Title: Global carbon intensity of crude oil production

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The global oil and gas industry consumes 3-4% of global primary energy supply to extract, transport, and refine energy products (*1*). The goals of the Paris Agreement pose challenges to the oil and gas sector given the need to meet energy demand globally while limiting greenhouse gas (GHG) emissions. We preliminarily quantify the heterogeneity of crude oil well-to-refinery carbon intensities (CIs) by performing field-by-field life-cycle analysis (LCA) of nearly 9,000 global oilfields representing ~98% of 2015 worldwide crude oil production. The global volume-weighted average upstream CI estimate is 10.3 g CO_2eq./MJ crude oil, with country-level emissions ranging from 3.3 to 20.3 g CO_2eq./MJ. Gas flaring and thermal extraction of heavy crude oils are the two major drivers of high GHG intensities. Global methane venting and fugitive emissions are poorly documented, yet evidence suggests they can increase the CI estimates considerably. Upstream gas management strategies alone could potentially mitigate ~18 Gt CO_2eq in the 21st century. Policy insights from this analysis regarding resource management, resource prioritization and emerging technologies could enable a reduction in the GHG footprint from the oil and gas industry.

Producing, transporting, and refining crude oil into fuels such as gasoline and diesel accounts for ~15-40% of the "well-to-wheels" life-cycle GHG emissions of transport fuels (*2*, *3*). Reducing emissions from petroleum production is of particular importance, as current transport fleets are almost entirely dependent on liquid petroleum products and many uses of petroleum have limited prospects for near-term substitution (e.g., air travel). Despite investments to improve efficiency, the energy intensity of oil and gas extraction has increased by ~33% since 1980 in OECD countries (*4*). Part of this increase is due to increased use of enhanced recovery techniques and growing reliance on unconventional resources such as heavy oil and oil sands, for which the production processes generally expend more energy. Furthermore, the climate impact of conventional oil extraction increases as oilfields age due to reservoir depletion (*5*, *6*). In the U.S., the oil and gas sector is the second-highest GHG-emitting stationary sector (*7*). In other fossil-fuel-net-exporting countries such as Russia (*8*), Norway (*9*), and Canada (*10*) over 20% of all national GHG emissions are from oil and gas extraction activities.

Regulations are beginning to address petroleum sector GHG emissions. California's Low Carbon Fuel Standard (LCFS) (*11*), the European Union's Fuel Quality Directive (*12*), and Canada's Clean Fuel Standard (*13*), all include emissions from oil extraction operations. At the same time, private investors are beginning to consider climate-related risk in oil investments (*2*, *14*, *15*). However, such efforts have generally struggled with both methodological and data challenges. First, no consistent and widely-adopted method exists for measuring the carbon intensity of oils. Second, comprehensive geographically-rich datasets are lacking that would allow evaluation and monitoring of the life-cycle emissions. Better understanding of crude oil GHG emissions can help to benchmark the environmental benefits of alternative fuels and identify the most cost-effective opportunities for oil-sector emissions reductions (*16*–*18*).

Emissions from oil production arise from many processes and can vary significantly among heterogeneous oil resources. In this international interdisciplinary collaboration, we quantify the well-to-refinery CI of all major active oilfields globally by employing an open-source, peer-reviewed oil sector GHG estimation tool (Oil Production Greenhouse Gas Emissions Estimator, or OPGEE, see SI section 1.1) (*19*, *20*). We estimate emissions in the year 2015 from 8,966 onstream oilfields in 90 countries (see SI section 1.4.4). These oilfields represent approximately 98% of 2015 global crude oil and condensate production. This analysis includes all major resource classes (e.g., onshore/offshore and conventional/unconventional), and accounts for GHG emissions from exploration, drilling and development, production and extraction, surface processing, and transport to the refinery inlet (collectively called "upstream" hereafter). The latest IPCC 100-year global warming potential (AR5/GWP_{100}) factors are used in this work (see SI section 1.2.1).

