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Capturing economic and social value from hydrocarbon gas flaring and venting: evaluation of the issues

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Abstract: Atmospheric emissions urgently need to reduce for natural gas to fulfill its potential role in the energy transition to achieve the Paris Agreement on climate change. This paper establishes the magnitude and trends of flaring and venting in oil and gas operations, as well as their emissions and impact on air quality, health, and climate. While global flaring and venting comprise 7.5 per cent of natural gas produced, their combined impact on health and climate (in terms of Social Cost of Atmospheric Release) accounts for 54 per cent. Many low- and middle-income countries are economically dependent on oil and gas production. Most premature deaths from air pollution in 2016 were in developing countries. Most natural gas losses and emissions are avoidable. If all natural gas flared and vented globally is captured and brought to market, it could supply annually more than the total South and Central America gas consumption, plus all of Africa's power needs. If 75 per cent of these volumes are captured, it provides an additional natural gas sales value of US$36 billion per annum (assuming an average gas price of US$4/MMBtu).

Key words: energy transition, gas, health, climate, air quality

JEL classification: Q3, Q4, Q5

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Notes: This study is complemented by another WIDER Working Paper written by the same authors (Romsom and McPhail 2021): 'Capturing Economic and Social Value from Hydrocarbon Gas Flaring and Venting: Solutions and Actions'. It investigates, evaluates, and proposes solutions and actions designed to reduce flaring and venting.

Abbreviations and units are at the end of the paper.

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1 Introduction

A large number of low- and middle-income countries are dependent on oil and gas production. In 2014, 48 countries had oil and gas exports greater than 30 per cent of their total merchandise exports (Addison and Roe 2018). Of these, 29 countries were either low- or middle-income countries. In 2018, 13 low- and lower-middle-income countries received more than 20 per cent of export revenues from oil and gas. For Angola, Cameroon, Chad, Nigeria, and Yemen, oil and gas accounts for more than 50 per cent of exports (Ericsson and Löf 2020).

There are opportunities for low- and middle-income countries dependent on oil and gas production to capture significant benefits from natural gas flaring and venting. Satellite data since 2005 show that 85 per cent of total gas flared is in developing countries. The volume of gas routinely flared is large, estimated to be circa 145 billion cubic meters (bcm) annually, which is approximately 4 per cent of global gas production. Capturing and processing the gas associated with the exploitation of upstream hydrocarbon resources significantly reduces negative social impact and could provide additional revenues that can be used to support achievement of the United Nations Sustainable Development Goals (UN SDGs). Our paper will show that the opportunity revenue value from capturing and utilizing upstream flared and vented natural gas in 2019 was US$48 billion, based on an assumed US$4/MMBtu gas price (see Table 13). However, this is a fraction of the estimated social cost impact.

There are substantial societal benefits from policies that prevent routine flaring and venting, reducing emissions such as carbon dioxide (CO_2), methane, nitrogen oxides, volatile organic compounds (VOCs), organic carbon, and black carbon (BC), as noted in the report of the high-level commission on carbon prices (Carbon Pricing Leadership Coalition 2017):

> Various co-benefits—for instance, lower air pollution, improved health, higher energy security, and lower expenditures—increase the value of reducing GHG emissions for the society. Some of these co-benefits have a direct *financial translation* (such as savings from reduced fuel use) while others (such as better health or the preservation of biodiversity) cannot be directly and consensually assigned a monetary value. Moreover, there are second-order impacts, including the freeing of public resources for alternative uses, and positive macroeconomic impacts (such as growth and higher employment) associated with climate-related investments. The co-benefits of mitigation can be substantial and are therefore often an important element in analyses by policy makers.

In addition to reducing deliberate emissions, further benefits can be obtained from policies and actions that reduce other 'fugitive' emissions (i.e. leakages) of natural gas. The socio-economic benefits from reducing natural gas pollutants include the impact of air quality and climate on health, aerosols-induced impact on regional climate, and global climate impact. Technical solutions exist for the upstream industry to capture, process, and utilize the wasted natural gas and obtain financial-economic benefits in addition to the socio-economic benefits.

This study aims to provide an overview of the causes of natural gas flaring and venting in oil and gas operations and the impediments to reducing these. Gas flaring and venting is a highly significant issue in the exploitation of hydrocarbon resources because of its impact in terms of energy wastage, air quality, BC emissions, and climate change. Solutions exist to capture, process, and utilize natural gas in oil and gas processes. Nevertheless, across the world, significant volumes of unprocessed natural gas continue to be flared or vented for commercial reasons.

Most of the global gas flaring occurs when associated gas, a by-product of upstream oil exploration and production, has insufficient economic value to be processed and transported to market. Pipeline infrastructure may be lacking to transport the gas, gas markets may be locally absent, or the economic value of the gas may be less than its processing and transportation costs. Even in cases where no viable proposition can be made for economic exploitation of the associated gas, proven solutions exist to avoid these unnecessary emissions into the environment. In such situations, it is often possible to process the associated gas and reinject this into the oil-producing reservoir to optimize oil recovery. Although gas reinjection is not always possible, it is a quite common, if underutilized, technique, as according to the US Energy Information Administration (EIA), of the 4,306 bcm of gas produced in 2014, 455 bcm (10.6 per cent) were reinjected and 144 bcm (3.3 per cent) flared (World Bank 2020).

Limitations in the application of gas reinjection as a standard methodology to avoid natural gas flaring and venting

The benefits of gas reinjection into oil reservoirs are multiple:

- Gas reinjection as voidage replacement in oil reservoirs provides reservoir pressure maintenance. The arrest of reservoir pressure decline is needed to maintain well flow rates and to overcome the back pressure caused by the weight of the fluids in producing wellbores.
- Gas reinjection can provide an improved macroscopic sweep of the reservoir, whereby oil is swept towards the producing wells and a higher oil recovery factor is obtained.
- Recycled natural gas is partially absorbed by the oil in the reservoir, improving its fluid characteristics (e.g., lower viscosity) to flow in the reservoirs towards the producing wells, leaving less residual oil trapped, i.e. an improvement of microscopic reservoir sweep.
- Gas reinjection can counterbalance aquifer ingress into the oil reservoir, particularly when this would lead to lower oil recovery and well-lift problems.
- Gas reinjection can contribute to a well offtake strategy, whereby excess gas is produced above the reservoir gas-oil ratio, thereby providing additional lift in the wellbore, avoiding the cost for deploying artificial lift to keep the oil wells flowing.

Consequently, gas reinjection not only can provide a mechanism for gas disposal, it can also result in higher oil recovery efficiency. However, not all oil reservoirs are suitable for gas reinjection, and in some situations a short circuit can occur between gas-injection wells and oil-producing wells, impairing oil recovery. In other oil reservoirs, a strong aquifer may counteract the beneficial impact of gas reinjection and cause lower oil recovery efficiency. In these cases, a more prudent approach than flaring or venting of the associated gas is to dispose the produced gas into a designated disposal reservoir that has been assessed and confirmed to be able to hold the gas volumes without leaking or spilling over into other reservoir structures or potable aquifers. Significant technical understanding exists on how to select and manage gas disposal reservoirs. This same approach is also a key methodology for carbon capture and storage. Produced gas can also be reinjected into commercial gas storage reservoirs, often depleted gas reservoirs, to manage seasonal swings in demand and to conserve gas for operational and strategic reasons. Furthermore, there are additional opportunities for gas utilization within upstream oil field operations, such as gas lift, engine fuel, and local power generation.

Another important source of upstream natural gas flaring occurs in remote gas exploration well testing. Before investments can be made to develop new gas reservoirs, it is essential to get early information on the size and deliverability (flow rates) of the reservoir. It is for this reason that exploration wells are being drilled and brought on stream for long-term production testing. For large and remote gas reservoirs, exploration well tests can last for many months while flaring the gas under high flow rates. Although these exploration gas flaring durations are typically less than continuous flaring of associated gas during the field life of oil production, the amount of gas flared per time unit for a gas well test can be a factor of one thousand or more than for a producing oil well. Although it is theoretically possible to reinject the produced gas in the gas reservoir, this would interfere with the objectives of the deliverability test. In offshore or coastal situations, an alternative solution to exploration well test gas flaring is the use of floating liquefied natural gas (floating LNG or FLNG) to capture the gas and its economic value.

In 2010, International Monetary Fund (IMF) published a comprehensive analysis (Daniel et al. 2010) on the tax treatment of oil, gas, and minerals to ensure that resource endowments set countries on a path of sustained and robust prosperity. It stated that gas flaring is 'universally discouraged and should be dealt with via regulation'. This emphasis was reiterated in a 2019 World Bank publication (Huurdeman and Rozhkova 2019): 'natural gas flaring international best practice is to ban and fine gas flaring, except in specific circumstances. Angola, Ghana, Mozambique, Nigeria, Tanzania, Uganda have adopted this approach'. Despite this recognition of international good practice and the existence of technical solutions to avoid wasteful emissions from unwanted natural gas into the atmosphere, about 8 per cent of global gas production is estimated to be flared, vented, or leaked. The considerations to flare are often based on commercial criteria rather than technical arguments. An example that illustrates this point is a recent case where the Texas regulator approved the application from oil company Exco Resources to flare gas, despite its oil field already being connected to a gas-gathering system. The owner of the gas gathering, Williams, was willing to take the gas and raised the objection against gas flaring, considering 'flaring is waste' if a company has pipeline access. The ruling by the Texas Railroad Commission (Rassenfoss 2019) made clear its view that:

- 'Flaring is a critical part of the well construction process and it is important companies be able to continue to use this tool';
- 'anytime there is a negative cost—you do not get as much (money) as you get otherwise—you can flare';
- If the commission blocked production of oil it would prevent burning of gas worth a fraction as much as the oil production lost.

The essence in this case is the definition of 'waste'. The Texas Railroad Commission opted for defining 'waste' as anything that does not optimize economic value, rather than the broader view that 'waste'[1] is an avoidable negative impact on the environment. In a subsequent section, we will review the status of gas flaring and venting in the United States and in other countries in more detail. It is worth noting that the perception that associated natural gas is 'waste' when the means for economic development are not readily available is shared by many producers and regulators globally.

When externalities are not priced in, a distorted view of 'waste' results. The consequence, as can be readily observed globally, is that valuable energy resources go up in smoke rather than being preserved because there is *momentarily* no financial economic return to utilize it. With gas providing 23.6 per cent of global primary energy demand, versus 32.7 per cent to oil, it is no longer viable to hold the point of view that gas is a waste product. It is long overdue that industry and regulators adopt policies and regulations that state:

To vent or flare routinely to produce is an unacceptable oil and gas industry practice.

There are certain situations that may necessitate emergency flaring or venting. For example, to protect human life and equipment, a process upset may trigger a gas blowdown scenario to avoid a fire or explosion. Such cases of emergency flaring are infrequent and of short duration. They

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[1] According to Lexico.com, 'waste' is: '1) an act or instance of using or expending something carelessly, extravagantly, or to no purpose; 2) material that is not wanted; the unusable remains or by-products of something'. Herein lies part of the problem, when associated natural gas in oil production is seen as a waste stream to be disposed of.

contribute, therefore, less to global emissions than routine flaring in upstream and downstream operations. Initiatives are underway to stop routine flaring. One of these is the Global Gas Flaring Reduction (GGFR) Partnership, led by World Bank Group. We will investigate and evaluate such programmes in more detail in the second WIDER paper that complements this paper.

