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Advances and Challenges in Methane Emission Measurement in the Oil and Gas Sector: A Review

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Abstract

Methane emissions from the oil and gas sector are a major contributor to climate change. It is essential to monitor and mitigate these emissions. In this review, sources of methane emissions, available monitoring techniques, emission estimation models, associated uncertainty, and newly emerging technologies, including AI-based monitoring techniques, are critically evaluated. A review was conducted following the PRISMA 2020 guidelines. A total of 480 records were retrieved from four databases: Scopus, Web of Science, ScienceDirect, and Google Scholar. Out of these, 126 studies were included in the review. The results showed that upstream activities contribute around 85% of total methane emissions from the O&G sector. However, a single monitoring technique is not sufficient to be used under all circumstances, and thus, hybrid monitoring frameworks are required. Several knowledge gaps, including a lack of consistent monitoring protocols, a lack of data from developing regions, especially the Middle East, and a high level of uncertainty associated with the emission estimates, are pinpointed. The review provides a comprehensive assessment of methane emissions from the O&G sector, including emission sources, monitoring, estimation, associated uncertainty, and newly emerging AI-based monitoring techniques, and presents a unified framework to support future mitigation and decision-making.

Keywords: Estimation, Evaluation, Fugitive Emissions, Oil Facilities, Quantification.

1. Introduction

Methane (CH_4) emissions from the oil and gas industry have recently become a major challenge for climate change mitigation efforts. Since natural gas is a transitional energy carrier with lower carbon emissions than other energy carriers, it can cause substantial emissions if not managed properly. Thus, reducing methane emissions from the oil and gas industry has become one of the main objectives of climate change policies and greenhouse gas mitigation strategies developed and implemented worldwide [1].

Fugitive methane emissions are those uncontrolled emissions of methane that are released throughout the oil and gas value chain from upstream production to midstream transportation and storage, and downstream processing and distribution. These emissions can include planned venting, incomplete combustion, process upsets, corrosion, and leaks from a variety of pieces of equipment throughout the value chain, including wellhead and production equipment, pipelines, storage tanks, custody transfer meters, and other measurement and process equipment through connections such as valves and flanges [2]. The majority of these fugitive emissions are believed to originate from a relatively small number of super-emitters, and it is therefore very important to be able to accurately identify and quantify these large emissions to manage them and report them accurately [3].

Measuring and quantifying methane emissions remain major challenges because of their high spatial and temporal variability. Therefore, reducing methane emissions is necessary because of their significant impact on climate change. Abnormal situations, such as equipment failure and infrastructure wear and tear, also cause releases that are not included in the bottom-up inventories. These types of inventories are mainly based on emission factors and activity data. Consequently, substantial discrepancies exist between the bottom-up estimations and the measurement data [1]-[3].

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Recent developments for methane monitoring include ground-based, airborne, satellite, drone, as well as AI-based measurement technologies. Most of the individual measurement techniques are limited in terms of spatial and temporal coverage as well as operational constraints. Therefore, hybrid measurement frameworks that combine different measurement techniques for improved detection and quantification of emissions are increasingly applied [4]-[6].

Methane emissions from the oil and gas sector and methods for their detection and quantification have been recently discussed in several review papers. However, these papers did not provide an integrated analysis of all factors that affect the detection and quantification of methane emissions from oil and gas operations. Thus, the current review summarizes the main sources of methane emissions, describes existing methane monitoring technologies, estimates their related uncertainties, and presents a discussion of their use in different parts of the world. This review also provides a more in-depth analysis of the policies developed at the national and international levels for the monitoring of methane emissions, as well as the currently available monitoring technologies and their applications. In addition, the challenges associated with the implementation of several of the recently developed monitoring technologies, as well as the challenges associated with the monitoring of methane emissions in the oil- and gas-producing developing countries, particularly in the Middle East, are also discussed [7], [8].

Various review articles discuss the methane emissions from the oil and gas industry as well as different methane monitoring technologies. Many of the available review articles focus on individual monitoring technologies for methane emissions and measurement methods to address specific challenges. For instance, monitoring using optical gas imaging, aircraft- and drone-based gas plume detection, fixed-site measurement systems, the use of top-down atmospheric observations, as well as AI-based methane detection and monitoring using satellites (Table 1) [7], [8].

Other reviews incorporate aspects of the different categories of emissions from the oil and gas industry, methane monitoring technologies, and the uncertainties involved in methane measurements. Importantly, however, some reviews also provide regional perspectives. While review articles for various countries have been recently published, none of the available review articles discuss all sources of methane emissions, the range of methane monitoring and measurement methods and technologies, the uncertainties in methane measurements, the climate change policies and their corresponding mitigation measures, as well as new emerging methane monitoring methods and associated technologies currently under development [8], [9].

Specifically, the available review articles deal with methane monitoring challenges in oil- and gas-producing countries with developed economies and do not adequately cover perspectives of oil- and gas-producing countries with developing economies, except for some very recent reviews. As already mentioned, the production of oil and gas is increasing in many countries in the Middle East, which poses significant methane monitoring challenges [7], [8].

The Middle East accounts for a relatively small amount of the current "research attention" on methane Emissions compared to other parts of the world, for reasons that relate to both the geography of methane Emissions research as well as to the energy-rich geography of the Middle East itself. By most accounts, the Middle East is home to some of the world's greatest oil and gas reserves and has long been one of the centers of global energy production. While a few countries in the region conduct some form of methane monitoring, the practice is not as well developed in the region to the same extent as it has been in North America and Europe. In many countries across the region, there is a lack of a monitoring infrastructure, a lack of emissions data that is freely available to the public, inconsistent or incomplete emissions information that is reported, and a constantly shifting landscape of rules and regulations concerning methane emissions. As such, there are considerable uncertainties in the regional emissions inventories developed to date. Therefore, there is a particular need for a uniquely regional perspective on current practices for monitoring methane Emissions, as well as on current and emerging methane monitoring technologies, and on the range of actions that can be taken for the purpose of mitigation of those emissions [9], [10].

Furthermore, recently developed monitoring methods and corresponding technologies are not covered by the existing review articles, such as methane detection using AI, drone-based methane quantification, satellite-based methane monitoring, as well as hybrid multi-scale measurement frameworks. [11]-[14].

As shown in Table 1, instead of reviewing studies on methane emission monitoring by means of a technology-oriented, source-oriented, or application-oriented approach, or by reviewing monitoring methods, satellite-based observations, and AI applications for methane monitoring. In detail, this review first provides an integrated overview of the methane emissions along the oil and gas value chain [9], [10].

By discussing the respective emission sources, the individual operational parts of the value chain, and the monitoring technologies and methods, as well as the estimation approaches, including their related uncertainties, the analysis is presented from a global perspective, with a special focus on differences between developed and less developed countries. This review, furthermore, discusses emerging methane monitoring using AI, drones, and satellites, as well as a hybrid, multi-scale approach, and it highlights the respective challenges, limitations, and needs for future research to improve the monitoring of methane emissions as well as their quantification [9], [12].

2. Methodology of the Review

This review was conducted in accordance with the PRISMA 2020 guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to identify studies on methane emissions from the oil and gas sector using leak detection and methane monitoring methods for emission quantification, as well as using Optical Gas Imaging (OGI) and other methodologies, and for estimating, monitoring, and mitigating. Relevant publications were identified through searches in the databases Scopus, Web of Science, ScienceDirect, and Google

Scholar in 2025. The literature search was updated in January 2026. Relevant publications were included in the review if they had been published between 2000 and 2024. A search string was used to search for relevant publications across all databases: ("methane emissions" or "fugitive methane" or "methane leakage" or "methane leaks" or "CH_4 emissions" or "CH_4 emissions") and ("oil and gas") and ("leak detection" or "methane monitoring" or "emission quantification" or "Optical Gas Imaging (OGI)").

Table 1. Comparison of Previous Review Studies and Representative Methane Monitoring Studies with the Present Review.

Study	Scope	Technologies Covered	Regional Analysis	AI Integration
Sun et al. [3]	Technologies & uncertainty	Multiple technologies	Limited	Limited
Yang et al. [4]	Direct measurements	Direct measurement technologies	Limited	No
Fox et al. [5]	Detection technologies	Close-range detection technologies	North America	No
Cooper et al. [6]	Satellite monitoring	Satellite	Global	No
Mehrdad & Du [7]	Satellite review	Satellite	Global	Limited
Zhang et al. [8]	Multi-scale framework	Multiple	Limited	No
Nejad et al. [9]	AI & estimation	Multiple	Limited	AI-based estimation
Fiorucci et al. [11]	Remote sensing + AI	Satellite/AI	Global	AI-based remote sensing
Yazdinejad et al. [12]	AI fusion framework	Multi-source	Canada	AI-based estimation
This Review	Integrated assessment	All technologies	Global, including developing oil- and gas-producing regions	Comprehensive

A full-text screening of the studies was conducted by the authors to select the most relevant studies that provided methodological information (detection and measurement of methane emissions, quantification of methane emissions, monitoring of methane emissions, and technologies and methods for estimation of methane emissions), technical information (Optical Gas Imaging and other detection methods and monitoring technologies), and quantitative information (estimation of methane emissions from different sources in the oil and gas sector and from different segments of the oil and gas industry) as well as information on mitigation and on policy and regulation on methane emissions from the oil and gas sector.

