

A REVIEW OF CURRENT RESEARCH ON METHANE EMISSION REDUCTION IN THE OIL AND GAS INDUSTRY AND THE ROMANIAN CONTEXT

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ABSTRACT

This review paper presents a comprehensive analysis of the current state of research on methane emission reduction in the oil and gas industry, with particular emphasis on the Romanian context. Methane is recognized as a highly potent greenhouse gas, with a global warming potential more than 80 times that of CO₂ over a 20-year horizon, making its reduction a priority for the short-term mitigation of climate change. The oil and gas sector is one of the main anthropogenic sources of methane, with emissions distributed across the entire value chain, from extraction and processing to transportation, storage and distribution. The paper examines the conceptual and terminological framework of methane emission research, including fugitive emissions, intentional emissions through venting and flaring, and emissions from inactive or abandoned wells. The regulatory framework is analysed from the perspectives of the Global Methane Pledge, OGMP 2.0, and EU Regulation 2024/1787 on methane, which introduces obligations for monitoring, reporting and verification (MRV), leak detection and repair (LDAR) and restrictions on venting and flaring. The paper synthesizes the main research directions identified in the recent literature: source identification, emission quantification, continuous monitoring, emission reduction measures, and cost-efficiency analysis. Special attention is given to the methodological transition from generic emission factors to direct measurement methods and the integration of bottom-up and top-down approaches. A case study on Romania illustrates the specific challenges and opportunities of a mature oil and gas infrastructure, based on the results of the ROMEO project, which documented significant differences between officially reported emissions and independently measured values.

Keywords: methane emissions, oil and gas industry, fugitive emissions, LDAR, MRV, OGMP 2.0, EU Regulation, Romania, detection and monitoring

INTRODUCTION

Climate change is one of the most serious challenges facing modern society, and methane (CH₄) is an important greenhouse gas due to its high global warming potential and relatively short atmospheric lifetime of about 12 years [1]. Although CO₂ still dominates long-term warming, methane is responsible for a significant share of current warming, and reducing it is one of the most effective short-term mitigation strategies available. According to recent

scientific assessments, a 45% reduction in methane levels could avoid 0.3 Celsius degrees of global temperature increase by 2045 [2].

The oil and gas industry is one of the largest anthropogenic sources of methane emissions globally, with losses occurring across the entire value chain, from wellhead surface equipment and separators to compressors, pipelines, storage facilities, and distribution networks [3]. Emissions arise both from unintentional leaks (fugitive emissions) and from intentional releases (venting and flaring), as well as from inactive and abandoned wells, which are often poorly documented and insufficiently monitored [4].

In recent years, independent measurement campaigns have repeatedly shown that actual methane emissions from oil and gas operations can be significantly higher than those reflected in conventional inventories based on generic emission factors [5]. This discrepancy has led to a fundamental methodological shift in the field, from high-level statistical estimates toward direct measurement approaches, continuous monitoring systems, and multi-scale integration of ground-based, airborne, and satellite observations [6].

At the regulatory level, the European Union has moved from voluntary commitments to legal obligations through Regulation (EU) 2024/1787 on methane emissions in the energy sector [7], which requires operators to implement MRV systems and LDAR programs and to limit venting and flaring. Internationally, the Global Methane Pledge and the OGMP 2.0 framework have established benchmark standards for reporting and transparency [8].

This paper aims to provide a coherent synthesis of the recent scientific literature on methane emissions from the oil and gas sector, to analyse methodological and regulatory developments, and to illustrate their relevance for a specific mature infrastructure context represented by Romania. The gap addressed by the study lies in integrating a critical review of the international literature with a detailed case study focused on Romania, based on the latest available measurement campaigns and regulatory guidance, a context that is still underrepresented in the literature dominated by North American studies.

MATERIALS AND METHODS

This paper is structured as a narrative literature review, supplemented by an analysis of the regulatory framework and a case study. The sources analysed include scientific articles published in journals indexed in international databases, reports from international organizations (IMEO, IEA, OGMP 2.0, Global Carbon Project), European and national regulatory documents, as well as technical reports from the ROMEIO project, the only large-scale systematic measurement project dedicated to methane emissions from the oil and gas sector in Romania.

