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Carbon dioxide, methane and black carbon emissions from upstream oil and gas flaring in the United States

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Carbon dioxide, methane and black carbon (BC) emissions from flaring during oil and gas production and processing contribute to the greenhouse gas footprints of fossil fuels. In the United States, more than 20,000 flares in the oil and natural gas supply chains emit an estimated 20–21 million metric tons in CO_2 equivalents (CO_2e) of greenhouse gases per year, accounting for 9% of the greenhouse gas emissions from the oil and gas sector. Less than 100 flares are estimated to account for more than half of the total emissions based on current reporting. Estimated emissions of methane and black carbon due to flaring have high degrees of uncertainty, which could be reduced through additional measurements.

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Introduction

Flaring of waste gases from oil and natural gas production and processing in the United States has increased over the past decade. The increase in flaring is due to increases in domestic natural gas and oil production and due to the introduction of new regulations that result in the use of flares to limit natural gas venting [1–4]. Flaring emissions can play an important role in determining the greenhouse gas footprints of oil and natural gas, since the emissions include, along with CO_2, short-lived climate forcing species such as methane and black carbon [5,6•,7–10,11•]. Methane emissions result from incomplete combustion of flared gases. Black carbon results from flares that are operated under conditions that result in soot formation.

This review assembles and critically assesses estimates of emissions of carbon dioxide, methane and black carbon from flaring in upstream oil and gas operations in the United States. For the purposes of this review, upstream operations include well pad activities and gas processing for natural gas. For oil production, estimates include well pad activities and associated gas processing. Data collection and analyses relied on publicly available data; the analyses focus on flaring emissions and volumes of flared gases, and emissions per volume or heating value of flared gases (emission factors), which serve as the basis for emission estimates. The goals of this review are to compare upstream oil and gas flaring emissions to total anthropogenic emissions of greenhouse gases and black carbon in the United States and to identify the approximate magnitudes of the uncertainties in the emission estimates.

Flaring emissions and flared gas volumes

Multiple sources of data are available on flared gas emissions in the United States and these data can be used to infer volumes of flared gases. The U.S. Environmental Protection Agency's Greenhouse Gas Reporting Program (US EPA GHGRP) [12••] reports data on approximately 21,000 individual flares in the oil and gas sector. A complementary data source is the U.S. EPA's Greenhouse Gas Emission Inventory (US EPA GHGEI) [13], which provides aggregated data on flaring by region. In addition, some state governments in the United States compile permit data for oil and gas activities that include information on flaring.

In this work, the primary source of data will be the GHGRP. The GHGRP is currently the most comprehensive source of information available on emissions from individual oil and natural gas facilities in the United States. The GHGRP data must be interpreted with caution, however. GHGRP emissions reporting in the oil and gas sector is only required for facilities that exceed a threshold quantity of greenhouse gas emissions. In addition, current GHGRP reporting omits gathering operations, although these facilities will be added in future GHGRP reports. Because of these limitations, in this work, GHGRP data on total emissions from flaring were compared to other sources of data on total flaring emissions, including the GHGEI and data from satellite observations.

Both the GHGRP and the GHGEI can be used to estimate total greenhouse gas emissions from flaring in

the oil and gas sector. Data for the GHGEI, while somewhat redundant with GHGRP data, is collected from different sources and provides an independent emission estimate. Both the GHGRP and the GHGEI report that oil and gas sector flares collectively release 20–21 million metric tons of CO_2e in greenhouse gases (including carbon dioxide and methane). These estimated emissions can also be compared to satellite observations. As described in Supplementary Material, estimates of flared gas volumes, based on observations from satellites, are generally consistent with total emissions based on the GHGEI and the GHGRP [3,14–17].

