Deep near-term mitigation of short-lived climate forcers in Oman: grand challenges and prospects

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Abstract
Over time, short-lived climate forcers (SLCFs) have gradually gained prominence as a rationale in the international global mitigation strategy to preserve temperature below 1.5 °C by the end of this century. Scientists cite the short-term gains in air quality and health co-benefits associated with reducing SLCFs as grounds for raising the pressure on governments to eliminate SLCFs rapidly and aggressively. There is little research on whether deep SLCF mitigation during the next decade is feasible in low- and middle-income nations, particularly the hydrocarbon-based economy. This study estimates current and future emissions of potent SLCFs as methane (CH₄), hydrofluorocarbons (HFCs) in Oman using the basic tier 1 approach of the Intergovernmental Panel on Climate Change (IPCC) greenhouse gases (GHG) inventory Guidelines of 2006. Current and future emission of black carbon (BC) was also quantified using specific emission factors. A total of 38,268 Gg of SLCFs were released into the atmosphere in Oman in 2015, accounting for 38.8% of the country’s total GHG emissions, and is expected to rise significantly over the next decade to reach 67,777 Gg by 2030. The analysis reveals that the source of Oman’s highly potent SLCF emissions is associated with key and critical economic sectors such as the oil and gas industry, heavy road transportation, residential air conditioning (RAC), and industrial refrigeration. These vital economic sectors impose a “Grand Challenge” on the immediate reduction of SLCFs in Oman and the Gulf Cooperation Council (GCC). Accomplishing a rapid, significant reduction in highly potent SLCFs from the three challenging sectors over a 5- to 10-year time period does not appear feasible or realistic in the context of international market mechanisms, socioeconomic factors, and mitigation targets. Achieving a significant reduction in SLCFs for a hydrocarbon-based economy requires a profound economic shift. Creating an effective long-term vision for a post-oil economy over the next two decades provides a sound foundation for implementing economic and societal transformation policies incorporating near-zero-emission measures for the potent SLCFs.

Keywords Short-lived climate forcers · Emission patterns · Trend forecasting · Mitigation challenge

Introduction
Over the last decade, short-lived climate forcers (SLCFs) have received widespread attention in mitigation strategies following conclusive scientific evidence that has established that they are responsible for half of observed global warming. The remaining half is derived from excessive CO₂ emissions (Rogelj et al. 2014; Haines et al. 2017; Cain et al. 2019; Fu et al. 2020; Smith et al. 2020). Furthermore, multiple scientific studies have demonstrated unequivocally that immediate and significant reductions in highly potent SLCFs such as CH₄, BC, HFCs, and tropospheric ozone are necessary to keep global warming below 1.5 °C by the end of this century (IPCC 2018; Allen 2020). Recently, modeling studies have concluded that cutting SLCFs would help prevent 0.6 °C global average warmings by 2050 and halve the current pace of global warming (Xu and Ramanathan 2017; Hanaoka and Masui 2020).

Despite the international commitment under the Paris Agreement to limit global mean temperature rise to less than 2 °C and strive for less than 1.5 °C and the mounting evidence that mitigation measures focused exclusively on CO₂ emissions will be insufficient to halt or significantly
reduce the pace of climate warming in the coming decades, necessitating fast-action for SLCF abatement, nonetheless, studies indicate that countries’ nationally determined contribution (NDCs) plans are insufficiently aggressive to achieve a 1.5 or 2 °C objective and often focus exclusively on CO₂ emission reductions without addressing SLCF cuts (Den Elzen et al. 2016; Fawcett et al. 2016; Rogelj et al. 2016; UNEP 2016; Vandyck et al. 2016; Harmsen et al. 2019). The focus on CO₂ emissions was driven by a focus on renewable energy sources and energy efficiency measures, which positively affect GDP, employment, wages, government income (through taxes), and capital formation (Stamopoulos et al. 2021). According to a recent study by the international council on clean transportation, a quick reduction of diesel black carbon emissions is critical in reducing global warming to an average of 0.5 °C over 25 years. To meet this goal, by 2030, emissions of BC from all sectors must be 75% lower than they were in 2010 (ICCT 2018). With the entry into force of the Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer on January 1, 2019, the world has taken an essential step in drastically cutting back on the production and use of HFCs and limiting global warming. If governments, the business sector, and people are actively supported, this amendment will avert up to 0.4 °C of global warming this century while preserving the ozone layer’s protections (UNEP 2019).