Country-Level Crude Oil Upstream Carbon Intensity

Fig. 1 presents the first upstream global CI map with country-level volume-weighted-average CI estimates and their corresponding uncertainty (see SI section 1.7). These results are based on a broad data collection effort of nearly 800 references including government sources, scientific literature, and public technical reports. Secondarily, proprietary databases are used to supplement when information are unavailable in the public domain (generally for small oilfields, see SI section 1.4.1, 1.4.4, and Table S17). The global volume-weighted average upstream CI estimate – shown by the horizontal dashed line in Fig. 1 – is 10.3 (error bar: +16.8 and -8.6) g CO_2eq./MJ crude oil, with country-level intensities ranging from 3.3 (Denmark) to 20.3 (Algeria) g CO_2eq./MJ. Carbon dioxide and methane contribute on average 65% and 34% of total CO_2eq. emissions, respectively (see SI section 2.2). All presented results treat co-products using a co-product displacement approach (see SI section 1.3 and 2.1). The total petroleum well-to-refinery GHG emissions in 2015 are estimated to be ~1.7 Gt CO_2eq., approximately 5% of total 2015 global fuel combustion GHG emissions (*21*). This estimate of total emissions is ~42% higher than an industry-wide scaling of an IOGP estimate for 2015 (based on datasets comprising 28%

of global production with uneven geographical coverage, see SI section 3 for exploration of the differences between our analyses) (*22*).

Emissions presented in Fig 1 can vary significantly over time (*5*), but time-series data are generally missing on a global basis and so are not explored here. In general, oil production declines with depletion but is also accompanied by substantial increase in per-MJ GHG emissions due to utilizing enhanced recovery practices (*5*). Other factors (e.g. oil price, geopolitics) could also affect oil production strategies and consequently the temporal CI.

Gas flaring practices have a considerable influence on the CI: countries that produce light oil but do not utilize or sell co-produced gas can have high emissions per unit of oil produced. If not economically salable, this gas is either flared, reinjected, or vented (directly emitting methane). Some important conventional crude oil producers with above-average global CI, such as Algeria, Iraq, Nigeria, Iran, and the U.S., are also among the top 10 countries in flaring observed via satellite (*23*). The contribution of routine flaring to the total volume-weighted average CI of these countries are estimated herein to be ~41, 40, 36, 21, and 18%, respectively. Venezuela's gas flaring (ranked 5th globally in 2015) (*23*) also contributes considerably (~14%) to the country's high upstream CI. In recent years, the U.S. has rapidly increased domestic oil production with associated increases in flaring (increased from 36 to 122 standard cubic feet – scf – per bbl oil from 2010 to 2015) (*23*), likely contributing to an increase in the U.S. petroleum CI.

Flaring data are not widely reported by governments or companies, so for most regions our analysis relies on satellite-estimated volumes computed using nighttime radiometry (*23*) (see SI sections 1.2 and 1.4.3). Variability between flaring data sources results in greater uncertainty for countries with high contribution of flaring to their CI. For example, the Nigerian government reports average flaring of 518 scf/bbl in 2015, while satellite-based estimates are 315 scf/bbl (*23*).

As the major global producers of unconventional heavy oils, Venezuela and Canada have high country-level CI. This is due to energy- and CO_2-intensive heavy oil extraction and upgrading. Enhanced oil recovery (EOR) using steam flooding contributes to high CI in other locations, such as Indonesia, Oman, and California (USA). In California, between 2012 and 2015, steam flooding increased by nearly 30% in heavy oilfields (*24*) leading to a commensurate increase in the state's volume-weighted average CI.

While some giant North Sea offshore fields have shown rapidly-increasing per-bbl emissions due to depletion (*5*), they have low upstream GHG intensities when compared to many other global oilfields. This is in part due to stringent regulations on gas processing and handling systems and renewable electric power-from-shore initiatives. Saudi Arabia is the largest global oil producer but has a small number of extremely large and productive reservoirs. The country has low per-barrel gas flaring rates and low water production (less mass lifted per unit of oil produced and less energy used for fluid separation, handling, treatment, and reinjection), contributing to low CI.

Data quality is formally assessed (see SI section 1.4.6 and 2.3), showing higher volume-weighted data quality scores and therefore more reliable CI estimates for countries where oil and gas data are available through government sources (e.g. U.K.), and more uncertain CI evaluations for data poor regions (e.g. Russia).

