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Introduction of the Odour Fugitive Emission Potential (OFEP) for the Characterization of Fugitive Odorous Emissions

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The evaluation of fugitive odorous emissions represents a key challenge in the assessment of odour impacts from industrial plants and installations. These emissions are characterized by diffuse release mechanisms, marked spatial and temporal variability, and considerable uncertainties in the estimation of emitted flows. Although fugitive sources are increasingly considered within regulatory and authorization frameworks, their characterization remains a topic of ongoing technical and scientific debate, due to the inherent complexity of these emission sources. Several approaches are currently adopted to estimate fugitive emissions, mainly based on mass flow calculations derived from emission factors, Leak Detection and Repair (LDAR) programs or direct measurements, such as Quantitative Optical Gas Imaging (QOGI). However, such methodologies generally provide results only in terms of mass emissions and do not allow a direct evaluation of Odour Emission Rates (OER), which are required for odour dispersion modelling and impact assessment. In this context, the present paper introduces the Odour Fugitive Emission Potential (OFEP) as a parameter intended to link estimated fugitive mass losses to the associated odour emissions, by coupling odour and Total Volatile Organic Carbon (TVOC) concentrations measured at the interface of the fugitive source. The proposed approach enables the inclusion of fugitive emission sources within the overall odour emission scenario, contributing to a more comprehensive and consistent assessment of industrial odour emissions.

1. Introduction

Fugitive emissions are unintended releases of gaseous substances from industrial facilities, typically originating from equipment leaks such as valves, flanges, connectors, pumps, and compressors (Szweda, 2000). Unlike point sources, fugitive emissions are characterized by their diffuse nature, lack of defined release points, and spatial dispersion across plant units (Yang et al., 2016). These emissions are commonly associated with the handling, processing, and storage of volatile compounds in sectors such as oil and gas, petrochemical, and chemical industries, but are also relevant in other contexts including landfills, waste treatment facilities, and anaerobic digestion plants. Due to their intrinsic characteristics, fugitive emissions are difficult to detect, quantify, and control, representing a persistent challenge in industrial emission management (Carrera et al., 2025).
The relevance of fugitive emissions extends across multiple dimensions, including environmental impact, safety, and economic performance (Al-Hamdani et al., 2017). In detail, from an environmental perspective, fugitive releases contribute significantly to atmospheric pollution, particularly through the emission of Volatile Organic Compounds (VOCs), which at the global scale are key precursor of photochemical smog and secondary pollutants, while at the local scale they may be responsible for odour nuisance on nearby community.
Fugitive emissions can represent a substantial fraction of total plant emissions, particularly under poor maintenance conditions. As instance, CONCAWE reports an emission factor of 0.2 kg_{VOC} per tonne of refinery feed, confirming their relevance in emission inventories (Hoven and Megaritis, 2019).
In recent years, regulatory frameworks have increasingly recognised the relevance of fugitive emissions in odour impact assessment. For instance, the Italian Directorial Decree n. 309 (MASE, 2023; Zalin and Sironi, 2024) explicitly requires their inclusion, while acknowledging the technical difficulties associated with their characterization. Despite the lack of fully standardized methodologies, fugitive emissions cannot be excluded a

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priori and must be identified and, where possible, quantified. A key challenge in this context lies in the mismatch between the outputs of existing estimation methodologies and the requirements of odour impact assessment. Most current techniques for fugitive emission quantification, including Leak Detection and Repair (LDAR) programs and optical or micrometeorological methods, provide results in terms of mass emission rates (e.g., kg/h). However, odour impact assessments rely on the estimation of Odour Emission Rates (OER), typically expressed in odour units per unit time (ou_E/s), which are required as input for atmospheric dispersion models. The lack of a direct relationship between mass emissions and odour emissions represents a critical limitation in the integration of fugitive sources into odour assessments.
This highlights the need for methodologies capable of linking fugitive mass emissions to their associated odour impact, enabling a more consistent and comprehensive evaluation of industrial emissions.