The criteria for inclusion were a focus on methane emissions from the oil and gas sector; studies in the English language; studies providing relevant information on the detection, measurement, quantification, and monitoring of methane emissions as well as on the technologies and methods for the estimation of methane emissions and on the ways for mitigating such emissions. Excluded from the review were studies not focused on the oil and gas sector, studies on greenhouse gases other than methane, studies with insufficient information, and studies that were duplicated.

The search yielded a total of 480 records. Excluding 60 duplicates, a total of 420 records were screened by title and abstract. By screening the title and abstract of 420 records, a total of 220 records were excluded. The full text of 200 articles was subsequently assessed for eligibility. Of these, 74 articles were excluded due to reasons such as a lack of relevant information or because the article dealt with a completely different topic. In total, 126 studies were included in the review and are summarized in the PRISMA flow diagram below in Fig. 1.

The included studies were categorized into five main groups:

1) the sources of emissions (well sites, pipelines, offshore platforms, etc.).
2) the segments of the operational activities of the oil and gas industry (exploration and production, transmission, storage, refining and distribution, etc.).
3) the measurement technologies (Optical Gas Imaging, point measurement using sensors and detectors, etc.).
4) the approaches to estimating emissions (bottom-up approach, top-down approach, etc.).
5) regional studies and studies on new technologies to reduce emissions.

The included studies were then analyzed and compared by several criteria, including methodological transparency, measurement accuracy, results uncertainty, detection capability, spatial and temporal resolution, applicability, costs, and study limitations.

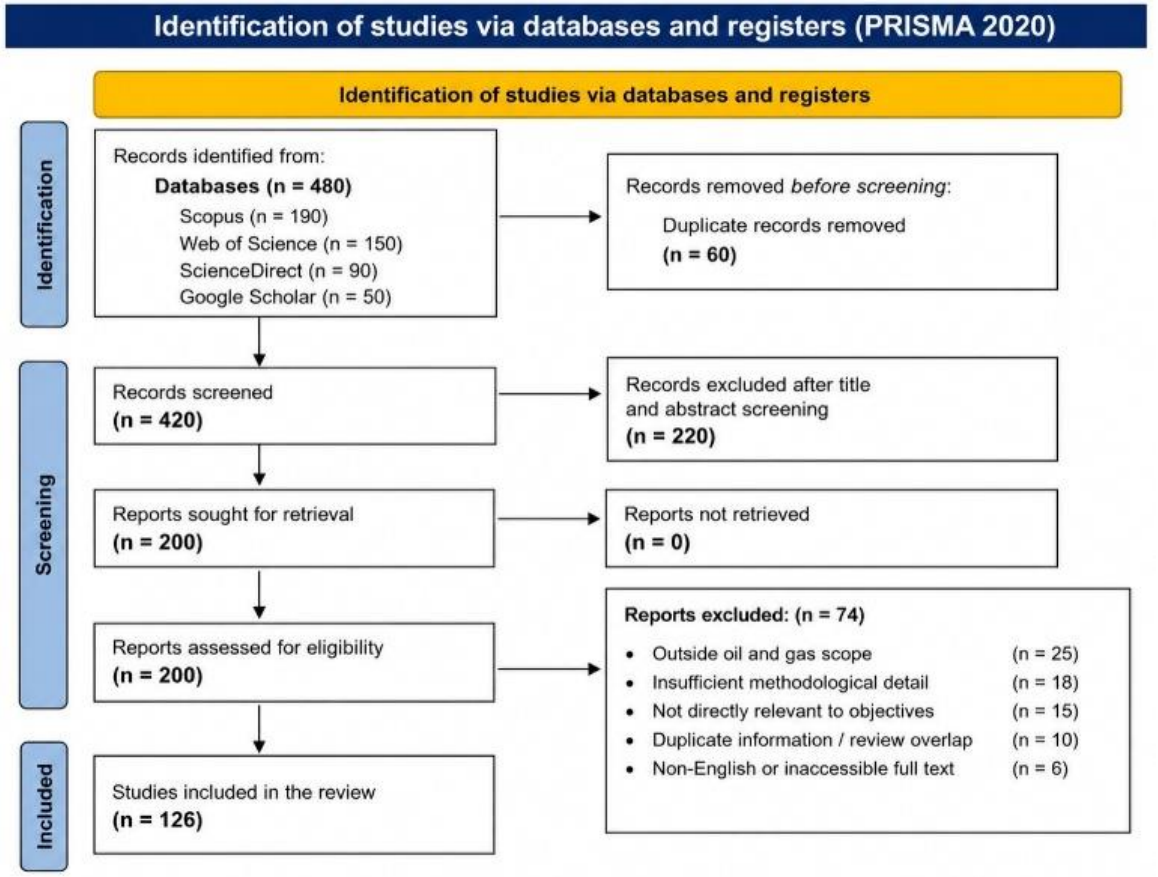

Figure 1. Identification of studies via databases and registers

3. Methane Emissions in the Oil and Gas Sector

3.1. Emission Sources

The oil/gas industry produces methane emissions through both planned and accidental release points, which generate emissions from various sources. The main sources of methane emissions originate from two activities, which include combustion slip and deliberate venting, as well as fugitive emissions that result from equipment leaks and storage and transport system releases [15]-[16]. Measuring these emissions is challenging because they emerge from various complex emission sources. Several studies have established the different pathways through which emissions occur. Smith et al. (2023) [17] report that upstream oil and gas production operations release methane emissions through three primary sources: deliberate venting and combustion slip, and accidental venting.

Fugitive emissions, venting, and flaring are terms often used, but they need to be clearly distinguished. Intentional venting and flaring of methane are occasionally included in methane accounting and in emission inventories of methane, for example, when it is considered to be an uncontrolled emission or when it is large in relation to production. In this review, attention will be on fugitive emissions of methane estimated to arise from gas production processes, and thus Venting and Flaring are only mentioned in the context of their emission of methane and included in the methane inventory.

Venting refers to the release of unburned gas from various vents and leaks in the gas processing system. Flaring is a measure used to burn excess gas. However, flaring can release a portion of the flare gas as unburned methane, either in the form of plume methane or in the form of diffused background emissions resulting from incomplete combustion. This review does not attempt to estimate the amount of flare gas released as methane but notes that the proportions are available to include venting and flaring in their methane accounting.

Smith et al. [17] reported that unregulated tank vents and hatches lead to major hydrocarbon releases. Wang et al. [18] revealed that offshore facilities produce significant methane emissions through the Gulf of Mexico facilities, according to the first study. The current data on oil and gas infrastructure emissions remains insufficiently documented, according to Zeng and Morris [19]. Conventional emission inventories often fail to capture all sources of emissions because they omit malfunctioning equipment and operational irregularities, thereby reducing the accuracy of emission estimates [7], [18]. Gålfalk et al. [20] demonstrated that ultra-emitters at facilities produce most of the worldwide fossil fuel-related methane emissions.

Advanced high-resolution monitoring systems are required because operational emissions from flaring require accurate tracking, and ultra-emitter events need reliable monitoring. The absence of exact methods to track emissions in space and time leads to unidentified and inaccurate measurements of source emissions, which creates major gaps in greenhouse gas inventory data worldwide [19]-[20].

3.2. Operational Segments

The oil and gas industry operates through three main operational phases: upstream, midstream, and downstream. The three segments of the sector use separate processes and infrastructure systems, which affect both emission amounts and types. The identification of these differences enables the development of specific emission reduction strategies [21].

3.2.1 Upstream operations

The upstream sector produces the highest methane emissions because extraction operations, well completion, and initial processing activities occur frequently under varying operational conditions [22]. Esparza et al. [23] and Saide et al. [24] showed that well sites and flaring operations generate most of their emissions from facilities that produce high levels of emissions. Ražnjević et al. [25] showed that maintenance activities result in substantial variations in emission output, producing sporadic methane emission peaks.

Large-scale assessment studies in recent years again clearly show that emissions from the upstream part of the oil and gas sector account for the majority of the emissions. Alvarez et al. [26] determined that the US oil and gas supply chain has even 60% higher methane emissions than presented in the inventory reports of the companies. Chan et al. [10] determined for the oil and gas sector in Western Canada a factor of about two for the methane emissions in comparison to the information presented in the corresponding inventory reports of the companies. Emissions from the upstream operations of the oil and gas sector should be considered as critical emission sources.

The Niger Delta area of Nigeria generates most of its upstream facility emissions through the practice of flaring and venting operations. The inefficient flaring process results in low combustion efficiency, which produces methane emissions together with volatile organic compounds [23]. The standard operating procedures of Iran's upstream flare system produce methane emissions because they use gas regeneration and system purging operations [24].

3.2.2 Midstream operations

The midstream activities generate methane emissions mainly through compression and transmission processes and storage operations, which result from equipment leaks and operational inefficiencies [25]. The compressor stations continue to operate as permanent locations that produce significant air pollution. Jia and Kikumoto [27] established that equipment leaks and faulty valves and vents lead to major methane losses during gas transmission operations in the United States. Zhou et al. [28] demonstrated that super-emitter infrastructure serves as a critical element for this industry because multiple faulty compressors and pipeline components produce emissions that exceed their individual total emission levels.

