Digging deeper into cutting methane emissions from the oil and gas industry in the era of volatile prices

Yassine Charabi¹

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Abstract

Although the Gulf Cooperation Council is the beating heart of the world's largest oil and gas reserves, it remains behind the curve on a critical issue facing the industry—the nature and extent of methane (CH₄) emissions and how to mitigate the same. This article uses Oman as a representative example of the Gulf Cooperation Council Countries (GCC) to uncover the CH₄ emission from the oil and gas industry, explore potential reduction policies, and discuss the viability of these policies in the current volatile and falling environment prices. The present study uses the Intergovernmental Panel on Climate Change (IPCC) guidelines and methodology of 2006 to assess CH₄ emission from the oil and gas supply chain. This paper contributes considerably to reducing knowledge gaps about Oman's CH₄ emissions through a detailed accounting of CH₄ emissions from the supply chain for oil and gas. Overall, CH₄ emission in Oman increased 1.86-fold from 288 Gg in 2000 to 825 Gg in 2015, while the CH₄ emission from oil and gas operations rose 1.7-fold from 234.4 Gg in 2000 to 634.4 Gg in 2015. CH₄ emissions from the supply chain of oil and gas are projected to add up to 30% to current emissions (2015) in the third decade of the 21st without a mitigation strategy. Curbing CH₄ emissions calls for a robust abatement policy in tandem with a robust monitoring system to ensure accuracy and transparency. Policymakers' efforts in Oman and other developing countries with similar hydrocarbon-based economies would be hampered by market mechanisms and fluctuations of oil and gas prices in enforcing CH₄ reduction policies. Enforcing tangible reductions of CH₄ from the oil and gas industry are a global dimension problem that cannot be addressed nationally. The UN Convention on Climate Change is an ideal frame of engagement for countries in negotiations to bridge the CH₄ emission gap from petroleum and gas industries and to agree on a roadmap for deep and continuous oil and gas CH₄ cuts. The United Nations agreement on reducing CH₄ from oil and gas seems unavoidable in achieving climate neutrality by the second half of this century and staying below two degrees as decided in the Paris Agreement.

Keywords CH₄ · Trend emission · Oil and natural gas supply chain · Abatement policy · Oman

✉ Yassine Charabi
yassine@squ.edu.om

¹ Center for Environmental Studies and Research, Sultan Qaboos University, Al Khoudh, Po. Box. 42. PC 123, Muscat, Oman

1 Introduction

The atmospheric concentration of CH₄ has increased 2.6 times since the pre-industrial era to reach 1850 ppb in 2017. This rise is primarily due to the unprecedented increase in human-induced agriculture activities, production and consumption of oil and natural gas, and waste management, related to population growth (Schaefer, 2019; Saunio et al., 2019). Atmospheric CH₄, as expressed by the Global Warming Potential (GWP), is a more potent greenhouse gas than carbon dioxide (CO₂). GWP of atmospheric CH₄ is 28 for a time of 100 years and without considering climate feedbacks. However, immediately after the release of CH₄, radiative forcing is about 120 times more than CO₂. The emission of CH₄ is a significant contributor to climate change but impacts global warming significantly differently from CO₂: CH₄ has a high degree of radiative efficiency but a relatively limited life cycle. Thus, the use of Global Warming Potentials over a single 100-year time frame has been frequently called into question as it hides a substantial variation in impact over time (Balcombe et al., 2018; Mallapragada & Mignone, 2020). A two-term greenhouse gas accounting standard has been proposed for The United Nations Framework Convention on Climate Change (UNFCCC); 20 years of the GWP alongside the generally approved 100-year GWP, which is currently accepted. Since countries develop emission targets under a “basket of gases” strategy where the GHG emissions are measured by GWP, adjusting GHG reduction targets to less than 20-year GWP raises short-lived gas weighting in any goal. This would significantly improve decreases in short-lived gas gases such as CH₄ and Hydrofluorocarbons (HFC) compared to CO₂ and other long-lived GHG (The United Nations Framework Convention on Climate Change, UNFCCC, 2020).

The worldwide CH₄ emission from anthropogenic sources is around 366 Mt CH₄ per year (yr⁻¹), representing only 3% of the global CO₂ human-induced emission in unites of carbon mass flux (Saunio et al., 2016). Since the pre-industrial era, the increase in atmospheric CH₄ has contributed to a further accumulation of radiative forcing of about 23 percent (~0.62 watts per square meter (W m⁻²)) in the lower layers of the atmosphere. The total radiative forcing related to anthropogenic CH₄ emissions is actually around 0.97 W m⁻² from an emission perspective (Myhre et al., 2013). CH₄ emissions contribute to ozone, stratospheric water vapor, and CO₂ production and significantly affect their lifetime (Shindell et al., 2012). The lifespan of CH₄ in the atmosphere is short (about 12.4 years for 2014), and stabilizing or reducing CH₄ emissions will rapidly result in stabilization or decrease in its concentration in the atmosphere, and hence, it is radiative forcing (Prather et al., 2012; Kumar & Sharma, 2012; Kumar et al., 2019).