Additionally, a recent study reports that India and China launched an ambitious effort in 2015 to reduce HFC, namely HFC-23 emissions, by 75% by 2017. However, the study demonstrates a significant gap between reported and inferred estimates of HFC-23 gases based on atmospheric observations, implying that they are most likely incapable of meeting the proclaimed reduction objective (Stanley et al. 2020). The study’s findings imply that implementing SLCF reduction in low- and middle-income countries will be difficult, casting doubt on the true potential for SLFC reduction that these countries genuinely possess.

The short-term gains of improved air quality and health co-benefits associated with reduced SLCF mitigation have dominated the scientific literature as a justification for increasing the pressure on taking swift and aggressive efforts to reduce SLCFs (Stohl et al. 2015; Rauner et al. 2020; Harmsen et al. 2020). Indeed, a dearth of studies investigating whether deep mitigation of SLCFs during the next decade is conceivable or practical in low- and middle-income countries in general or in the hydrocarbon economies in particular. The GCC controls the world’s largest oil and natural gas reserves and ranks eighth in the world in terms of greenhouse gas (GHG) emissions (1245.43 Mt CO₂-e) in 2018 (World Resources Institute 2021). Additionally, the GCC has a high ambient temperature and accounts for 40% of the world’s market for district cooling (GMI 2021). HFC levels have risen rapidly throughout the GCC over the last decade, and under a business-as-usual scenario, they will continue to rise over the next decade (CEIC 2021). The cooling industry’s need will continue to grow over the next decade, escalating demand for HFCs in the coming years, based on various countries’ national aspirations for economic diversification. Additional megaprojects are planned in the GCC region, including the Dubai Metro, the Yas Island Development project, and the Doha Metro, which will increase demand for air cooling over the next decade.

The GCC is a critical piece of the global mitigation efforts and is still perceived as resistive and reluctant to ambitious GHG emission reduction initiatives (Charabi 2021). 2015 nationally determined contributions (NDCs) reveal that the majority of GCC countries have shown little or no intention to commit to carbon neutrality over the next several decades. Furthermore, the 2015 NDCs suggest that GHG emissions would rise over the next decade in most GCC, with Bahrain’s emissions per capita growing by 29%, Kuwait’s by 8%, Saudi Arabia’s by 5%, and Qatar’s by 3%. In contrast, GHG emissions per capita are predicted to fall slightly by 5% in Oman due to the country’s ambitious target of generating 30% of its electricity from renewable sources by 2030. The UAE’s GHG emissions per capita are also predicted to fall significantly by 29% by 2030, owing to the country’s heavy reliance on nuclear energy (NDC and INDC 2017). The second NDCs of UAE and Oman pledges to reduce GHG emissions by 23.5% and 7%, respectively, by 2030 compared to business as usual (BAU). The second NDCs of Bahrain prioritizes adaptation measures (particularly those with mitigation co-benefits) over mitigation. This paper discusses GCC’s potential to significantly reduce SLCFs during the next decade. The paper then examines the extent to which SLCFs may be effectively integrated into GCC mitigation efforts and make a significant contribution to the Paris agreement’s goal. The Sultanate of Oman is a GCC member, which we use as a case study to assess the trend of SLCF emissions and prospect the practical pathways and feasible technical solutions that motivate decision-makers to act.

Climate change is no longer a distant risk in the GCC, particularly in Oman, but a present-day reality. Global warming has accelerated over the last few decades, increasing the frequency and severity of tropical storms, flooding, and record temperatures in Oman. Global warming is expected to severely impact several Oman’s economic sectors if carbon emissions are not drastically decreased worldwide. The world’s leaders have set an audacious aim for the next decade: to achieve net-zero emissions by 2050. The oil-producing countries’ contribution is critical to achieving this goal by 2050. Over the next few decades, the world will require the assistance of all oil-producing countries, even little ones like Oman. Without the help of oil producers, regardless of current production levels, achieving net-zero emissions by 2050 is a faraway dream. According to the
International Energy Agency’s new global roadmap, global oil demand must fall from around 90 million barrels per day to fewer than 25 million barrels per day by 2050. This would reduce net income by 75% for oil-producing countries, which rely on oil exports and profits (IEA 2021). Oman’s vulnerability to climate change goes beyond the impacts of extreme climate events and rising temperatures; the country’s reliance on hydrocarbons makes it especially vulnerable to the transition away from fossil fuels and toward cleaner energy sources. Petroleum and natural gas have developed into an integral part of Oman’s economy during the last 50 years, accounting for nearly 70% of government revenue and 28% GDP in 2019. Oman confronts a major challenge in balancing its objectives for a quick transition post-oil economy and low-carbon-resilient development. The scientific knowledge about the GHG emission in Oman is still emerging, and the published research focuses primarily on assessing GHG emissions and nexus with economic activity and developing pathways for reducing GHG for the most often emitted sector such as transportation and energy (Abdulwahab et al. 2015; Charabi et al. 2018). Currently, no relevant SLCF reports have been conducted in Oman. Therefore, critical knowledge gaps regarding SLCFs in Oman motivate this research to fully understand their current and projected trends and determine the emission reduction potential that maximizes synergies for the transition to a post-oil economy and low-carbon-resilient climate development.