Section 2 provides a definition of ‘flaring’ and identifies the different types and causes of this. Section 3 provides a similar definition and analysis of ‘venting’. Section 4 discusses the different definitions of ‘fugitive emissions’ and the uncertainty in assessment and measurement. Section 5 sets out the scale and trends over time of global flaring and venting. Section 6 combines different data sets and establishes an integrated assessment of natural gas flared and vented that includes the amounts and damages of chemicals released in the atmosphere. Section 7 delivers a consistent representation of the social impact of these atmospheric releases because different emissions affect climate, air quality, health, and the environment differently. Section 8 introduces solutions to overcome impediments that hinder utilization of associated gas. Section 9 concludes.

2 What is flaring?

The importance of well-operated flares

- Natural gas flaring in the oil and natural gas industry is defined as the controlled combustion of natural gas for operational, safety, or economic reasons.
- A well-operated flare can achieve a 98 per cent destruction efficiency of natural gas by thermal oxidization (i.e. 98 per cent of hydrocarbons destroyed).
- Many natural gas flares fail to meet this operational target and produce a range of chemicals, such as nitrogen oxides (NO_X), sulphur oxides (SO_X), VOCs, and BC, that are toxic and affect air quality, as well as have a negative impact on the climate.
- There is increasing concern that flare systems are inadequately monitored and that flare combustion processes cause chemical emissions much higher than estimated by regulators.

Natural gas flaring in the oil and natural gas industry is defined as the controlled combustion of natural gas for operational, safety, or economic reasons. Natural gas flaring occurs for operational reasons; for example (US Department of Energy 2019):

- during drilling to dispose of gas influx into the wellbore;
- during exploration well testing to determine well deliverability and minimum connected reservoir volumes;
- during production well testing to stabilize flow and clean up the well before fluids are routed through production facilities;
- during flow diversion from regular process equipment in situations of production upsets, maintenance operations, and/or emergency pressure relief;
- during regular operations to dispose of small volumes of waste gas, such as from gas evaporation from oil storage tanks;
- during regular operations as pilot flame for instantaneous ignition of any diverted gas flows.

In addition, flaring also occurs for economic reasons:

- during operations, in situations when oil production facilities are available, but where gas processing infrastructure is under construction or not yet operable;

- during production to avoid impairment of hydrocarbon recovery from shutting in wells while processing facilities are temporarily unavailable;
- during operations, in situations where oil can be produced but there is no opportunity to bring the associated gas to market;
- during operations, when technical solutions exist to process and capture the gas and bring it to market, but when this is less economic, then flaring and the associated gas is seen as a waste product.

Flares are cost-effective and useful safety devices in operations as they can dispose of sudden releases of large amounts of gas, even if gas flows are intermittent or highly variable. Flare systems (EPA 2016a) typically cost US$10,000 to US$3 million, depending on size and degree of sophistication (EPA 2019).

The importance of operating flares well

This paper details the significant pollution and social costs that result from flares that do not fully combust their feed gas. Flare volumes can vary from almost zero to 1.4 Bcf/d of gas, and commercially available flare burner tips range from 2.5-cm to 2.3-m diameter. A well-operated flare can achieve a VOC destruction efficiency of 98 per cent (equating to a combustion efficiency, i.e. full conversion into CO_2, of 96.5 per cent) (EPA 2012). However, flares are not suitable for halogenated compounds.[2]

If the heat content of the gas exceeds 300 Btu/scf, flares can sustain combustion without auxiliary fuel. Flares create combustion at high temperatures in the range 500–1,100 °C and are very concentrated. These characteristics of concentration and temperature profile allow remote-sensing technologies to identify gas flares and differentiate these from other heat sources, such as wildfires. This enables remote monitoring of individual gas flares by satellite.

Flares do not pose a safety concern for high concentration of organics in the feed because they use an open combustion process, significantly reducing the risk for an explosive environment. Flares are generally elevated to create distance between the open flame and to disperse products from the combustion.

Flare combustion quality depends on flame temperature, combustion residence time, turbulent mixing of gases and air flow, and presence of any heavy elements (e.g., liquids) in the feed. If the airflow is insufficient or irregular, smoking, flickering, and soot forming (BC) can occur and the combustion process will be incomplete, creating other organic compounds such as aldehydes and acids. Primary air is added to the gas before the mixture enters the flame. The volume of oxygen needed to ensure a clean burn depends on gas composition and increases from a factor of 9.6 for methane to 38.3 for pentane (EPA 2018). In addition to insufficient oxygen, smoking occurs when crosswinds reduce the effective flare height and therefore the temperature of the flare combustion zone.

The presence of liquids in the gas stream also will deteriorate the combustion process. Most flare systems have a knock-out vessel to remove liquid content. If liquids enter the flare, they can cause sprays of burning chemicals, smoking, and/or extinguishing of the flame.

Concern is growing that flare systems are inadequately monitored and that flare combustion processes cause chemical emissions orders of magnitude higher than estimated by regulators. Instead of process measurements and emissions monitoring, industry and regulators often rely on decades-old formulas for estimating pollution from flaring (Hasemyer 2016) that do not cover super-emitter flares.

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[2] A halogenated compound is a VOC onto which a halogen (e.g., fluorine, chlorine, bromine, or iodine) is attached. Streams containing high concentrations of halogens or sulphur containing compounds are not usually flared because of corrosion of the flare tip and formation of secondary pollutants (e.g., sulphur dioxide [SO_2]). If these vent types are to be controlled by combustion, thermal incineration followed by scrubbing to remove the acid gases is the preferred method (Stone et al. 1992).

3 What is venting?

Venting is harder to detect and has larger impact on the climate than flaring

- Natural gas venting in the oil and natural gas industry is defined as the direct release of natural gas into the atmosphere, creating emissions of methane as well as other components in the gas.
- Venting happens regularly in oil and gas operations to avoid pressure build-ups and when vapour recovery technologies are uneconomic.
- Methane emissions have a much larger radiative forcing impact on climate than CO_2. Therefore, well-operated gas flaring is preferred over venting.
- Emissions from venting are harder to detect than gas flaring.

Venting is the direct release of natural gas into the atmosphere. Venting of natural gas not only releases methane but also any other chemical components that are in the gas. Natural gas venting occurs for operational reasons, for example (US Department of Energy 2019):

- during routing liquid unloading of low-pressure gas wells;
- during flow diversion from regular process equipment in situations of production upsets and/or emergency pressure relief;
- during blowdown of process equipment in situations of production upsets and/or emergency pressure relief;
- during maintenance operations, to bleed off gas pressure from devices and control equipment;
- during regular operations to avoid pressure build-up from evaporation of liquid hydrocarbons in processing and storage facilities without vapour recovery systems;
- during regular operations as routine emissions from flash tanks, dehydration columns, amine units, etc.;
- during regular operations as routine emissions from loading and unloading of liquid hydrocarbons for transport;
- during boil off during LNG transportation and LNG storage, as part of the cooling process.

Venting should only occur for small volumes where it is not possible or reasonable to install vapour recovery or flare systems. Venting of hydrocarbons in large volumes could cause gas explosion risks. Furthermore, the climate impact from venting a certain volume of hydrocarbons is significantly higher than from flaring that same volume, as described in the following section. There is no valid reason to routinely vent associated gas as a waste product stream in oil production operations. The points raised above why routine flaring can occur for commercial reasons are invalid for venting. If flaring to produce is bad, venting to produce is worse. Nevertheless, operators that wish to dodge emission regulations may resort to venting as a waste disposal mechanism because gas flares are easy to spot and gas vents are harder to trace. However, (satellite) technology to identify sources of methane venting has improved significantly in recent years.

4 What are fugitive emissions?

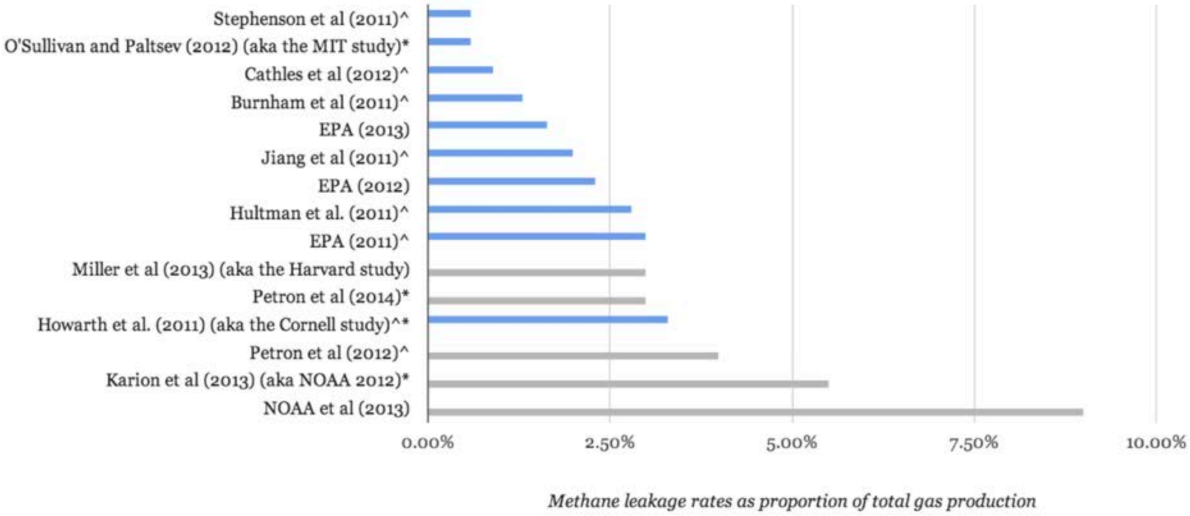
Fugitive emissions from oil and gas operations include strong pollutants to health and climate

- Definitions of fugitive emissions are evolving as to whether these include all emissions, i.e. also deliberate flaring and venting, or only uncontrolled streams such as leakages of natural gas.
- Methane is a large contributor of fugitive emissions from leaked or vented natural gas. However, other components, such as C_{2+} alkanes, VOCs, and contaminants (e.g., CO_2, hydrogen sulfide [H_2S]), also contribute.
- Even more than gas flaring, fugitive emissions are difficult to measure. Estimated leakage rates for methane as a proportion of natural gas production range from 1 per cent to 9 per cent, with consensus at ~3 per cent.
- Compared to CO_2, methane releases have a stronger negative impact on global warming in the short term, but methane also has a shorter half-life, and therefore, the degree of negative impact versus CO_2 reduces faster with time.
- Intergovernmental Panel on Climate Change (IPCC) assessments show a global warming potential (GWP) for methane, relative to CO_2, of 72 and 25 for a 20-year and 100-year time horizon, respectively.
- A 'well-to-burner-tip' methane leakage rate of 3.2–4.5 per cent is identified as the tipping point where climate benefits of gas-fired power plants over coal-fired power plants are fully eroded.