Global ambient CH₄ has shown long periods of growth over the past three decades due to the rising of human-induced emissions. Atmospheric CH₄ rose significantly by around 0.7% per year from the 1980s to the beginning of the 1990s but stabilized during the 1999–2006 period (Bader et al., 2017). Recently, the global CH₄ levels have reached new heights after a “flatlined” period from 1999 to 2006 (Rice, 2016). The isotopic signature of CH₄ realized in the atmosphere indicates fossil fuel production and consumption, responsible for 175 Mt CH₄ yr⁻¹, or about 48% of the observed increase mid-2000s (IEA, 2020).

The United Nations (UN) Environmental Program reported in 2019 during the COP25 discussions that the world is not on a pathway to achieve the target of the Paris Agreement of holding global temperatures above pre-industrial levels to 1.5 °C by 2050 but is instead much more likely to exceed 3.2 °C (UN News, 2019). The GCC is home to the world’s largest oil and natural gas reserves. In 2017, GCC was ranked the third emitter of greenhouse gas with around 1411 Mt CO₂e after China (13,000 Mt CO₂e) and India (3000 Mt

CO₂e). As the third decade of the twenty-first century begins, GCC is still viewed as a laggard on decisive contribution to UN mitigation targets due to the lack of efficient strategies to contain CH₄ emission from their oil and gas industries. The CH₄ decarbonization of the oil and gas industries in GCC countries poses existential questions:

1. How do they establish realistic plans to phase out CH₄ from their oil and gas industries while continuing reviving their economies in a context of high uncertainties about the future growth of global oil and gas?
2. How will they handle the CH₄ decarbonization of the oil and gas industry facing an existential crisis if it does not fix CH₄ emissions and given the competing realities of a soured financial market, volatile prices, and compliance with import requirements such as those contemplated in Europe?

The Sultanate of Oman is a member of the GCC, which we use as a case study to address the questions mentioned above. Oman faces a compelling challenge to harmonize its ambitions for rapid economic growth through hydrocarbon resources and the urgent need to tackle low carbon and environmentally resilient development. Over these last five decades, the oil and gas industry has become the backbone of Oman's economy. In 2017, the oil and gas industry made about 70% of the government revenues and 28% of GDP. (Central Bank of Oman, 2018). Oman's hydrocarbon-proven resources include 4.7 billion barrels of oil and 25 trillion cubic feet of natural gas reserves.

The average daily production of crude oil and condensate in 2017 was 927,000 barrels a day (b/d) (NCSI: National Center for Statistics and Information, 2019). The annual production of natural gas was 1447.4 billion cubic feet (Bcf), roughly Bcf 3.96 per day in 2017. Enhanced oil recovery (EOR) techniques have powered Oman's oil recovery since 2007, after a several-year downturn in the early 2000s. Oman consumed 198,000 b/d and exported 806,000 b/d of crude oil in 2017, primarily to China, receiving 70% of crude oil exports (NCSI: National Center for Statistics and Information, 2019). The domestic consumption of natural gas is around 70% of the national production in 2017. Between 2007 and 2017, natural gas consumption more than doubled, from 384 to 775 (Bcf). In 2017, Oman mainly exported 394 Bcf of natural gas to South Korea and Japan, comprising 84% of all exports (NCSI: National Center for Statistics and Information, 2019).

The available literature reviews about Oman focus dominantly on assessing the total GHG emission and the nexus between emission and economic activities and broadly acknowledge that there are significant gaps in anthropogenic CH₄ emissions inventories (Abdul-Wahab et al., 2015; Charabi et al., 2018, 2020). There are no reported specific studies for Oman on CH₄ emissions from oil and gas industries. Hence, this paper aims to improve the understanding of the scale of CH₄ emissions from oil and gas industries and to discuss the potential regulatory frameworks for phasing it out. This study uses IPCC guidelines and methodologies of 2006 to inventory CH₄ emissions from the oil and gas sector from 2000 to 2015 (IPCC: IPCC Guidelines for National Greenhouse Gas Inventories, 2006). The IPCC approach is used in most countries for their periodic emissions inventories submitted to UNFCCC. CH₄ emissions from the oil and gas sector inventory based on the IPCC approach are currently the most readily accessible emission data in most countries and are periodically submitted to UNFCCC and commonly used by international organizations (IPCC: IPCC Guidelines for National Greenhouse Gas Inventories, 2006). The trend analysis of CH₄ emission within the oil and gas sector will serve as a point of comparison with a business-as-usual (BAU) scenario to explore policy options to be considered toward

decarbonization. The analysis of CH₄ emissions from fossil fuel emissions will also contribute to scientific knowledge in regional and international literature.

This paper has the following organization: Section 2 describes the datasets and methodology. The current trend of total GHG emissions by sector and gas is presented in Section 3. The pattern of CH₄ emissions by industries from 2000 to 2015 is underlined in Section 4. Section 5 deals with the trends between 2000 and 2015 regarding CH₄ emissions by the oil and gas industry. Section 6 discusses pathways to curb CH₄ emission from fossil fuels industries.

2 Material and methods

The present study uses IPCC guidelines and methodology of 2006 (IPCC: IPCC Guidelines for National Greenhouse Gas Inventories, 2006). This guideline was developed to allow countries to report their national GHG emissions to the Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC). The 2006 IPCC Guidelines structured the GHG inventory emission methods around three levels of volume of data required and the degree of analytical complexity: (i) tier 1, the default method that is based on IPCC emission factors and uses national average data that is sufficient to approximate the level of emission per source of categories. (ii) Tier 2 is an intermediate level of detail and complexity grounded on national emission factors developed based on specific country data. Generally, tier 2 activity data is based on estimation or modeling that reflects the local change in use or behavior in an accurate manner. (iii) Tier 3 is the most complex and detailed approach that requires country-specific emission by each gas and fuel-burning technology. Tier 3 is founded on metered activity data by each GHG emission source. Progress from tier 1 to tier 3 typically reflects a reduction in GHG estimation uncertainty but at the expense of raising the sophistication of measurement processes and analyses.