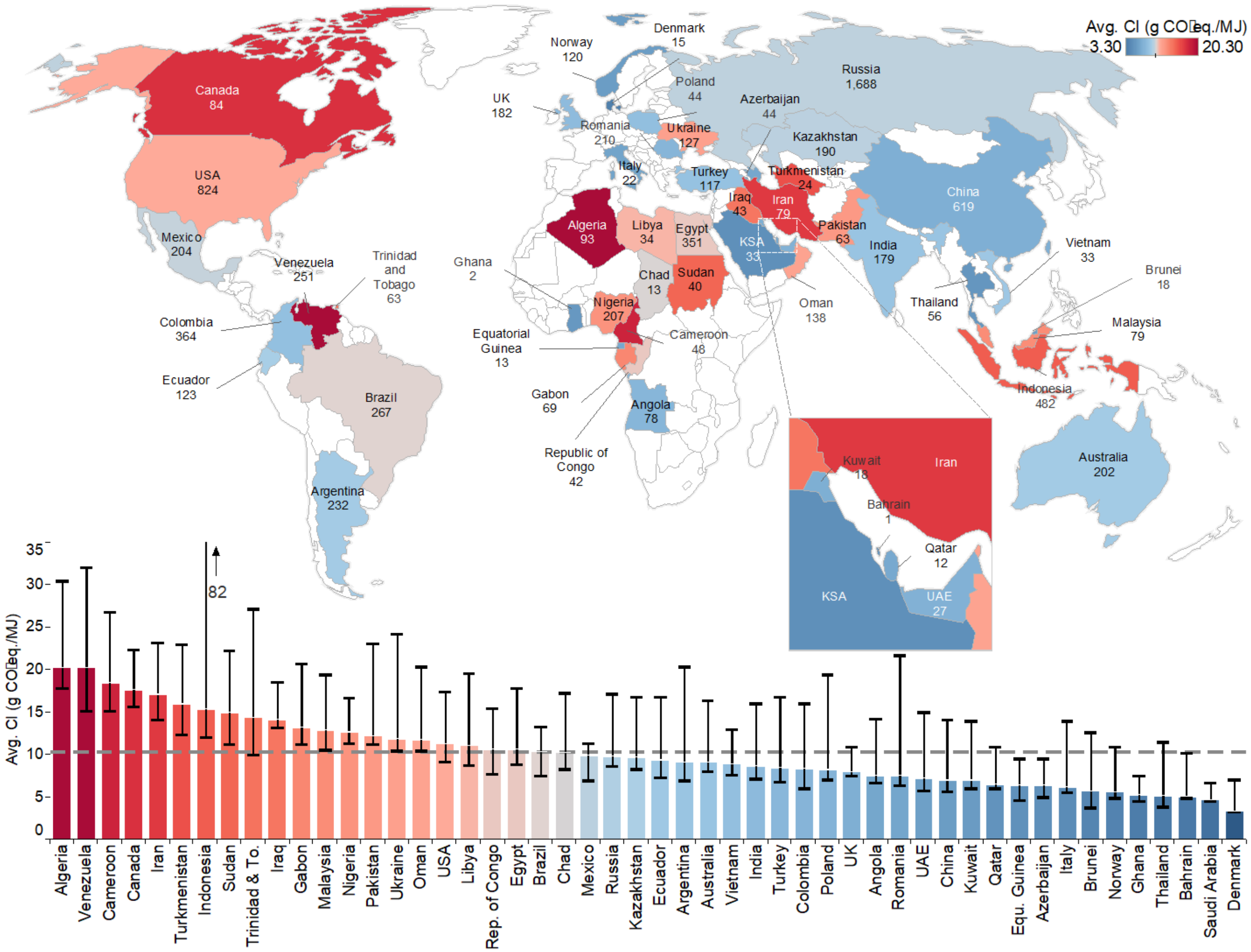

Fig. 1. Estimated global upstream crude oil carbon intensity (2015). National volume-weighted-average upstream GHG intensities in g CO_2eq./MJ crude oil delivered to refinery (color) with corresponding error bars (5-95%ile of Monte Carlo simulation, see SI section 1.7). Map shows number of fields analyzed below each country name. The global volume-weighted CI estimate is shown by the dashed line (~10.3 g CO_2eq./MJ). Reference year is 2015. Only countries with ≥0.1% of global oil production share are mapped (see the SI Results Data Excel file for full list). Color scheme reflects volume-weighted average CI: dark blue for lowest CI, dark red for highest CI, gray: volume-weighted average CI.

Field-Level Crude Oil Upstream Carbon Intensity

A global field-level CI supply curve (cumulative, sorted, field-level CI) in Fig. 2 illustrates the carbon footprint heterogeneity of global crudes (see SI Fig. S19 and Results Data Excel file for break-down of emissions). Similar supply curves could be drawn for each country for national-level emission mitigation analysis. Fields in the highest 5%ile emit over two times more than the median field. Upstream environmental mitigation measures should primarily be focused on fields in the upper end of the CI supply curve.

