complex facilities with many components • QOGI provides simultaneous Article 14 detection and Article 12 quantification • TRL 9 for standard OGI; TRL 7–8 for QOGI • De facto industry standard for facility-level LDAR surveys globally • FLIR GF320 available in ATEX-certified variant for hazardous areas	• Standard OGI satisfies Type 1 only, cannot confirm 500 ppm for Type 2 • QOGI quantification uncertainty approximately factor of two • Performance dependent on thermal contrast reduced in isothermal or humid conditions • High equipment capital cost (€80–145k including QL320) • Single-source dependency for QOGI (FLIR QL320 only) • Requires specialist operator training and ongoing proficiency
Opportunities	**Threats**
• QOGI at CNG units and high-priority AGIs addresses both Art. 14 and Art. 12 • Fixed OGI cameras for continuous monitoring at	• Implementing act may require lower quantification uncertainty than QOGI currently achieves

highest-value assets • Developing competition (Opgal, Sensia) may reduce cost and dependency	• Irish maritime climate (high humidity, low thermal gradients) reduces detection windows • Cooled detector supply constraints may extend procurement lead times

Vehicle-Mounted CRDS

Strengths	Weaknesses
• ppb-level sensitivity enables detection of buried leaks from street level • Coverage rates of 100–400 km/day, order of magnitude faster than walking surveys • Proven technology for distribution network screening (TRL 8–9) • GPS-tagged data enables systematic network coverage tracking • Established primary distribution LDAR survey method across 50+ European DSOs (TRL 9), with operators including Italgas, Cadent, and Netz Niederösterreich deploying for EU Regulation 2024/1787 compliance	• Primary survey pass requires ground follow-up for component-level localisation and repair initiation; does not provide Article 12 quantification • Ground follow-up required at every flagged location for compliance • Ethane co-measurement capability discriminates thermogenic pipeline methane from biogenic agricultural sources significant advantage in Ireland's rural landscape • High capital cost (€150–300k) or significant service contract commitment • Single dominant supplier (Picarro)
Opportunities	**Threats**
• Efficient prioritisation of ground crew deployment across 12,000 km distribution network • Repeat surveys build trending data for risk-based frequency adjustment • Integration with walking survey planning to optimise total programme efficiency • European DSO adoption at scale (800,000+ km/year coverage) provides strong regulatory precedent and peer benchmarking for GNI	• Biogenic methane sources across Irish agricultural landscape increase false positive rates • Technology does not address transmission or AGI survey requirements • Biogenic methane sources may complicate interpretation where ethane co-measurement is not deployed or where biogenic concentrations are very high

UAV-Mounted TDLAS (Closed-Path and Open-Path/Gimbal)

Strengths	Weaknesses
• Access to infrastructure that cannot be reached by walking or vehicle survey • Closed-path (Sniffer4D) demonstrated at GNI Parteen Bridge, direct operational precedent • 1 ppm detection, sub-2m proximity achievable, reliable at Type 1 and Type 2 thresholds • Dual-purpose capability: methane detection combined with photogrammetric inspection • Gimbal open-path offers improved spatial coverage over nadir-only configurations • Only aerial technology with demonstrated detection capability at both Article 14 Type 1 (17 g/hr) and Type 2 (500 ppm) thresholds	• TRL 7–8 for closed-path; 7–8 for open-path/gimbal detection, 5 for quantification • Limited controlled release validation specific to pipeline crossing geometries • Aviation authority approvals required for each operational site/scenario • Flight endurance constraints limit survey duration per sortie • Open-path quantification workflows (AIRINS.ai) require further validation for Article 12
Opportunities	**Threats**

• BVLOS approvals would enable corridor surveys replacing some helicopter flying hours • Annual crossing programme builds structural baseline for change detection over time • Integration of methane + RGB + thermal payloads on single platform • BVLOS approvals would enable drone TDLAS to transition from site-specific access solution to primary Article 14 compliance survey method for the transmission corridor, the only aerial technology capable of meeting both detection thresholds • Emerging quantification workflows (AIRINS.ai) position drone TDLAS as a potential Article 12 pathway, pending controlled release validation	• Regulatory status uncertain pending implementing act Article 14(4) provides pathway • IAA BVLOS approval timeline uncertain for Irish airspace • Rapid technology evolution may strand early equipment investments

