DOI:10.5937/IIZS25237M

IMPACT OF GAS FLARING AND VENTING PROCESSES IN THE OIL INDUSTRY ON AIR QUALITY

Milan Markovic[1*], Marko Blažić[1], Katarina Vignjević[1], Jasna Tolmač[1]
[1]University of Novi Sad, Technical Faculty "Mihajlo Pupin", Zrenjanin, Serbia
e-mail: milan.markovic@uns.ac.rs

Abstract: This review paper examines the impact of gas flaring and direct venting in the oil and gas industry on air quality and climate change. Flaring generates CO_2, NO_x, SO_2, and fine particulate matter, including black carbon, while venting directly releases methane with a high short-term global warming potential. Due to variable combustion efficiency, unlit flares, and systematic venting, actual emissions often exceed reported inventories. We summarize findings from studies based on satellite assessments and targeted field measurements, including the identification of 'ultra-emitters' and epidemiological evidence of local health effects. Regulatory trends (EU, USA) toward banning routine flaring/venting, introducing mandatory MRV/LDAR programs, and aligning with international initiatives are discussed. Technological mitigation measures are presented (gas capture and reuse, replacement of pneumatic equipment with low-emission alternatives, closed-loop systems, and, where applicable, CCS) along with their medium-term cost-effectiveness. We conclude that the rapid implementation of available solutions is crucial for achieving sustainable development goals, improving air quality, and supporting the energy transition.

Key words: gas flaring; venting; methane; air quality; black carbon; MRV/LDAR; ultra-emitters; energy transition

INTRODUCTION

The oil industry, through its operations of gas flaring and direct venting, represents a significant source of air pollution and greenhouse gas emissions [3, 5]. Gas flaring releases a wide spectrum of pollutants — including CO_2, CO, NO_x, SO_2, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and black carbon — which exert local, regional, and global climate effects [1–3, 5]. Venting, on the other hand, releases large quantities of methane — a super greenhouse gas with a substantially higher short-term global warming potential compared to CO_2 [3, 5]. Due to inconsistent reporting and the intermittent nature of these processes, actual emissions are often significantly higher than officially reported [1–5]. The aim of this paper is to provide a concise overview of existing studies on the impact of flaring and venting in the oil industry on air quality, with a particular focus on harmful gas emissions, climate change, and human health. The paper draws upon analyses from the literature that include satellite-based emission assessments, health impacts, and emission reduction methods, with the goal of providing a relevant review for conference presentation [2, 3, 5]. In the context of global climate challenges, particularly within the framework of the Paris Agreement and the 2030 Agenda, methane reduction has emerged as one of the key issues for achieving a sustainable energy transition. Flaring and venting are increasingly viewed not only as technical or safety processes but also as critical factors in climate policy, public health, and sustainable development. Their connection to air quality, regional community health, and global climate effects makes them a topic of particular importance for scientific gatherings and international initiatives. Moreover, the continuous development of satellite technologies and monitoring systems enables more accurate quantification of emissions, thereby narrowing the gap between reported and actual data. This, in turn, provides a foundation for more precise regulations, stronger oversight, and broader implementation of emission reduction measures in the oil and gas sector. The following sections provide a detailed discussion of flaring and venting processes, their environmental and health impacts, as well as possibilities and perspectives for their mitigation.

MATERIAL AND METHODS

This review synthesizes peer-reviewed literature, satellite-based assessments, targeted field measurements, and epidemiological studies, complemented by regulatory and policy documents (EU/US frameworks and UN initiatives). Sources were screened for methodological transparency and relevance to (i) flare efficiency and emissions composition, (ii) methane venting magnitudes, (iii) health impacts, and (iv) mitigation options and costs. Evidence was organized into two process streams—flaring and venting—to enable consistent comparison of emission pathways, measurement approaches, and reported uncertainties. Where available, cross-study contrasts (e.g., aircraft campaigns vs. satellite retrievals) were used to contextualize inventory gaps and to inform the subsequent discussion of technological and regulatory mitigation.