While crude density (requiring thermal extraction methods) and flaring are key determinants of a high CI (see SI section 1.5), the Fig. 2(a) field-level supply curve shows that flaring is the more prevalent driver: For the highest CI quartile in Fig. 2(a), 51% of crude volume comes from high flare fields (yellow, red), while 18% comes from heavy oil fields (black).

The CI estimate uncertainty modeled in Fig 2(b) relates to the use of model defaults for missing data. When an input datum is not available, OPGEE supplies a default value derived from statistical analysis of the petroleum engineering literature and commercial datasets (see SI section 1.4.3). Monte Carlo (MC) simulations in Fig 2(b) replaced missing data for each oilfield with values from the governing distributions (300 simulations, see SI section 1.7). Despite extensive data gathering efforts and utilization of commercial datasets, the CI dispersion and the low data quality scores for certain countries highlight the need for improved data from most producing countries (see SI section 1.4.6). Fig. 2(b) shows that static OPGEE defaults used without MC analysis result in conservatively low estimates of the CI near the 25%ile probability curve for the MC analysis.

CI supply curves for four hypothetical GHG mitigation case studies are shown in Figure 2(c) (see SI section 1.2.2) along with the baseline 2015 supply curve. Cases with no routine flaring (moderate and extreme) and achievable minimal methane fugitives and venting, have global volume-weighted average CI reduced from 10.3 to 8.7, 8.3, and 7.9 g CO_2eq./MJ. These case studies mitigate 15% (262 Mt CO_2eq.), 19% (332 Mt CO_2eq.), and 23% (397 Mt CO_2eq.) of the current annual global upstream estimate, respectively. A fourth case study including both gas-related strategies (extreme flaring reduction plus minimal fugitives/venting) reduces the average to 5.8 g CO_2eq./MJ and results in ~43% (~743 Mt CO_2eq.) annual CI reduction.