2. State of the art on fugitive emission quantification

The quantification of fugitive emissions has been the subject of extensive research and regulatory development over the past decades, leading to the establishment of several methodologies based on different measurement principles and levels of complexity. These approaches can be broadly classified into indirect estimation methods, such as emission factors (Hoven and Megaritis, 2019; U.S. EPA, 1997), and direct or semi-direct measurement techniques, including Leak Detection and Repair (LDAR) programmes (Sotoodeh, 2021), optical methods (Ilonze et al., 2024; Ravikumar et al., 2017), and micrometeorological techniques (Lotesoriere et al., 2023).

2.1 LDAR methodology: principles and applications

LDAR program represents the reference methodology for the quantification and management of fugitive emissions (Lotrecchiano et al., 2025), enabling both emission estimation and reduction through systematic field inspection, and are therefore widely adopted across major industrial sectors. LDAR program was initially developed in the United States in the 1970s within the framework of the EPA and the Clean Air Act, in response to the need to address VOC emissions from industrial sources. This method was designed to identify, monitor, and repair leaks from pressurized components through standardized procedures and portable detection instruments. The methodology has been progressively formalized through technical reference documents, including the EPA Protocol for Equipment Leak Emission Estimates (U.S. EPA, 1997) and Method 21 (U.S. EPA, 2017). From an operational perspective, LDAR programs are based on the periodic screening of plant components such as valves, flanges, pumps, compressors, and connectors. Measurements are typically carried out using Flame Ionization Detectors (FID) or PhotoIonization Detectors (PID), capable of detecting VOC concentrations in the proximity of potential leak points. The monitoring procedure follows standardized protocols to ensure consistency in probe positioning, measurement conditions, and data recording. Each component is uniquely identified and tracked over time, allowing for systematic inspection and maintenance planning. The measured concentration values, commonly referred as “screening values”, are subsequently converted into mass emission rates through the application of empirical correlation equations. These correlations, developed by the EPA based on extensive experimental datasets, establish relationships between measured concentrations and emission rates, given the type of component and the magnitude of the detected signal (Invernizzi et al., 2021). In the European context, the importance of LDAR has been progressively recognized within the framework of integrated pollution prevention and control. The introduction of the IPCC Directive and its subsequent evolution into the Industrial Emission Directive (IED) (European Commission, 2010) has led to the inclusion of LDAR programs among the Best Available Techniques (BAT) for sectors such as oil and gas refining (European Commission, 2015), making its implementation a regulatory requirement for many industrial installations. In parallel, technical standardization efforts have led to the development of harmonized European methodologies, such as EN 15446:2008, which provide guidelines for the measurement of fugitive VOC emissions from equipment leaks, in agreement with the EPA guidelines. Despite its widespread adoption and proven effectiveness, several limitations are associated with the LDAR methodology. The accuracy of emission estimates depends strongly on the validity of the correlation equations, which may not fully capture site-specific conditions or variability in fluid composition. Moreover, LDAR measurements are typically performed at discrete time intervals, providing only a snapshot of emission conditions and potentially overlooking temporal variability. Finally, accessibility constraints may further limit the inspection of certain components in complex or hazardous environments.

2.2 Recent developments: Smart LDAR and QOGI

In recent years, significant efforts have been devoted to enhancing traditional LDAR programs through the integration of advanced detection technologies and more flexible monitoring strategies, leading to the development of so-called “Smart LDAR” method.