Of the midstream sources, the largest emissions have been found to come from the compressor stations at transmission and storage facilities [26]. Furthermore, Wang et al. [18] emphasized that methane accounting requires multi-scale measurements because emissions can vary substantially between individual facilities and infrastructure components.

3.2.3 Downstream operations

Historically, the downstream processes received less emphasis until recent times, when their cumulative methane emissions gained more attention. Fredenslund et al. [29] projected that downstream operations, such as Liquefied Natural Gas (LNG) facilities and petrochemical plants, would generate substantial emissions, increasing the sector's overall output by 2030. These developments have led to the creation of regional initiatives as an answer to the problem. The oil and gas sectors of Canada, the United States, and Mexico agreed to reduce methane emissions by 40–45% below 2012 levels by 2025. The sector faces challenges in emissions measurement and control because its downstream operations are complex, and it lacks an adequate real-time monitoring system.

The majority of methane emissions in the oil and gas industry originate from upstream activities (vent-, flare-, well completion-, liquid unloading-, and also production-related releases) [19], [27], [28]-[30]. Several studies in the recent past have included these activities in their assessments to quantify the relevant methane releases, in contrast to the inventory data provided by the industry, which typically assesses the production segment only. For the Upstream activities, even the inventories provided by the industry represent only a fraction of the actual emissions [2], [31]-[33]. However, in great contrast, the methane emissions of these activities are up to 60 % higher than the values already provided in the inventories for the U.S. shale gas supply chain, as reported by Alvarez et al. [26]. Worldwide, super emitters, denoted as ‘ultra-emitters’ in contrast to ‘normal’ high emitters, are mostly located in the Upstream activities of the oil and gas industry. Many of these so-called ‘ultra-emitters’ emit the corresponding amounts of methane by far in excess of those released by the typical ‘normal’ high emitters, as reported by Lauvaux et al. [2].

In contrast to the relatively small number of sources in the upstream sector, the methane emissions from the midstream sector are attributed to a relatively large number of sources, including leakages and background emissions from compressor stations, from transmission and storage pipelines, and from facilities used for the storage of gas [23], [34], [35]. Losses of methane from the various elements of the midstream sector are strongly influenced by the operation of compressors, the integrity of associated equipment, and the practices with respect to maintenance and repair of such elements [23], [36]. In the downstream part of the value chain, the widespread nature of sources of methane emissions leads to correspondingly low emission intensities [26], [37].

The emissions of methane from oil and gas are not distributed equally throughout the value chain of crude oil and natural gas. The greatest opportunity to reduce the emissions of methane from oil and gas exists in the upstream activities. The reduction of emissions in the midstream and the downstream activities can be improved by better management of the infrastructure, the detection of leaks, and an increased efficiency of all activities in the midstream and the downstream of the oil and gas value chain [25], [38]-[40].

The data presented in Table 2 indicates that the upstream sector contains the majority of the emissions for each of the oil and

gas value chain stages. According to the International Energy Agency, 85% of the emissions from the oil and gas value chain are attributed to the upstream sector. The large number of potential emission sources at production-related activities in the upstream sector greatly exceeds those found in other value chain sectors. A large number of sources are responsible for emissions from the upstream sector, including well completion activities, the use of pneumatic equipment for liquid unloading, venting, and flaring, as well as methane emissions from fugitive emissions from equipment. In contrast, 15% of the emissions from the oil and gas value chain are from the midstream and downstream sectors. These emissions come from a variety of sources, including compressor stations, transmission and storage systems, petroleum refineries, liquefied natural gas terminals, as well as natural gas distribution to end-users. Even though the absolute level of emissions from these sectors is low when compared to the upstream sector, the absolute level of emissions remains substantial due to the large amount of associated infrastructure, as well as the difficulty of identifying and repairing ongoing leaks from these systems.

4. Regional Overview

The reporting of methane emissions and their patterns show differences between regions because of different regulatory systems, technological maturity, infrastructure conditions, and operational methods [40]. The combination of routine monitoring activities with a leak detection system and a transparent reporting system under North American and European regulatory agencies results in the development of dependable emission inventories. These areas have established a strong institutional system that unites sophisticated sensor networks with a complete measurement system that uses both top-down and bottom-up methods [41]-[42]. The Middle East, along with particular Asian regions, experiences three major challenges, which include an insufficient monitoring system, non-existent regulations, and inadequate infrastructure that results in unreliable reporting [43]. The section evaluates regional development through the case of Iraq to understand how oil resources create economic obstacles and potential advantages [44].

The Middle East is one of the world's largest oil- and gas-producing regions, and therefore also of particular relevance for methane emissions reduction. However, countries in the region have lately increased their involvement.

Table 2. Comparative Synthesis of Methane Emission Contributions, Major Sources, and Key Challenges Across the Oil and Gas Value Chain.

Segment	Typical Contribution (%)	Major Sources	Key Challenges	Representative References
Upstream	≈85%	Well completion, production equipment, pneumatic devices, liquid unloading, venting, flaring, fugitive equipment leaks, super-emitters	Intermittent emissions, inventory underestimation, remote facilities, super-emitter events	[29], [31], [39],[42]
Midstream	Part of the remaining ≈15%*	Compressor stations, transmission pipelines, storage facilities, valves, and seals	Leak localization, compressor emissions, and long transmission networks	[23], [31], [41], [37]
Downstream	Part of the remaining ≈15%*	Refineries, petrochemical plants, LNG terminals, and the distribution system	Numerous small leaks, aging infrastructure, and continuous monitoring	[31], [35], [39],[42]

Note: The International Energy Agency notes that upstream operations account for around 85% of oil and gas methane emissions, with gas transportation and other downstream activities and midstream accounting for the remaining 15%. Note also that it could not find any globally accepted split between midstream and downstream activities. This is to a large extent due to variations between countries, types of infrastructure, and measurement methodologies.

In initiatives to cut methane emissions, when it comes to the monitoring of practices, emissions data, and the rules and regulations to be applied, the region lags behind North America and Europe. While Saudi Arabia, the UAE, Qatar, Kuwait, Oman, and Iran recently participated in initiatives by space agencies to monitor methane emissions from space, as well as in efforts to cut methane emissions, independent verification of measures, as well as of monitoring practices and emissions data reported, is still lacking in most countries in the region. As a result, there is considerable uncertainty when it comes to the methane emission data compiled for the region, and additional monitoring networks, improved emissions reporting practices, as well as more regional cooperation are required in order to trigger and support actions of methane reduction.

There is also a lack of a framework of institutions and measures for the monitoring and control of methane emissions, on the one hand, and the geographical and climatic characteristics of the majority of countries in the region are of critical importance and present specific challenges for such monitoring, on the other hand. The desert geography and high temperatures of the region, together with periodic events of severe dust storms, very high levels of solar radiation, and the location of a significant proportion of oil and gas facilities in very remote areas on the ground as well as offshore locations, create significant challenges for ground-based monitoring, and some of the monitoring technologies cannot provide reliable continuous measurements in the field. Taking into account the very large geographical area of oil and gas infrastructure in the majority of countries in the region, spread over very large desert areas as well as over offshore locations, the challenges and the corresponding substantial operational costs of the regular inspections of all facilities increase significantly.

These findings present several specific challenges for the monitoring of methane emissions in the region that are different from the ones posed in the other developing regions of the world and would require a combined approach that would include monitoring and the use of information derived from space-borne platforms as well as from airborne sensors, and continuous ground-based monitoring [26], [28], [35], [41]. Iraq is another large oil producer in the Middle East, where development in terms of the monitoring of methane emissions and reporting is still limited.

Multiple research studies in Iraq have conducted assessments of greenhouse gas releases from petroleum operations. Hashim et al. [36], and Razaq and Hassoon [37] both observed increasing CO_2 emissions, while the reported decrease in methane emissions was due to political instability, which cut production levels rather than reducing actual emissions. Hashim et al. [36] and Razaq and Hassoon [37] noted that the reported emission figures do not reflect Iraq's actual methane emissions. Johnson et al. [44] used satellite data to demonstrate that upstream activities produce more emissions than the official statistics indicate. Razaq and Hassoon [37] studied pollutant dispersion from the Daura refinery, while Hashim et al. [36] used the Intergovernmental Panel on Climate Change (IPCC) framework to calculate multiple greenhouse gases from refining and electricity generation. The results show that Iraq needs urgent measures to improve emission-reporting precision and implement global standards for open-data accessibility.

Advancements in independent methane measurement technologies have significantly improved the understanding of regional emissions from the oil and gas sector. An independent airborne LiDAR air quality monitoring system was tested using controlled methane release experiments as well as surveys of 167 oil and gas facilities [45]. Johnson et al. [44] show that the independent airborne monitoring system can detect and quantify emissions at an operational scale. When comparing the independent airborne LiDAR measurements to facility-reported emissions, using field-measured wind data for analysis, the independent system had a measurement uncertainty of ±31%, and when using the best available atmospheric wind estimates, the system had an accuracy of ±68%. Recent independent field measurements of methane emissions from the oil and gas sector have consistently found that official emissions inventories are significantly underestimating actual emissions.

Independent measurement and monitoring using different technologies can provide critical evidence to challenge reported emission inventories for methane. There is large-scale field measurement work that shows clearly that the reported inventories of methane emissions contain a large underestimate.