The selection of sources aimed to cover the main research directions in the field: the conceptual and terminological framework of methane emissions, methodological developments in emission quantification and monitoring, the international and European regulatory framework, and applied studies relevant to mature infrastructures. Priority was given to works from the last decade, with emphasis on recent studies marking the methodological shift from generic emission factors to direct measurements. For the Romanian context, the results of the ROMEIO campaigns, published in journals with an impact factor in atmospheric chemistry and environmental sciences, were analysed in detail [9-13].

The analysis was organized around four main thematic axes: (i) the conceptual framework of emission typologies; (ii) methodological evolution and major research directions; (iii) the international and European regulatory framework; and (iv) the particularities of the Romanian oil and gas sector, with emphasis on discrepancies between reported and measured emissions, reduction potential, and identified obstacles.

RESULTS AND DISCUSSIONS

Conceptual and terminological framework of methane emissions

Methane (CH_4) is the simplest organic compound in the alkane series. Under normal conditions, it is an odorless, colorless gas with a boiling point of -161.49 Celsius degrees and a density of 0.656 g/L at 25 Celsius degrees, making it lighter than air [14]. This low density facilitates its rapid dispersion in the atmosphere after release, which is an essential factor in understanding emissions dynamics in the oil and gas sector.

CH_4 is a powerful greenhouse gas, approximately 25-30 times more effective than CO_2 at trapping heat over a 100-year horizon (GWP100) and more than 80 times more potent over a 20-year horizon (GWP20) [15]. Its superior heat-trapping capacity results from its complex tetrahedral molecular geometry, which allows multiple vibrational and rotational modes capable of absorbing infrared radiation at several specific wavelengths [16]. Its relatively short atmospheric lifetime of about 12 years means that methane reductions can produce rapid and measurable impacts on the global warming rate. Atmospheric methane concentrations have increased to approximately 1.900 ppb (Figure 1), more than two and a half times pre-industrial levels (~ 700 ppb), amplifying its indirect effects through tropospheric ozone formation [17].