One of the most relevant technological advancements in this field is the increasing adoption of Optical Gas Imaging (OGI) systems. OGI is based on infrared cameras capable of visualizing gas plumes by exploiting the absorption of infrared radiation at specific wavelengths characteristic of target compounds, such as hydrocarbons and methane. Compared to conventional LDAR technique, based on sniffing techniques, OGI allows for rapid screening of large plant areas, enabling operators to identify leaks in a non-intrusive manner and significantly reducing inspection times. The growing relevance of OGI has been recognized in both regulatory and technical frameworks. In the United States, the EPA has introduced an Alternative Working Practice (AWP) (U.S. EPA, 2006) allowing the use of OGI in addition to the traditional methods described in Method 21. Similarly, in the European context, OGI has been increasingly acknowledged in technical guidelines EN 17628:2022 and BREFs documents (European Commission, 2015).
Building upon OGI principles, Quantitative Optical Gas Imaging (QOGI) technique has been developed to estimate emission rates from visualized gas plumes (Wilson, 2016). This method relies on image processing algorithms, based on camera configuration and environmental parameters (i.e., wind speed, temperature, gas properties) to infer mass flow rates. Although further studies on the reliability of the technique and measurement uncertainty are needed, the QOGI technique represents a promising step toward the direct quantification of fugitive emissions using optical techniques. This is particularly relevant as it enables the quantification of fugitive emissions also in non-traditional sectors such as landfills and anaerobic digestion plants (Cangialosi et al., 2024).

3. From mass emissions to odour emissions

The integration of fugitive emissions into odour impact assessment is hindered by a fundamental methodological gap between the quantities typically provided by emission estimation techniques and those required for odour modelling. Existing methods, including LDAR and advanced optical techniques, quantify emissions in terms of mass flow rates (e.g., kg/h), whereas odour impact assessment relies on the estimation of OER, expressed in odour units per unit time (ou_E/s). This mismatch prevents the direct inclusion of fugitive emissions in atmospheric dispersion models and limits the completeness of odour impact studies.

3.1 OTV-based approach: conversion through chemical speciation

In principle, if the chemical composition of the emitted fluid is known, a theoretical conversion from mass emissions to odour emissions can be performed by exploiting Odour Threshold Values (OTVs) available in literature (Nagata, 2003; Polvara et al., 2025). The contribution of each flow to the overall odour emission can be estimated individually. Under these assumptions, the OER associated with a given compound, i, can be expressed as:

$$\mathrm{OER_i} = \mathrm{L_{FE,i}} \cdot \frac{1\ \mathrm{ou_E/m^3}}{\mathrm{OTV_i}} \cdot \frac{\mathrm{R \cdot T}}{\mathrm{MW_i \cdot P}} \tag{1}$$

where:

- OER_i [ou_E/s] is the odour emission rate of compound i;
- $L_{FE,i}$ [mg/s] is the fugitive mass emission rate of compound i;
- OTV_i [ppm] is the Odour Threshold Value of compound i, corresponding to and odour concentration of 1 ou_E/m^3;
- MW_i [g/mol] is the molecular weight of compound i;
- R [J/mol/K], T [K], and P [Pa] are the gas constant, temperature (i.e., 293 K) and pressure (i.e., 101325 Pa), respectively

The total OER can then be estimated by summing the contributions of each individual species.
However, this approach is often impracticable in real industrial contexts. Fugitive emissions typically consist of complex and variable mixtures, whose composition is not known or easily measurable. Moreover, odour perception does not follow simple additive rules, and interactions between compounds can lead to synergistic or masking effects. These limitations significantly reduce the applicability of OTV-based method for fugitive emission assessment.

3.2 OFEP approach: field measurement of the leakage

In the absence of reliable compositional information, a direct experimental characterization of fugitive emissions becomes necessary. This requires the measurement of both odour concentration and a representative chemical parameter at the emission interface.
In this context, the present work introduces the Odour Fugitive Emission Potential (OFEP) as a novel parameter aimed at bridging the gap between mass emissions and odour emissions. OFEP parameter is based on the

relationship between odour concentration and Total Volatile Organic Carbon (TVOC) concentration, both measured at the interface of a fugitive emission source. By coupling these parameters, it is possible to define a parameter that expresses the odour potential per unit of emitted VOC mass (i.e., ou_E/mg_C).
The proposed methodology is schematically illustrated in Figure 1.