Underestimation of methane emissions from the oil and gas sector could lead to unnecessary delays in the development and implementation of effective methane mitigation strategies. Field measurements of the entire supply chain of the U.S. oil and gas sector found emissions to be 60% higher than reported in official emissions inventories [46]. Methane emissions from the Western Canadian oil and gas sector were found to be nearly double those reported by companies in their official emissions inventories [10]. Upstream emissions in the Alberta oil and gas sector are significantly under-reported by official emissions inventories [47], [48].

Rapid industrial growth of Gulf nations creates identical environmental monitoring problems because their development happens before they can build an effective environmental monitoring system.

The main reasons behind monitoring differences become evident when analyzing the differences between regulatory enforcement, technological capacity, and economic priorities. The United States operates various networked monitoring systems for Leak Detection and Repair (LDAR) regulations, but Middle Eastern countries continue using outdated methods because their enforcement lacks strength. The absence of monitoring in several Middle Eastern countries enables unregulated emissions to take place, which hinders international climate negotiations and prolongs the duration of climate change mitigation program execution. The monitoring system of developed nations tracks climate targets through an open tracking system, which improves business operations and public trust [49], [50].

The various conditions between these areas need separate strategic plans to address their problems. The nations in Iraq and its surrounding area should develop their institutional capabilities, merge satellite observation data with ground-based observation efforts, and establish international partnerships to close existing data deficiencies [51]. The proposed solutions will improve national greenhouse gas inventory precision, which will help countries fulfill their Paris Agreement obligations through joint regional climate mitigation plans that account for both local constraints and common environmental responsibilities [52], [53].

Methane source identification and emission intensity, in addition to regional regulations, are key parameters to determine the optimal technology for the implementation of a methane monitoring project. This section describes the most common technologies currently used to monitor and detect methane emissions in the oil and gas sector.

4.1. International Methane Reporting Standards

There is an increasing tendency to turn to measurement-based monitoring, reporting, and verification (MRV) for international methane reporting [39]. National greenhouse gas inventories are to be prepared in line with the IPCC guidelines within the framework of the Enhanced Transparency Framework under the Paris Agreement [28]. Oil and gas companies must report methane emissions under the United Nations Environment Program (UNEP) Oil and Gas Methane Partnership 2.0 (OGMP 2.0) measurement-based reporting framework. International Energy Agency IEA's new guidance, Global Methane Tracker 2026, in particular, underlines the importance of transparent and harmonized MRV and exposes the discrepancies between reported greenhouse gas inventories and measurement-based data. Above all, for developing countries with oil- and gas-rich regions, a harmonized reporting system will improve the accuracy, comparability, and transparency of respective methane inventories [28], [39], [41].

5. Measurement Techniques for Methane Emissions

The measurement of methane emissions from oil and gas operations requires reliable methods to produce accurate results [54]. As illustrated in Fig. 2, methane emissions can be assessed through direct measurements, bottom-up emission inventories, and top-down atmospheric observations, using hybrid monitoring approaches. The assessment of emissions for their reduction, as well as for the implementation of corresponding regulations, by means of the above-mentioned methods can be integrated to improve their assessment, to reduce their uncertainty, and to support effective methane mitigation and regulatory implementation [54],[55].

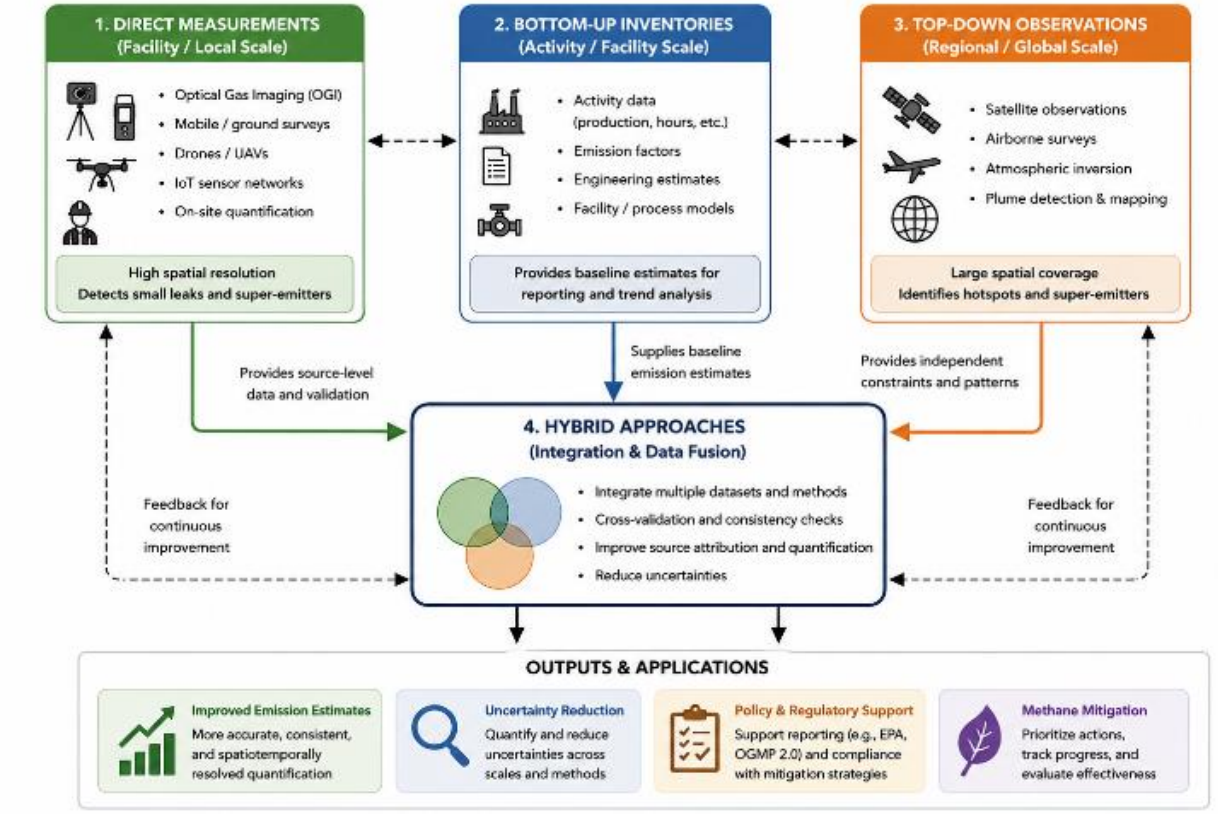

Figure 2. Integrated approaches for methane measurements.

5.1. Direct Measurement Techniques

The direct measurement approach enables scientists to measure methane concentrations and emission rates directly at their sources [55]. The measurement techniques for direct assessment include Optical Gas Imaging (OGI), Fourier Transform Infrared Spectroscopy (FTIR), cavity ring-down spectroscopy, and flame ionization detectors [56].

The infrared camera-based OGI method enables operators to visually detect methane leaks. The detection sensitivity of OGI depends on environmental conditions and operator skill, as stated by You et al. [57], while its non-invasive nature makes it suitable for Leak Detection and Repair (LDAR) programs. The OGI method produces independent qualitative results, but it requires a plume modeling system to generate quantitative results [58]–[59].

The performance of Optical Gas Imaging (OGI) has been evaluated in several studies under different operating conditions. Its performance varied based on the camera specifications, system design, and environmental conditions. For the controlled release test of methane emission, 0.1–2.9 kg CH_4 h^{-1} were found [60]. For the multi-platform measurements, the reported emission rates varied considerably, i.e., 0.01–50 kg h^{-1} [61]. For an optimized OGI system, even low detection limits of 3 scfh have been reported under ideal conditions [62]. However, also for OGI, large variations in the detection of gas leaks and in the resulting measurement uncertainty have been reported in several studies [63], [64]. The variations were found to depend on several environmental parameters such as wind speed, thermal differences, cloud cover, and ambient temperature.

The combination of portable analyzers with bagging methods allows flux measurement, but these methods need large amounts of labor to operate and can only measure accessible infrastructure. Mobile ground-based platforms with methane analyzers on vehicles detect leaks in real time at the facility level but need further processing to identify leak sources [65].

5.2. Bottom-Up Emission Inventories

The bottom-up method calculates emissions through the combination of activity data (e.g., number of valves, compressors) with emission factors obtained from laboratory or field measurements. The method serves as a standard approach for regulatory reporting and national inventory purposes [66].

The use of average emission factors in bottom-up inventories leads to an underestimation of actual emissions because these

factors do not reflect the range of super-emitters or their emission intensities. The method faces challenges when trying to track time-dependent emission patterns, including sporadic venting and equipment breakdowns. The bottom-up method serves as the main approach for developing emission baselines and executing scenario analyses, although scientists recognize its limited use cases [67].

5.3. Top-Down Atmospheric Observations

The top-down methods use atmospheric concentration data from aircraft, towers, and satellites to perform inverse modeling, which allows scientists to calculate facility-level and regional emissions. Scientists create high-resolution emission maps through aircraft-based research, which enables them to detect major pollution plumes during short observation periods [68]. However, these systems remain relatively expensive, and their operation depends on weather conditions.