Helicopter-Mounted Gimballed TDLAS with RGB Imaging

Strengths	Weaknesses
• Leverages existing I.S. 328:2021 surveillance flights, incremental cost, not new programme • Covers full 1,900 km transmission corridor per existing flight schedule • Triple output: surveillance compliance + supplementary methane screening for significant emission sources + corridor documentation • RGB imagery delivers digital baseline for encroachment and condition monitoring • Immediate response and deterrence function retained through manned helicopter	• Cannot satisfy Article 14 Type 1 (17 g/hr) or Type 2 (500 ppm) detection thresholds at I.S. 328 surveillance altitudes of 150m+; detection limited to significantly larger emission sources • No Article 12 quantification from aerial TDLAS at survey altitude • Requires contracted sensor operator, data processing pipeline, and storage • Weather-dependent, flight cancellations create survey gaps • QOGI not viable from moving helicopter platform
Opportunities	**Threats**
• RGB corridor data supports photogrammetric analysis and ML-based encroachment detection • Sensor data may contribute to site level Article 12 reconciliation, though altitude-dependent sensitivity constraints limit detection to significant sources only; methodology requires development and competent authority agreement • Cost argument is strongest when framed as extracting additional value from existing expenditure	• Contractor must integrate sensor capability, procurement specification required • Fixed-wing BVLOS UAVs may erode the cost advantage of manned helicopter in medium term • Data volume from RGB capture requires storage and processing infrastructure • Drone TDLAS operating at 25–50m altitude achieves superior detection sensitivity at both Article 14 thresholds, potentially reducing the compliance value proposition of helicopter-mounted systems as BVLOS operations mature

Emerging Technologies (LiDAR Cameras, Aerial GML, DTS/DAS)

Strengths	Weaknesses
• LiDAR cameras offer inherent quantification, potential to satisfy Art. 14 + Art. 12 simultaneously	• LiDAR cameras at TRL 5–6 with limited gas TSO deployment • Bridger 2 kg/hr threshold exceeds Type 2

• Bridger GML provides basin-scale coverage with EPA-accepted methodology • DTS/DAS enables continuous surveillance of linear assets 24/7 • Active illumination (LiDAR) independent of thermal contrast advantage over OGI	requirement; no European service provider • DTS/DAS does not satisfy Article 14 or Article 12; retrofit requires substantial civil works • Limited controlled release validation under Irish conditions for any of these technologies
Opportunities	**Threats**
• LiDAR cameras for continuous monitoring at CNG units as pilot programme • Bridger or equivalent aerial GML as future transmission corridor screening • DTS/DAS fibre installed during new construction at marginal incremental cost • Significant cost reduction potential once validated and accepted	• Reliance on emerging technology for near-term compliance is indefensible • Regulatory acceptance uncertain may not appear in implementing act • Single-source or limited-source supply chains for all three technology classes

11.2 Structural and Visual Inspection Technologies

The photogrammetric and ML-based inspection technologies described in Sections 6 and 7 serve a distinct but complementary function within the broader pipeline integrity programme. These technologies address structural condition assessment rather than methane detection, but their integration with UAV-based LDAR surveys creates operational efficiency and data synergies.

Strengths	**Weaknesses**
• SfM photogrammetry at TRL 9 for survey applications mature, well-understood methodology • Sub-centimetre GSD achievable from UAV platforms at typical inspection distances • YOLO and SAM 2 enable automated defect detection and pixel-level segmentation • 3D Gaussian Splatting provides immersive photorealistic visualisation for review • Dual-purpose UAV sorties: methane detection + structural inspection from single mobilisation • Digital baseline enables quantitative change detection between survey epochs	• Integrated pipeline application at TRL 6–8 limited published datasets for pipeline defect classes • ML models require training data specific to GNI asset types and defect categories • Processing pipeline (SfM → dense cloud → mesh → ML inference) requires specialist capability • 3DGS provides visualisation value but lower geometric precision than mesh for measurement • No direct regulatory requirement for photogrammetric inspection under EU Reg. 2024/1787
Opportunities	**Threats**
• Builds pipeline-specific training datasets through operational deployment over time • Addresses I.S. 328:2021 Section 15.6 inspection requirements alongside LDAR • Emerging capability for automated report generation via YOLO → SAM 2 → LLM pipeline • Early adoption establishes GNI data advantage for condition-based maintenance	• Technology investment without direct regulatory mandate may face internal cost justification challenge • Model accuracy for pipeline-specific defects unproven at operational scale • Requires ongoing model retraining as new defect types and asset conditions are encountered