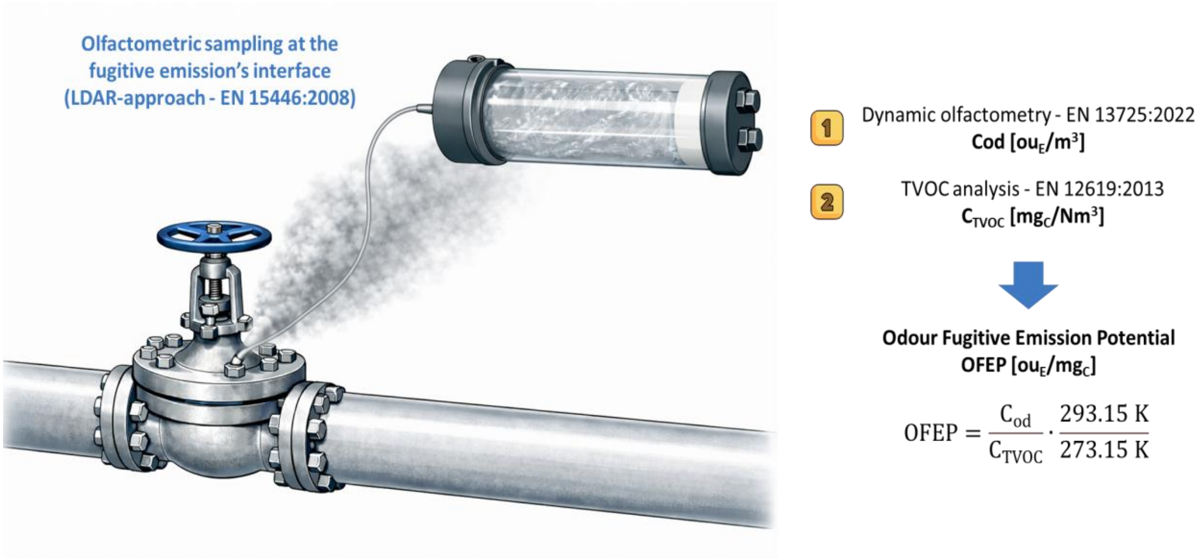

Figure 1: Proposed methodology for OFEP estimation

The approach consists of sampling the fugitive emission directly at the interface, following a procedure analogous to LDAR measurements. The sampling is performed by collecting the emitted gas into suitable sampling bags, in compliance with EN 13725:2022. The collected samples are then analyzed in the laboratory to determine:

- the odour concentration (C_{od}), using dynamic olfactometry in accordance with EN 13725:2022;
- the TVOC concentration (C_{TVOC}), measured by FID, according to EN 12619:2013.

Given these measurements, and the corresponding normalization temperatures of the analytical techniques involved (i.e., 293.15 K for dynamic olfactometry and 273.15 K for TVOC analysis), it is possible to estimate the OFEP parameter (ou_E/mg_C), as:

$$\mathrm{OFEP} = \frac{C_{od}}{C_{TVOC}} \cdot \frac{293.15\ K}{273.15\ K} \quad (2)$$

where the temperature correction term ensures consistency between measurement conditions.
Once the OFEP has been determined, it can be combined with mass emission estimates obtained from LDAR or equivalent methodologies to derive the corresponding OER.

$$\mathrm{OER} = L_{FE} \cdot \mathrm{OFEP} \quad (3)$$

A point worth noting is that OFEP is expressed on a carbon basis (ou_E/mg_C), whereas fugitive emission rates derived from LDAR or equivalent methodologies are typically reported as total VOC mass fluxes (e.g., kg/h). However, this apparent mismatch is mitigated by the fact that LDAR measurements are commonly performed using FID, which respond to carbon content rather than specific molecular species, thus ensuring consistency between the parameters. Moreover, it should be noted that EPA correlation equations used in LDAR inherently rely on empirical relationships derived from heterogenous datasets, encompassing different monitoring instrumentation and operating conditions. In this context, the level of approximation introduced by the carbon-based formulation of OFEP is largely consistent with the assumptions already embedded in current fugitive emission estimation methodologies.
However, some limitations must be acknowledged. The large number of fluids potentially involved in fugitive emissions may require the development of plant-specific inventories, making the full characterization process time- and resource-consuming. In practice, the level of detail achievable depends on how fugitive emissions are managed within the plant inventory: while a single representative OFEP value at plant scale may be insufficient to capture heterogeneity, a more refined characterization can be achieved by grouping emissions according to fluid type or process units, depending on data availability.