Gas flaring process

Gas flaring is the controlled combustion of excess gas at a flare stack, applied when the gas cannot be captured or utilized due to safety, operational, or infrastructural reasons [1]. Three main types are typically distinguished: emergency flaring during abnormal pressure events, temporary flaring during plant start-ups or shutdowns, and routine flaring where no gas recovery systems are in place [6]. Although the intended outcome of combustion is to convert methane into carbon dioxide, actual efficiency depends on gas composition, flow rate, and atmospheric conditions, and often deviates from the idealized 98% assumed in emission inventories [8]. Major emissions include CO_2 and CO, nitrogen oxides (NO_x), sulfur dioxide (SO_2), volatile organic compounds, and fine particulates, with black carbon being of particular concern [1]. Aircraft-based measurements in the Bakken Basin (North Dakota) revealed that a portion of flares operate with substantially lower efficiency, leading to higher methane and black carbon emissions than predicted by standard factors [7]. An analysis of more than 300 flares in the United States demonstrated that inefficient and unlit flares reduce the effective methane destruction rate to an average of about 91%, significantly increasing its contribution to global warming [8]. Measurements in the North Sea showed a median combustion efficiency of around 98%, but also significant NO_x emissions, confirming that even at high efficiency, pollutants relevant to air quality are generated [6]. The health impact of flaring has also been epidemiologically confirmed: in the Eagle Ford region of Texas, intensive flaring was associated with increased incidence of preterm births [9]. Regional studies in Nigeria demonstrated that meteorological factors and flare characteristics influence the dispersion of CO, SO_2, and black carbon into populated areas, thereby worsening air quality [10]. At the global scale, satellite data (e.g., Sentinel-3A SLSTR) have enabled the quantification of flaring and black carbon emissions, with Russia and the United States identified as the largest contributors [11]. These analyses confirm that flaring remains a significant source of CO_2, NO_x, SO_2, particulates, and methane, with implications for local air pollution episodes and global climate change [1].

Gas venting process

Venting refers to the intentional release of unburned natural gas (predominantly CH_4) into the atmosphere from equipment and processes in the oil and gas industry, typically during testing, maintenance, start-up/shutdown procedures, operation of pneumatic devices, or in the absence of gas handling infrastructure [2]. Unlike flaring, venting does not oxidize methane into CO_2, so its primary climate impact derives from the direct release of CH_4 [2, 12]. In practice, some processes are even designed to periodically or continuously release gas (e.g., tank venting, safety valves), making venting a systematic emission source when gas capture and utilization are absent [12]. Methane has a much stronger warming effect per ton than CO_2; recent radiative forcing calculations have revised upward the impact of CH_4 compared to earlier estimates, which makes the climate consequences of venting proportionally greater [13]. Given methane's relatively short atmospheric lifetime (~12 years), rapid venting reduction delivers immediate climate benefits and high cost-effectiveness of mitigation measures [14]. In heavy oil recovery operations without combustion (e.g., CHOPS), venting is frequent and often underestimated in inventories [4]. Field measurements at five CHOPS facilities in Alberta revealed large discrepancies between measured and reported rates, identifying venting (particularly 'casing gas') as the dominant source [15]. Broader measurement syntheses in the United States indicate that methane emissions in the production segment are ~1.5–2× higher than official inventories, with a portion of emissions stemming from processes that deliberately vent gas [12]. Satellite analyses also reveal episodes of 'ultra-emitters' in oil and gas basins worldwide (maintenance, malfunctions, venting), which account for a significant share of total emissions and are a target for rapid mitigation [16]. These findings are driving regulatory policies toward 'zero routine venting,' mandatory measurement, and faster source elimination [17]. In 2024, the European Union adopted a methane emissions reduction regulation in the energy sector that bans routine venting/flaring (with safety exceptions) and introduces mandatory MRV and LDAR practices [17, 18]. In addition, UN initiatives (e.g., UNEP OGMP 2.0 and the Global Methane Pledge) encourage companies and governments to transition from estimates to measurements and to reduce intentional venting [19, 20]. Technical measures (gas capture and reuse, replacement of pneumatic devices with low-emission alternatives, compression and closed-loop systems) have been identified as widely available and cost-effective options for rapid venting reduction [12, 14].