11.3 Cross-Cutting Risks and Dependencies

Regulatory Uncertainty: Regulation (EU) 2024/1787 establishes binding LDAR obligations under Article 14 but anticipates further Commission implementing acts to specify detailed technical requirements, including minimum detection limits, survey methodologies, and performance criteria. While LDAR survey and reporting obligations apply from August 2025, the corresponding implementing acts defining approved detection techniques and technical thresholds had not been adopted at the time of writing. In the absence of these detailed acts, operators are required to comply using state-of-the-art and best available detection technologies consistent with existing regulatory and industry practice. This creates an incentive to anchor LDAR programmes on technologies with established regulatory precedent, such as FID, TDLAS, and OGI methods referenced in EPA and other supervisory frameworks, and to document technology selection against "best available techniques" criteria. When the implementing acts are adopted, LDAR programmes built on precedent-backed technologies are unlikely to require material revision, whereas technologies without established regulatory acceptance should remain supplementary or pilot-scale until their formal status is clarified. A second source of uncertainty has emerged since the Regulation entered into force: the Regulation itself is also now subject to amendment pressure under the EU simplification agenda. This debate concerns the import provisions (Articles 27 to 29: importer reporting, equivalence, and methane intensity), which do not apply to GNI as a network operator. While some industry positions have also referenced domestic LDAR and MRV requirements, the operator obligations under Articles 12 and 14 are already in force and no plausible amendment would retrospectively relieve obligations already due. The debate therefore provides no basis for deferring any element of the LDAR programme; as with the implementing act delay, the appropriate response is to remain anchored on precedent-backed technologies and review the position if an amending act is formally proposed.

Skills Availability: The Irish market has a limited pool of experienced LDAR professionals. Gas Networks Ireland, ESB, and the broader energy sector compete for engineers and technicians with relevant instrumentation, survey, and data analysis skills. Article 14(16) certification requirements add a formal competency standard that must be satisfied before personnel can conduct compliance surveys. Recruitment, training, and retention of qualified LDAR personnel is a programme risk that applies regardless of delivery model, though outsourcing partially transfers the risk to the service provider.

Data Management and Reporting Infrastructure: Article 12 reporting requires a systematic emissions inventory integrating data from multiple survey methods, quantification results, emission factors, and facility metadata. No single commercial platform currently provides end-to-end LDAR data management tailored to EU Regulation 2024/1787 requirements for a gas TSO. GNI must either develop internal data management capability, adapt existing asset management systems, or procure a specialist LDAR data platform. Early resolution of this infrastructure decision would reduce the risk of survey data being captured without a structured management framework, which can be difficult to retrospectively organise for compliance reporting.

PART VII: CONCLUSIONS

12. Conclusions

12.1 Regulatory Requirements

The following obligations are established by EU Regulation 2024/1787 and cannot be avoided, deferred, or substituted. They define the minimum scope of any compliant LDAR programme.