This article seeks better to understand the current and future pattern emissions of SLCFs and discuss various regulatory framework mechanisms for their reductions. The SLCFs emission trend analysis is used to compare a BAU scenario to policy choices for emission reduction. Additionally, investigating SLCFs emissions will advance regional and international scientific understanding. The following sections comprise this paper: the “Material and methods” section discusses the datasets and methods used in this study. The “Emission patterns and trend forecasts for SLCFs” section presents emission patterns and trend forecasts for SLCFs. “The Grand challenges of SLCFs mitigation” section examines the challenges, impediments, and potential pathways for reducing SLCF emissions.

Material and methods

This paper proposes the latest high-resolution emission inventory of the SLCFs compiled in Oman’s Biennial update report framework. This study purposefully concentrates on SLCFs with high global warming potentials (GWP) referred to the 5th assessment report of IPCC such as CH₄ (84 for 20-year GWP, and a 100-year GWP of 28), BC (3200 for 20 years GWP and a 100-year GWP of 900), and major HFCs (GWP for 20 years can range from 473 for HFC-152a to 12,000 for HFC-23 and 100-year GWP the span varies from 138 for HFC-152a to 12,400 for HFC-23) which can be precisely quantified using well-established methods and worldwide agreed guidelines (IPCC 2013).

Since 1995, IPCC has established and continuously revised Guidelines for National GHG Inventories to assist governments in creating accurate GHG inventories with the fewest potential uncertainties. The most recent IPCC GHG Inventory Guidelines (2006) include a methodology for quantifying GHG and removals such as CO₂, CH₄, N₂O, HFCs, PFCs, SF₆, NF₃, and other halogenated gases, but not for SLCFs except for CH₄ and HFCs.

The IPCC GHG Inventory Guidelines (2006) cover various approaches, from the relatively basic tier 1 approach based on default emission factors to the increasingly complex and data-intensive tier 2 and tier 3 procedures. Tiers 2 and 3 approaches are often deemed more accurate. For the present study, IPCC tier 1 was used to quantify the baseline growth of CH₄ and HFCs in Oman from 2000 to 2015 and anticipated their growth for 2030 under a continuation of the “no action” scenario, commonly known as the BAU scenario.

Tier 1 follows a relatively straightforward equation in general (1):

\[ E = A_C \times E_F \]

(1)

where \( E \) is the amount of gas emitted in Gg, \( A_C \) denotes sectoral activity data, and \( E_F \) is the emission factor (mass of gas emitted per unit of activity).

IPCC inventory software, version 2.691, was applied to calculate long-lived GHG (LLGHG) emissions (CO₂, N₂O, PFCs, SF₆, and other halogenated gas) and SLCFs (CH₄ and HFCs) from different sources of activities. The quantification of the BC is not included in the IPCC inventory software, and the following Eq. (2) was used to calculate the BC’s emission:

\[ E_{BC} = (A_F \times D_F) \times EF_{BC}/1000 \]

(2)

\( E_{BC} \) is the black carbon emissions (Gg), \( A_F \) is the fuel activity data (thousands of m³), \( D_F \) is the fuel density (t/m³), and \( EF_{BC} \) is the BC emission factor (g/kg) (Montelongo-Reyes et al. 2015).

For this study, the critical drivers for the BAU were determined based on the most likely assumptions estimated by various national entities for their projected growth over the next decade. The “Forecast Drivers” listed in Table 1 are the critical assumptions used in forecasting each type of GHG emission through 2030. The BAU scenario is a scenario that asks what Oman’s economy and greenhouse gas emissions will look like by 2030 under “Growth without Constraints.”
The storyline essentially assumes that the country would develop without considering constraints, particularly constraints on carbon and other factors, for example, no constraints on oil and gas industry. The narrative would assume that no climate impacts were highly damaging to the economy. Oman’s economy is assumed to continue to be based purely on the oil and gas industry with expansion of downstream activities mainly with the establishment of two new refineries totaling 370 thousand barrels/day. The Oman economy is also assumed to continue evolving around the minerals–energy complex with expansion in metal, cement, and petrochemical industries. The population is assumed to grow by 22% by 2030, implying a substantial growth in fuel demand for transportation, electricity supply, and waste generation.