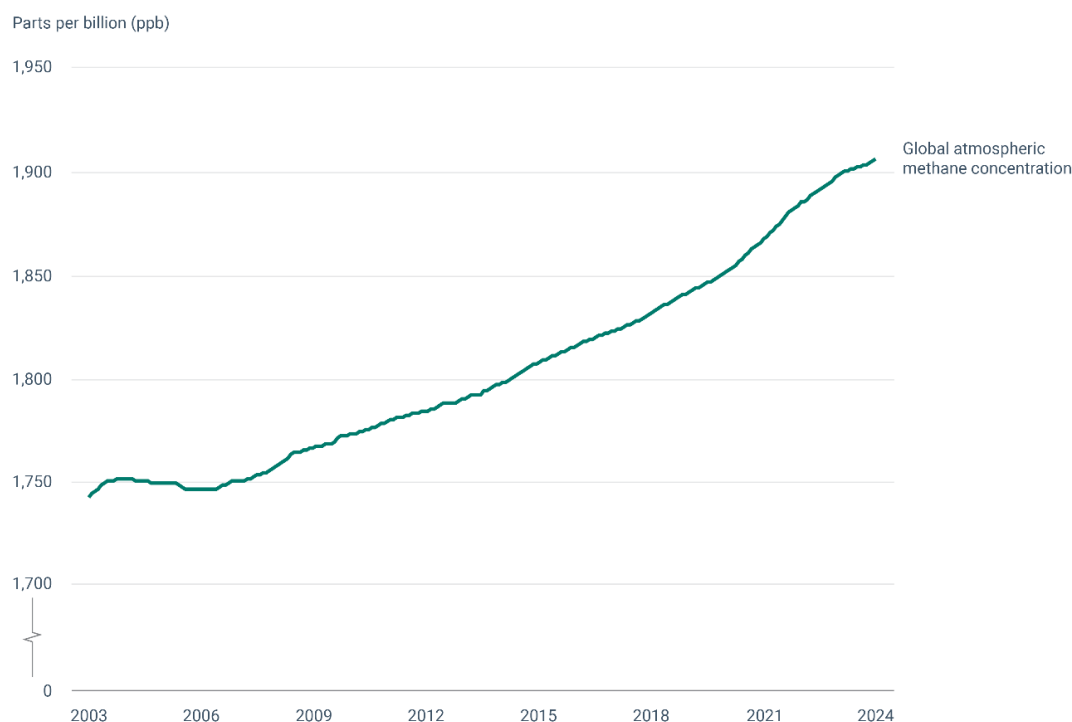


Figure 1. Atmospheric methane measured in ppb [17].

In the oil and gas sector, methane emissions are classified into three main typologies: fugitive emissions, intentional emissions, and emissions from inactive and abandoned wells [18].

Fugitive emissions (unintentional emissions) are unplanned methane releases caused by equipment failures, leaks at joints, valves, flanges, compressors, separators, and pipelines (Figure 2). These may remain undetected for long periods without systematic detection programs, and direct measurements have consistently shown that actual emissions often exceed inventory-based estimates [19]. A well-implemented LDAR program can reduce fugitive emissions by more than 70-90% in inspected areas, making it one of the most effective mitigation approaches [3].

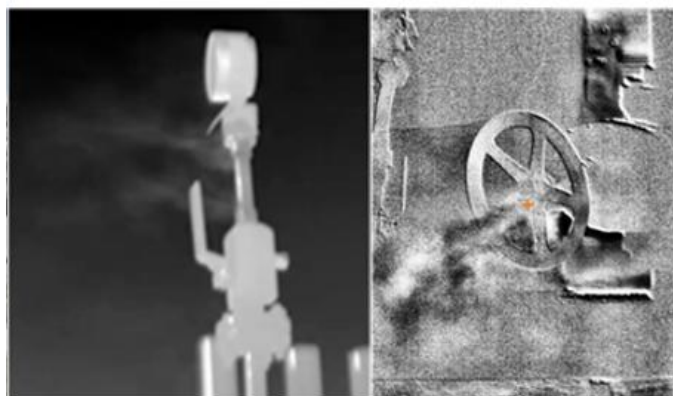


Figure 2. Fugitive emissions identified with OGI [3].

Intentional emissions (venting and flaring) refer to the controlled release of gas into the atmosphere as part of operational or safety procedures, and the burning of gas that cannot be recovered or processed (Figure 3). Both practices can generate significant methane volumes, especially when flaring is incomplete or when routine venting is used as a substitute for infrastructure modernization [18].



Figure 3. Intentional emissions – venting identified with OGI [21].

Emissions from inactive and abandoned wells represent a distinct and often underestimated category. These wells can continue to emit methane for decades if they are not properly plugged and abandoned, yet they are frequently poorly documented, difficult to locate, and

insufficiently included in national inventories [4]. For countries with mature oil and gas sectors, this category is particularly significant.

In addition to source typology, the literature uses a set of essential operational concepts. LDAR (Leak Detection and Repair) programs involve systematic inspections of potentially emitting components using OGI cameras or portable sensors, followed by prompt repair of identified leaks [19]. MRV (Monitoring, Reporting and Verification) framework provides the structure for collecting, transmitting, and independently verifying emissions data; within OGMP 2.0, it is organized into reporting levels that progressively evolve from generic emission factors to source-specific data measured directly [20]. Super-emitters are sources that generate disproportionately large emissions; studies have shown that 1% of sources can account for 40-80% of total emissions [22] and that 60% of emissions in a production region can originate from only 10% of wells [23]. Continuous monitoring uses fixed sensor networks for real-time measurement, identifying 3-5 times more leaks than periodic manual inspections [24]. Emission factors are coefficients used to estimate methane released per unit of activity or equipment type; although they historically formed the basis of national inventories, their limitations are well documented, and the transition toward source-specific factors derived from direct measurements is a central feature of modern emissions accounting [25].