The IPCC Guidelines 2006 apply a tiered approach across decision trees. A decision tree directs the selection, given national circumstances, of the tier that can be used to estimate the category under consideration. National circumstances embrace the availability of relevant data and the category's relation to overall national emissions and their trend over time. Considering the national circumstances of the Sultanate of Oman in terms of data availability, the tier 1 approach based on 2006 IPCC guidelines for fugitive emission from oil and gas operations using default emission factors is the only possible approach. The tier 1 approach is mainly based on the application of the following equations:

Equation (1): Estimating fugitive emissions from an industry segment.

$$E_{\text{gas, industry segment}} = A_{\text{industry segment}} EF_{\text{gas, industry segment}} \quad (1)$$

Equation (1): Total fugitive emissions from industry segments

$$E_{\text{gas}} = \sum_{\text{industry segments}}^n E_{\text{gas, industry segment}} \quad (2)$$

$E_{\text{gas, industry segment}}$	annual emissions (Gg).
$EF_{\text{gas, industry segment}}$	emission factor (Gg/unit of activity).
$A_{\text{industry segment}}$	activity value (unit of activity).

For the present analysis, the IPCC Inventory software (version 2.69) that incorporates the tier 1 approach of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories was used. The data were collected from the Ministry of Oil and Gas for the period of 2000 to 2015. The IPCC GHG inventory software covers four major areas: energy, industrial process, and product use, agriculture, forestry, Waste, and other land use. Fugitive emissions from oil and gas systems are a part of the IPCC sub-category of the energy sector, as shown in Fig. 1. GHG emissions in Oman were expressed in carbon dioxide equivalent ($\text{CO}_2\text{-eq}$) over 100 years, derived from the IPCC Fifth Assessment Report (IPCC: Climate Change, 2014). $\text{CO}_2\text{-eq}$ is a metric calculation used to compare emissions from different greenhouse gasses based on their GWP by converting other gasses to carbon dioxide equivalent to the same GWP.

The use of satellites is one of the most recent and promising advancements in understanding CH_4 emissions globally. Various satellites currently in service can measure atmospheric CH_4 concentrations across various geographical areas. The Sentinel 5P satellite (precursor), part of the European Space Agency (ESA) Copernicus program, offers CH_4 concentration readings in 5 km by 7.5 km and covers the entire planet on average every 4 days. The Global Emissions Monitoring (GHGSat) satellite covers a much smaller area each day but can provide very fine-tuned data (about 50 m by 50 m) (IEA, 2020).

A significant benefit of satellites is that they can help rapidly identify large emitting sources and quickly repair the leaks' sources. The growing amount of satellite data and information would further enhance global awareness and opportunities to minimize CH_4

Fig. 1 Sub-categories of the energy sector in the 2006 IPCC guidelines for national GHG inventory

emissions. Satellites, however, have limits mainly related to high uncertainty because the method of using changes in CH₄ atmospheric concentration to estimate emissions from a given source may depend on a high level of auxiliary data and be highly uncertain. Satellites can only collect CH₄ emissions from large sources and, therefore, can fail to capture small-scale sources of emissions (IEA, 2020). Considering the limitations of the satellite approach and the need for accurate data over the years for this study, the tier 1 methodology remains the most reliable for the inventory of CH₄ emissions from the oil and gas supply chain in Oman.

3 Trend of CH₄ emissions by IPCC aggregated sector

The Sultanate of Oman's total GHG emissions nearly tripled from 2000 to 2015, from 21,639 Gg CO₂-eq in 2000 to 96,072 Gg CO₂-eq in 2015. CO₂ continues its rapid rise in the Sultanate of Oman, from 13,452 Gg in 2000 to 58,565 Gg in 2015 with an increase of 3.3 times. CH₄ also grew 1.86 times, from 288 Gg in 2000 to 825 Gg in 2015. Nitrous oxide (N₂O) emissions increased from 0.426 Gg in 2000 to 1.86 Gg in 2015.

The energy sector produced almost 80% and 77% of CH₄ in 2000 and 2015, respectively. Waste sector contributions to overall CH₄ emissions in Oman rose from 10% in 2000 to 17% in 2015. CH₄ from the energy sector increased 1.72 times, from 234.7 Gg in 2000 to 639 Gg in 2015 (Fig. 2). CH₄ from Waste grew faster 4.1 times than the energy sector, from 26.93 Gg in 2000 to 137.42 Gg in 2015, followed by the agriculture sector where the emission has grown 0.63 times from 26.6 Gg in 2000 to 43.4 Gg in 2015 (Fig. 2).