Emission patterns and trend forecasts for SLCFs

Total GHG emissions rose 300% in the last 15 years, from 22,084 to 98,381 Gg of CO₂e. Over this period, LLGHG and SLCFs have almost grown at the same annual growth rate and percentage change (Fig. 1). LLGHG dominated the emission pattern, comprising 61% of overall emissions in Oman in 2015, and the vast bulk of these emissions are CO₂. In 2015, CO₂ emissions accounted for 59.5% of overall emissions. CH₄ and HFCs account for most overall SLCF emissions, making up 23.5% and 13.1% of total 2015 emissions, respectively. In 2015, BC’s contribution to the total emission was only around 2.3%, while the annual growth rate (11.48%) and the percentage growth (4.5 times) over the study period were the highest among all LLGHG and SLCFs emissions. The emission of HFCs in Oman started in 2010 as substitutions for a set of ozone-depleting substances eliminated by the original Montreal Protocol. The implementation of the aluminum sector in 2006 triggered emissions of PFCs in Oman. Oman’s total GHG emissions are projected to continue expanding at a 140% over the following decade, reaching 231,503 Gg CO₂e in 2030 under the BAU scenario. LLGHG emissions will continue to dominate the pattern of total GHG emissions at 71%, while the contribution of SLCFs will decrease slightly to 29% from 39.5% in 2015, owing to the addition of new LLGHG such as SF6 and other halogenated gases (C₂F₆) to the emission pattern. By 2030, SLCFs are expected to have increased 0.7 times since 2015 to 67,777 Gg CO₂e. With a 130% increase compared to 2015 levels, BC is expected to break new records for SLCFs, followed by HFCs with a 90% increase and CH₄ with a 40% increase. Thus, by 2030, the overall pace of change in SLCFs will be slightly greater than LLGHG emissions.

Table 2 presents the CH₄ emissions at sectoral levels for Oman in 2015. In 2015, the fugitive emission from the oil and natural gas supply chain contributed the most at 76.9%, solid waste disposal at 14.6%, enteric fermentation, and wastewater treatment at 5.3% and 2%. The oil and natural gas industry is the backbone of Oman’s economy. In 2015, the country produced 385.1 million barrels of oils, 32,873 million Sm3 of natural gas, and held a refinery capacity of 220,000 b/d. CH₄ leaks from oil and gas supply chains increased 1.7 times with an annual growth rate of 6.4% from 2000 to 2015. CH₄ leaks occur at all levels of upstream and downstream activities of the oil and gas industry. Almost 90% of CH₄ leaks in Oman for 2015 are associated with natural gas upstream activities. The oil and gas industry’s CH₄ emissions are predicted to increase 0.16 times in the next decade compared to 2015, owing to the entry of discoveries, primarily in the gas segment. Solid waste disposal was Oman’s second significant source of CH₄ emissions in 2015.

Moreover, the solid waste disposal sector in Oman’s is the fastest-growing source of CH₄ emissions from 2000 to 2015. Solid waste disposal CH₄ emission has increased six times from 2000 to 2015, with an annual growth rate of 13%, due to the increase of the municipal solid waste disposal generation from 0.64 kg/capita/day in 2000 to 1.2 kg/ capita/day in 2015. Also, the population has almost doubled over the study period from 2.2 to 4.2 million inhabitants. The total solid waste disposal reached 1868 million tons in 2015. The composition of the solid waste in Oman for

| Category                          | Growth rate projected for 2030 relative to the base year of 2015 |
|-----------------------------------|-------------------------------------------------------------------|
| Number of population              | 22%                                                               |
| Electricity supply                | 12%                                                               |
| Fuel demand for transport         | 10%                                                               |
| Oil and gas industry (upper stream activities) | 14%                                                     |
| Oil and gas industry (downstream activities) | 120%                                                              |
| Energy industries                | 115%                                                              |
| Waste generation                  | 80%                                                               |
| Livestock                         | 150%                                                              |

Table 1: Key forecasting drivers for BAU assumptions

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2015 is dominated by food and organic waste (27%), plastic (21%), paper cardboard (15%), glass (6%), garden and green waste (5%), wood (2%), and other waste (24%). The high biodegradability of Omani solid waste results in significant CH₄ generation. The solid waste disposal CH₄ emission is expected to grow 1.4 times by 2030 compared to the 2015 level, due to the expected increase of the population to more than 6 million inhabitants and the rise of solid waste disposal generation to 2.5 kg/capita/day in 2030.