In addition to deliberate flaring and venting in oil and gas operations, there are fugitive emissions of methane and other greenhouse gases (GHGs) along the hydrocarbon supply chain. IPCC uses a definition for fugitive emissions from oil and gas systems that includes all GHG emissions (Boettcher 2019) except contributions from fuel combustion for the production of useful heat or energy. Therefore, the fugitive emissions definition by IPCC specifically includes flaring and venting of natural gas, even though these latter emissions are not 'fugitive' in the strict sense of the word. On the contrary, the US Environmental Protection Agency (EPA) uses an alternative definition for fugitive emissions as those emissions (of GHGs) that could not reasonably pass through a stack, chimney, vent, or other functionally equivalent opening. EPA's definition of fugitive emissions therefore excludes flaring and venting (EPA 1999). For the purpose of this work, we are focusing on flaring and venting as deliberate emissions of collected GHGs as the area of focus and as targets for solutions to increase the usefulness of these sources and reduce their negative impact. However, as data sources often do not distinguish between deliberate venting and inadvertent leaks, we have adopted the IPCC definition of fugitive emissions for this paper.

Particularly when assessing the environmental and climate impact from the exploration, production, transportation, storage, distribution, and use of energy carriers (fuels), all emissions should be considered. Inadvertent methane leaks contribute to carbon emissions, just as venting and flaring do. Some of the techniques to identify and measure fugitive emissions are the same as for venting. However, a systematic approach for consistent quantification of fugitive emissions is lacking. Bottom-up approaches can give a detailed snapshot for the emissions for a given asset or piece of equipment but do not 'follow the molecules' across the full supply chain, creating an incomplete record of emissions related to the use of an energy source. This makes it difficult to compare total emissions (e.g., for the full supply chain of a gas-fired versus coal-fired power solution). Top-down approaches to assess, for example, methane emissions over a larger area lack specificity on the emission sources of methane within a given area and may result in a high estimate when allocating these measurements to a specific asset (Hope 2014).

Figure 1: Broad range for methane leakage rate estimates from upstream oil and gas operations



Source: reproduced from CarbonBrief (2017), under the CC license Attribution-NonCommercial-NoDerivatives 4.0 International.

The top-down estimates for methane leakage rates (the grey bars in Figure 1) are generally higher than the bottom-up data (blue bars), with some overlap across both data sets and around 3 per cent leakage rates. The estimates in Figure 1 may also contain methane contributions from deliberate venting and/or incomplete carbon combustion in flares. Further methane losses in addition to the upstream oil and gas leakages could occur and require a comprehensive well-to-burner-tip assessment. For natural gas to be considered a 'lighter carbon fuel', i.e. with less impact on climate change than coal, it is imperative that losses of GHGs caused by the industry are kept as low as practically possible. Compared to CO_2, methane releases have a stronger negative impact on global warming in the short term, but methane also has a shorter half-life, and therefore, the degree of negative impact versus CO_2 reduces faster with time.[3] Depending on the time horizon, methane has a GWP of 72 and 25 for a 20-year and 100-year time horizon, respectively (Forster et al. 2007).[4] There are various studies that compare the relative climate impact of gas-fired power versus coal-fired power as a function of methane emissions. One study concludes that natural gas is only better for the climate if total methane emissions along the gas supply chain are less than 10–11 per cent and 4.0–4.5 per cent for a 100-year and 20-year time horizon, respectively (Law 2018). Another study assesses this tipping point for methane emissions at 3.2 per cent (at all time horizons) (Alvarez et al. 2012). This latter study also compares the climate impact as a function of methane emissions for using compressed natural gas (CNG) as an alternative fuel in automotive transport.

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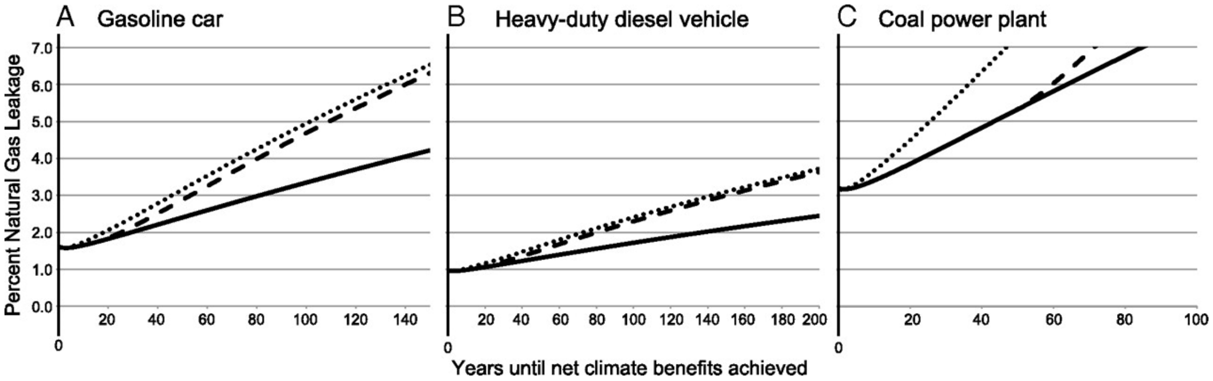
[3] Methane is oxidized to CO_2 with a half-life of seven years. In comparison, CO_2 is chemically inert and is removed from the atmosphere by dissolving into oceans and conversion through biological photosynthesis.

[4] The GWP of 1 kg of a chemical element such as methane is normalized relative to 1 kg of CO_2 (GWP=1).

Figure 2: 'Well-to-wheel' and 'well-to-burner-tip' natural gas emissions as a function of the number of years before net climate benefits are obtained from the use of natural gas instead of alternative fuels.



Note: The dotted lines represent the impact under incidental use, the dashed line represents the impact for the full-service life of the asset (15 years for automotive, 50 years for power plant), and the solid line represents permanent use with identical asset replacement after its service life.

Source: reproduced from Alvarez et al. (2012), with permission.

Although we recognize the importance of considering all emissions (gas flaring, gas venting, leaks, and emissions from energy use, i.e. energy efficiency) across the supply chain when assessing the impact of using certain fuels, this paper focuses primarily on deliberate emissions from gas flaring and venting during the oil and gas production process. These considerations on flaring and venting emissions will also have some relevance for possible approaches for other fugitive emissions, such as leaks, particularly once measurements of methane emissions along the supply chain (e.g., through remote-sensing techniques) obtain sufficient volumetric and spatial accuracy to detect large numbers of smaller leaks.

5 Global scale of hydrocarbon flaring and venting

Global fugitive emissions (in MtCO2e) increased by 35 per cent between 1994 and 2014

- Natural gas flared and vented worldwide is estimated at circa 150 bcm and 155 bcm per annum, respectively, and 3.7 per cent and 3.8 per cent (total 305 bcm or 7.5 per cent) of global gas production.
- If gas flared and vented globally is captured and brought to market, it could supply more than all of South and Central America gas consumption, plus all of Africa's power.
- Flaring volumes decreased from 1996–2010 but thereafter started slowly trending up; venting volumes have increased gradually as global gas production increased.
- In 2019, five countries (Russia, Iraq, Iran, US, and Venezuela) contributed 54 per cent of global flaring; developing countries account for more than 85 per cent of total gas flared.
- The total contribution of energy losses from flaring, venting, and other fugitive emissions comprises 5.2 per cent of global GHG emissions, or 7.2 per cent of global energy GHG emissions.
- Global flaring and venting volumes are highly significant as an opportunity cost but even more so from a social cost perspective, i.e. because of their impact on air quality, health, and climate.
- Of the 16 largest fugitive emission countries in 2014, 11 were in the global top 15 oil-producing countries. However, when assessing individual countries, we observe that large oil production with zero or low levels of routine flaring is possible.

Natural gas flared and vented worldwide is estimated at circa 300 bcm annually—3.7 per cent and 3.9 per cent of global natural production, respectively. These volumes wasted are emitted into the atmosphere, affecting air quality and climate. Most of the gas flared and vented is associated gas, a by-product from producing oil. Global associated gas is estimated at 20 per cent of total gas produced (World Bank 2020), and therefore, the fraction of associated gas flared and vented in upstream oil operations could be as high as one-third.

According to World Bank (2020), the volume of global gas flared was equivalent to the total gas consumption of South and Central America in 2018 (or 30 per cent of the European Union's total gas consumption that year). This flare volume also releases annually the equivalent of 360 million tons of CO_2 into the atmosphere, which is equivalent to the yearly CO_2 emissions of 77 million cars.

Developing countries account for more than 85 per cent of total gas flared and vented. Africa flares 32 bcm and vents 24 bcm of natural gas annually, about 19 per cent of the global volume, and this is equivalent to 40 per cent of its yearly power consumption (or 290 terawatt-hours of electricity).

If gas flared and vented globally is captured and brought to market, it could supply more than all of South and Central America gas consumption, plus all of Africa's power.

If flared and vented natural gas is added to other fugitive emissions, the total contribution of these energy losses comprises 5.2 per cent of global GHG emissions, or 7.2 per cent of global energy GHG emissions (see Figure 3) (Center for Climate and Energy Solutions 2020). This degree of loss in the global energy system is highly significant, particularly because most of these are avoidable losses. As discussed in the sections before, natural gas flaring and venting in particular should be easier to avoid as these are deliberate and concentrated emissions as opposed to (other) fugitive emissions that are mostly dispersed and caused by leaks.