Fig. 2 Trend of CH₄ emission by sector in Oman, 2000–2015

4 Trend of CH₄ emission from oil and natural gas supply chain

Energy-related CH₄ emissions from fuel combustion activities represent only a small fraction, less than 1% in 2015, and 99% of the CH₄ emissions in Oman are from fugitive emissions from oil and gas operations. The overall CH₄ from oil and gas operations increased 1.7 times from 234.4 Gg in 2000 to 634.5 Gg in 2015. The natural gas supply chain is the primary source of CH₄ emission, and their share contribution increased substantially from 56% in 2000 to 84% in 2015. CH₄ emission from natural gas operations rose three times from 132.33 Gg in 2000 to 529.96 Gg in 2015, primarily due to the sharp increase in natural gas production from 8.208 million cubic meters in 2000 to 32.837 million cubic meters in 2015 (Figs. 3 and 4). CH₄ leaks occur from the different segments of the natural gas supply chain. In 2015, wells producing natural gas and venting operations were the two major sources of CH₄ leaks, with 76% and 14%, respectively. Over the last 16 years, the rise in natural gas output has been followed by a significant increase in the total number of wells producing natural gas in Oman to ensure output from the new reserves using horizontal drilling. In conjunction with the rise in production wells, venting activities have also increased to maintain secure conditions during natural gas production and processing.

Over the last 16 years, the production of crude oil in Oman has seen profound variance. Crude oil production decreased from 394.5 million barrels in 2000 to less than 259 million barrels in 2006 due to the main oilfields' ripening onshore. The crude oil production rose from 277.3 million barrels in 2007 to 363.6 million barrels in 2015 due to the intensive use of enhanced oil recovery.

In previous years, Oman's domestic crude oil production has relied heavily on the three clean carbon enhanced oil recovery (EOR) techniques (miscible gas injections, concentrated solar power steam injections, and polymers injections) due to its matured oil fields and limited reserves. Steam injection produced with concentrating solar power (CSP)

Fig. 3 Trend of CH₄ emission from the natural gas supply chain, 2000–2015

Fig. 4 Trend of CH₄ shares contribution sub-categories of fugitive emissions from fuels in Oman, 2000–2015

technology is the preferred EOR method, especially for heavy crude with high viscosity in the oil fields located in the southern part of Oman. EOR techniques have allowed Oman to saved natural gas generally used in the conventional enhanced oil recovery and redirected it to exportation. The extensive use of clean carbon enhanced oil recovery techniques also permitted the country to control its CH₄ emission at a steady level while maintaining crude oil production at its maximum level. Overall, Oman's oil production increased in 2007–2015, by about 31.2%, with the massive use of clean carbon EOR techniques, while CH₄ emissions from oil production and upgrade only increased by 26% during the same time. In other words, EOR has increased oil production but has effectively contributed to reducing CH₄ intensity relative to production.

5 Pathways to mitigate CH₄ emission from oil and natural gas supply chain

5.1 Need for sound policy and regulation

CH₄ emission from the oil and gas industry is the first contributor to Oman's total GHG emission of about 17,765.9 CO₂ eq, representing 18.5% of overall GHG emissions in 2015 (Table 1). CH₄ emissions from oil and natural gas supply chains will continue to dominate Oman's overall GHG emission for decades due to the hydrocarbon-based economy, boosted recently by substantial upstream investment to develop the new reserves of natural gas and offshore oilfields. Over the next decade of 2020–2030, the extensive oil recovery usage will continue to stabilize Oman's crude output of around 1 million b/d. Natural gas production is expected to grow steadily by 16% from 1447.4 Bcf in 2017 to 1678.9 Bcf per year by 2025, changing Oman's gas-oil production mix significantly from around 35% gas in 2015 to over 50% in 2025 (Rystad Energy, 2019).

Table 1 Key source analysis of greenhouse gas emissions for Oman in 2015

IPCC sector	GHG source	GHG type	Emissions (Gg)		Level assessment (%)	
			Per type	CO ₂ e	Per category	Cumulative
Energy	Fugitive emissions (oil & gas)	CH ₄	634.5	17,765.9	18.5%	18.5%
Energy	Energy industries	CO ₂	16,775.9	16,775.9	17.5%	36.0%
Energy	Transport	CO ₂	13,419.9	13,419.9	14.0%	49.9%
IPPU	Refrigeration and stationary air conditioning	HFCs	1.04	12,859	13.4%	63.3%
IPPU	Lime production	CO ₂	9360	9360	9.7%	73.1%
Energy	Manufacturing & construction	CH ₂	8927.5	8927.5	9.3%	82.4%
Energy	Fugitive emissions (oil & gas)	CO ₂	3777.4	3777.4	3.9%	86.3%
IPPU	Mineral industry-cement	CO ₂	2366	2366	2.5%	88.7%
Waste	Solid waste-unmanaged waste disposal sites	CH ₄	66	1862	1.9%	90.7%
IPPU	Methanol	CO ₂	1441	1441	1.5%	92.2
AFOLU	Enteric fermentation	CH ₄	43.4	1216	1.3%	93.4
IPPU	Ammonia	CO ₂	1162	1162	1.2%	94.7
IPPU	Aluminum	PFCs	0.15	1056	1.1%	95.7
Subtotal-key categories				91,988.6	95.7%	
Total national emissions				96,072	100%	

In 2015, Oman pledged through their Nationally Determined Contributions (NDCs) to the Paris Agreement to reduce their absolute GHG emission by 2% in 2030. To achieve the Sultanate of Oman's commitment in 2018, a firm policy aimed at reaching a minimum level of renewable energy penetration of 10% of the electrical generation by 2025. Oman's renewable energy development plan encompasses solar, wind, and waste-to-energy. The Omani renewable energy plan aims to secure more than 2600 MW by 2025 under the independent power producer (IPP) model and reduce approximately 5737.55 Gg CO₂ eq. These efforts to lowering national GHG emissions by focusing only on renewable energy penetration in the energy mix embrace a high risk of fails to achieve the pledge of the Paris Agreement given the projected rise in CH₄ emission due to the steady expansion of natural gas production. During the third decade of the twenty-first century, the CH₄ emission from the oil and natural gas supply chain is projected to rise steadily, without a mitigation policy of up to 30% of the current emission (2015). In short, the projected increase of CH₄ emission due to the expected entrance of new natural gas reserves into production will be enough to erase the greenhouse gas benefits of renewables penetration in the electricity supply in the short term.