Table 3 shows the BC emission in Oman per source categories for 2015. The transportation sector is the major direct source of BC emission and accounting for 98% of the BC total emission of 2015. Diesel-powered heavy trucks and buses contribute to more than 87% of BC emissions in 2015. Petroleum product consumption for the transportation sector in Oman has nearly quadrupled, from 842 Ktoe in 2000 to 4190 Ktoe in 2015 with an annual growth rate of 11.3%. Remarkably, diesel consumption for heavy trucks and buses increased 4.3 times from 260 Ktoe in 2000 to 1375 Ktoe in 2015, with an annual growth rate of 11.7%, slightly above the pace of overall consumption of petroleum products for transportation in Oman.

Since 2010, Oman’s usage and emission of HFCs have increased steadily due to the progressive phase-out of ozone-depleting refrigerants. In Oman, HFC emissions climbed at a rapid annual rate of 175%, from 2.361 Gg in 2010 to 1073 Gg
in 2015. This growth was expected due to residential air conditioning (RAC) consumption of sizable HFC consumption. The weather of Oman is sweltering and humid throughout the year, and comfort cooling is a necessity for public health and economic prosperity. Oman and the GCC as a whole have the highest air conditioning penetration rate in the world, with 100% of households having air conditioning. Accordingly, residential energy consumption accounts for 50% of total electricity demand in Oman, and a sizable portion of residential energy consumption is devoted to air conditioning. The demand for residential cooling is in a steady spike due to the rise of residential and non-residential units. The total number of residential and non-residential units increased steadily from 731,968 in the 2010 census to 1,312,327 in the 2020 census (a rise of 79%). Although there are no reliable figures on the number of RAC units installed in Omani houses, however, based on 2020 census data, we estimate that between 9 and 10 million RAC units of various cooling capacities are placed in Omani houses. The second source of HFC usage and leakage is cold chain logistics, which includes refrigerated warehouse storage, refrigerated transportation, distribution, and refrigerated retail, as Oman imports a substantial portion of its fresh food supply and pharmaceuticals. Meat and seafood importers and exporters make the most use of cold storage facilities, followed by poultry and egg producers. In 2015, Oman imported 25% of its veggies, 71% of its poultry meat, 64% of its meat, 69% of its dairy, and annually exports over 205,000 tonnes of fish. The proliferation of supermarkets and restaurants has increased the demand for cold storage and transportation systems to keep food fresh.

Oman’s SLCFs performance in the recent timeframe of 2020 is challenging to track without an accurate emission inventory in place. Even yet, Oman’s SLCFs emissions pattern is discernible based on some broad indicators. In Oman, the

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### Table 2 Oman’s key sources of CH₄ emissions in 2015

| IPCC sector                          | Source                        | Emission Gg | CH₄ | CO₂-e (GWP, 20 years) | CO₂-e (GWP, 100 years) | Per category (%) |
|--------------------------------------|-------------------------------|-------------|-----|----------------------|------------------------|-----------------|
| Energy                               | Fugitive from oil and gas     | 634.4       |      | 54,566.7             | 17,765.9               | 76.9            |
| Waste                                | Solid waste disposal          | 120.5       |      | 10,369.1             | 3,376.0                | 14.6            |
| Agriculture, forestry, and other land use | Enteric-fermentation       | 43.4        |      | 3,734.6              | 1,215.9                | 5.2             |
| Waste                                | Wastewater treatment and discharge | 16.8      |      | 1,449.4              | 471.9                  | 2.0             |
| Industrial processes and product use | Petrochemical (methanol)      | 4.9         |      | 425.2                | 138.4                  | 0.5             |
| Energy                               | Transport                     | 4.0         |      | 347.3                | 113.0                  | 0.4             |
| Energy                               | Energy industries             | 0.3         |      | 29.6                 | 9.6                    | 0.4             |
| Energy                               | Manufacturing industries and construction | 0.1     |      | 13.6                 | 4.4                    | 0.01            |
| Industrial processes and product use | Iron and steel production     | 0.1         |      | 12.6                 | 4.1                    | 0.01            |
| Industrial processes and product use | Others sectors                | 0.040       |      | 3.4                  | 1.1                    | 0.01            |
| Total emissions (Gg)                 |                               | 825         |    | 70,952               | 23,101                 | 100             |