Table 27: Regulatory Obligations Under EU Regulation 2024/1787 estimated status February 2026

Obligation	Requirement	Deadline	Reference	Status
LDAR programme submission	Comprehensive programme submitted to competent authority	5 May 2025	Art. 14	Complete
First Type 2 survey	All existing sites surveyed at ≥500 ppm / ≥1 g/hr	5 Aug 2025	Art. 14, Annex I	Complete
First emissions report	Source-level quantification (generic emission factors acceptable)	5 Aug 2025	Art. 12	Complete
Type 1 surveys ongoing	Every 4–24 months depending on asset category	Per Annex I	Art. 14, Annex I	In progress
Type 2 surveys ongoing	Every 8–36 months depending on asset category	Per Annex I	Art. 14, Annex I	In progress
Repair obligations	First attempt within 5 working days; completion within 30 calendar days	Upon detection	Art. 14	Ongoing
Measurement-based reporting	Source-level measurement data for operated assets	5 Feb 2026	Art. 12	Due
Venting/flaring restrictions	Prohibition on routine venting and flaring	5 Feb 2026	Art. 15/16	Due
Personnel certification	Certification or equivalent qualification for LDAR personnel	Ongoing	Art. 14(16)	Ongoing
Site level reconciliation	Independent site level measurement reconciled with source-level inventory	5 Feb 2027	Art. 12	Forthcoming

12.2 Viable Compliance Pathways

Given the regulatory requirements, network characteristics, and technology capabilities assessed in this report, the following compliance pathways satisfy both Article 14 (detection and repair) and Article 12 (quantification and reporting) obligations across GNI's full asset base. GNI's foundational LDAR programme is operational and the initial compliance milestones have been met. The pathways below therefore address both the continuation of established survey activities and the programme enhancements required to satisfy the progressively more demanding obligations now in effect in particular, measurement-based source-level reporting (from 5 February 2026) and site level reconciliation (from 5 February 2027). Each pathway is presented by asset type, reflecting the distinct survey challenges and technology requirements for each network segment.

Transmission Pipelines (c. 1,900 km protected steel): The transmission corridor presents two distinct requirements: rapid screening for significant emission sources across the full 1,900 km, and Article 14 Type 1 and Type 2 compliance surveys at detection thresholds of 17 g/hr and 500 ppm respectively. For rapid screening, integrating gimballed open-path TDLAS and high-resolution RGB imaging into the existing helicopter surveillance flights conducted under I.S. 328:2021 Section 15.5 extracts additional operational value from an existing expenditure, producing supplementary methane screening and systematic corridor documentation alongside pipeline surveillance compliance. For Article 14 compliance on the transmission corridor, drone-mounted TDLAS operating at 25–50 metres altitude represents the most viable aerial pathway, with demonstrated detection capability at both Type 1 (17 g/hr) and Type 2 (500 ppm) thresholds. Operational constraints, principally flight endurance, BVLOS regulatory requirements, and corridor logistics, are addressed through phased survey programmes prioritising higher-risk sections (crossings, older steel, areas of known ground movement), fixed-wing drone variants for extended range, and the progressive enabling of BVLOS operations under the EU U-space framework. Type 2 compliance is additionally achieved through targeted ground-based walking FID or closed-path TDLAS at accessible above ground sections, and UAV closed-path TDLAS at crossings and inaccessible locations. Article 12 quantification for transmission assets is achieved through high-flow sampling at every confirmed detection, supplemented by measurement-informed emission factors for non-leaking components and undetected background emissions.

AGIs, DRIs, Metering/Regulating Stations, and CNG Units (c. 1,100 AGIs and DRIs, 10 CNG units): Walking FID or closed-path TDLAS for Type 1 and Type 2 detection   these are accessible, component-dense sites where handheld instruments are proven and effective, and where GNI's existing survey capability is strongest. Type 1 surveys are required every 4 months for CNG units and regulating/metering stations, with Type 2 surveys every 8 months for CNG units and every 18 months for regulating/metering stations. The near-term enhancement is ensuring that every confirmed detection is accompanied by Article 12 quantification through high-flow sampling, building the measurement-based dataset required to replace generic emission factors in annual reporting. For AGIs with high component counts or where survey efficiency justifies the investment, QOGI (FLIR GF320 + QL320) provides simultaneous detection and quantification, eliminating the need for separate high-flow sampling at each leak. QOGI deployment at selected high-priority facilities represents the next programme maturity step, with the technology serving as the primary candidate for in-house deployment by trained GNI technicians.