International and European regulatory framework

At the international level, the Global Methane Pledge, launched in 2021 by the EU and the United States, commits signatory states to a collective 30% reduction in global methane emissions by 2030 relative to 2020 levels [8]. International Methane Emissions Observatory (IMEO) aims to improve the quality of methane emissions data by integrating company reports, scientific measurements, and satellite observations. Within IMEO, the Methane Alert and Response System (MARS) (Figure 4) provides near-real-time detection of major emissions events, enabling faster intervention [8]. OGMP 2.0 (Oil and Gas Methane Partnership 2.0) is currently the international benchmark standard for methane reporting in the oil and gas industry, promoting a shift from estimates based solely on generic emission factors toward source-level attribution and asset-level data reconciliation [8].

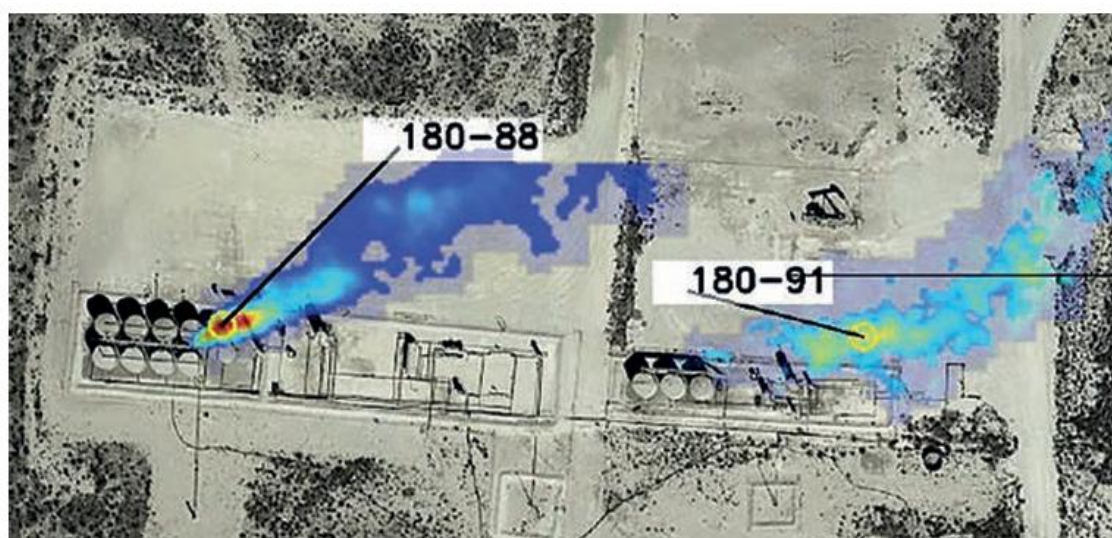


Figure 4. Methane Alert and Response System (MARS) [8].

At the European Union level, Regulation (EU) 2024/1787 on methane emissions in the energy sector [7] is the first act explicitly dedicated to this issue. Key obligations include: a mandatory MRV framework requiring source-level quantification and independent verification; LDAR programs with defined inspection intervals and repair deadlines; strict limits on routine venting and flaring, with exceptions only for technically justified situations; requirements for Member States to inventory inactive and abandoned wells and to develop mitigation plans; and the gradual extension of reporting requirements to cover fossil fuel imports [7]. For companies in the oil and gas sector, compliance requires substantial changes in monitoring systems, data management, and operational procedures.

Methodological evolution and major research directions

Research on methane emissions from the oil and gas industry has undergone a fundamental methodological transformation over the last decade. Whereas earlier stages focused on national inventories and estimates based on generic emission factors, the recent literature is increasingly oriented toward direct measurements, independent verification, and the integration of multiple data types into a coherent analytical framework [26].