3.3 Preliminary results

Preliminary field tests were carried out to assess the repeatability and reproducibility of proposed OFEP methodology. These tests were conducted across different industrial contexts, including refineries, petrochemical plants, and landfills, to account for a range of fugitive emission scenarios. Repeatability was evaluated by collecting three samples at defined time intervals (approximately 2 minutes) by the same operator. Reproducibility was assessed by collecting three samples at the same time intervals by different operators.
Although these results are preliminary, they provide initial insight into the robustness of the method. Measurement performed by the same operator showed a good agreement, with an average standard deviation of around 20%. Conversely, when different operators were involved, a larger variability was observed, with OFEP values varying by up to a factor of approximately 3. This variability, in terms of the extreme limits of the measurements, is nevertheless comparable to the inherent uncertainty of the olfactometric method - on the order of a factor of 2 - which is linked to its own resolution.

4. Conclusions

The introduction of the Odour Fugitive Emission Potential (OFEP) provides a practical and consistent approach to address the current methodological gap between mass-based fugitive emission estimates and odour impact assessment requirements. In particular, the proposed method responds to the need, highlighted by recent regulatory frameworks such as the Italian Directorial Decree n. 309 of MASE, but also indirectly by IED 2.0, to include fugitive emissions within odour impact studies, despite the intrinsic difficulties associated with their characterization. By linking mass emissions to OER, OFEP enables the systematic inclusion of fugitive emissions in the overall odour emission scenario.
The proposed approach is not limited to the oil and gas sector, where LDAR programs are most commonly applied, but can be extended to a wide range of industrial contexts. Its applicability relies on the availability of two key elements: the localization of fugitive emission sources and the estimation of their mass flow rates, which can be obtained through established techniques such as LDAR, bagging or optical methods. This flexibility makes OFEP a valuable tool for integrating fugitive emissions into odour assessments across different industrial sectors. Future developments of this work will focus on the experimental validation of the proposed methodology through controlled released tests under known conditions of composition. Such studies will allow the assessment of repeatability and reproducibility of the OFEP parameter, as well as the refinement of the methodology for its broader application.

References

Al-Hamdani Y., Hassim M. H., Salin, S. M., 2017, Occupational Health Risk Assessment and Control of Fugitive Emissions in Chemical Processes, Chemical Engineering Transactions, 56, 817–822, doi.org/10.3303/CET1756137

Cangialosi F., Milella L., Fornaro A., 2024, Assessing the Significance of Fugitive Emissions from a Landfill Biogas Collecting System using a Quantitative Optical Gas Imaging (QOGI) Method: a Case Study, Chemical Engineering Transactions, 112, 19–24, doi.org/10.3303/CET24112004

Carrera L., Sironi S., Invernizzi, M., 2025, Toward Effective Monitoring of Diffuse VOC Emissions: A Critical Discussion and Review of the Applications of EN 17628:2022, Sensors, 25(5), 1561, doi.org/10.3390/s25051561

EN 12619:2013, Stationary source emissions - Determination of the mass concentration of total gaseous organic carbon - Continuous flame ionisation detector method, CEN - Comité Européen de Normalisation, doi.org/10.31030/1907768

EN 13725:2022, Stationary source emissions - Determination of odour concentration by dynamic olfactometry and odour emission rate, CEN - Comité Européen de Normalisation, doi.org/10.31030/3290685

EN 15446:2008, Fugitive and diffuse emissions of common concern to industry sectors - Measurement of fugitive emission of vapours generating from equipment and piping leaks, CEN - Comité Européen de Normalisation, doi.org/10.31030/9877839

EN 17628:2022, Fugitive and diffuse emissions of common concern to industry sectors - Standard method to determine diffuse emissions of volatile organic compounds into the atmosphere, CEN - Comité Européen de Normalisation, doi.org/10.31030/3311361

European Commission, 2010, Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) (IED).