Valve Stations (c. 15 locations, TBC): Type 1 surveys every 9 months and Type 2 surveys every 18 months. Walking FID or closed-path TDLAS is appropriate given the relatively small number of locations and modest component counts at typical valve stations. The low site count means these can be incorporated into existing AGI survey routes with minimal additional resource. Article 12 quantification via high-flow sampling at confirmed detections.

Buried Steel at Installations (c. 1,100 locations): Buried non-protected steel at DRIs (c. 900 locations) requires Type 1 surveys every 9 months and Type 2 surveys every 18 months. Buried protected steel at transmission installations (c. 200 locations) requires Type 1 surveys every 15 months and Type 2 surveys every 30 months. These surveys target the ground-atmosphere interface above buried steel pipework at installation boundaries and entry/exit points. Walking FID, closed-path TDLAS, or open-path TDLAS at ground level provides the required detection capability. The volume of locations   particularly the 900 DRI sites   represents a significant survey workload that must be factored into resource planning and route optimisation.

Distribution Networks (c. 12,250 km): Vehicle-mounted CRDS as the primary survey method for distribution network LDAR, consistent with the established compliance methodology now deployed by over 50 European DSOs including Italgas, Cadent, and Netz Niederösterreich. The vehicle CRDS survey constitutes the primary detection pass, with walking FID or closed-path TDLAS providing confirmation, localisation, and component-level compliance at flagged locations and at district regulating installations. The ethane co-measurement capability of CRDS platforms provides discrimination between thermogenic pipeline methane and biogenic agricultural methane, a significant operational advantage across GNI's predominantly rural distribution network. Walking FID or closed-path TDLAS for confirmation, localisation, and component-level Type 2 compliance at flagged locations and at district regulating installations. Type 2 surveys are required every 24 months for non-protected steel (7.6 km across 1,242 individual segments) and every 36 months for polyethylene (12,160 km) and protected steel (80 km across 2,192 individual segments). UAV closed-path or open-path TDLAS for hard-to-access sections, elevated crossings, congested sites, and locations where ground access is impractical. Article 12 quantification via high-flow sampling at confirmed detections, supplemented by measurement-informed emission factors for the wider network. For distribution assets, the priority enhancement is systematic quantification at detected leak locations to support the transition from estimation-based to measurement-based reporting.

Foreshore and Offshore Assets: GNI's four foreshore pipelines require Type 1 surveys every 12 months for components above sea level and every 24 months for components below sea level, with Type 2 surveys every 24 months for above-sea-level components. Subsea pipelines in the Irish Sea require Type 1 surveys every 24 months. Components below the seabed are subject to a 36-month Type 1 frequency, though the practical survey methodology for this category requires clarification. The foreshore and offshore environment presents specific access, safety, and instrumentation challenges ATEX compliance, marine working requirements, and limited access windows due to tidal and weather conditions. OGI and handheld TDLAS are viable for above-sea-level components; methodology for below-sea-level and seabed components warrants engagement with the competent authority to agree practicable approaches.

Hard-to-Reach and Inaccessible Sections: UAV-mounted TDLAS (closed-path for close-proximity inspection, open-path for broader coverage) building on the Parteen Bridge precedent. Structural inspection via photogrammetric survey and ML-based defect detection integrated into the same UAV deployment, delivering dual-purpose sorties addressing both LDAR and I.S. 328:2021 Section 15.6 inspection requirements. Each successive annual survey builds the photogrammetric baseline, improving change detection accuracy over time.

Article 12 Site level Reconciliation: This obligation takes effect from 5 February 2027 and represents the most significant outstanding compliance milestone. For discrete facilities (AGIs, CNG units, valve stations), independent site level measurement using mobile CRDS, OTM-33A methodology, or tracer-based methods provides the second estimate required for reconciliation with source-level inventories. For linear transmission assets, helicopter TDLAS screening data and drone TDLAS compliance survey data may contribute to an independent validation layer; however, the methodology for converting aerial detection data into a corridor-level emission estimate must be developed and agreed with the competent authority. Helicopter TDLAS data is limited by altitude-dependent sensitivity constraints, meaning it captures only significant emission sources rather than the full emission profile. Drone TDLAS data, operating at lower altitudes with superior detection capability, may provide a more robust basis for reconciliation as drone corridor survey coverage expands. Separately, GNI should establish a documented response procedure for satellite-derived super-emitter notifications under Article 30, as described in Section 5.5. This is a low-cost programme element that should be in place in advance of any notification being received, rather than developed reactively under the Regulation's response timelines.