A key finding that triggered this evolution was documented by Alvarez *et al.* [27], who showed through a synthesis of facility-scale measurements in the United States that methane emissions from the oil and gas supply chain were underestimated in the official inventory, largely because conventional methods tend to miss emissions occurring under abnormal operating conditions. Table 1 illustrates the comparison between bottom-up measurements and EPA inventory estimates.

Table 1. Bottom-up estimates of CH₄ emissions and comparison with the Greenhouse Gas Inventory [27].

Industry segment	2015 CH ₄ emissions (Tg/year)	
	Bottom-up	EPA GHGI
Production	7.6 (+1.9/–1.6)	3.5
Gathering	2.6 (+0.59/–0.18)	2.3
Processing	0.72 (+0.20/–0.071)	0.44
Transmission and storage	1.8 (+0.35/–0.22)	1.4
Local distribution*	0.44 (+0.51/–0.22)	0.44
Oil refining and transportation	0.034 (+0.050/–0.008)	0.034
U.S. O/NG total	13 (+2.1/–1.7)	8.1 (+2.1/–1.4)

This finding confirmed that the methodological approach is critical and initiated a global shift toward direct measurement methods and hybrid bottom-up/top-down frameworks [1],[27].

Based on the analysis of the recent literature, five major research directions can be identified.

Source identification. Studies have consistently shown that emissions follow strongly skewed distributions, in which a small fraction of sources contributes a disproportionate share of total emissions [26]. Zavala-Araiza *et al.* [22] demonstrated that super-emitters are often linked to abnormal operating conditions: equipment failures, process upsets, or maintenance operations, rather than normal operation, implying that targeted monitoring and rapid response are more effective than uniform baseline inspections. Complementary identification methods, ranging

from optical gas imaging and mobile measurements to airborne campaigns and satellite observations, have expanded the coverage and resolution of source attribution [25].

Emission quantification. Bottom-up approaches start from component or facility-level measurements and extrapolate upward, while top-down approaches use atmospheric measurements from aircraft or satellites to capture the aggregated signal. Each method has advantages and limitations, and reconciling them has become a central challenge in the field [27]. MacKay *et al.* [28] showed for Canada that integrating nearly a decade of multi-scale measurements significantly improves the robustness of total emissions estimates and enables verification of reductions reported by industry and governments.

Continuous monitoring. Methane emissions are not constant over time; many sources are intermittent or episodic, linked to equipment states or operational decisions. Studies confirm that short measurement campaigns can miss precisely those events that contribute most to annual totals [29]. Sensor-based continuous monitoring systems can capture episodes missed by periodic inspections, but they also face technical challenges, including signal interpretation, sensor calibration, and integration with dispersion models for source attribution [6].

Emission reduction. The literature shows that a significant share of methane emissions from the oil and gas industry can be reduced using technologies that are already available. Studies indicate that reductions are more effective when they target high-contributing sources rather than being applied uniformly across all assets. Assessments of offshore infrastructure have shown that direct measurements and detailed facility-level reporting make it possible not only to compare against inventories, but also to prioritize interventions where the discrepancy is greatest [25].

Cost and efficiency analysis of mitigation measures. Recent studies have shown that many mitigation measures are cost-effective, especially where recovered gas can be monetized or where losses are large enough for the investment to pay back relatively quickly [30]. The availability of direct measurement data is essential for credible cost analyses, because without a realistic quantification of emissions, the potential benefits of mitigation measures may be systematically underestimated.

Recent technological trends

The field is experiencing rapid innovation in monitoring technologies. Unmanned aerial vehicles (UAVs) are increasingly used for detecting and quantifying methane from hard-to-access sources, with recent studies demonstrating real-time detection at distances of up to 10 meters [31] and their applicability for quantification workflows comparable to traditional methods [32]. Satellite methane monitoring has advanced substantially in spatial resolution and sensitivity, enabling the detection of point sources and super-emitter events at a global scale [33]. Systems such as MARS integrate satellite data with rapid notification protocols for near-real-time intervention [8].

Digitalization is emerging as a related factor, integrating data from multiple platforms into centralized management systems, automating anomaly detection, and enabling predictive risk assessment [34]. This shifts methane management from retrospective documentation to proactive and anticipatory control, one of the most important developments in the field.