European Commission, 2015, Best Available Techniques (BAT) Reference Document for the Refining of Mineral Oil and Gas.

Hoven L., Megaritis T., 2019, Air pollutant emission estimation methods for E-PRTR reporting by refineries, CONCAWE Reports, 4/19.
Ilonze C., Wang J., Ravikumar A. P., Zimmerle D., 2024, Methane Quantification Performance of the Quantitative Optical Gas Imaging (QOGI) System Using Single-Blind Controlled Release Assessment, Sensors, 24(13), 4044, doi.org/10.3390/s24134044
Invernizzi M., Roveda L., Polvara E., Sironi S., 2021, Lights and Shadows of the VOC Emission Quantification, Chemical Engineering Transactions, 85, 109–114, doi.org/10.3303/CET2185019
Lotesoriere B. J., Invernizzi M., Panzitta A., Uvezzi G., Sozzi R., Sironi S., Capelli L., 2023, Micrometeorological Methods for the Indirect Estimation of Odorous Emissions, Critical Reviews in Analytical Chemistry, 53(7), 1531–1560, doi.org/10.1080/10408347.2022.2036092
Lotrecchiano N., Pecci A., Zappimbulso N., Ilacqua M. A., Ferranti F., 2025, Efficacy of the Leak Detection and Repair Program in the Italian Industrial Plants, Chemical Engineering Transactions, 116, 823–828, doi.org/10.3303/CET25116138
Ministero dell’Ambiente e della Sicurezza Energetica (MASE), 2023, Decreto Direttoriale n.309 “Indirizzi per l’applicazione dell’articolo 272-Bis del Dlgs 152/2006 in materia di emissioni odorigene di impianti e attività.”
Nagata Y., 2003, Measurement of Odor Threshold by Triangle Odor Bag Method, 118–127.
Polvara E., Scolieri G. D., Invernizzi M., Sironi S., 2025, Experimental secondary reference odour mass (SROM) measurement for selected four odorants, Environmental Sciences Europe, 37(1), 129, doi.org/10.1186/s12302-025-01179-6
Ravikumar A. P., Wang J., Brandt A. R., 2017, Are Optical Gas Imaging Technologies Effective For Methane Leak Detection?, Environmental Science & Technology, 51(1), 718–724, doi.org/10.1021/acs.est.6b03906
Sotoodeh K., 2021, Fugitive emissions from piping and valves, Prevention of Valve Fugitive Emissions in the Oil and Gas Industry, 37–65, doi.org/10.1016/B978-0-323-91862-6.00002-2
Szweda R., 2000, Fugitive emissions: The matter of imperfect seals, Sealing Technology, 2000(83), 9–11, doi.org/10.1016/S1350-4789(00)80052-5
U.S. EPA, 1997, Protocol for Equipment Leak Emission Estimates.
U.S. EPA, 2006, Alternative Work Practice to Detect Leaks from Equipment.
U.S. EPA, 2017, Method 21: Determination of volatile organic compound leaks, www.epa.gov/emc/method-21-volatile-organic-compound-leaks
Wilson A., 2016, New Optical Gas-Imaging Technology for Quantifying Fugitive-Emission Rates, Journal of Petroleum Technology, 68(08), 78–79, doi.org/10.2118/0816-0078-JPT
Yang J.C., Chang P.E., Chie W.C., Liu J.P., Wu C.F., 2016, Large-scale search method for locating and identifying fugitive emission sources in petrochemical processing areas, Process Safety and Environmental Protection, 104, 382–394, doi.org/10.1016/j.psep.2016.09.015
Zalin M., Sironi S., 2024, New Guidelines in Italy for the Regulation of Odour Emissions, Chemical Engineering Transactions, 112, 13–18, doi.org/10.3303/CET24112003