The Ministry of Environment and Climate Affairs, Oman, is the public authority responsible for climate mitigation policies and setting-up standards for the sectorial lowering of GHG emissions. The new Ministry's climate mitigation policies focus mainly on deploying on-grid solar and wind energy to reduce national GHG emissions substantially. Going forward, the Ministry should set policies that address CH₄ emission directly from oil and gas operations to maximize overall GHG reductions and achieve their climate goals. The expansion of Oman's natural gas production offers opportunities for developing policies to phase out CH₄ and investment in abatement technology. The technologies that can avoid vented and fugitive emission of CH₄ from natural gas production is well-known and economical (IEA, 2020). The investment in CH₄ reduction technologies from natural gas supply chain segments is cost-effective because the saved CH₄ leaks pay quickly for the improved equipment or the innovative operating procedures. The deployment of the CH₄ reduction technologies in Oman is very challenging without government regulations and incentives. The enforcement of regulatory framework and incentive mechanisms for CH₄ abatement from the natural gas supply chain segment is not feasible in Oman without in-depth studies that quantify the potential CH₄ reduction, the associated cost, and the expected income from selling the recovered gas (Warner et al., 2015; ICF International, 2016; Gas Infrastructure Europe (GIE), MARCOGAZ, 2019). These studies form the basis for successfully implementing a near-zero CH₄ emission strategy for Oman's natural gas supply chain. Based on the circumstances of Oman, the national oil and gas CH₄ mitigation policy can be founded on three pillars:

- Apply to both upstream and downstream operations on oil and gas

Even though CH₄ emissions in Oman are predominately from the natural gas supply chain, the policy should also apply for crude oil production due to the important volume of the petroleum-associated gas produced in Oman and accounted for 17% of the total natural gas production in 2017. Furthermore, CH₄ emission varies from facility to facility, depending upon the equipment, the operation processes, and the maintenance practices. The CH₄ reduction measures should not be restricted to a single segment of the supply chain, but they should be designed to cover both the petroleum industry's upstream and downstream activities.

- Emphasis on flexibility and cost-efficiency

The petroleum and gas industry stakeholders need to be engaged in the entire policy formulation process to ensure that the measures introduced are realistic and practical. Economically and administratively, policies should be useful in aligning legislation with market-based mechanisms. Cost-effectiveness checks are also necessary for all planned measures to ensure that legislation has a clear benefit. Furthermore, policies should motivate the oil and gas industry to maximize the value of reductions by allowing adequate flexibility to find investment opportunities to achieve maximum reductions at the lowest possible cost.

The policy mentioned above to reduce CH₄ emissions from the oil and natural gas supply chain is complicated, making it difficult for Oman's oil and gas sector to coordinate long-term investment plans credibly and understandably. The market, the financial, and the social future of oil and gas companies are becoming more and more at stake within the global energy transition framework. Several international petroleum companies operating in Oman already have a peer-to-peer regulatory support program, supporting developing countries for their initiatives to reduce CH₄ emissions from oil and gas. The government of Oman should maximize the benefit from these support schemes to enforce a broad sector-based policy to control CH₄ emissions and obtain technical and policy support for implementing regulations in a fast and cost-effective way (Climate and Clean Air Coalition (CCAC), 2020).

- Encourage innovation and continuous improvement in CH₄ leak detection systems

The designed policies should encourage the oil and gas industry to use the most sophisticated and advanced technologies standards that control the CH₄ abatement efficiently and supporting the use of new monitoring tools such as aerial light detection and ranging sensors (LiDAR) and satellite assessment for CH₄ leaks. Furthermore, a national platform or a dedicated CH₄ reduction technology fund should be initiated for R&D projects and where oil and gas actors exchange information about good practices and innovative monitoring technologies that offers low cost, accurate, and rapid inspection using drone-based CH₄ detection integrated with sophisticated sensors capable of detecting the thermogenic CH₄ from oil and gas industries efficiently (Journal of Petroleum Technology, 2020).

5.2 Need for a robust CH₄ monitoring program

A problem ahead is that there is no robust monitoring program for CH₄ emission from oil and industry in Oman, suggesting that any policy and regulation solution are not currently feasible. The Ministry of the Environment and Climate Affairs launched a climate change strategy in 2019, following up on Oman's international climate commitments under the UNFCCC and the newly developed universal framework for accurately, transparently, and extensively informing gas emissions the Paris Agreement. The establishment of a national measurement, reporting, and verification (MRV) program according to UNFCCC criteria and guidelines was one of the main compounds of Oman's climate change strategy. The MRV program targets only factories, facilities, and industries. In general, only large GHG suppliers that emit more than 2000 tCO₂ eq per year are obligated to disclose their annual GHG emissions according to international standards of scopes 1, 2, and 3. In general, the current GHG reporting system is well developed but not sufficient to ensure the accuracy, harmonization, consistency, and transparency of the CH₄ emission data from the oil and gas industry. To achieve an effective CH₄ reduction strategy, implementing a robust monitoring and reporting program for the petroleum and gasses industry is mandatory.