Satellite observations have become increasingly valuable because they provide extensive geographical data and better image quality. Instruments like the Tropospheric Monitoring Instrument TROPOMI) can detect greenhouse gases (GHGs) and high-emission events globally [69]. The system demonstrates restricted operational capabilities when operating under cloudy weather conditions and when used in urban areas because they fail to detect specific leak points [70].

The methods enable researchers to expand their current ground-based measurement approaches, which they employ for emission report validation and hidden emission site detection.

5.4. Comparative Assessment

A more detailed comparison of the major methane detection and measurement techniques in terms of their spatial and temporal resolution is given in Table 3. The table also provides the major strengths and weaknesses of different methane monitoring techniques, along with a qualitative assessment of detection capability, accuracy, cost, operational complexity, and Technology Readiness Level (TRL). While techniques such as aerial and satellite observation are superior in terms of large-scale surveys of emissions from methane at spatially distributed sources, individual sources such as industrial facilities can be more accurately measured using OGI and mobile analyzers. Bottom-up-based emission inventories, which are also used for other air pollutants, provide a cost-effective means for providing data required for reporting under regulation, but cannot detect intermittent as well as so-called super-emitters. As a result, no single monitoring technique is most suitable for all monitoring goals, and thus an integrated approach will be required to monitor methane emissions from human activities [71], [72].

Comparison of methane monitoring technologies to assess detection limit, spatial resolution, cost, and uncertainty gives insight into their applicability. Local-scale instruments such as optical gas imaging cameras and mobile trace gas instruments provide detailed spatial information at the location of emitters and are highly effective at identifying individual point sources and are easily deployable in a first- or second-derivative approach. However, the detection limit can be highly variable at different times and depending on the operational skills of the users. The detection limit of the local-scale sensors can vary depending on the strength of thermal gradients, the presence of wind shears, and the skill level of the operator, and can be diminished in the presence of wind.

Conversely, space-based and airborne top-down instruments provide broad spatial coverage with the potential to observe large areas and source sectors in finer detail than locally, and are effective in identifying large emission plumes and sectors with high emissions that correspond to emission hotspots. These top-down measurements, while offering a broader spatial extent, have typically provided fewer details in spatial resolution of the overall signal, and there is generally greater uncertainty in determining the individual contributions from the sources identified. Consequently, a combination of local- and top-down approaches is needed to compensate for differences in spatial detail.

Bottom-up inventories serve as a common tool for regulatory and policy reporting, but they rely on general emission estimates that fail to detect occasional high-emission events at specific sites and intermittent emissions. Their calculations are less accurate because they use typical emission factors, which do not provide exact results when operations become complicated [73]. Scientists employ aircraft- and satellite-based top-down emission detection methods to analyze both local emission patterns and major pollution sources that span extensive areas. These detection methods face multiple challenges because they require major financial backing and suitable weather conditions, yet they cannot pinpoint the exact origins of emissions [74].

The table emphasizes that each method contributes uniquely to methane quantification and that no single technique is sufficient on its own. The need for integrated monitoring strategies exists because these systems need multiple methods that generate precise results and monitor all areas through time-based observations.

The most suitable methods for methane measurement in low-resource settings include Optical Gas Imaging (OGI) and mobile analyzers because they provide affordable and flexible field-deployable solutions. The visual leak detection capabilities of OGI are fast but become quantitative only when combined with additional modeling for leak detection and repair programs. The facility-level assessments from mobile ground-based analyzers mounted on vehicles operate in real time with moderate technical expertise, which makes them suitable for areas with limited resources. Bottom-up inventories serve regulatory reporting needs well because they are inexpensive, but their use of static emission factors results in underestimation, particularly for super-emitter events. The wide spatial coverage of aircraft surveys and satellite observations helps detect unreported emission hotspots, but their high operational costs, advanced infrastructure requirements, and meteorological sensitivity limit their suitability for regular monitoring in resource-limited areas. The combination of OGI and mobile analyzer approaches offers the most suitable solution for methane monitoring in resource-constrained environments because they balance cost-effectiveness with accessibility and reliability [75].

In many cases, the operational feasibility and cost of the monitoring technology also play a role in the choice of monitoring method. A large number of ground-based monitoring activities, including OGI and mobile methane monitoring, can be implemented in an economically and operationally efficient way. These methods are often low-cost and simple to apply, which is an advantage in developing countries with limited infrastructure. Airborne and satellite-based methods are expensive to apply and require complex data processing, which is therefore often limited to occasions when it is needed for validation or verification of emissions, such as verification of emission reductions claimed for inclusion in a target, or for checking the accuracy of reported inventory data [76].

The suitability of the current methane monitoring technologies for application in a specific region also largely depends on the environmental and operational conditions of that region. In the oil-rich Middle East, with high ambient temperatures, arid conditions, occasional severe sandstorms, and very large areas of oil and gas field infrastructure, some of the common ground-based monitoring techniques, such as OGI and mobile monitoring using trace gas analyzers, can be less effective for a number of reasons. In this region, there is also an ongoing development of frameworks for the monitoring of air pollutants. In such an environment, while some of the ground-based techniques can be used in conjunction with aerial and satellite monitoring for methane monitoring, using ground-based measurements as a reference, an integrated approach that incorporates a combination of ground-based, airborne, and satellite monitoring would be more effective for a region such as the Middle East [26], [28], [35], [41], [75],[76].

Table 3. The key characteristics of the measurement method.

Method	OGI	Mobile Analyzers	Bottom-Up Inventory	Aircraft Surveys	Satellites
Spatial Scale	Facility-level	Local to regional	National/ facility	Regional	Global
Temporal Resolution	Instantaneous	Short-term	Annual	Episodic	Daily to weekly
Strengths	Visual leak detection, non-invasive	High mobility, quantitative	Cost-effective, policy-oriented	High-resolution plume mapping	Wide coverage, useful for trend analysis
Limitations	Qualitative, sensitive to conditions	Source attribution complexity	Misses variability, super-emitters	Expensive, limited by the weather	Low spatial resolution, cloud interference
Typical Detection Capability	Moderate	High	Low for intermittent and super-emitters	High	Moderate–High (large emitters)
Accuracy	Moderate–High	High	Moderate	High (≈ ±31–68%)	Moderate
Cost Level	Medium	Medium	Low	High	Medium–High
Operational Complexity	Moderate	Moderate	Low	High	Moderate
Technology Readiness Level (TRL)	Commercial deployment (TRL 9)	Operational (TRL 8–9)	Mature methodology (TRL 9)	Operational (TRL 8–9)	Commercial deployment (TRL 9)
References	[77],[78]	[79]	[80], [81]	[76], [82]	[83], [84]

Note: the qualitative assessments of detection capability, cost level, operational complexity, and technology readiness level (TRL) are largely based on literature and could change significantly based on many factors, including the specific instrumentation used, site-specific characteristics, and prevailing practices.

5.5. Integration and Uncertainty

No single method provides a complete picture of methane emissions. Hybrid approaches that integrate top-down observations with bottom-up inventories are increasingly promoted to reduce uncertainties and improve emission accuracy [77]. The process of cross-validation between methods enables researchers to find differences between methods while improving emission factor accuracy and determining which pollution reduction efforts need immediate attention [78].

Methane quantification employing different methods for measurement and data processing greatly varies in uncertainty. For airborne LiDAR detection of methane sources, the uncertainty of the quantified methane source (i.e., emission rate) was found to vary between ±31% (when using field-measured wind) and ±68% (when using atmospheric models). A recent controlled release intercomparison study employed ten different methane quantification techniques [79]. The resulting performance of the different methods varied greatly, with the average absolute error of the LiDAR methods approximately equal to 29–33%, the average absolute error of the different tracer methods approximately equal to 19%, the average absolute error of the different Optical Gas Imaging (OGI) techniques approximately equal to 63–80%, and the average absolute error of the different drone-based techniques approximately equal to 140–239% [80]. The reported uncertainty of the different emission quantification methods often underestimates the intercomparison results, and thus an independent validation of the different emission quantification methods, as well as a cross-validation between the different techniques, is strongly recommended.

The uncertainty in methane emission quantification depends on several factors, including the instrumentation used, wind effects, the investigated methane source, and the methods applied for data processing and methane emission quantification. Thus, for reliable methane emission quantification, a combination of different techniques is recommended to increase robustness [81]-[83].

The analysis contains various uncertainties because different testing methods generate different results, and developing nations lack enough data. The analysis contains various sources of uncertainty because different measurement techniques may produce varying results. In addition, developing countries often lack sufficient monitoring infrastructure and standardized measurement protocols, which further increases uncertainty in reported methane emissions [84]. The future research agenda requires the development of standardized testing protocols together with an improved real-time detection system and expanded surveillance of areas that lack proper monitoring.

6. Estimation Models and Data Analysis

The process of measuring methane emissions from oil and gas operations needs both direct field observations and analytical models and data processing methods to convert collected data into useful results [85]. The models transform collected data into emission readings, which scientists employ to identify pollution origins, and they allow scientists to study information from various time spans and locations while assessing measurement precision [86]. The following section describes the primary estimation approaches, which include bottom-up models together with top-down inverse models and hybrid frameworks.