Emissions are reported in units of carbon dioxide equivalents (CO_2e). For carbon dioxide, emissions in CO_2e are equal to the mass of carbon dioxide emitted. For methane, the CO_2e is based on the mass of methane emitted multiplied by a global warming potential. The global warming potential (GWP) for a gas is a measure of the total energy that a gas absorbs over a particular period of time (usually 100 years), compared to carbon dioxide. For methane, the 100-year GWP, used in current US EPA reporting, is 25, which means that methane mass emissions reported through the US EPA GHGEI and GHGRP are multiplied by 25 to arrive at the emissions expressed as CO_2e [18]. Shorter time horizons for calculating the radiative forcing of the atmosphere would result in larger GWPs (the 20 year GWP is 84 and the immediate GWP is 120) and higher emissions, expressed as CO_2e.

Emissions of 20–21 million metric tons of CO_2e are equivalent to the combustion of 9–10 billion cubic meters of natural gas, which is roughly 1% of the 0.9 trillion cubic meters of natural gas withdrawals in the United States in 2015 [2] (see supplementary material for details of the calculations). No comprehensive national data are available for black carbon emissions from flaring. The 20–21 million metric tons of CO_2e greenhouse gas emissions, reported for flaring in the United States, represents 9% of the US greenhouse gas emissions reported for natural gas and petroleum industry sources (reported as CO_2e) and 0.3% of the US total for anthropogenic greenhouse gas emissions (6673 million metric tons CO_2e) [13].

Emissions from flaring in the US natural gas and petroleum sector, reported through the GHGRP, can be categorized into three major source sectors (natural gas production; natural gas processing and associated gas production). More than half, 57%, of all greenhouse gas emissions from flaring are attributed to flaring in systems where gas is co-produced in oil production (associated gas). In all three source categories, a relatively small fraction of the flares account for the majority of the methane emissions (see supplementary material). For the 19,719 flares in natural gas production reported through the GHGRP, 3.7% of the flares account for 80% of the emissions. For the 608 flares in natural gas processing, 15% of the flares account for 75% of the emissions; 7.8% of the 503 associated gas flares account for 87% of the emissions [12••]. Both the total number of flares and the highest emitting natural gas production and processing flares are distributed in multiple US oil and gas production regions. Mappings are provided in Supplementary Material. Associated gas flares, as a category, have the highest emissions per flare, and less than 100 associated gas flares in the US account for more than half of all GHGRP reported flaring emissions (both methane and CO_2) from the 21,000 flares in the oil and natural gas sector.

The limitations of the GHGRP data suggest that the total GHGRP flare counts are a lower bound. Additional flares are likely to be associated with facilities that do not exceed the GHGRP reporting threshold or that are not included in the current report (gathering operations). Nevertheless, the general agreement between total flared gas volumes estimated using the GHGRP, the GHGEI and satellite data supports the conclusion that a small number of flares dominate total greenhouse gas emissions, even if the total count of flares reported through the GHGRP is a lower bound.

Flaring technologies

While there are no comprehensive data sets on the types of flaring technologies used in upstream oil and gas operations, analyses of the vent gas flows (inferred from CO_2 emissions) suggest that a vast majority of the flares are likely to be pipe flares capable of managing relatively low flow rates. In the US, reported carbon dioxide emission rates suggest that a very small number of associated gas flares manage more than half of all flared gas volume and account for approximately half of all flaring emissions. These flares are likely to be much larger capacity flares than those used in production operations, possibly including systems for blowing air into the combustion zone (air assisted flares) [19].

Emissions per volume or heating value of flared gases (emission factors)

Reported emissions for flares depend on counts of flares, volumes and compositions of flared gases, and emission factors (EFs), where emission factors are the assumed rate of emissions per unit volume or unit heating value of flared gas [20]. Emission factors for carbon dioxide emissions are based on the stoichiometry of complete combustion (one mole of carbon combusted yields one mole of CO_2 emitted), and in general, the uncertainty in these CO_2 emission factors is small. In contrast, however, EFs for methane and black carbon are based on a relatively small number of measurements of flares in operation, and uncertainties are large (up to multiple orders of magnitude).

The EFs for methane that are in most common use in the United States are those recommended by the US EPA. These emission factors apply to well-operated flares [21],