Figure 3: Global manmade GHG emissions by sector (2013)

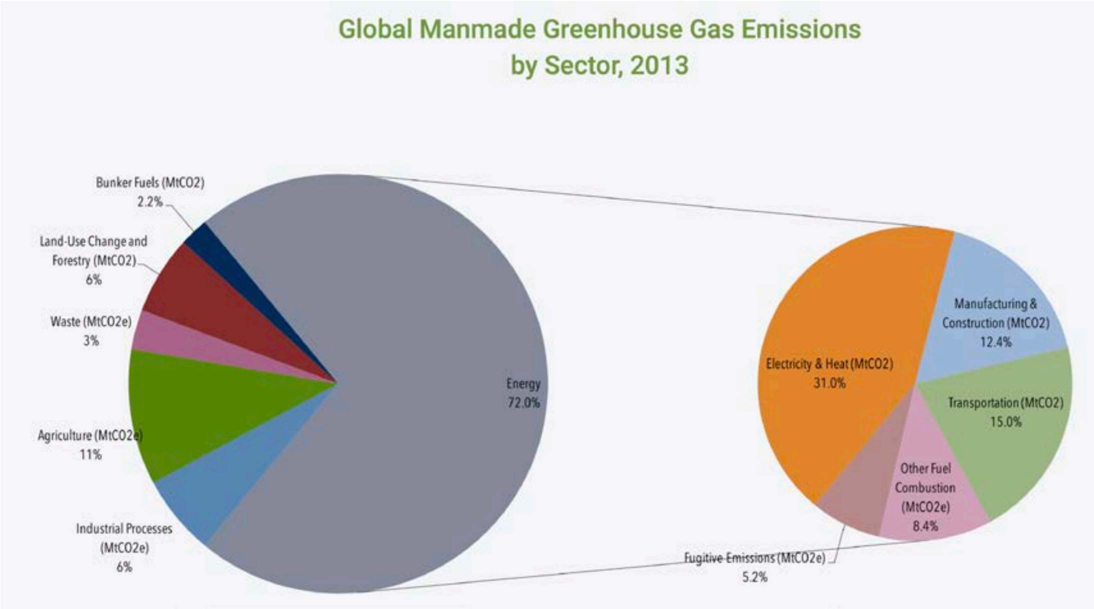


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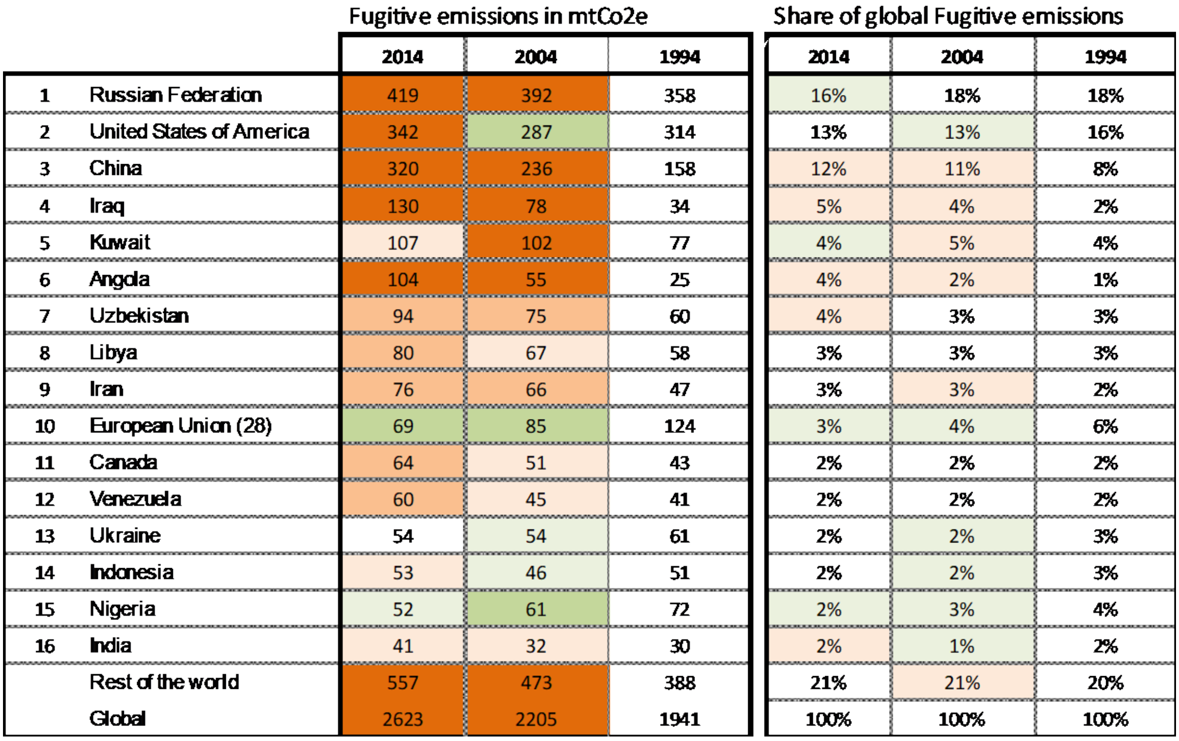
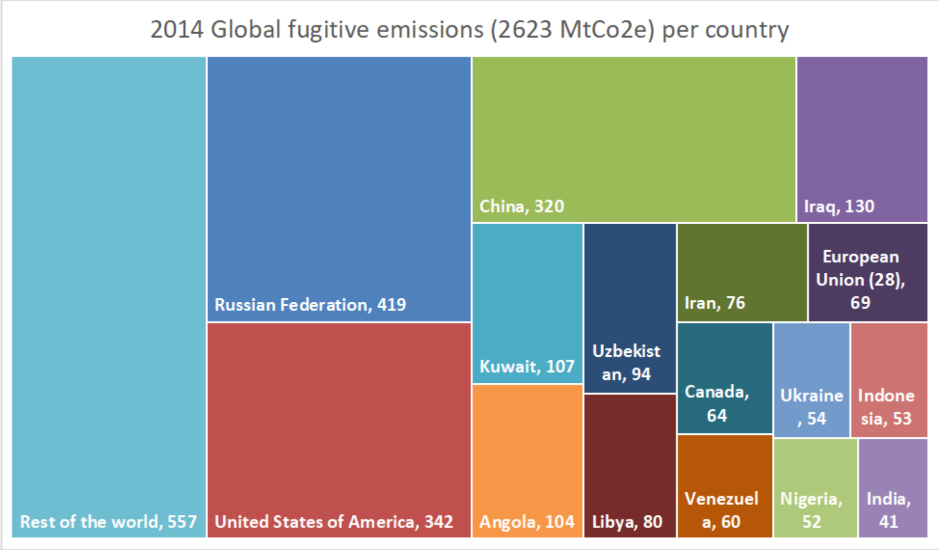
Table 1: Fugitive emission trends per country from 1994–2014

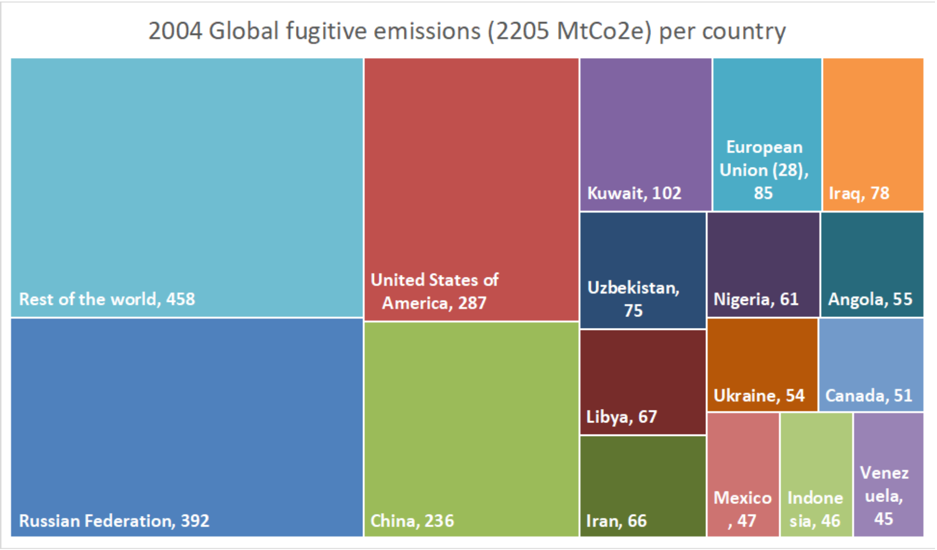


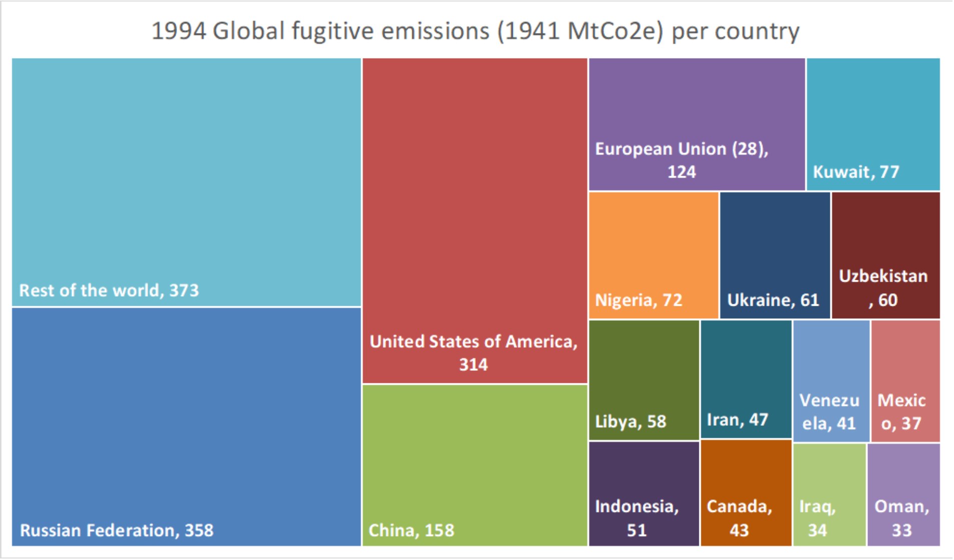
		Fugitive emissions in mtCo2e			Share of global Fugitive emissions		
		2014	2004	1994	2014	2004	1994
1	Russian Federation	419	392	358	16%	18%	18%
2	United States of America	342	287	314	13%	13%	16%
3	China	320	236	158	12%	11%	8%
4	Iraq	130	78	34	5%	4%	2%
5	Kuwait	107	102	77	4%	5%	4%
6	Angola	104	55	25	4%	2%	1%
7	Uzbekistan	94	75	60	4%	3%	3%
8	Libya	80	67	58	3%	3%	3%
9	Iran	76	66	47	3%	3%	2%
10	European Union (28)	69	85	124	3%	4%	6%
11	Canada	64	51	43	2%	2%	2%
12	Venezuela	60	45	41	2%	2%	2%
13	Ukraine	54	54	61	2%	2%	3%
14	Indonesia	53	46	51	2%	2%	3%
15	Nigeria	52	61	72	2%	3%	4%
16	India	41	32	30	2%	1%	2%
	Rest of the world	557	473	388	21%	21%	20%
	Global	2623	2205	1941	100%	100%	100%

Source: authors' calculations based on data from World Resources Institute CAIT Climate Data Explorer (2017).

Figure 4: Fugitive GHG emissions by country in 2014, 2004, and 1994







Source: authors' illustrations based on data from World Resources Institute CAIT Climate Data Explorer (2017).