RESULTS AND DISCUSSION

Flaring and venting processes involve different mechanisms and environmental consequences, yet both represent significant sources of greenhouse gas emissions [1, 2]. Flaring primarily converts methane into CO_2 but simultaneously produces NO_x, SO_2, and black carbon, contributing to air pollution and short-term climate warming [1, 5, 6]. Venting, by contrast, directly releases methane into the atmosphere, emitting a gas with a substantially higher global warming potential over shorter timescales [2, 12, 13]. The combined effects of these processes are reflected in both local health outcomes and global climate change. Studies in Texas have shown a correlation between intensive flaring and increased risk of preterm births, highlighting the health implications of exposure to a mixture of pollutants [9]. In Canada, measurements at heavy oil production facilities confirmed that venting is frequently underestimated and that actual emissions can be several times higher than reported [4, 15]. At the global level, satellite analyses have identified the occurrence of 'ultra-emitters,' i.e., massive methane release events that significantly contribute to total emissions and demand urgent mitigation measures [16]. Technological options for emission reduction include gas capture and reuse systems, installation of low-emission equipment in place of pneumatic devices, closed-cycle compression systems, and carbon capture and storage (CCS) technologies [12, 14]. According to assessment models, rapid implementation of these measures could substantially reduce global methane emissions by 2050 at relatively low costs [14]. The regulatory framework is becoming increasingly stringent, particularly in the EU and the USA, where routine venting and flaring are prohibited, mandatory monitoring programs and super-emitter detection are introduced, along with international initiatives such as UNEP OGMP 2.0 and the Global Methane Pledge [17–20]. These trends emphasize the transition to sustainable technologies and the growing pressure from international organizations to reduce methane emissions as quickly as possible.

CONCLUSION

Gas flaring and venting in the oil and gas industry are significant sources of air pollution and greenhouse gas emissions. Flaring generates a mixture of CO_2, NO_x, SO_2, and particulates (including black carbon), while venting directly releases methane with a high short-term climate impact [1,2]. Variable combustion efficiency, unlit flares, and systematic venting contribute to actual emissions exceeding reported levels, thereby amplifying both local health risks and global climate impacts [6,8,9,12]. Satellite observations and targeted measurement campaigns have identified episodes of 'ultra-emitters' and demonstrated that emissions in the production segment are often 1.5–2× higher than inventories, underscoring the need for evidence-based measurements and rapid interventions [12,16]. Reducing emissions requires a combination of technical and regulatory solutions: gas capture and reuse, replacement of pneumatic devices with low-emission alternatives, closed-loop systems, and complementary measures (e.g., CCS where justified), alongside mandatory MRV/LDAR programs and super-emitter detection [12,14]. The new regulatory frameworks in the EU and USA, as well as initiatives such as OGMP 2.0 and the Global Methane Pledge, are steering the sector toward a 'zero routine flaring/venting' regime and more transparent reporting [17–20]. Looking ahead, the rapid implementation of available measures, coupled with stronger oversight and standards, can deliver significant and cost-effective reductions, support sustainable development goals, and accelerate the energy transition, while simultaneously improving air quality and public health [14,17–20]. The key challenge in the coming period will be balancing the economic interests of oil and gas companies with increasingly stringent regulatory requirements. Although technologies capable of substantially reducing emissions are already available, their widespread adoption will depend on political will, financial incentives, and international cooperation. Ultimately, this combination of factors will determine the pace at which the industry transitions to more sustainable practices and contributes to mitigating climate change.

REFERENCES

[1] Fawole, O. G., Cai, X.-M., & MacKenzie, A. R., Gas flaring and resultant air pollution: A review focusing on black carbon, Environmental Pollution, vol. 216, pp. 182–197, 2016. doi:10.1016/j.envpol.2016.05.075

[2] Soltanieh, M., Zohrabian, A., Gholipour, M. J., & Kalnay, E., A review of global gas flaring and venting and impact on the environment: Case study of Iran, International Journal of Greenhouse Gas Control, vol. 49, pp. 488–509, 2016. doi:10.1016/j.ijggc.2016.02.010

[3] Tran, H., Polka, E., Buonocore, J. J., Roy, A., Trask, B., Hull, H., & Arunachalam, S., Air quality and health impacts of onshore oil and gas flaring and venting activities estimated using refined satellite-based emissions, GeoHealth, vol. 8, no. 3, e2023GH000938, 2024. https://doi.org/10.1029/2023GH000938

[4] Festa-Bianchet, S. A., Tyner, D. R., Seymour, S. P., & Johnson, M. R., Methane venting at Cold Heavy Oil Production with Sand (CHOPS) facilities is significantly underreported and led by high-emitting wells with low or negative value, Environmental Science & Technology, vol. 57, no. 8, pp. 3021–3030, 2023. https://doi.org/10.1021/acs.est.2c06255

[5] Chen, C., McCabe, D. C., Fleischman, L. E., & Cohan, D. S., Black carbon emissions and associated health impacts of gas flaring in the United States, Atmosphere, vol. 13, no. 3, 385, 2022. https://doi.org/10.3390/atmos13030385