13.1 Key Findings

This technology assessment has examined the detection, quantification, and inspection technologies available to support GNI's LDAR programme under EU Regulation 2024/1787. The findings are summarised below in the context of GNI's existing operational capabilities and network characteristics.

GNI's current survey approach, walking TDLAS and FID at accessible point assets, vehicle mounted CRDS surveys on the distribution network (now the established primary distribution LDAR methodology across European DSOs), and manned helicopter flights for visual pipeline surveillance, provides a sound operational foundation. The technologies currently deployed are mature (TRL 9), have the strongest regulatory precedent of any LDAR method, and satisfy Article 14 Type 1 and Type 2 detection requirements at accessible locations. The principal areas where programme enhancement can extend compliance coverage and improve cost efficiency relate to the transmission corridor, Article 12 quantification, and hard-to-reach assets.

GNI's existing helicopter surveillance programme under I.S. 328:2021 represents a significant recurring expenditure. Mounting a gimballed open-path TDLAS system and high-resolution RGB camera onto these flights would extract additional operational and screening value from flying hours already being incurred, delivering supplementary methane screening for significant emission sources and systematic corridor documentation alongside pipeline surveillance. This produces three regulatory outputs from one flight programme at incremental rather than standalone cost. QOGI is not currently viable from a moving helicopter platform; quantification of detections flagged by the airborne TDLAS would require ground-based or UAV follow-up, with emission rate estimation following a methodology comparable to that described in Sections 5.9 - 5.12 for open-path data processing.

Walking FID and TDLAS remain well suited to the high-volume survey task across GNI's approximately 1,100 AGIs, DRIs, and regulating stations, where ground access is straightforward and component-level detection at the 500 ppm Type 2 threshold is routine. These instruments are proven in the Irish operating environment and align with GNI's existing workforce capability. For urban and suburban distribution networks, vehicle-mounted CRDS provides the primary compliance survey pass, consistent with the methodology now adopted by over 50 European DSOs, with walking FID or TDLAS providing confirmation and component-level compliance at flagged locations.

For hard-to-reach and inaccessible sections, pipeline crossings, bridge-mounted pipelines, elevated infrastructure, UAV-mounted TDLAS (closed-path for close-proximity detection, open-path for broader spatial coverage) addresses a genuine access gap that cannot be practically served by walking or vehicle survey. GNI's Parteen Bridge survey provides direct operational precedent for this capability. Integration of photogrammetric inspection into the same UAV deployment delivers dual-purpose sorties addressing both LDAR and structural condition assessment.

Beyond site-specific access solutions, drone mounted TDLAS represents the most viable aerial pathway to Article 14 Type 1 and Type 2 compliance for the transmission corridor. Operating at 25–50 metres altitude, drone TDLAS achieves detection sensitivity at both regulatory thresholds a capability that cannot be matched by helicopter-mounted systems at I.S. 328 surveillance altitudes. As BVLOS regulatory approvals progress and fixed-wing drone platforms mature, drone TDLAS is positioned to transition from site-specific deployment to recognised and widely used compliance survey method for transmission pipeline corridors.

Article 12 quantification, the transition from generic emission factors to measurement-based reporting, is achieved through high-flow sampling at confirmed leak detections identified by the survey programme. This applies across all asset types: detections from walking surveys, UAV surveys, and helicopter-flagged locations are followed up with high-flow sampling to produce the source-level measurement data required under Article 12. Measurement-informed emission factors developed from accumulated high-flow data progressively replace the generic factors used in initial reporting.

For compressor stations, CNG units, and other locations requiring ATEX-rated equipment, walking FLIR QOGI provides simultaneous Article 14 detection and Article 12 quantification within a single survey visit, where the controlled facility environment and lower wind speeds favour OGI performance. Handheld FID and TDLAS in ATEX-certified variants serve as alternative or supplementary detection methods. Fixed camera systems OGI or emerging LiDAR cameras are viable for continuous monitoring at the highest-priority facilities where emission risk and asset value justify the capital investment.