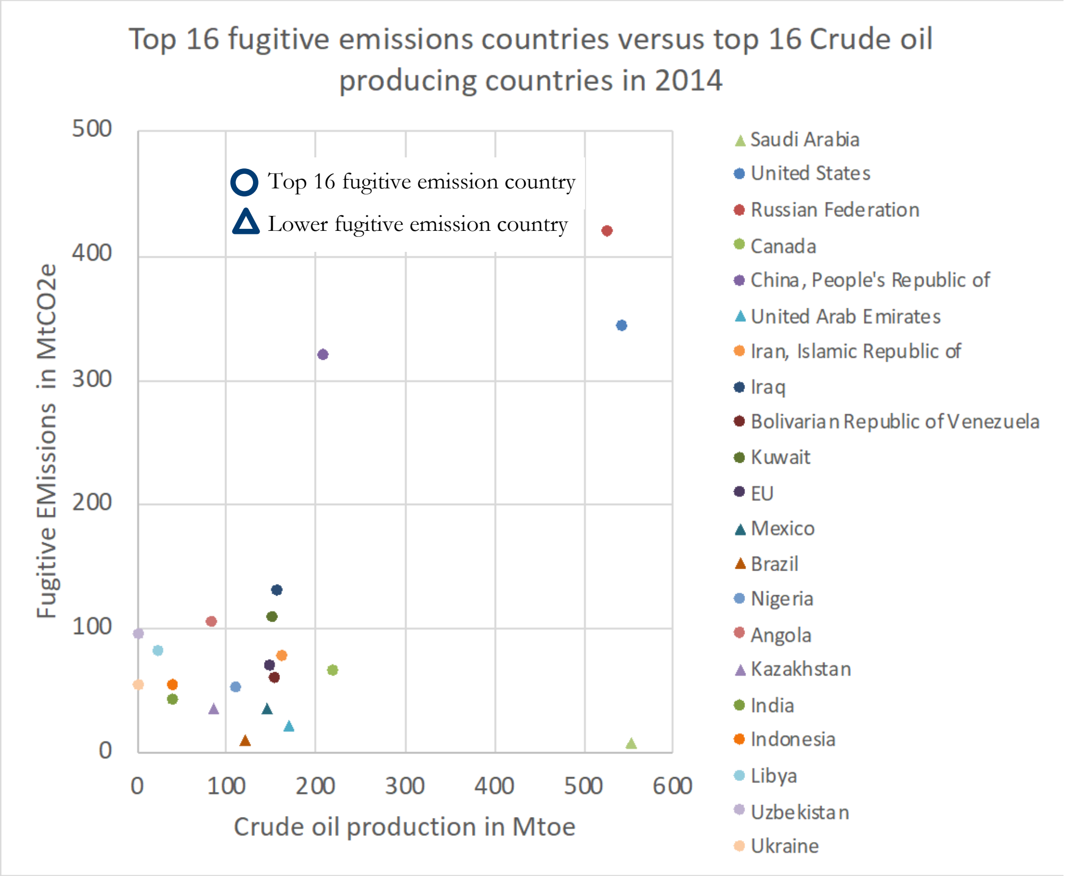
In the period 1994–2014, the global fugitive emissions (in $MtCO_2e$) increased by 35 per cent. What is remarkable from the representations in Figure 4 and Table 1 is that over the course of 20 years, the top 16 global emitters have barely changed. In 2004, Oman dropped out of the list being replaced by the growing volumes in Angola. In 2014, India replaced Mexico, which had seen a significant reduction in fugitive emissions from 47 $MtCO_2e$ in 2004 to 36 $MtCO_2e$. These are the only two changes in the world rankings of top fugitive emitters in 20 years.

A further key observation is that almost all large emitters are growing their emissions, with the exception of the European Union (EU) (-44 per cent), Nigeria (-28 per cent), and Ukraine (-11 per cent), which have reduced their emissions since 1994.

The top five emitters (Russia, US, China, Iraq, and Kuwait) were responsible for 50 per cent of the global fugitive emissions in 2014. This was consistent over the years, with 50 per cent also in 2004 and 53 per cent in 1994. The only difference during these years was the displacement of the EU by Iraq in the top five.

The top three emitters, unchanged in their standing since 1994, have grown their fugitive emissions much faster the rest of the world combined, i.e. twice as much since 2004 and one-and-a-half times as much since 1994 (in terms of $MtCO_2e$), representing 40 per cent and 37 per cent of global fugitive emissions growth, respectively.

Figure 5: Comparison of countries with large fugitive emissions and those with large oil production



Note: countries listed in order of declining crude oil production volumes.

Source: authors' illustration based on data from World Resources Institute CAIT Climate Data Explorer (2017) and IEA (2020a).

Of the 16 largest fugitive emissions countries in 2014, 11 were also in the global top 15 oil-producing countries[5] (see Figure 5). The other five largest emitting countries (and their rankings in global oil production) were: Uzbekistan (ranked 53rd), Libya (30th), Ukraine (55th), Indonesia (25th), and India (ranked 22nd). However, there are also large oil-producing countries with relatively low fugitive emissions, such as those shown in Table 2. This demonstrates that it is possible to have large oil production without having large fugitive emissions. The argument that fugitive emissions are necessary and inevitable to produce oil is therefore flawed.

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[5] In Table 1 and in Figure 5, we have shown the 28 countries of the European Union as a single entity.

Table 2: Large oil-producing countries with relatively low fugitive emissions and flaring volumes

Country	2014 oil production (Mtoe)	2014 global oil producer ranking	2014 fugitive emissions (MtCO$_2$e)	2014 global fugitive emissions ranking	2014 flaring volume (bcm)	2014 global flaring ranking
Saudi Arabia	553	**1**	8	**44**	1.9	**19**
United Arab Emirates	171	**6**	23	**24**	0.9	**29**
Mexico	145	**11**	36	**20**	4.9	**8**
Brazil	121	**12**	10	**39**	1.5	**22**
Norway	85	**15**	1	**74**	-	**-**
Kazakhstan	84	**16**	36	**21**	3.9	**9**
Qatar	78	**17**	3	**50**	1.3	**26**

Note: Mtoe=million tonnes of oil equivalent.

Source: authors' calculations based on data from World Resources Institute CAIT Climate Data Explorer (2017) and IEA (2020a).

When we look at flaring as a subset of fugitive emissions, we see again a very consistent picture: of the 16 countries with the largest fugitive emissions in 2014, 10 were also in the global top 16 oil-flaring countries (see Figure 6).

Between 2013 and 2019, the global annual volume flared increased by 7.5 per cent, from 139.6 bcm to 150 bcm. The top five flaring countries in 2019 were responsible for 50 per cent of the globally flared volumes during 2013–19 (54 per cent in 2019). During the years, there has been very little variability in the ranking order of the top flaring countries: 1) Russia, 2) Iraq, 3) US, 4) Iran, and 5) Venezuela.[6] Since 2016, the United States has doubled its flaring under its growing shale developments. Under economic sanctions, Iran significantly reduced flaring (20 per cent) in 2019 (see Table 3 for details).

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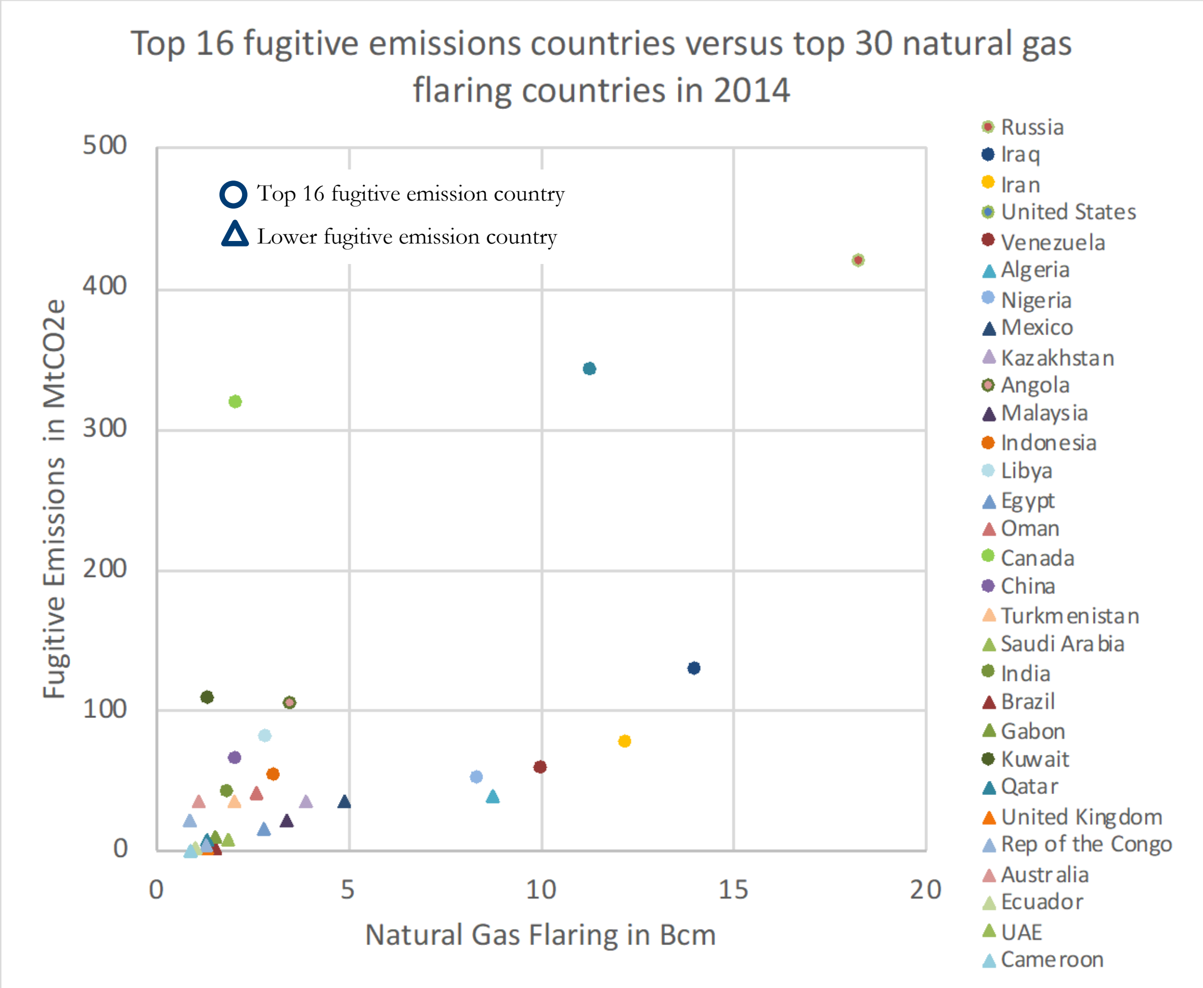
[6] In 2019, the United States displaced Iran for third place. Algeria is a close contender for fifth place (and had fifth position in 2018).

Figure 6: Comparison of countries with large fugitive emissions and those with large flaring



Note: countries listed in order of declining flaring volumes.

Source: authors' illustration based on data from World Resources Institute CAIT Climate Data Explorer (2017) and IEA (2020a).

As shown in Figure 7, the five largest flaring countries grew their annual flare volumes fastest, with a total increase in volumes from 62.8 bcm to 81.7 bcm, an increase of 30 per cent between 2013 and 2019. Remarkably, the 'rest of the world' countries outside the flaring top 30 have been able to reduce their flaring volumes by 35 per cent in the same period, from 13.1 bcm to 8.5 bcm. This is especially noteworthy as the flaring top five have some of the most developed and mature oil and gas infrastructure. The argument that routine flaring occurs mainly in the early production phase to allow gas infrastructure development to catch up is not substantiated by the data.