CASE STUDY: METHANE EMISSIONS IN THE ROMANIAN OIL AND GAS SECTOR

Romania is one of the oldest and historically most developed oil and gas producers in Europe, with hydrocarbon extraction dating back to the nineteenth century [35]. This history has resulted in an extensive and heterogeneous infrastructure, with a high density of onshore wells, gathering systems, processing plants, compressor stations, and distribution networks concentrated in southern Romania (Figure 5) and the Transylvanian Basin [36]. The infrastructure is characterized by pronounced heterogeneity: it ranges from recently modernized facilities to very old assets designed and operated without explicit methane emission control requirements [37]. One of the most significant findings of recent research on Romania is a substantial gap between officially reported emissions and independently measured values [10],[11].

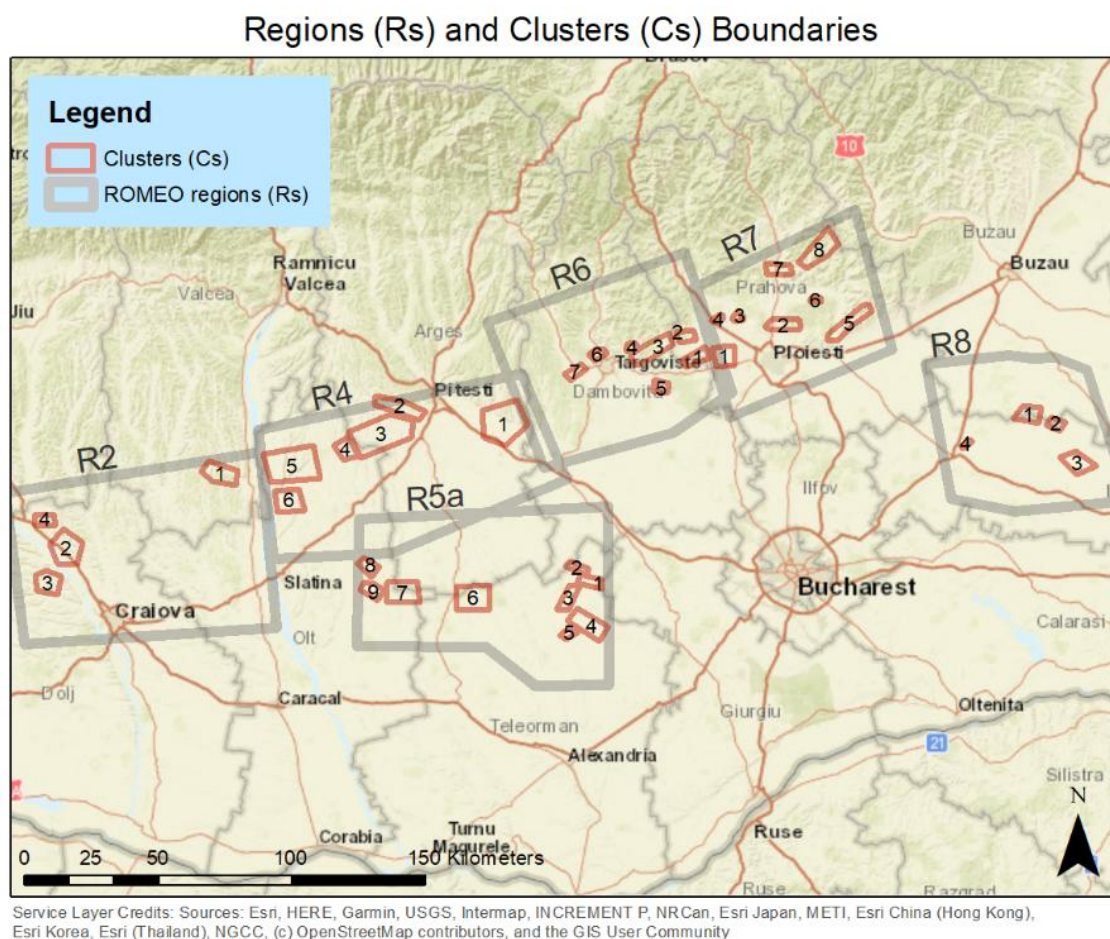


Figure 5. Regions (gray polygons) and clusters (red polygons) that were targeted during the ROMEO 2019 campaign; circular or raster flights were performed within or around these boundaries [9].