Lower-TRL technologies assessed in this report notably Bridger Photonics aerial gas mapping LiDAR and distributed fibre optic sensing present a credible pathway toward reduced survey cost and workload in the medium term, particularly for transmission corridor coverage and remote or continuous monitoring applications. These technologies are not at the maturity or regulatory acceptance level required for primary compliance reliance at present, but their development trajectory supports monitoring and pilot engagement as part of future programme optimisation.

The combination of technologies described above addresses the substantive requirements of both Article 14 (detection and repair) and Article 12 (quantification and reporting) across GNI's asset base. The principal remaining compliance challenge is Article 14 Type 1 and Type 2 survey coverage for the full 1,900 km transmission corridor, where helicopter mounted TDLAS at surveillance altitudes does not meet either detection threshold. The viable near-term approach combines drone TDLAS for Article 14 compliance surveys (the only aerial technology demonstrated to meet both thresholds), ground-based FID or TDLAS at accessible above ground sections, and helicopter TDLAS screening data for prioritisation of drone and ground survey effort. As BVLOS operations are progressively enabled under the EU U-space framework, drone TDLAS coverage of the transmission corridor will become increasingly scalable, with fixed-wing drone variants offering the extended range required for efficient corridor survey.

13.2 Areas Requiring Further Investigation

No established and regulatory-accepted methodology currently exists for producing an independent site level emission estimate for a linear transmission corridor at the scale of GNI's 1,900 km network. Methodologies validated for discrete facility reconciliation, such as OTM-33A and tracer flux, do not readily transfer to linear assets. The helicopter TDLAS screening approach and drone TDLAS compliance survey data described in Section 12.2 are technically plausible as inputs to site level reconciliation, though drone TDLAS data, operating at altitudes where both Type 1 and Type 2 thresholds are achievable, provides a more robust detection basis than helicopter data constrained by altitude-dependent sensitivity limitations.

The dual-payload helicopter concept, mounting gimballed TDLAS and RGB imaging onto existing surveillance flights for corridor screening and documentation purposes, would benefit from a procurement or contract specification. This specification should clearly define the role of helicopter TDLAS as supplementary screening rather than Article 14 compliance, to ensure expectations are aligned between GNI and the service provider.

The implementing acts anticipated under Article 14(6) to specify minimum detection limits, approved techniques, and survey methodologies had not been adopted at the time of writing. Programmes anchored on FID, TDLAS, and OGI methods are unlikely to require material revision when these acts are adopted, but GNI may wish to review the position once the acts are published. The same review point should encompass the wider EU simplification debate concerning the Regulation, the regulatory position should be re-confirmed as part of each annual programme review.

The use of gimballed open-path TDLAS data from helicopter surveys to support Article 12 quantification, through concentration path-length processing, atmospheric modelling, and emission rate estimation as described in Section Sections 5.9 - 5.12, is technically emerging but has not been validated at operational scale for regulatory reporting purposes. Drone TDLAS data, with demonstrated detection capability at both Article 14 thresholds, may provide a more viable basis for aerial quantification as drone corridor coverage expands.

Article 12 reporting draws on survey data from multiple methods, quantification results from high-flow sampling and QOGI, emission factors, and facility metadata across all asset types. GNI may wish to consider how this data is integrated into a systematic annual emissions inventory, including whether existing systems are sufficient or whether a dedicated LDAR data management platform would support more efficient and auditable reporting.

The detection performance data underpinning this assessment is drawn from published studies conducted predominantly in North American and continental European environments. Irish maritime conditions, high humidity, persistent wind, frequent precipitation, and biogenic methane from agricultural sources, may affect detection probability and false positive rates differently from published benchmarks. A controlled release programme at representative GNI assets, or participation in collaborative industry validation initiatives such as those coordinated through MARCOGAZ or GERG, could strengthen the evidentiary basis for technology performance claims in the Irish context should GNI consider it beneficial.

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