### Table 3 Oman’s key sources of BC emissions in 2015

| Sector      | Fuel       | BC source             | Emissions (Gg) | Per type | CO₂-e, (GWP, 20) year | CO₂-e, (GWP, 100) years | Per category (%) |
|-------------|------------|-----------------------|----------------|----------|-----------------------|------------------------|-----------------|
| Transport   | Diesel     | Heavy truck & bus     | 2.26           |          | 7263.3                | 2042.8                 | 87.2            |
|             | Gasoline   | Car                   | 0.18           |          | 581.1                 | 163.4                  | 6.9             |
|             | Gasoline   | Light truck           | 0.02           |          | 84.0                  | 23.6                   | 2.4             |
|             | Diesel     | Domestic marine marine| 0.02           |          | 69.0                  | 19.4                   | 0.8             |
|             | Kerosene   | Domestic aviation     | 0.01           |          | 39.4                  | 11.0                   | 0.4             |
|             | Gasoline   | Motorcycle             | 0.00           |          | 4.0                   | 1.1                    | 0.0             |
| Energy      | LPG        | Residential            | 0.03           |          | 107.6                 | 30.2                   | 1.2             |
|             | Residual Fuel | Refinery            | 0.01           |          | 58.8                  | 16.5                   | 0.7             |
|             | Diesel     | Electricity            | 0.00           |          | 0.19                  | 0.05                   | 0.00            |
| Total national emissions (Gg)        |                       | 2.5                   |    | 8207.8               | 1769.1                 | 100             |
importation of HFCs has remained at the same level, showing a steady demand for HFCs in the refrigeration and domestic cooling sectors. In contrast, it is most likely that the oil and gas industry’s CH4 emissions have decreased due primarily to cuts in oil production in Oman as a result of the continued support for the OPEC+ alliance’s efforts to stabilize the global oil market and their assistance in recovering crude demand that had collapsed following the COVID-19 pandemic. The first Biennial Transparency Report, which will begin in 2023, plans to update the GHG emission inventory for 2020–2021.

The grand challenges of SLCFs mitigation

The oil and gas industry

The above emission patterns analysis shows that CH4 from the oil and gas supply chain dominated the SLCFs in Oman. Several technologies and methods effectively curb CH4 emissions from the oil and gas industry. Although CH4 abatement technologies, leakage monitoring, recovery, and use are within reach, considerable barriers still exist that will reduce the likelihood that the oil and gas industries in Oman will take those activities. The primary impediments to curbing CH4 from oil and gas supply chains include a lack of regulation, inadequate infrastructure, and insufficiency of investment stimuli. In this regard, the government plays a critical role in paving the way to climate neutrality via CH4 abatement by removing barriers, strengthening regulatory measures, and collaborating with stakeholders to ensure that companies have the tools and incentives necessary to phase out CH4 from the oil and gas supply chain. The anticipated expansion of Oman’s oil and gas industry presents prospects for developing regulations to eliminate CH4 and investment in abatement technology. Implementing CH4 reduction technology in Oman necessitates in-depth studies quantifying the possible CH4 reduction, the associated cost, and the anticipated revenue from the sale of recovered gas (Gie and Marcogaz 2019). These studies are essential to creating the groundwork for successfully implementing a near-zero CH4 emission strategy for Oman’s oil and gas supply chain. This strategy should involve industry stakeholders fully participating in the policy development process to ensure that the proposed actions are realistic and achievable. Policies should help bring legislation into line with market mechanisms from an economic and administrative standpoint. Cost-effectiveness checks are also essential to guarantee that legislation has a demonstrable benefit for all intended actions. Furthermore, the government should encourage the oil and gas industry to maximize the value of reductions by enabling appropriate flexibility to find investment opportunities to achieve maximum reductions at the lowest possible cost.