6.1. Bottom-Up Estimation Models

The Bottom-up models are used to calculate the methane emissions by multiplying the respective activities by the corresponding emission factors. These models are mainly used for reporting for environmental purposes and for the national Greenhouse Gas Inventories on a yearly basis and for long-term monitoring of the emissions.

While measurement technologies are used for direct detection or quantification of methane emissions in the field, estimation models are used to derive the emission rates from the observational data at the facility, sector, or country level. Therefore, estimation models act as a bridge between measurement technologies, resulting emission inventories and assessments. Calculation of emissions through bottom-up

models require activity data that includes equipment counts and operating hours, which are used with emission factors obtained from controlled experiments or previous measurements [87]. The main tools for building a national inventory system and enforcing regulations consist of these models (e.g., IPCC Tier 1–3 methods). Examples include:

- The IPCC 2006 Guidelines function as worldwide standards for national GHG inventory development because they provide a tiered system that adjusts to different data quality and complexity levels.
- The GHGRP (U.S. EPA's Greenhouse Gas Reporting Program) requires facilities to submit emissions data through established equations and emission factors.

These models provide cost-effective scalability, but they cannot track high-emission variations that result from equipment breakdowns, operational irregularities, and environmental factors. They also typically underrepresent super-emitters, resulting in an underestimation in some sectors [88].

6.2. Top-Down Inverse Modeling

Top-down models use atmospheric measurements on a regional or national scale to estimate methane emissions. The application of top-down models allows for the identification of so-called emission hotspots and for the verification of reported emissions in national inventories against real emissions.

The Top-down models use atmospheric methane concentration data, which aircraft, towers, and satellites detect, to perform inverse modeling (Bayesian inversion) for surface emission calculation. The models calculate emission rates through the combination of meteorological data with transport models and remote sensing observations [89].

Users can benefit from multiple advantages when they use top-down observation techniques [90]. The system functions best for verifying emission data, which scientists create through bottom-up methods, while it helps identify both new and concealed pollution sources. The system works well for both local and national emission monitoring because it offers an extensive geographic reach, which supports traditional field measurement methods. The research methods employed for this study contained multiple essential restrictions that affected the study. The accuracy of these models depends on the precision of atmospheric transport models, but their ability to detect pollution remains limited by the sensor technology used for monitoring. The ability to detect specific sources through top-down observations becomes limited when signals from different locations overlap in urban areas and complex terrain environments [90].

6.3. Hybrid Estimation Approaches

The hybrid approach allows for estimating the emissions using bottom-up inventories (which are often used for reporting to the regulation, for the national GHG inventory, and for the long-term tracking of the emissions) and to complete them with direct measurements as well as with top-down observations to improve the results, decrease the uncertainties, and compensate for the limits of the single approaches used.

The bottom-up and top-down estimation methods show different results, which has led researchers to develop hybrid models as their solution [88]. The models achieve improved results through the combination of empirical data with remote sensing information and atmospheric models [90].

Researchers used hybrid methods to develop new approaches for methane emission measurement according to these examples [91]. The combination of satellite data with aircraft surveys and ground-based measurements through multiscale frameworks allows researchers to achieve a complete understanding, which includes all spatial and temporal scales

[86]. The data assimilation process merges observational data with model predictions to produce more accurate and detailed emission maps [92]. The hybrid models function to eliminate individual technique weaknesses because they implement a dependable and balanced estimation system. The execution of these methods needs powerful computers and a suitable data acquisition system, which prevents their use in systems with restricted processing capabilities [93].

6.4. Advanced Estimation Frameworks

Methane emission estimation nowadays is no longer restricted to bottom-up inventories and simple top-down observations. Recent years have seen a move towards more advanced methodologies, i.e., towards methane emission estimation by means of inversion, atmospheric modeling, and data assimilation. All these advanced methodologies for emission estimation are listed in Table 4 already. In the following, these methodologies are described in more detail, i.e., their principles, their advantages and disadvantages, as well as recent developments are elaborated upon [94], [95].

A method that is currently more commonly used than the others for estimating emissions from point sources is Bayesian Inversion. This type of framework has the advantage that a priori information, as well as atmospheric observations, can be used in a probabilistic framework to estimate a posteriori emission. Such a framework can take into account the uncertainty of prior emissions, as well as of the transport model and the atmospheric observations, as well as a priori information. There are many studies that have used the framework of Bayesian Inversion to improve a priori information on methane emissions. Recently, there have been more and more studies in which the framework of Bayesian Inversion is coupled with atmospheric transport models as well as with hybrid variational–ensemble Kalman filter (VEKF) approaches. Such a combination allows efficient computation as well as a good spatial representation of methane emissions at a regional scale, as well as at an even smaller scale (i.e., at city scale) [94].

Table 4. Comparison of Advanced Methane Emission Estimation Frameworks.

Estimation framework	Principle	Main strengths	Main limitations	Typical applications	Representative references
Bayesian inversion	Updates prior emission inventories using atmospheric observations within a probabilistic framework	Quantifies posterior uncertainty; improves emission inventories; integrates multiple observations	Sensitive to prior assumptions and transport-model errors; computationally demanding	Regional and national methane inventory refinement	[96]
Atmospheric transport models (Eulerian/Lagrangian)	Simulate methane transport and source–receptor relationships	Suitable for regional-scale inversion; supports aircraft and satellite observations	Dependent on accurate meteorological inputs and boundary-layer representation	Top-down regional emission estimation and hotspot identification	[96]
Gaussian plume models	Estimate emissions from concentration enhancement under steady atmospheric conditions	Simple, computationally efficient, suitable for point-source estimation	Reduced accuracy under variable wind fields and complex terrain	Facility-scale leak quantification	[97]
Inverse dispersion modelling	Uses stochastic atmospheric dispersion to estimate emission rates	Better representation of atmospheric turbulence; improved uncertainty estimation	Higher computational complexity; requires detailed meteorological information	Facility and farm-scale methane emission estimation	[97]
Machine-learning estimation frameworks	Integrate multi-platform observations for emission prediction and data fusion	Automated plume detection, source attribution, real-time analysis, improved scalability	Requires high-quality training datasets and field validation	Multi-scale methane monitoring and integrated emission estimation	[77], [96], [98]-[100]

Atmospheric transport models are one of the core tools for estimating methane emissions using a top-down approach, on a global, regional, country, or even city scale. They are typically run in conjunction with corresponding methane observations (e.g., from aircraft, spaceborne sensors, or ground-based stations) to estimate the transport of methane to a given receptor (or to compute footprints that can be used for inversion). This transport can occur through several different atmospheric regimes, but the primary regime for the transport of methane is the atmospheric boundary layer. As noted previously, there have been tremendous improvements in our ability to understand and analyze wind fields, but the representation of the atmospheric boundary layer (where most transport of methane occurs) remains highly variable and one of the largest sources of uncertainty in the transport step of an emission estimate.

In recent years, there has been a significant amount of work carried out using Gaussian plume models and inverse dispersion modeling for determining methane emissions from

individual facilities. Some of the advantages of these models include: (1) the ability to make rapid assessments of emissions for a given set of weather conditions; (2) the ability to take into account many of the aspects of atmospheric transport that affect the behavior of a plume, including turbulence; and (3) recent studies have used Bayesian methods for determining the uncertainty in the model parameters, which can be used to make improved assessments of the emissions from a given source.

However, as with other methods for determining emissions using atmospheric transport models, there are many uncertainties associated with the use of such models for determining emissions, not the least of which is the uncertainty in the current weather. Thus, even with the best of models, there is considerable uncertainty in the results obtained.

Other aspects, such as the propagation of errors of single sources, have to be considered during emission estimation. These errors are numerous, and they affect the emission estimates of single sources, such as the accuracy of methane sensors, the methane background concentration, wind speed, the errors of atmospheric transport models, the emissions of intermittent sources, and also the uncertainties of model parameters. All these errors can be propagated through Monte Carlo simulations or by a Bayesian analysis using the uncertainties of prior information. Studies that use a top-down inversion approach to estimate the emissions of multiple sources reported a range of posterior uncertainties (11%–28%) for improved bottom-up emission inventories for climate policy and monitoring [95].

Recent advances in methane monitoring have incorporated machine-learning-based (ML) methods into the broader range of methane monitoring approaches using multiple data. For example, satellite imagery, as well as data from airborne surveys, Optical Gas Imaging (OGI), and mobile and ground-based monitoring stations, can all be used to improve detection and attribution of methane sources, and even to estimate the emissions of individual sites. Hybrid approaches have also been developed, which combine AI with more traditional modeling and inversion techniques to improve source estimation and allow for near real-time updates to methane emission estimates using several types of monitoring data [96]-[99].

Methane emission estimation has recently moved on from bottom-up inventories and simple top-down observations. New advanced estimation frameworks of methane emissions are based on inversion, atmospheric modeling, and data assimilation (Table 4). In this paper, the individual tools for methane emission estimation are described in more detail. Their principles, advantages, disadvantages, and recent developments are discussed for application in methane emission estimation [100]-[104].

6.5. Data Analysis Tools and Uncertainty Quantification

The process of data analysis serves as a fundamental step for methane measurement processing, emission estimation, and uncertainty evaluation [105]. The following tools and methods are used for this purpose:

- Statistical analysis: Regression models, bootstrapping, and uncertainty propagation [106].
- Monte Carlo simulation: Often used to simulate variability in emission factors and operational parameters [107].
- Machine learning: Emerging tools such as neural networks and decision trees are being used to identify emission patterns and optimize leak detection strategies [108].