95%ile

%ile

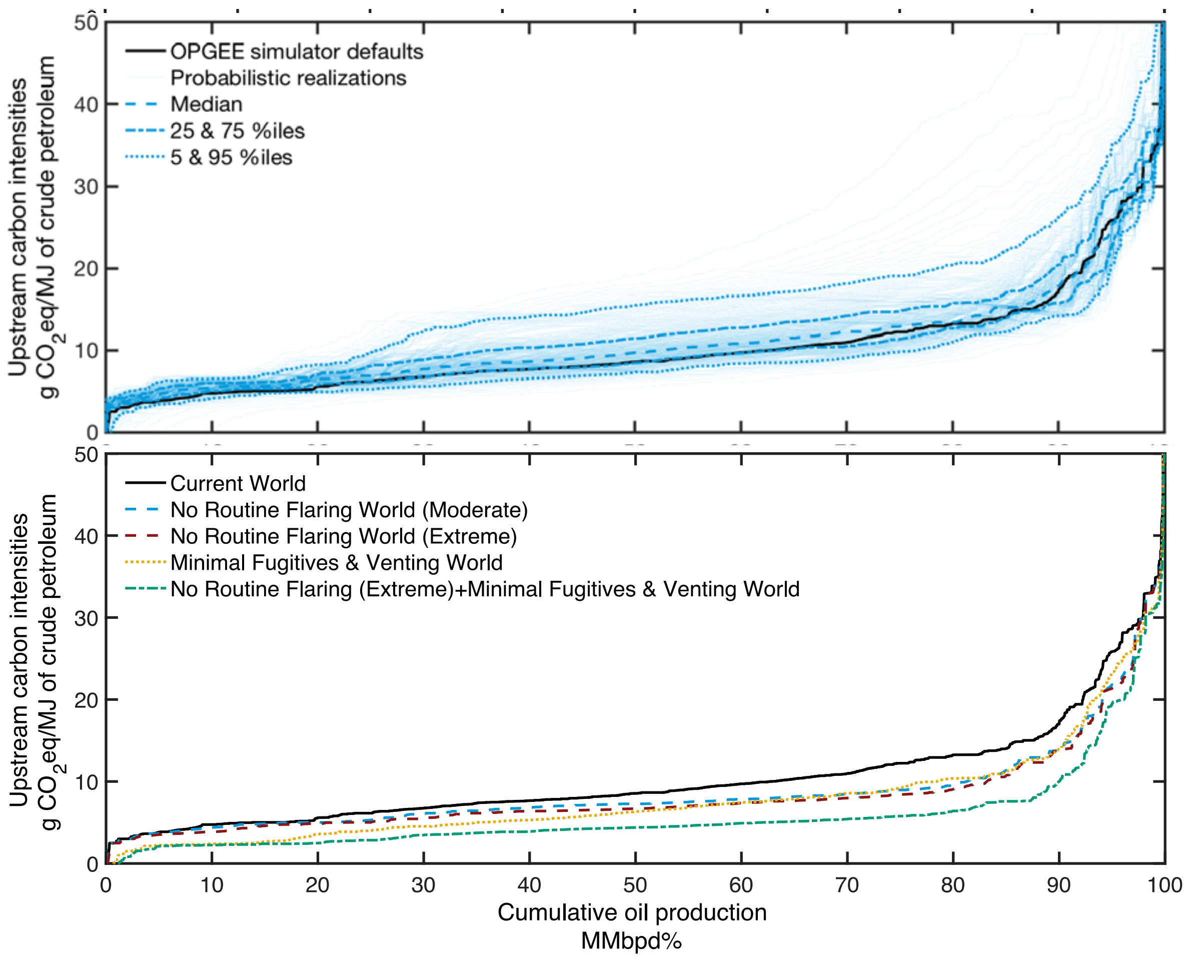

Fig. 2. Global field-level upstream carbon intensity supply curve (2015). (a) Contribution of high flaring (labeled "Flare" with flare-oil-ratio (FOR)>75%ile of all fields) and oil density (labeled "Heavy" with API gravity ≤22°). Bar width is the oil production of a particular field in 2015. Global GHG intensity percentiles (5%, 25%, 50%, 75%, 95%) are 4.7, 7.3, 9.1, 11.2, and 19.5 g CO_2eq./MJ crude oil, respectively. (b) CI probabilistic uncertainty associated with the fields' missing input data using a Monte-Carlo simulation (300 realizations per field). The narrower dispersion for the lowest and highest CI 5%iles in frame (b) is due to relatively higher data quality of the corresponding fields, e.g. in Denmark/Norway/Saudi Arabia and California (USA)/Canada/Nigeria, respectively. (c) Effect of hypothetical flaring (moderate and extreme) and methane fugitives/venting reduction cases on the CI.

Policy Implications

While oil alternatives like electric vehicles are rapidly growing, society is likely to continue to use large volumes of oil in the coming decades (*25*), (*26*). Thus, multiple strategies to reduce GHG impacts are needed: (1) prioritization and (2) management of oil resources and (3) innovative technologies.

Performance-oriented fuel quality standard programs based on LCA models have been implemented successfully (*27*), and created new regional market drivers (e.g. in California, British Columbia, the EU). Relying on both market forces and credit/debit mechanisms, these fuel-agnostic policies do not dictate specific technologies to reduce the emissions but encourage innovation to comply with the quality mandates. To achieve greater impacts, such regional fuel standard policies are and likely will continue to emerge nationally (e.g. Canada's Clean Fuel Standard expected in 2019), and subsequently worldwide to reward improved production practices with clear per-barrel incentives for the lowest CI producers (*26*).

The current lack of transparency about global oil operations makes this type of analysis particularly challenging. Labor-intensive data gathering (as undertaken here) still results in large uncertainty in emissions estimates (see SI section 1.4.6). Thus, it is important to adopt policies to make oil and gas operations technical data publicly available. If done correctly, these data can be released without affecting competitiveness of enterprises. Countries including Norway, Canada, U.K., Denmark, and Nigeria have led in this respect. As countries pledge their commitments to reduce country-level GHG emissions and transparent reporting under the Paris Agreement, it is essential for energy intensive industries (such as the oil and gas sector) to regularly report their annual carbon footprints. New industry efforts such as the Oil and Gas Climate Initiative are beginning to tackle this challenge (*28*).

There is significant debate about the risks of continued fossil fuel investment under climate uncertainty and increasingly binding constraints on cumulative emissions (*2*, *14*). A simple calculation suggests that upstream emissions from oil extraction can materially affect meeting cumulative emissions caps. Assume a reduction of the current global volume-weighted average CI (10.3 g CO_2eq./MJ) to the current 25th percentile (7.3 g CO_2eq./MJ). Such reductions would be possible using a combination of “no routine flaring”, and “minimal fugitives and venting” case studies from Fig. 2(c). Given that a typical barrel of crude oil yields ~6,000 MJ, this would result in ~18 kg CO_2eq./bbl emissions reduction. Also note that IPCC scenarios with aggressive adoption of alternative fuels used for transport (*25*) still result in projected cumulative oil consumption of >1 Tbbl in the 21st century. Thus, at least 18 Gt CO_2eq. (~12 Gt as CO_2 and ~6 Gt as CH_4) could be saved over the century by mitigating oil sector emissions through wise resource choices and improved gas management practices. Considering additional mitigation opportunities across the crude oil supply chain (e.g. improved refining), 18 Gt is likely a significant underestimate (*29*); up to 50 Gt CO_2eq. reduction potential has been estimated (*26*). For a >66% chance to keep global average temperature increases below 2 ºC, a total of approximately 800 Gt CO_2 can be emitted from 2017 forward (*30*). The petroleum sector reduction potentials outlined above are material on this scale.