The airborne measurement study by Maazallahi *et al.* [9], conducted within the ROMEO project, estimated annual methane emissions from oil and gas infrastructure in southern Romania at approximately 227 ± 86 kt CH₄/year, significantly higher than values derived

from national UNFCCC reports or EDGAR estimates for the analysed area. At the facility level, Stavropoulou *et al.* [12] estimated emissions (Figure 6) from onshore oil production sites in the analysed areas at approximately 120 kt CH₄/year, about 2.5 times higher than the value reported for the entire national oil production sector in the UNFCCC inventory for 2020 [11].

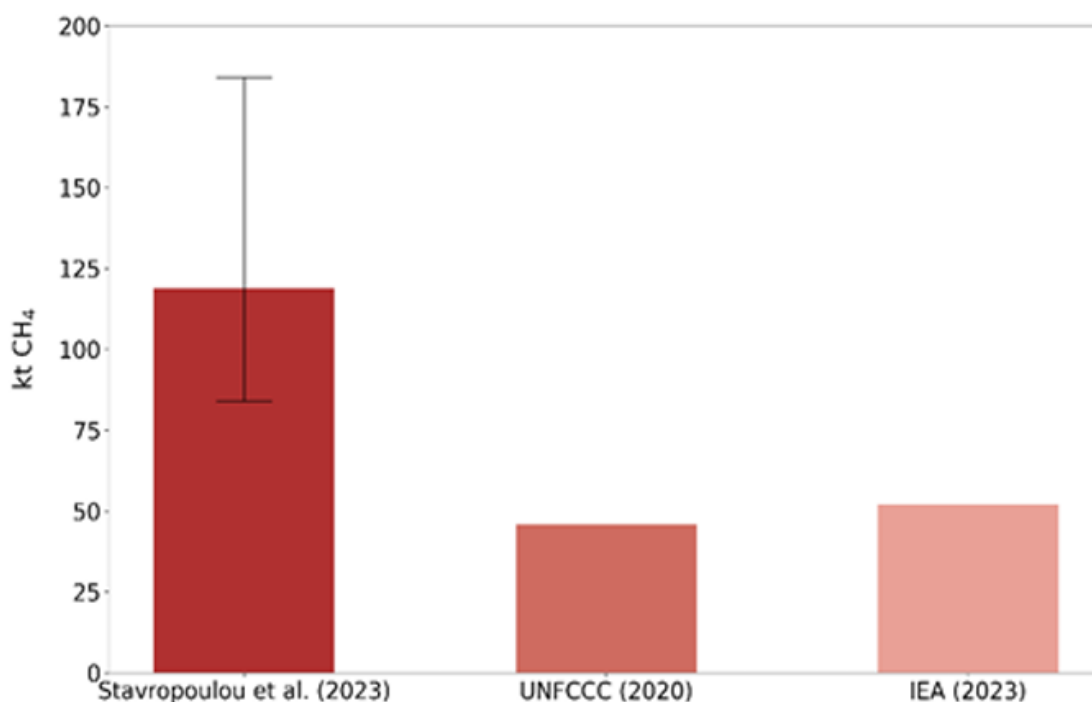


Figure 6. Comparison of annual CH₄ emissions estimated in Stavropoulou *et al.* [12] for 2019, reported to the UNFCCC for 2020, and derived by the IEA for 2023 [36].

The emissions distribution is strongly unbalanced: the top 10% of sites are responsible for more than 70% of the measured emissions [10],[11]. The facility-level ROMEO study found that up to three-quarters of the emissions detected at oil production facilities were associated with operational venting [13], a finding with direct implications for prioritizing mitigation measures, since venting is in many cases easier to address through technical and operational changes than diffuse fugitive emissions [39].