The different sources of uncertainty in methane emission estimates result from measurement inaccuracies and the assumptions used in emission factors and meteorological conditions, as well as the restrictions of sampling time and space. The various factors affecting reported data accuracy and comparison potential exist together as a system. The accurate measurement of uncertainty stands as a fundamental requirement for generating dependable reports that enable scientists to evaluate emission data across different research approaches.

The three main approaches to methane emission estimation receive a detailed comparison in Table 5. The three methods for methane emission estimation require different amounts of data and produce results at varying resolutions, while varying in cost and operational readiness for policy and operational applications [109]. Bottom-up methods persist in widespread use because they offer easy implementation and large-scale deployment and work well with existing regulatory systems. The application of fixed emission factors in these methods produces lower than actual emission rates because it fails to capture super-emitter events [110].

The observation-based top-down methods use atmospheric data to perform emission estimation through atmospheric data analysis. The methods enable researchers to locate hidden emission sources while validating national emission records [111]. The methods have restricted spatial precision for pinpointing exact locations, but their accuracy depends on both meteorological modeling and atmospheric transport models [112].

The use of hybrid methods has spread across advanced research and policy-making environments because these methods unite bottom-up site-specific data collection with top-down broad-scale measurement capabilities [113]. The integrated frameworks require additional resources to function, but they provide better reliability and robustness for methane emission estimation according to [114]. Table 5 shows that researchers must select suitable estimation techniques based on their research objectives and financial resources, and their required level of precision for methane management.

There is no better method for estimating methane emissions than others. While the bottom-up method is very useful for reporting, it has big underestimation problems, mainly for intermittent emission events as well as for so-called super-emitters. The top-down approach is only suitable for the verification of reported emissions on a regional scale; however, it is not possible to attribute the emitted methane to single sources. Therefore, Hybrid multi-scale models are the most appropriate tools to fill the current gaps and to reduce uncertainties. These frameworks are also very suitable for the challenging region of the Middle East, where only very limited monitoring infrastructure is in place, and the environmental

conditions are also challenging. An independent verification of the emissions does not exist yet for this region.

Table 5. Comparison of Methane Emission Estimation Approaches.

Approach	Description	Strengths	Limitations	Typical Application	Reference
Bottom-up	Estimates based on activity data and emission factors.	- Cost-effective- Scalable for national inventories- Compatible with regulatory frameworks	- May miss super-emitters- Depends on average factors- Low temporal resolution	IPCC inventories, facility reporting (e.g., EPA)	[83]
Top-down	Uses atmospheric methane observations with inverse modeling.	- Captures actual atmospheric burden- Identifies unreported sources- Effective for large areas	- High uncertainty in source attribution- Expensive (e.g., aircraft)- Weather sensitive	Regional assessments, validation of inventories	[82]
Hybrid	Combines bottom-up and top-down data for improved accuracy.	- Balanced approach- Reduces uncertainties- better source attribution and scaling	- Requires extensive datasets- Computationally intensive- Data integration challenges	Advanced research, policy planning, verification system	[100]

7. Emerging Technologies and Innovations in Methane Detection

This sub-section will provide an overview of the types of emerging technologies used to measure and detect emissions of methane using new techniques and methods of monitoring. The innovations presented in Table 6 work to overcome traditional method restrictions through their combination of improved sensitivity, expanded spatial reach, automated operation, and immediate data collection capabilities.

Table 6. Summary of Emerging Technologies for Methane Emission Detection and Analysis.

Technology	Advantages	Limitations	Readiness Level	Representative References
Enhanced OGI	Improved leak visualization, higher detection sensitivity, rapid field inspection, and non-contact monitoring	Performance affected by environmental conditions (wind, humidity), qualitative interpretation, and operator-dependent analysis	Commercial deployment	[96], [99]
Image Analysis (AI + OGI)	Automated leak identification, quantitative image processing, reduced human bias, improved processing speed	Requires large, annotated datasets, algorithm training and validation, computational requirements, and limited generalization under varying field conditions	Emerging to operational deployment	[98]-[100]
Drone-based Platforms	Access to remote and hazardous facilities, high spatial resolution, rapid deployment, and reduced inspection time	Limited flight duration, weather sensitivity, payload restrictions, aviation regulations, and battery limitations	Operational deployment	[96], [101]
High-Resolution Satellites	Large-scale coverage, repeated observations, detection of super-emitters, and regional and global emission monitoring	Cloud interference, revisit-time limitations, lower sensitivity for small leaks, and atmospheric effects	Commercial deployment	[96]-[98]
AI-based Data Fusion	Integrates satellite, airborne, and ground-based observations, improves source attribution, enhances emission estimation accuracy, supports near-real-time analysis	Complex data integration, high computational demand, dependence on data availability and interoperability, need for standardized validation	Emerging deployment	[96], [101]
IoT-Based Sensors	Continuous real-time monitoring, automated alerts, scalable network deployment, supports predictive maintenance	Sensor calibration and maintenance requirements, communication reliability, power consumption, and reduced performance in harsh environments	Operational deployment	[96]

While new technologies have the potential to be applied for the detection of greenhouse gas emissions, the applicability, depending on the scale, complexity, and intensity of the applications, differs greatly. Thus, the detection capabilities of, for example, artificial intelligence-based image analysis and drone surveillance can be greatly increased both in terms of accuracy and spatial coverage [115]. To deploy the technology on a larger scale, however, this usually requires an optimized operational workflow, large high-quality training datasets, high-performance computing, as well as logistics [80].

Furthermore, satellite-based methane detection is proving highly suitable for mapping methane emissions on a global level; however, there are still many applications for which the small emissions are difficult to register, as well as complex industrial areas where it is difficult to attribute the source of the emissions [83],[98]. In this regard, emerging detection technologies should be applied in a multi-scale detection concept where ground-level, air, and space-based technologies can be deployed

a- Enhanced Optical Gas Imaging (OGI)

Using AI to improve the efficiency of emission detection and to automatically detect leaks and unusual situations will greatly reduce the time that personnel have to spend carrying out inspections of monitoring points. This technology is already

being widely used for methane monitoring in various types of applications in North America and Europe, where it processes data from the huge amounts of data from on-site monitoring points. In the Middle East, with its extensive oil and gas infrastructure and harsh environmental conditions, this technology will also improve the efficiency of emission detection and reduce the time spent carrying out inspections of monitoring points [115], [116].

Traditional OGI cameras, which use infrared technology, have proven useful for leak detection when operators are within short distances [117]. The detection of low concentration levels has become possible through recent advancements, which have improved the thermal sensitivity of these detectors [118], [119]. The system achieves better feature detection because of its improved image resolution. The system now operates with built-in automated leak quantification algorithms, which function together with the detection system. The system from Li et al. successfully operates in challenging environmental settings [120].

The integration of modern OGI tools with machine learning algorithms for image classification improves leak detection precision because these systems deliver enhanced consistency and objectivity [121]. The new technologies help scientists

reduce human errors while they improve their ability to detect and measure methane plumes.

b- Image Analysis Techniques for Methane Quantification

While in the US, Canada, and Europe, drone-based methane monitoring is mainly used for facility inspections as part of LDAR (Leak Detection and Repair) programs, in the Middle East Drone monitoring could increase the efficiency of inspections significantly, especially for the monitoring of remote pipelines, well pads, etc., which are hard to access and for which the cost of on-site work would be too high and for which the frequency of monitoring could be increased significantly [121], [122].

The current state of digital image processing and computer vision technologies enables them to perform complex data analysis of OGI and drone imagery information [76]:

- Frame differencing and motion tracking algorithms are used to isolate gas plumes from the background [101].
- Scientists use pixel intensity-based quantification to determine plume density and emission rates [88].
- The combination of machine learning and deep learning models enables methane emission detection and classification through training CNNs with annotated thermal video datasets. 2022).
- The system enables temporal plume tracking and leak size estimation through its analysis image software integration, which becomes more effective when users add environmental data, including wind speed measurements.

The image analysis techniques serve as essential steps to convert OGI video data from qualitative to quantitative methane emission measurements, which improves the usefulness of visual inspection tools.

c- Drone-Based Methane Monitoring

Methane monitoring by Satellite is applied around the world; several space missions are in operation that continuously survey regions for methane emissions on a daily basis using satellite sensors such as TROPOMI and the Canadian commercial satellite GHGSat. The vast desert landscapes of the Middle East, with their many oil and gas installations on land as well as at sea, provide a unique monitoring challenge that can be filled by satellite emissions monitoring from space [123], [124].

Unmanned Aerial Vehicles (UAVs) use infrared cameras together with small methane sensors to detect areas that standard monitoring techniques fail to reach, including offshore rigs and flare stacks [125], [126]. The research by [120] identifies three essential advantages, which are:

- High-resolution surveys over targeted infrastructure.
- Vertical profiling of emissions.
- The system allows for quick deployment of emergency detection and needs to work with existing image and gas analysis pipelines, which will process data after the flight.

d- Satellite Constellations and High-Resolution Remote Sensing

Airborne monitoring systems are deployed for regional methane mapping and for emission verification in North America and Europe. Due to the large area of the Middle Eastern oil fields, such a monitoring system provides the required flexibility for effective and cost-efficient area monitoring in a short time frame [70], [96].