[6] Shaw, J. T., Foulds, A., Wilde, S., Barker, P., Squires, F. A., Lee, J., Purvis, R., Burton, R., Colfescu, I., Mobbs, S., Cliff, S., Bauguitte, S. J.-B., Young, S., Schwietzke, S., & Allen, G., Flaring efficiencies and NOx emission ratios measured for offshore oil and gas facilities in the North Sea, Atmospheric Chemistry and Physics, vol. 23, pp. 1491–1509, 2023. doi:10.5194/acp-23-1491-2023

[7] Gvakharia, A., Kort, E. A., Brandt, A., Peischl, J., Ryerson, T. B., Schwarz, J. P., Smith, M. L., & Sweeney, C., Methane, black carbon, and ethane emissions from natural gas flares in the Bakken Shale, North Dakota, Environmental Science & Technology, vol. 51, pp. 5317–5325, 2017. doi:10.1021/acs.est.6b05183

[8] Plant, G., Kort, E. A., Brandt, A. R., Chen, Y., Fordice, G., Gorchov Negron, A. M., Schwietzke, S., Smith, M., & Zavala-Araiza, D., Inefficient and unlit natural gas flares both emit large quantities of methane, Science, vol. 377, pp. 1566–1571, 2022. doi:10.1126/science.abq0385

[9] Cushing, L. J., Vavra-Musser, K., Chau, K., Franklin, M., & Johnston, J. E., Flaring from unconventional oil and gas development and birth outcomes in the Eagle Ford

Shale in South Texas, Environmental Health Perspectives, vol. 128, no. 7, pp. 077003-1–077003-10, 2020. doi:10.1289/EHP6394

[10] Fawole, O. G., Cai, X., Abiye, O. E., & MacKenzie, A. R., Dispersion of gas flaring emissions in the Niger delta: Impact of prevailing meteorological conditions and flare characteristics, Environmental Pollution, vol. 246, pp. 284–293, 2019. doi:10.1016/j.envpol.2018.12.021

[11] Caseiro, A., Gehrke, B., Rücker, G., Leimbach, D., & Kaiser, J. W., Gas flaring activity and black carbon emissions in 2017 derived from the Sentinel-3A Sea and Land Surface Temperature Radiometer, Earth System Science Data, vol. 12, pp. 2137–2155, 2020. doi:10.5194/essd-12-2137-2020

[12] Rutherford, J. S., Sherwin, E. D., Ravikumar, A. P., Heath, G. A., Englander, J., Cooley, D., Lyon, D., Omara, M., Langfitt, Q., & Brandt, A. R., Closing the methane gap in US oil and natural gas production emissions inventories, Nature Communications, vol. 12, p. 4715, 2021. doi:10.1038/s41467-021-25017-4

[13] Etminan, M., Myhre, G., Highwood, E. J., & Shine, K. P., Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing, Geophysical Research Letters, vol. 43, pp. 12614–12623, 2016. doi:10.1002/2016GL071930

[14] Höglund-Isaksson, L., Gómez-Sanabria, A., Klimont, Z., Rafaj, P., & Schöpp, W., Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe – results from the GAINS model, Environmental Research Communications, vol. 2, 025004, 2020. doi:10.1088/2515-7620/ab7457

[15] Roscioli, J. R., Herndon, S. C., Yacovitch, T. I., Knighton, W. B., Zavala-Araiza, D., Johnson, M. R., & Tyner, D. R., Characterization of methane emissions from five cold heavy oil production with sands (CHOPS) facilities, Journal of the Air & Waste Management Association, vol. 68, no. 7, pp. 671–684, 2018. doi:10.1080/10962247.2018.1436096

[16] Lauvaux, T., Giron, C., Mazzolini, M., d'Aspremont, A., Duren, R., Cusworth, D., Shindell, D., & Ciais, P., Global assessment of oil and gas methane ultra-emitters, Science, vol. 375, pp. 557–561, 2022. doi:10.1126/science.abj4351

[17] Olczak, M., Piebalgs, A., & Balcombe, P., A global review of methane policies reveals that only 13% of emissions are covered with unclear effectiveness, One Earth, vol. 6, pp. 519–532, 2023. doi:10.1016/j.oneear.2023.04.009

[18] European Parliament and Council, Regulation (EU) 2024/1787 of the European Parliament and of the Council on methane emissions reduction in the energy sector, Official Journal of the European Union, L, 2024. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R1787

[19] United Nations Environment Programme, Oil and Gas Methane Partnership 2.0: A new standard in methane emissions reporting, UNEP, 2020. https://www.ogmpartnership.org

[20] European Commission, Global Methane Pledge, European Commission & U.S. Department of State, 2021. https://www.globalmethanepledge.org