The strongly concentrated distribution of emissions means that targeted interventions at a relatively small number of high-emitting facilities can achieve disproportionately large absolute reductions. There are also signs of recent positive trends: integrated assessments suggest a decline in emissions in southern Romania of approximately 20-60% between 2019 and 2021, potentially linked to ongoing intervention activities [38],[39].

However, the implementation of mitigation measures in Romania faces significant obstacles. The complexity and geographic dispersion of assets increase the operational cost of systematic monitoring and repair programs. Many facilities were designed without provisions for gas capture or leak detection, requiring infrastructure upgrades that go beyond simple operational changes [37],[39].

A significant methodological obstacle is the limited compatibility between the activity data used in direct measurements and that used in official Tier 1 reporting, complicating the

transfer of results derived from the ROMEO project into national inventories [10],[11]. This illustrates that the barriers are not only technical but also institutional, requiring a broader reform of data governance systems.

The new European framework also offers significant opportunities. Regulation EU 2024/1787 can act as an external driver needed to overcome institutional and economic barriers to modernization in the sector, encouraging investment in new monitoring technologies and accelerating the adoption of solutions that would previously have been considered optional [37]. Romania thus has the chance to become an example of the transition from conventional inventories to empirically based assessment systems, with relevance for the entire Central and Eastern European region.

CONCLUSIONS

This paper examined the current state of research on methane emission reduction in the oil and gas industry, with particular attention to methodological developments, the regulatory framework, and the specific characteristics of the Romanian context. Overall, the literature shows that methane is a priority greenhouse gas for short-term climate mitigation, both because of its high atmospheric warming potential and its relatively short atmospheric lifetime. At the same time, reducing methane emissions from the oil and gas sector is not only technically feasible using existing technologies, but also economically attractive in many operational settings.

A central finding emerging from the reviewed literature is the existence of a systematic and well-documented discrepancy between emissions estimated through conventional inventory methods and those obtained through direct measurements. This gap is largely explained by the inability of generic emission factors to capture the strongly unbalanced, source-concentrated distribution of real methane emissions, a pattern consistently observed at both the global level and in Romania through the ROMEO project. In this respect, field-based measurements remain essential for accurately characterizing actual emission volumes and improving the quality of national inventories.

The current research trajectory also indicates a clear methodological shift from generic emission factors toward direct measurement approaches, continuous monitoring, and hybrid bottom-up/top-down integration. This evolution is increasingly reflected not only in the scientific literature, but also in the regulatory framework, particularly through OGMP 2.0 and Regulation (EU) 2024/1787. As a result, methane accounting is progressively moving away from aggregate estimates and toward more precise, source-based systems supported by independent verification.

Recent technological developments further expand the practical toolkit available for methane detection, quantification, and mitigation. UAV-based monitoring, high-resolution satellite observation, and digital emissions management platforms are improving source coverage, enabling faster intervention, and providing a more detailed understanding of the spatial and temporal variability of emissions. These tools strengthen the sector's capacity to move from reactive responses to preventive control and from retrospective reporting to near-real-time operational management. Romania represents a particularly relevant case for both research and policy because it combines mature and heterogeneous infrastructure with well-

documented underreporting, a high mitigation potential concentrated especially in operational venting, and the need to comply with new mandatory European regulations.

The findings of the ROMEO project provide a valuable empirical basis for assessing actual emissions, while also highlighting the urgent need for methodological harmonization between field measurements and official inventory systems. Two directions appear promising for subsequent research. The first is a dedicated, in-depth analysis of the ROMEO results, in which the facility-level measurement data are examined in detail and the findings updated in the light of the more recent measurement campaigns. The second is the development of mathematical modelling of methane dispersion adapted to the conditions of the Romanian oil and gas production regions, which would complement such empirical work. From this perspective, Romania can serve not only as a case study, but also as a model for the transition from conventional inventory-based approaches to modern systems grounded in directly measured data.

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