The next generation of satellites (e.g., GHGSat, Sentinel-5P, Carbon Mapper) offers [113]:

- Daily revisit times,
- Sub-100-meter spatial resolution,
- Global super-emitter detection capability.

The development of machine learning algorithms for satellite signal correction and interpretation has started, but their operational readiness remains limited because cloud cover and atmospheric interference prevent source identification in complex environments [114], [119].

e- Artificial Intelligence and Data Fusion

Wireless sensor networks for monitoring methane are increasingly being used for permanent monitoring at industrial sites. The number of on-site inspections required to inspect large processing facilities on a regular basis is being reduced in order to improve leak detection in real time.

AI-based platforms now combine satellite data, drone footage, and ground sensor readings into real-time emission maps. Applications include [111], [113].

- Leak detection and localization,
- Predictive maintenance modeling,
- Source attribution using environmental and operational metadata.

Data fusion from a multi-scale and multi-sensor system helps mitigate the limitations of any single technology and creates more robust and continuous emission profiles [29].

f- Internet of Things (IoT) and Miniaturized Sensors

The installation of IoT-connected methane sensors throughout large facilities enables facilities to perform continuous system monitoring, which detects immediate leaks that trigger alerts that get sent to the SCADA system and cloud platforms [93]. The sensors produce inaccurate readings because of their affordable price and ability to expand, making them suitable for identifying system issues and monitoring network compliance in extensive distributed networks [100], [103]. New technologies operate with established techniques to generate enhanced results through better image quality and an automated system and combine data from multiple scales. The future development of methane detection and quantification methods will rely on three essential advancements, which combine the OGI system with image analysis algorithms and drone and satellite technology, and an AI-based data fusion system [109], [110]. The combination of these tools allows researchers to develop an affordable methane reduction system that produces precise results when implemented at large oil and gas facilities [95], [99]

A Hybrid system that integrates the above monitoring system and platforms has recently been put into operation in some of the most advanced methane management projects around the world. This system can be highly effective in countries in the Middle East where there are numerous environmental conditions and a limited ground-based monitoring system.

When considering environmental conditions in the Middle East, as detailed in Section 4, several of the above-mentioned limitations become more pronounced. These limitations are mainly influenced by high ambient temperatures, by the occasional occurrence of large dust storms, by high solar radiation, and by the typical "dispersed" character of the oil and gas production facilities. These facilities are spread over large areas in remote desert locations as well as offshore locations. The performance of various monitoring tools and their operational use is affected by these conditions [26], [28], [35], [41], [70].

8. Challenges and Future Research Directions

-Technical challenges with methane monitoring in the oil and gas sector.

Existing methane monitoring technologies for the oil and gas sector have limitations. There are numerous methods to monitor methane emissions from the oil and gas sector individually. Thus, a standardization of these monitoring methods is not possible, as different methods can be used to estimate the same emissions, and thus different results are possible [92]. Bottom-up estimates of emissions from the oil and gas sector on the basis of all individual sources are typically lower than actual emissions because general emission factors for various categories of sources are usually not sufficient to account for local conditions at individual sources [34]. Top-down estimates of total emissions for a sector or region from monitoring data typically do not identify individual sources, especially when there are hundreds to thousands of sources [34]. Also, there are significant technical challenges with the integration of ground-based, aerial, and space-based monitoring systems with a variety of measurement methods that use different spatial resolutions and require different data processing [90].

- Implementation-related challenges.

Due to their high complexity and the large number of single monitoring points, methane monitoring systems are very costly. Under harsh weather conditions and in the absence of validation in real fields, the use of such a system is impeded. For oil- and gas-producing countries, especially those in the Middle East, severe environmental conditions at the locations of production on land and at sea, as well as a lack of infrastructure at the sites, pose substantial challenges for methane monitoring [41], [70], [89], [90], [92], [103], [109].

- Cost to Implement

Modern technologies used for methane monitoring using aircraft and satellites, as well as continuous ground measurements and sophisticated AI-based platforms for monitoring, require significant initial investment to install and ongoing costs for personnel to collect and analyze data, as well as to manage information technology (IT) platforms to process the data collected. A cost-effective system, a hybrid monitoring approach, and a risk-based approach that identifies the greatest polluters will likely be the most economically effective approach to effective environmental protection and reduction of impacts.

- Policy and regulatory challenges.

A number of the oil- and gas-producing countries worldwide are hindered by an incomplete monitoring infrastructure, a lack of technical expertise, a lack of emissions reporting, and a weak regulatory framework for methane monitoring. The quantitative determination and reporting of methane emissions is further challenged by a lack of political stability and funds required for emission databases and measures for the reduction of emissions. For Iraq, also, despite a large number of oil and gas fields, the existing institutional and infrastructure framework hampers the quantitative determination and reporting of methane emissions.

- Future Research Priorities

A review of current challenges of methane monitoring in oil and gas industry to identify research priorities for improving methane monitoring revealed several areas of concern that need to be addressed in future research. The first area of concern relates to the lack of standard protocols for monitoring methane emissions from the oil and gas industry, and the significant differences between bottom-up, top-down, and direct measurement methods of emissions from oil and gas sources. These challenges need to be addressed through the development and implementation of standard MRV (measurement, reporting, and verification) frameworks and methodologies that enable monitoring to be 'harmonized' to enable monitoring to be compared and contrasted.

Additionally, most current monitoring techniques lack data to quantify and to characterize emissions from various sources due to several limitations inherent to each monitoring technology. In order to quantify and to characterize emissions from various sources of methane with the required accuracy, monitoring frameworks with various spatial scales are required. These frameworks would benefit from the implementation of a diversity of direct on-ground measurements (e.g., OGI) as well as from the utilization of aerial vehicles, aircraft, and space-borne sensors, and from the application of computational methods for the integrated data analysis (e.g., AI, big data).

Methane monitoring for oil- and gas-producing countries outside of North America faces a lack of monitoring infrastructure and a lack of technical capability to perform the monitoring required to measure emissions. It is common that emissions from oil- and gas-producing activities in these countries are not reported. Even where they are reported, the quality of reported emissions is often poor, and there are additional environmental challenges, such as high temperatures, that can affect monitoring as well as mitigation of emissions. Establishing a monitoring network on a regional basis, increasing institutional capacity to monitor oil- and gas-producing activities, creating open public data on emissions databases, as well as validating satellite data using good quality ground-based measurements, are critical in enhancing emission transparency and enabling required actions to mitigate emissions in these countries [126].

Most important for future research on methane emissions from oil and gas production would be the establishment of a monitoring framework for methane monitoring that is standardized, integrated, and region-specific. It should make best use of all available monitoring technologies and, by doing so, reduce the uncertainty of the existing inventories for all oil and gas-producing countries worldwide. For the growing number of oil and gas-producing countries in the Middle East, such a monitoring framework is particularly important.

9. Conclusion

Methane monitoring of the oil and gas sector has seen considerable progress through the combination of measurement and remote sensing. Combining bottom-up information with top-down information has improved characterization of emissions. Significant regional, technical, and reporting gaps remain, however.

The advancement of technology has not eliminated all major restrictions that persist. A single detection method fails to deliver a complete and uniform picture of methane emissions. The bottom-up inventory system cannot identify super-emitters, but top-down assessment methods cannot identify emission sources. The Middle East, together with other areas, lacks a proper monitoring system, standardized protocols, and a clear reporting system. The present technical obstacles, together with institutional limitations, stop data integration between systems that use different measurement systems and operate on different platforms.

Future progress should focus on three areas: (1) development of standardized monitoring and reporting frameworks; (2) cost-effective technologies for low-resource environments; and (3) integrated multi-scale monitoring systems. By addressing these areas, it is possible to decrease uncertainty related to existing greenhouse gas inventories, improve emission reporting, and support development of more effective policies to mitigate methane emissions.

Abbreviations

(CEMS)	Continuous Emission Monitoring System
(E&P)	The Emission and Production
(EPA)	Environmental Protection Agency
(ESG)	Environmental, Social, and Governance
(LES)	Large-Eddy Simulations
(LDAR)	Leak Detection and Repair
(STE)	Software Test Environment
(sUAS)	Small Unmanned Aircraft System
(LiDAR)	Light Detection and Ranging
(UAVs)	Unmanned Aerial Vehicles
(MRV)	Monitoring, Reporting, and Verification
(IPCC)	Intergovernmental Panel on Climate
(UNEP)	United Nations Environment Programme
(OGMP)	Oil and Gas Methane Partnership
(IEA)	International Energy Agency

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in this review.

Author Contribution Statement

Israa M. Altameemi (PhD student): Conceptualization, Investigation, Data curation, Writing – original draft, Writing – review & editing.

Noor Faizah Fitri Md Yusof (Professor, Environmental Engineering): Critical review of manuscript.

Use of LLM and AI

During the preparation of this manuscript, the authors used ChatGPT (developed by OpenAI) to improve readability and language clarity. After using this tool, the authors carefully reviewed and edited the content to ensure accuracy and integrity. The authors take full responsibility for the content of the published article.

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