Transparency of CH₄ emissions is the core element of the monitoring systems to create trust, reliability, and consistency in the petroleum and gas industry. The pathway to ensure transparency is to establish compulsory harmonized methodologies for quantification and disclosing CH₄ emissions from the entire oil and gas supply chain segments. Furthermore, the reported CH₄ emission data should be available for verification by an independent third party.

6 Conclusions

This study clearly shows that CH₄ emissions from the oil and gas sectors are the primary contributor to the country's total GHG emissions, and the trend of emission has almost doubled between 2000 and 2015. There is no sign that this trend will slow down or be inversed in the coming decade due to the important reserve of oil and gas, boosted recently by the entrance of natural gas discoveries into production. Curbing CH₄ emission requires a comprehensive policy setting alongside a robust monitoring program to ensure accuracy and transparency.

The risk of price volatility is a significant barrier impeding the CH₄ abatement policy from the oil and gas supply chain segments in Oman. The market was extremely volatile between 2014 and 2020 due to the abundance of crude oil and gas. Natural gas is famous for being very seasonal and unpredictable due to higher demand during the cold season. Nevertheless, the downturn caused by the worldwide spread of the COVID-19 pandemic, the slowdown of the Asian market demand, and the disagreement between OPEC and OPEC + about production reductions has sunk oil and gas prices historically at low rates. In this context of volatility price and high uncertainty about market stability, there are very few chances that the CH₄ reduction policy will be developed by policymakers or enforcing the companies to engage in investments. Since the second half of 2014, the crude oil price and natural gas have been rapidly declining, profoundly impacting the global natural gas industry chain. Under such a low natural gas price situation, several petroleum companies cut capital expenditure to such a degree that the oil and gas output would be of particular concern in the future. A decline in oil and gas revenues may result in companies paying less attention to tackling CH₄ emissions. Low natural gas prices may result in rises in flaring or venting, and regulatory control of oil and gas activities may be reduced. Such a low natural gas price will severely impact the cost-effectiveness of CH₄ reduction technologies. Therefore, given the low prices with high uncertainty of future demand, CH₄ reduction technologies may no longer be cost-efficient. There are no in-depth studies in Oman about the cost of the CH₄ capture by companies, but we can advance a rough estimation based on some unpublished technical reports of leading oil and gas companies, indicate the benchmark cost of \$5–6/MMBtu. Over the period 2015–2020, the natural gas average selling price was around \$2.63/MMBtu and dropped below \$2/MMBtu during 2020 due to the COVID-19 pandemic crisis. In the context of the current market situation, the companies capturing CH₄ emission from natural gas in Oman will incur profit losses because of the stagnation of selling price at the lowest historical levels. In simple words, the oil and gas companies will not adopt the CH₄ abatement technology since it costs more than the captured gas potential revenue.

The current petroleum regime prices were introduced in the late 1980s, where OPEC can no longer set reference prices. Exporting countries are now selling oil on international markets based on demand formulas that reference the spot or future prices of certain

marker crudes, namely WTI, Brent, or Dubai. The price operation of the world oil market is essentially that of these crude markers. Volatility occurs in the complex and interrelated spot, futures, and other derivative markets. In the era of volatile oil and gas prices, the market mechanisms will not resolve the problem of CH₄ leaks. Price volatility creates wide-ranging instability in investment, human resources, corporate efficiency, and economic growth. Volatility causes confusion, and confusion would deter policymakers from setting-up CH₄ abatement policies and hinder investment in mitigation technologies.

Oman's dilemma is how to find the long-run equilibrium between the climate benefit of reducing CH₄ emissions and maintaining adequate financial resources from the oil industry for development in a context of a soured financial market and volatile prices. Price volatility creates widespread instability in investment, human resources, corporate efficiency, and growth. Volatility causes ambiguity, and confusion would dissuade policymakers from establishing CH₄ abatement policies and hamper investment in mitigation technologies. CH₄ reduction strategies from the oil and gas industry are a global dimension that cannot be solved at a national scale. The only pathways to regulate the compulsory phasing out of CH₄ emission from the oil and natural gas industry are to launch an international framework to incentivize the CH₄ reduction policies globally. The UN climate change framework conventions are the ideal frame to engage countries in negotiations to bridge the gap about CH₄ emission from oil and gas industries and to agree on a roadmap for deep and sustained cuts CH₄ from the oil and gas sector. Indeed, to reach climate neutrality by the second half of the century and to stay below two degrees as decided in the Paris Agreement, the UN agreement about CH₄ reduction from oil and gas seems inevitable. Without a UN international agreement, the GCC's response to adopting a firm policy for reducing CH₄ emission will stay on the sidelines.