Extraction and processing of heavy oils and oil sands with current technologies is very energy- and carbon-intensive and the ability to reduce the intensities is challenging. While market forces have recently led to investment shifts based on economics alone (*31*, *32*), other mechanisms exist to reduce emissions. Solar-powered steam generators developed for heavy oilfields in Oman and California (*33*) can provide significant mitigation benefit. More broadly, use of solar energy could result in sector-wide emissions reductions on the order of 5 kg CO_2eq./bbl (~1.7 g CO_2eq./MJ) (*1*). For some key regions with high seasonality and poor solar economics (like Canada), using energy inputs with low carbon intensity (e.g. using hydrogen sourced from wind and biomass), capturing CO_2 from oil sands extraction and upgrading facilities, and investing in novel low-carbon technologies (e.g. nanoparticle-assisted in-situ recovery (*34*), or CO_2-free production of H_2 from CH_4 via catalytic molten metals (*35*)) would be beneficial. In addition, low-value but high-carbon products such as petroleum coke from oil sands upgrading could be sequestrated in lieu of combustion (*26*). Global initiatives led by Canada are a step toward carbon footprint reduction for unconventional resources (*36*). Countries with diverse resources could reduce their national CI by prioritizing less carbon-intensive assets (e.g. tight oil), accompanied by stringent flaring and venting management.

Flaring rates can also be reduced. The Global Gas Flaring Reduction Partnership (GGFR) reported a nearly continuous increase in global flared gas from 2010 to 2016 (*37*). Flaring is a management and infrastructure problem and is not an unavoidable outcome of crude oil properties. Plans for new oilfield development should incorporate conservation methods (i.e., capture, utilization and/or reinjection) to eliminate routine flaring. Canadian regulations point to a method for enforcement: for offshore fields where flaring is excessive, production rate restrictions are imposed until flaring reductions are made (*38*). Initiatives like the World Bank GGFR Zero Routine Flaring by 2030 are a start, though these could be strengthened with international advisory, financial, and technical aid to help countries implement flaring reduction policies. Moreover, continuous monitoring and verification are essential for not only flare management, but also for eliminating venting and fugitive methane emissions in the oil and gas sector. Modern surveillance using remote-sensing technologies (e.g. flare and methane-sensing satellites (*39*)) could be supported and expanded (*26*).

Methane fugitive emissions and venting from oil and gas facilities are poorly detected, measured, and monitored, and thus, can increase the uncertainty associated with the presented CI estimates significantly. Recently, IEA estimated 76 Mt methane emissions from global oil and gas operations in 2015, with ~34 Mt due to oil production (*40*). This prorates to ~4.6 g CO_2eq./MJ crude oil, higher than this study's estimate of methane contribution (~2.6 g CO_2eq./MJ averaged from all global fields, from all fugitives and venting). In many cases, reducing methane emissions can result in additional revenues from the captured methane. IEA estimates that around 40-50% of current methane emissions could be avoided at no net cost (*40*). The cost of mitigation is generally lowest in developing countries in Asia, Africa and the Middle East, but in all regions, reducing methane emissions remains a cost-efficient way of reducing greenhouse gas emissions (*40*).

Important questions remain with regard to the interactions of economics and emissions. The supply curve in Fig. 2 reflects differences in CI, but crude oil production choices are obviously influenced by the interaction of local production costs and the global price of oil. A market structure without carbon prices neglects differences in supply regions and crude types shown in

Fig 2. Future work needs to examine the interaction of supply economics and emissions intensity for a different resource classes.

Data-driven CI estimates such as this work combined with refining and final combustion emissions can encourage prioritizing low-CI crude oil sourcing, point to methods to manage crude oil CI, and enable governments and investors to avoid "locking in" development of high-CI oil resources. However, future progress in this direction will rely fundamentally on improved reporting and increased transparency about oil sector emissions.

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