At the international level, emerging countries with a hydrocarbon-based economy, such as Oman and the GCC, face a fundamental and intractable dilemma in reducing CH4 emissions due to oil and gas price volatility. The abrupt reduction in global oil consumption and the resulting drop in oil production and pricing throughout 2015–2020 has hindered investment in CH4 mitigation. In 2020, the world economy contracted by 3.5% owing to the COVID-19 pandemic. The world economy began rebounding in 2021 and early 2022, with a growth of 5.9% in 2021 and 4.4% in 2022. Oil prices have also recovered, but they have been unpredictable in the past decade. OPEC basket price went from USD109.45 per barrel in January 2012 to USD143.31 on April 24, 2020, amid COVID-19 pandemic. Following Russia’s war on Ukraine, the OPEC basket price hit USD128.46 per barrel on March 9, 2022 (Mahmoud et al. 2022). In the short term, the rise in oil prices will increase the adoption of CH4 mitigation in the oil and gas industries. Still, in the long term, the volatility of oil and gas prices creates instability in investment, human resources, corporate efficiency, and economic growth. Volatility causes confusion, which deters policymakers from setting methane abatement policies and slows investment in mitigation technologies (Charabi 2021). The second decade of the twenty-first century has been dubbed “the age of oil abundance” due to the increased productivity of conventional oil reservoirs and the rapid rise of the oil-shale industry (IMF 2020). The abundant supply of oil, growing concern about the rapid pace of global warming, worldwide deployment of renewable energy, and the political discourse of the world’s largest oil importer to reduce their dependency on oil and gas all conspired to drive oil and gas prices to all-time lows. With the new politics of the oil abundance age resulting in substantial price fluctuation and market uncertainty, investment in CH4 reduction technologies is no longer cost-beneficial. There are minimal prospects that policymakers will adopt a CH4 reduction policy in Oman.

The new politics of the oil abundance age, the decreasing and volatile prices, and the uncertainty surrounding the future of oil and gas are substantial impediments to implementing policies aimed at significant reductions in CH4 emissions. On the other hand, waste is a promising sector to achieve deep cuts in CH4 emissions. Under the hypothetical scenario where all organic waste food is collected and treated, it will recover 32 Gg of CH4 per year and generate 504,615 MWh of electricity in Oman, according to 2015 data. In addition, anaerobic wastewater treatment in Oman can also recover 4.5 Gg of CH4 methane per year while producing 70.4 MW of electricity in 2015. Overall, the anaerobic process of organic solid food waste and wastewater treatment can reduce almost 4.4% of total CH4 emissions in Oman in 2015. By 2030, CH4 recovery from organic solid food waste and wastewater treatment could reach 93.95 Gg and 6.9 Gg, respectively, and decrease 8.1% from the total CH4 emissions.
Heavy road transportation

Diesel-powered road vehicles transport most heavy goods and a small percentage of the people in Oman. However, this reliance on diesel technology results in sizeable BC emissions. Technical solutions that are cost-effective and capable of significantly reducing BC emissions from diesel-powered vehicles are now on the market. Soot-free diesel engines that comply with European emission standards such as Euro VI for heavy-duty diesel vehicles released in 2009, Euro 5Bb for light-duty diesel vehicles enforced in 2011, or US 2010 standards can eliminate BC emissions compared to older diesel engines. The usage of ultralow-sulfur diesel is required to comply with European or US emission regulations for soot-free engines. Oman is nearing the completion of a low-sulfur fuel oil refinery with a capacity of 230 barrels per day. This may pave the way for the subsequent years’ establishment of standards enforcing the adoption of soot-free diesel engines for heavy, light-duty trucks and buses. Indeed, economic diversification is expected to quadruple the number of heavy, light, and buses by the decade’s end. Therefore, adopting framework standards for soot-free diesel engines is a realistic option in Oman and will reduce black carbon emissions. For the next two decades, conventional diesel technology will continue to be utilized in the current light and heavy fleets and buses. The rate at which black carbon emissions decline in Oman following the introduction of soot-free diesel engines is governed by the degree to which conventional diesel engines are phased out.

Air conditioning and refrigeration industry

Several technical solutions and equipment capable of replacing the use of HFCs in refrigeration systems, including a refrigerant with lower GWP or which does not require HFCs, have been proposed and tested (US EPA 2013; Ragnauth et al. 2019). CO₂ and ammonia (NH3) have several advantages for replacing HFCs in industrial refrigeration. CO₂ and NH3 have zero ozone depletion potential (ODP) and GWP, are highly cost-effective, are widely available, are nonflammable, have a tiny compressor swept volume, and have other technical advantages. However, CO₂ risks human health if it leaks into restricted locations uncontrollably. In addition, when large quantities of NH₃ are emitted, its toxicity is substantially greater than that of CO₂. Propane (R290) is a highly flammable hydrocarbon-efficient refrigerant with a GWP of 5 and is widely advocated as an alternative for HFCs in ice making. R-513A is a blend of hydrofluorocarbon refrigerants with no ODP and a GWP of 631 that the cold industry has recommended to replace the refrigerant R134a, which has a GWP of 1430 in industrial refrigeration. The R-513A may cause harm if it is misused or intentionally inhaled. For the RAC, the US EPA suggests using R466A inflammable refrigerants with a GWP 733 to replace the current refrigerant R410A with a GWP 2088 for the US market. The utilization of the R466A refrigerant requires the design and manufacturing of a new RAC system to adopt the new refrigerant.