Today's world has reached a crucial juncture where even the most aggressive carbon emissions reductions by developed countries will not be enough to prevent us from experiencing climate impacts at 2 °C. As long as nothing shifts in the oil and gas industry that decreases CH₄, the world could be on track of increasing global temperatures between 4 and 6 °C. The world has entered a new era that demands global solidarity to fight climate change, and the GCC contribution is ever more crucial. The Secretary-General of the UN Conference on Environment and Development, Earth Summit, Rio de Janeiro, 1992, Maurice Strong, said that "History reminds us that what is not possible today, maybe inevitable tomorrow." The world cannot stay helpless staring at this high level of CH₄ emission from the oil and gas industry, and there is a need for an emergency international plan to take action.

CH₄ abatement policy from the oil and gas industry has a long way to go in Oman and the rest of the GCC countries. Aside from the policy and regulatory options, the only alternative left on the table is that CH₄ detection and measurement technologies continue developing over time and allowing lower-cost cuts to move forward.

References

- Abdul-Wahab SA, Charabi Y, Al Rawas G, Al-Maamarri R, Gastli A, Chan K (2015) Greenhouse gas (GHG) emissions in the Sultanate of Oman. *Greenh Gases Sci Technol* 5(3). <https://doi.org/10.1002/ghg.1501>
- Bader W, Bovy B, Conway S, Strong K, Smale D, Turner AJ, Blumenstock T, Boone C, Collaud Coen M, Coulon A, Garcia O, Griffith DWT, Hase F, Hausmann P, Jones N, Krummel P, Murata I, Morino I, Nakajima H, O'Doherty S, Paton-Walsh C, Robinson J, Sandrin R, Schneider M, Servais C, Sussmann R, Mahieu E (2017) The recent increase of atmospheric methane from 10 years of ground-based

- NDACC FTIR observations since 2005. *Atmos Chem Phys* 17:2255–2277. <https://doi.org/10.5194/acp-17-2255-2017>
- Balcombe P, Speirs JF, Brandon NP, Hawkes AD (2018) Methane emissions: choosing the right climate metric and time horizon (2018). *Environ Sci Process Impacts* 20:1323–1339. <https://doi.org/10.1039/C8EM00414E>
- Central Bank of Oman (2018) Annual report 2018. <https://cbo.gov.om/Pages/AnnualReport.aspx>. Accessed Mar 2020
- Charabi Y, Al-Awadhi T, Choudri Bs (2018) Strategic pathways and regulatory choices for effective GHG reduction in a hydrocarbon-based economy: case of Oman. *Energy Rep* 4:653–659. <https://doi.org/10.1016/j.egyr.2018.10.005>
- Charabi Y, Al Nasiri N, Al Awadhi T, Choudri BS, Al BA (2020) GHG emissions from the transport sector in Oman: trends and potential decarbonization pathways. *Energ Strat Rev* 32(2020):100548. <https://doi.org/10.1016/j.esr.2020.100548>
- Climate & Clean Air Coalition (CCAC) (2020) Oil and gas peer-to-peer regulatory support. <https://www.ccacoalition.org/en/activity/oil-and-gas-peer-peer-regulatory-support>. Accessed Nov 2020
- Gas Infrastructure Europe (GIE), MARCOGAZ (2019) Potential ways the gas industry can contribute to the reduction of methane emissions. <https://www.gie.eu/index.php/gie-publications/methane-emission-report-2019>. Accessed Nov 2020
- ICF International (2016) Economic analysis of methane emission reduction potential from natural gas systems. <https://onefuture.us/wp-content/uploads/2018/07/ICF-Study.pdf>. Accessed Nov 2020
- IEA (2020) Methane Tracker 2020, IEA, Paris. <https://www.iea.org/reports/methane-tracker-2020>. Accessed March 2020
- IPCC: Climate Change (2014) 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.). Cambridge 2955 University Press
- IPCC: IPCC Guidelines for National Greenhouse Gas Inventories (2006) The National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). The Intergovernmental Panel on Climate Change, IPCC TSU NGGIP, IGES. Institute for Global Environmental Strategy, Hayama, Kanagawa, Japan. Available online at: http://www.ipccnggip.iges.or.jp/support/Primer_2006GLs.pdf. Accessed 10 Nov 2016
- Journal of Petroleum Technology (2020) ExxonMobil field tests new methane leak detection systems. <https://pubs.spe.org/en/jpt/jpt-article-detail/?art=6884>. Accessed Nov 2020
- Kumar A, Sharma MP (2012) Greenhouse gas emissions from hydropower reservoirs. *Hydro Nepal J Water Energy Environ* 11. <https://doi.org/10.3126/hn.v11i0.7159>
- Kumar A, Yang T, Sharma MP (2019) Greenhouse gas measurement from Chinese freshwater bodies: a review. *J Clean Prod* 233. <https://doi.org/10.1016/j.jclepro.2019.06.052>
- Mallapragada DS, Mignone BKA (2020) theoretical basis for the equivalence between physical and economic climate metrics and implications for the choice of Global Warming Potential time horizon (2020). *Clim Change* 158:107–124. <https://doi.org/10.1007/s10584-019-02486-7>
- Myhre G, Shindell D, Bréon F-M, Collins W, Fuglestad J, Huang J, Koch D, Lamarque J-F, Lee D, Mendonza B, Nakajima T, Robock A, Stephens G, Takemura T, and Zhang H (2013) Anthropogenic and natural radiative forcing. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) *In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York
- NCSI: National Center for Statistics and Information (2019) <https://www.ncsi.gov.om>. Accessed Mar 2020
- Prather MJ, Holmes CD, Hsu J (2012) Reactive greenhouse gas scenarios: Systematic exploration of uncertainties and the role of atmospheric chemistry. *Geophys Res Lett* 39:L09803. <https://doi.org/10.1029/2012gl051440>
- Rice AL, Butenhoff CL, Teama DG, Röger FH, Khalil MAK, Rasmussen RA (2016) Atmospheric methane isotopic record favors fossil sources flat in 1980s and 1990s with recent increase (2016). *Proc Natl Acad Sci* 113(39):10791–10796. <https://doi.org/10.1073/pnas.1522923113>
- Rystad Energy (2019) Gas to out-produce oil in Oman. <https://www.rystadenergy.com/newsevents/news/press-releases/Gas-to-out-produce-oil-in-Oman/>. Accessed Apr 2020
- Saunio M, Bousquet P, Poulter B, Peregon A, Ciais P, Canadell JG, Dlugokencky EJ, Etiope G, Bastviken D, Houweling S, Janssens-Maenhout G, Tubiello FN, Castaldi S, Jackson RB, Alexe M, Arora VK, Beerling DJ, Bergamaschi P, Blake DR, Brailsford G, Brovkin V, Bruhwiler L, Crevoisier C, Crill P, Covey K, Curry C, Frankenberg C, Gedney N, Höglund-Isaksson L, Ishizawa M, Ito A, Joos F,