Consistent with our views on fugitive emissions, we can similarly conclude that large oil production can occur with relatively low flaring, as illustrated in Table 2 and Figure 8. Flaring is therefore not a necessary evil associated with the production of oil. Countries such as Saudi Arabia, Norway, Kuwait, Qatar, and UAE have relatively low flaring in view of the size of their oil production.

Table 3: Top 30 countries with largest flaring volumes in 2019 [7]

Gas flaring volumes 2013-19 (billion cubic meters)

Rank	Country	2019	2018	2017	2016	2015	2014	2013
1	Russia	23.2	21.3	19.9	22.4	19.6	18.3	19.9
2	Iraq	17.9	17.8	17.8	17.7	16.2	14.0	13.3
3	United States	17.3	14.1	9.5	8.9	11.9	11.3	9.2
4	Iran	13.8	17.3	17.7	16.4	12.1	12.2	11.1
5	Venezuela	9.5	8.2	7.0	9.3	9.3	10.0	9.3
6	Algeria	9.3	9.0	8.8	9.1	9.1	8.7	8.2
7	Nigeria	7.8	7.4	7.6	7.3	7.7	8.4	9.3
8	Libya	5.1	4.7	3.9	2.4	2.6	2.9	4.1
9	Mexico	4.5	3.9	3.8	4.8	5.0	4.9	4.3
10	Oman	2.6	2.5	2.6	2.8	2.4	2.6	2.4
11	Malaysia	2.4	2.2	2.8	3.2	3.7	3.4	2.8
12	Egypt	2.3	2.3	2.3	2.8	2.8	2.8	2.4
13	Angola	2.3	2.8	3.8	4.5	4.2	3.5	3.2
14	Saudi Arabia	2.1	2.3	2.3	2.4	2.2	1.9	2.0
15	China	2.0	1.8	1.6	2.0	2.1	2.1	1.9
16	Indonesia	2.0	2.1	2.3	2.8	2.9	3.1	3.1
17	Rep of the Congo	1.7	1.6	1.1	1.1	1.2	1.3	1.4
18	Kazakhstan	1.6	2.0	2.4	2.7	3.7	3.9	3.8
19	Gabon	1.5	1.4	1.5	1.6	1.6	1.5	1.4
20	Australia	1.4	0.9	0.7	0.7	1.1	1.1	0.8
21	Turkmenistan	1.3	1.5	1.7	1.8	1.8	2.0	2.3
22	Qatar	1.3	1.0	1.0	1.1	1.1	1.3	1.4
23	India	1.3	1.3	1.5	2.1	2.2	1.9	1.7
24	Brazil	1.1	1.0	1.1	1.4	1.3	1.5	1.3
25	United Kingdom	1.1	1.2	1.4	1.3	1.3	1.3	1.4
26	Canada	1.1	1.3	1.3	1.3	1.8	2.1	1.5
27	Cameroon	1.0	1.1	1.0	1.1	1.1	0.9	0.8
28	Argentina	0.9	0.7	1.2	0.6	0.7	0.7	0.7
29	Syria	0.9	0.7	1.2	0.6	0.5	0.4	0.4
30	Ecuador	0.9	0.9	1.1	1.2	1.1	1.0	0.8
	Top 30 Countries	**141.5**	**136.3**	**131.9**	**137.3**	**134.3**	**131.0**	**126.5**
	Rest of the World	8.5	8.7	8.7	10.3	11.3	12.9	13.1
	Global Total	**150**	**145**	**141**	**148**	**146**	**144**	**140**

Note: increases from 2018 to 2019 in red; GGFR countries plus Saudi Arabia (Saudi Aramco) in green. The amount of gas flared in 2019 was the largest since 2009 (GGFR 2020).

Source: authors' calculations based on data from GGFR (2020).

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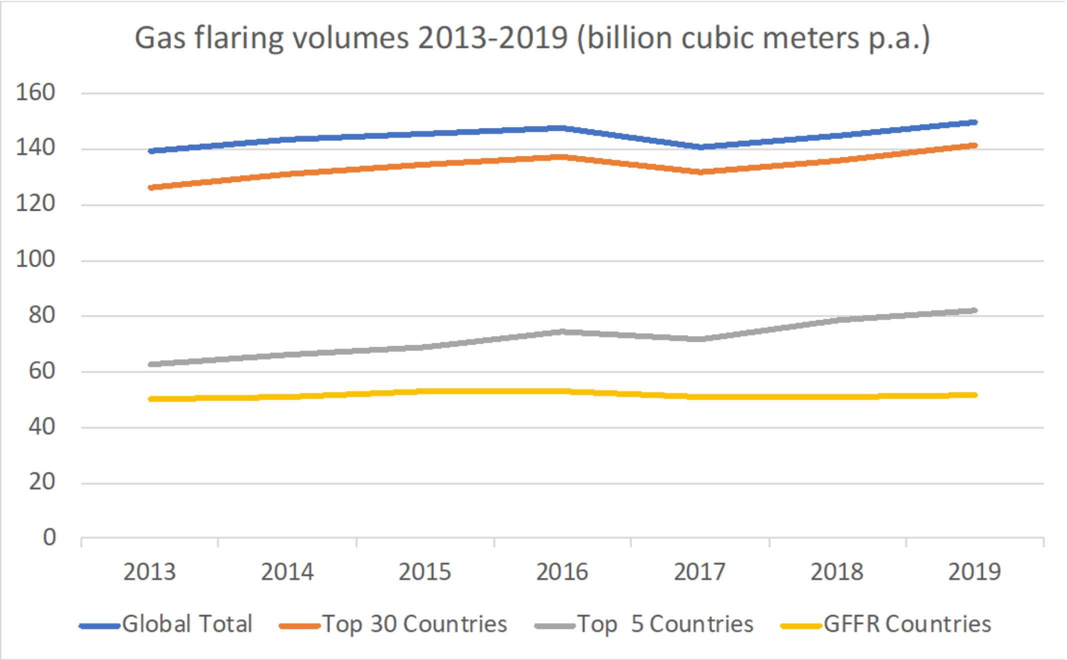
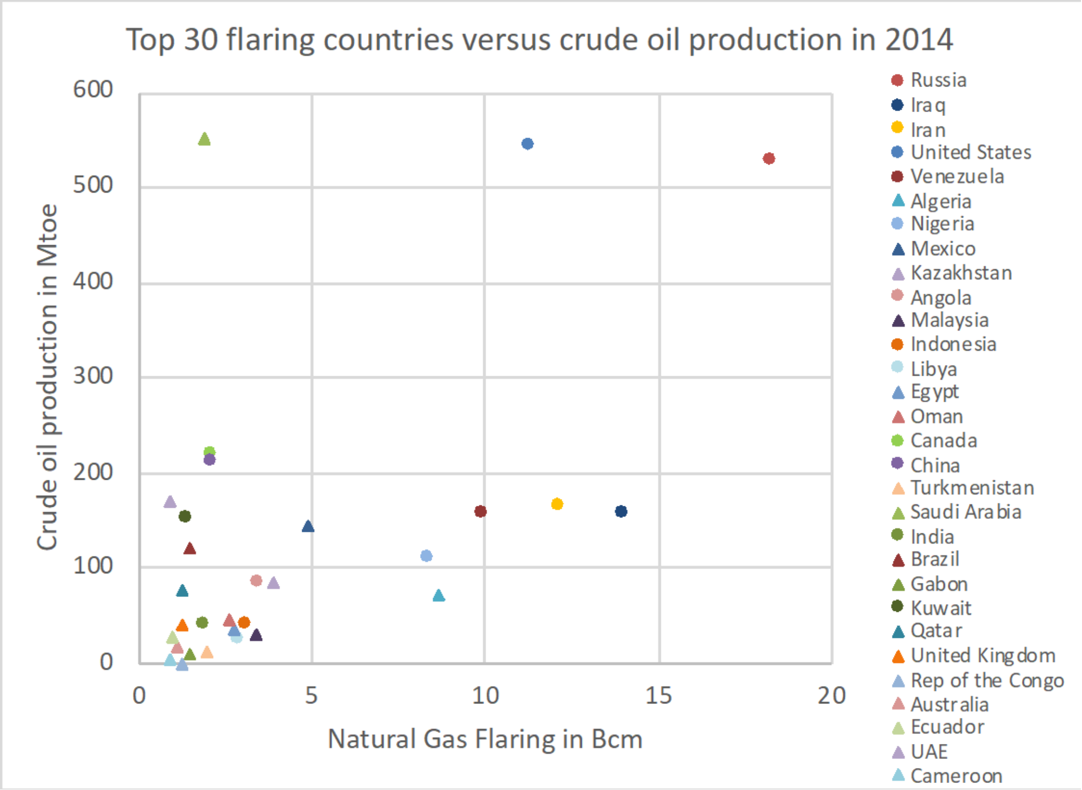
[7] Each cubic meter of natural gas produces circa 2.3 kg of CO_2e emissions under full combustion (see Appendix A). The 2016 global flaring volume of 147.6 Bcm is equivalent to 340 $MtCO_2e$. Hence, the 2017 reduction in gas flaring of nearly 5 per cent equates to an emissions reduction of 16 $MtCO_2e$. However, in 2018 and 2019, flaring volumes increased again, increasing emissions to 345 $MtCO_2e$ in 2019 (assuming full combustion).

Figure 7: Large natural gas flaring countries appear to have disproportionally grown their flare emissions, while small flaring countries have reduced their flaring



Source: authors' illustration based on data from GGFR (2020).

Figure 8: Comparison of countries with large oil production and those with large flaring volumes



Note: countries listed in order of declining flaring volumes.

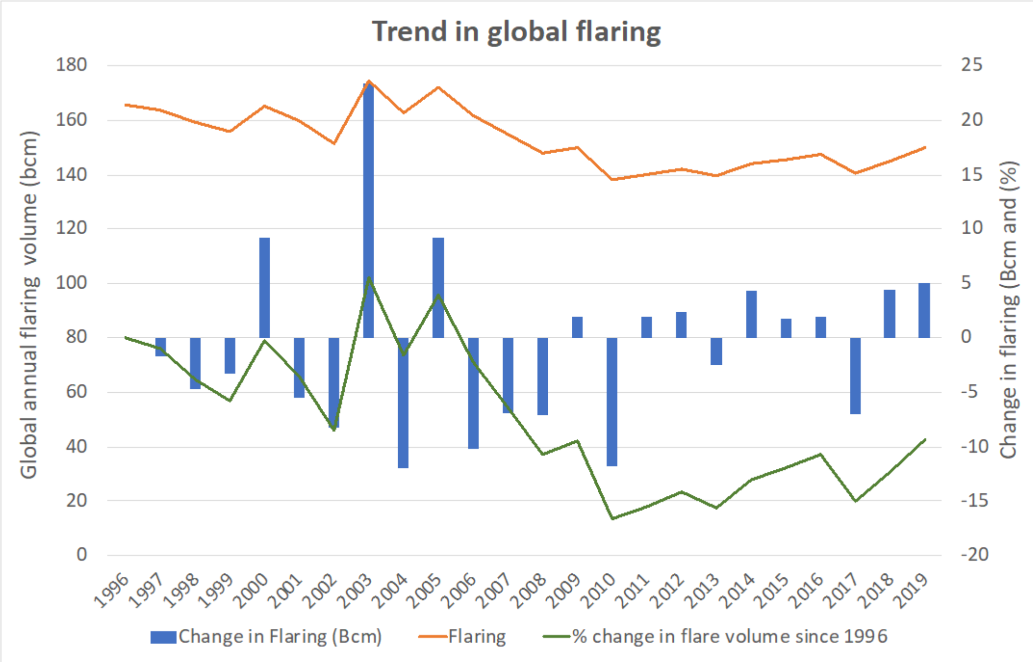
Source: authors' illustration based on data from World Resources Institute CAIT Climate Data Explorer (2017) and IEA (2020a).