In Oman’s case, assuming that conventional air conditioning and refrigeration equipment will not be prematurely retired or retrofitted before their lifespan, the complete phase-out and transition to other refrigeration technologies using lower GWP HFCs will take decades. Even under the hypothetical scenario of phasing out all high GWP HFC equipment in Oman, favoring low GWP HFC equipment, this scenario results in a quick decline in HFC consumption. However, it does not eliminate it, as HFCs are still necessary for servicing the old conventional HFC equipment. Parallel to the gradual phasing out of the high GWP HFC equipment, reduced leakage and proper handling techniques throughout the manufacture, installation, operation, and disposal processes are potentially viable options for reducing Oman’s high GWP-HFC emissions. Efficient refrigerant management, which includes recovery and reuse, can also help to reduce the demand for virgin refrigerant.

Conclusions

This study quantifies the current and predicted emissions of very potent SLCFs such as CH₄, BC, and HFCs in Oman in great detail. Under current BAU conditions, highly potent SLCFs will continue to expand steadily until 2030 and beyond. The source emission of highly potent SLCFs in Oman is connected with critical and substantial economic sectors, such as the oil and gas industry, heavy road transportation, and RAC and industrial refrigeration. These critical economic sectors create grand challenges to immediately reduce SLCFs in Oman and the GCC. The first aspect of this grand challenge is the oil and gas industry’s efforts to reduce CH₄ emissions, which have been hampered by price volatility and new international politics associated with the era of abundant oil. Leaving the reduction of CH₄ emissions from the oil and gas industry to national policies that are driven by market dynamics would not result in near-term demonstrable reduction plans. Indeed, to prevent the climate shock of temperature exceeding 2 degrees by the end of the century, a worldwide convention laying the framework for mandatory reductions based on equifinancial and economic arrangements between producers and consumers is essential.

The second major challenge is connected with BC emissions from heavy road vehicles, necessitating the phase-out of conventional diesel engines and significant investment in soot-free diesel engines that meet international requirements. This challenge requires a government policy; because diesel
engines can survive up to 20 to 30 years or longer, it will be several years before most existing diesel engines are retired and replaced with more rigorous pollution requirements. As a result, it is critical to provide incentives for retrofitting or replacing these current engines with BC control equipment. Finally, the third dimension, aimed at phase-out of high-GWP HFC refrigeration equipment, is contingent on global progress in developing energy-efficient and cost-effective products and the government’s approach to incentivizing the deployment of equipment using low-GWP hydrofluorocarbon (HFOs) refrigerants.

Achieving a rapid, significant reduction in highly potent SLCFs from the three challenging sectors over a 5- to 10-year time period does not appear feasible or realistic in the context of Oman’s hydrocarbon-based economy, as it entails balancing complex links between government aspiration and international market mechanisms, socioeconomic factors, public regulator and private sector, and mitigation targets. Realizing a deep SLCF reduction for a hydrocarbon-based economy is rooted in a vast economic transformation. The future Omani vision for a post-oil economy over the next two decades provides an appropriate framework for executing economic and societal transformation policies incorporating near-zero-emission measures for the potent SLCFs.

The findings presented in this paper are consistent with the earlier UNEP Reports (UNEP 2016, 2021), World Resources Institute (2021), Climate and Clean Air Coalition (2014), and The World Bank (2013) that emphasize the importance of developing robust knowledge about the magnitude and trend of emissions of short-lived climate forcers and providing policymakers with practical suggestions for adding or strengthening targets, policies, and actions on CH4 HFCs and BC. In supporting the mitigation of SLFC, the present study has some limitations associated with IPCC tier 1, which implies a degree of uncertainty in the obtained emission results. Future studies should employ higher tiers that use more complex procedures and source-specific, technology-specific, and/or country-specific emission variables, frequently based on measurements, requiring more granular activity data. Further analysis of the economic and financial policies, procedures, the impact of activities, and options is still needed in Oman to fine-tune mitigation efforts of SLCFs.

Author contribution Yassine Charabi is the sole author of the paper and was entirely responsible for the study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

Data availability All data generated or analyzed during this study are included in the manuscript.

Declarations

Ethical approval The author confirms that the submitted work is original and has not been submitted in any form or language to any journal.

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Competing interests The author declares no competing interests.

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