- Kim HS, Kleinen T, Krummel P, Lamarque JF, Langenfelds R, Locatelli R, Machida T, Maksyutov S, McDonald KC, Marshall J, Melton JR, Morino I, Naik V, O'Doherty S, Parmentier FJW, Patra PK, Peng C, Peng S, Peters GP, Pison I, Prigent C, Prinn R, Ramonet M, Riley WJ, Saito M, Santini M, Schroeder R, Simpson IJ, Spahni R, Steele P, Takizawa A, Thornton BF, Tian H, Tohjima Y, Viovy N, Voulgarakis A, van Weele M, van der Werf GR, Weiss R, Wiedinmyer C, Wilton DJ, Wiltshire A, Worthy D, Wunch D, Xu X, Yoshida Y, Zhang B, Zhang Z, Zhu Q (2016) The global methane budget 2000–2012. *Earth Syst Sci Data* 8:697–751. <https://doi.org/10.5194/essd-8-697-2016>
- Saunio M, Stavert AR, Poulter B, Bousquet P, Canadell JG, Jackson RB, Raymond PA, Dlugokencky EJ, Houweling S, Patra PK, Ciais P, Arora VK, Bastviken D, Bergamaschi P, Blake DR, Brailsford G, Bruhwiler L, Carlson KM, Carrol M, Castaldi S, Chandra N, Crevoisier C, Crill PM, Covey K, Curry CL, Etiope G, Frankenberg C, Gedney N, Hegglin MI, Höglund-Isaksson L, Hugelius G, Ishizawa M, Ito A, Janssens-Maenhout G, Jensen KM, Joos F, Kleinen T, Krummel PB, Langenfelds RL, Laruelle GG, Liu L, Machida T, Maksyutov S, McDonald KC, McNorton J, Miller PA, Melton JR, Morino I, Müller J, Murgia-Flores F, Naik V, Niwa Y, Noce S, O'Doherty S, Parker RJ, Peng C, Peng S, Peters GP, Prigent C, Prinn R, Ramonet M, Regnier P, Riley WJ, Rosentreter JA, Segers A, Simpson IJ, Shi H, Smith SJ, Steele LP, Thornton BF, Tian H, Tohjima Y, Tubiello FN, Tsuruta A, Viovy N, Voulgarakis A, Weber TS, van Weele M, van der Werf GR, Weiss RF, Worthy D, Wunch D, Yin Y, Yoshida Y, Zhang W, Zhang Z, Zhao Y, Zheng B, Zhu Q, Zhu Q, Zhuang Q (2019) The Global Methane Budget 2000–2017. *Earth Syst Sci Data Discuss* 2019. 10.5194/essd-2019-128. in review
- Schaefer H (2019) On the causes and consequences of recent trends in atmospheric methane. *Curr Clim Change Rep* 5:259–274. <https://doi.org/10.1007/s40641-019-00140-z>
- Shindell D, Kuylenstierna JCI, Vignati E, van Dingenen R, Amann M, Klimont Z, Anenberg SC, Muller N, Janssens-Maenhout G, Raes F, Schwartz J, Faluvegi G, Pozzoli L, Kupiainen K, Höglund-Isaksson L, Emberson L, Streets D, Ramanathan V, Hicks K, Oanh NTK, Milly G, Williams M, Demkine V, Fowler D (2012) Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science* 335:183–189. <https://doi.org/10.1126/science.1210026>
- The United Nations Framework Convention on Climate Change, UNFCCC (2020) <https://unfccc.int/gcse?q=dual%20term%20GWP20/GWP100%20accounting%20standard>. Accessed Nov 2020
- UN News (2019) COP25: UN climate change conference, 5 things you need to know <https://news.un.org/en/story/2019/12/1052251>. Accessed Mar 2020
- Warner E, Steinberg D, Hodson E, Heath G (2015) Potential cost-effective opportunities for methane emission abatement. Joint Institute for Strategic Energy Analysis, <https://www.nrel.gov/docs/fy16osti/62818.pdf>. Accessed Nov 2020

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