In 2002, at the World Summit on Sustainable Development, the Global Gas Flare Reduction (GGFR) partnership was launched by Norway and the World Bank. The first priority was to work with the National Oceanic and Atmospheric Administration (NOAA) in the U.S. Department of Commerce to fill measurement gaps by producing the first flaring estimates based on satellite observations for 60 countries. In 2015, a further initiative was launched by the World Bank, Norway, and other parties to stop routine flaring by 2030. An increasing number of countries, companies, and organizations have pledged their support since then. Despite urgency for material progress on this initiative, efforts to date have made insufficient impact on global flare reduction.

However, in the period 1996–2010, the industry was able to reduce global flaring volumes by almost 17 per cent; Russia and Nigeria are noteworthy in their reduction of gas flaring. An explanation for this is the development of gas markets and the growth of LNG in these years (Romsom and McPhail 2020). LNG has been a key technology in bringing remote stranded gas to markets and in growing new markets for gas. Although the global use of gas (and LNG in particular) has continued to grow rapidly since, this has not resulted in a further decline in gas flaring (Figure 9).

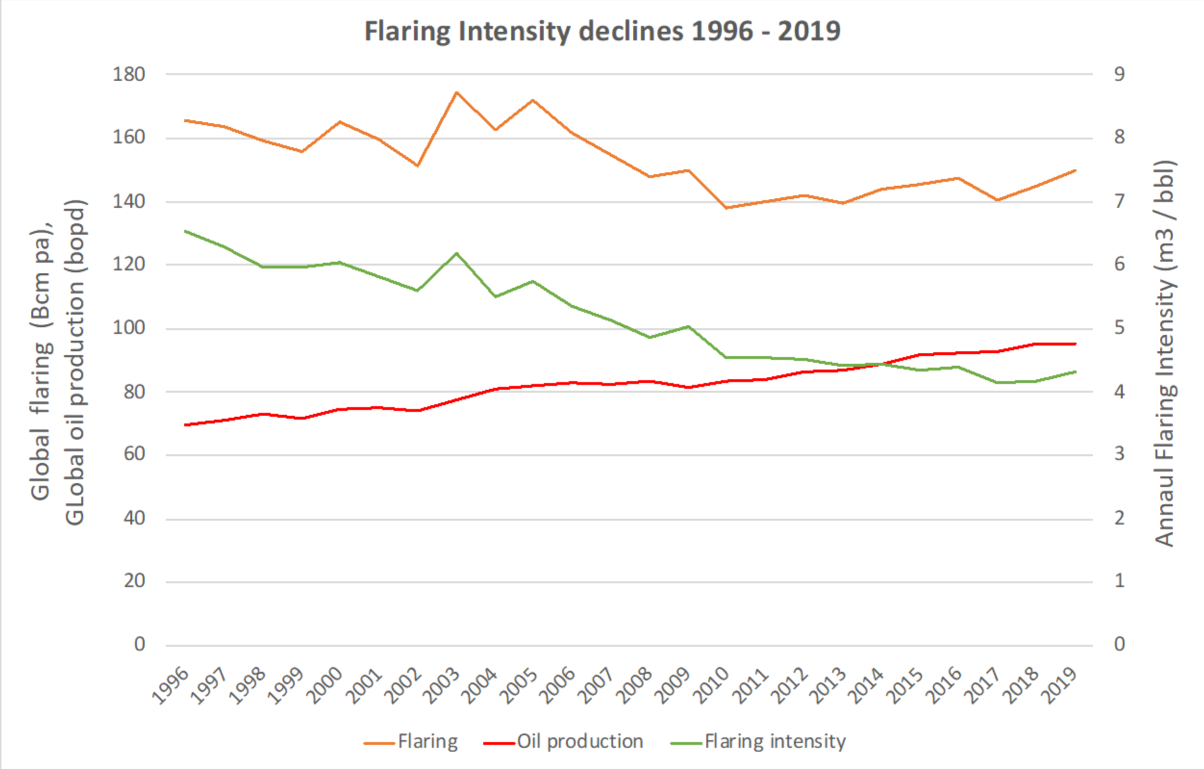
The assumption that flaring is necessary to grow oil production to meet demand is not borne from the evidence. From 1996 to 2010, global oil production grew from 69.5 mbopd to 83.4 mbopd (+20 per cent), whilst global flaring reduced in the same period by 16.7 per cent. Consequently, flaring intensity decreased from 6.52 m^3/bbl in 1996 to 4.15 m^3/bbl in 2017, a reduction of 36.4 per cent. Since 2017, this rose again to 4.32 m^3/bbl in 2019 (see Figure 10). Flaring intensity is often hailed as a success in flare-reduction efforts. However, this measure is only relevant when comparing the relative flaring performance of assets, companies, and countries. Regarding the impact of flaring, only absolute measures, such as cumulative volumes flared and/or vented, are relevant. This is because our resource base and our environment have absolute, instead of relative, limits and constraints.

Figure 9: The gas flaring reduction trend during 2005–10



Source: authors' illustration based on data from GGFR (2020).

Figure 10: Flaring intensity during 1996–2019



Source: authors' illustration based on data from GGFR (2020) and BP (2020).

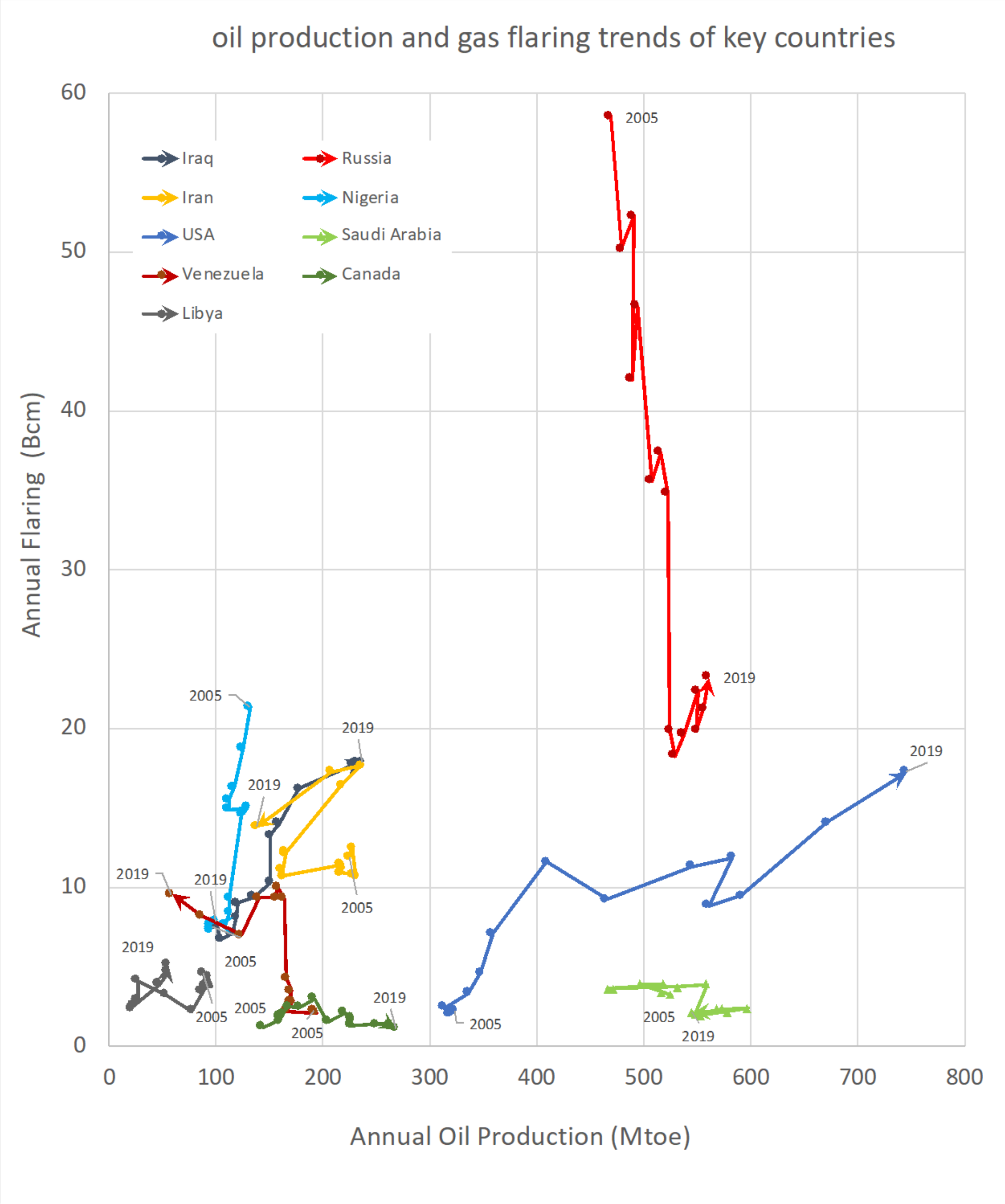
When evaluating flaring and crude oil production trends from individual countries during 2005–17, we observe a marked variation in individual country trends (see Figure 11 and Table 4). This further illustrates that oil production growth does not have to imply an increase in gas flaring.

Table 4: Individual country trends in oil production and flaring (in bold countries in Figure 11)

Top 21 Flaring Countries During 2005–17	Oil Decrease	Oil Stable	Oil Increase
Flaring Decrease	**Nigeria** Uzbekistan	Angola China Kuwait	**Russia** Kazakhstan Qatar
Flaring Stable	**Libya** Indonesia	Malaysia Oman	**Saudi Arabia** **Canada**
Flaring Increase	**Venezuela** Algeria Mexico	**Iran** Egypt	**USA** **Iraq**

Source: authors' calculations based on data from GGFR (2020) and IEA (2020a).

Figure 11: Individual country trends in oil production and flaring during 2005–19



Source: authors’ illustration based on data from GGFR (2020) and IEA (2020a).

6 Impact of hydrocarbon flaring and venting

Flaring and venting each have their own specific emissions impacts and affect climate, health, and the environment differently

- There is considerable uncertainty in the assessment of fugitive emissions. Emissions data are sparse, and uncertainty ranges are large. This has consequences on the transparency in polluting sources, pollutants emitted, and the impacts thereof.
- Progress in remote-sensing technologies using satellite data, as well as in modelling of transport and impact assessments, are important developments to reduce these uncertainties.
- Flaring and venting each have their specific emissions impacts and affect climate and the environment differently.
- Different data resources use different variables for emissions (e.g., natural gas, CO_2, methane, CO_2-equivalent), different quantities (e.g., volume, mass, energy), and different units (e.g., ton, tonne, kg, lb). This makes data comparison and data integration difficult.
- Most impact assessments for natural gas flaring and venting focus on CO_2 and methane emissions and their impacts on climate in terms of US$/tonne CO_2e.
- In addition to CO_2 and methane, large amounts of strong pollutants on health and climate, such as VOCs, organic carbon, NO_X and SO_X, carbon monoxide (CO), ammonia (NH_3), hydrogen sulphide (H_2S), and BC, are emitted when natural gas flares are not designed or operated properly.
- In absence of published integrated impact assessments that combine climate, air quality, and health impacts for the wide range of pollutants emitted during flaring and venting, the authors adopted Shindell's SCAR methodology, presented in this paper.

Having evaluated the scale and trends in global flaring and venting in the previous section of this paper, we will now discuss the impact of these oil and gas activities in terms of emissions. As described earlier, there is considerable uncertainty in the determination of fugitive emissions. The data are sparse, and there is a widespread between individual estimates, as illustrated in Figure 1. Progress in remote-sensing technologies using satellite data, as well as in modelling of transport and impact assessments, are important developments to reduce these uncertainties in terms of completeness, accuracy, and consistency of emission measurements. Flaring and venting each have their specific emissions impacts and affect climate and the environment differently. While all flaring is deliberate, methane and other emissions have the additional complexity that these can be deliberate or accidental (e.g., leaks). Emissions that are part of process streams are easier to eliminate by diverting these to other uses. Methane emitted from oil and gas operations in 2019 comprised 81.5 million tonnes (138 million tonnes of natural gas), and this contributed some 60 per cent of the total methane emitted from the energy sector and 6 per cent of GHG emissions from the global energy sector (IEA 2020c).[8]

The combined amount of natural gas flared and vented has stayed relatively constant during 2000–19.[9] However, the contribution of gas flared decreased from 58 per cent in 2000 to 49 per cent in 2019. In this period, natural gas flaring reduced in absolute amounts by 13 mtpa, while natural gas venting emissions increased by 32 mtpa (19 mtpa of which is methane) (see Figure 12).

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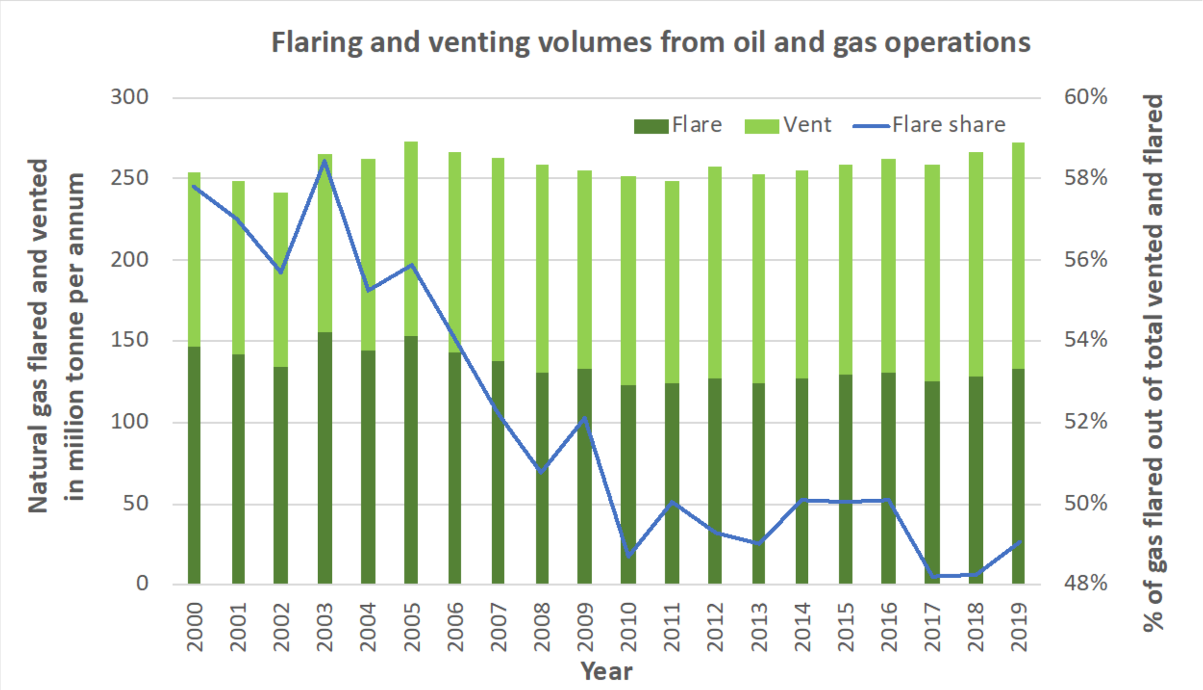
[8] However, since 2017, both flaring and methane emissions are on the rise.

[9] The IEA 2019 estimate for global methane emissions is 81.5 mtpa, an increase of 2.5 Mt since 2019 (+3.2 per cent). Upstream oil emits 46.5 per cent, upstream gas 34.5 per cent, and downstream gas 19 per cent (IEA 2020b).

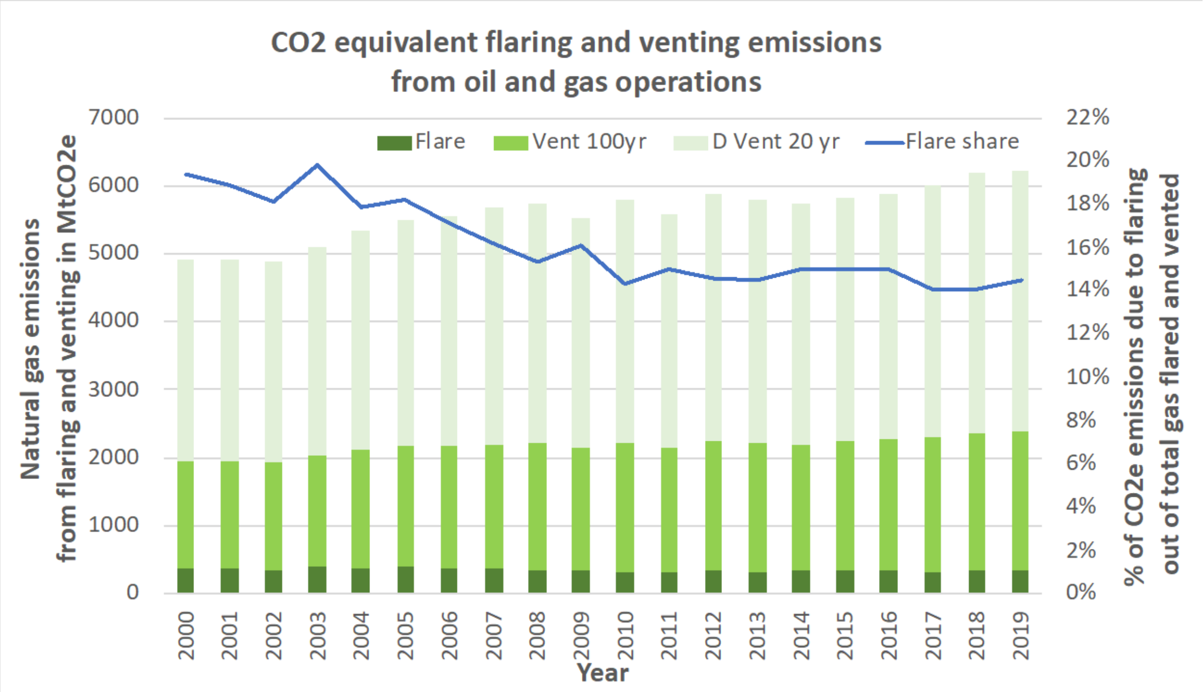
Figure 12: Flaring and venting from oil and gas operations during 2000–19



Note: methane mtpa emissions as per IEA have been converted to natural gas mtpa using methane density and raw gas properties described in Appendix A.

Source: authors' illustration based on data from GGFR (2020) and IEA (2020c).

Figure 13: CO_2-equivalent emissions from flaring and venting in oil and gas operations during 2000–19



Note: for flaring, a 100 per cent combustion efficiency has been assumed; for venting, only methane emissions (as per IEA) have been counted, split into a 100-year time horizon and the incremental impact from assuming a 20-year time horizon.

Source: authors' illustration based on data from GGFR (2020) and IEA (2020c).

Although flaring contributes 48–58 per cent of the global natural gas flared and vented in oil and gas operations under the assumption of perfect combustion, its climate impact in terms of CO_2-equivalent emissions seems significantly less, i.e. 14–20 per cent based on a 100-year time horizon and 5–8 per cent based on a 20-year period (see Figure 13). Methane emission avoidance is a major opportunity in reducing the short-term emissions impact on global warming.

However, this does not mean that flaring emissions can be ignored. Other than CO_2, significant pollutant emissions result from poor flare combustion processes. Flaring was not considered to be an important source of air pollution for a long time, and hence, non-CO_2 emissions from flaring were not inventoried nor included in IPCC assessments. More recent climate models now include emissions such as particulate matter (PM), aerosols, and other agents causing climate change.

In 2015, the eight member states of the Arctic Council (four of which are major oil and gas producers—Canada, Norway, Russia, and the United States) adopted the 'Enhanced Black Carbon and Methane Emissions Reductions: An Arctic Council Framework for Action' (Arctic Council 2019) given the impact on human health and the environment. The following year, and for the first time, the IEA's (2016) World Energy Outlook analysed the links between energy, air pollution, and health. It focuses on how the energy sector can contribute to improved air quality as the fourth-largest threat to human health. The IEA finds that 'energy production and use—mostly from unregulated, poorly regulated or inefficient fuel combustion—are the most important man-made sources of key air pollutant emissions: 85 per cent of particulate matter and almost all of the sulfur oxides and nitrogen oxides'.

6.1 Hydrocarbon flaring often does not meet performance standards

A flare is prone to fail to ignite or to be blown out, particularly if the heating value of its feed gas is too low. Instead of the natural gas being flared, these volumes are then vented with increased climate impact in terms of $MtCO_2e$. To avoid the occurrence of these situations, EPA prescribes a minimum heating value of the gas to be flared of 300 Btu/scf (EPA 2012).

Flare gas emissions are seldom measured but estimated based on assumptions for flow rates, gas composition, and quality of the combustion process. Without measurements, it is very difficult to assess if these assumptions are correct, and hence, large deviations between assumed and actual flare emissions can occur. EPA prescribes a 98 per cent destruction efficiency for a well-operated flare system, equating to a 96.5 per cent combustion efficiency (EPA 2016b). The flare emission factors are defined based on this assumption, although many flare systems may not achieve this destruction efficiency.

In the United States, emission factors for flares were developed in 1991 based on pilot-test data from the 1980s. Under the Clean Air Act, the emission factors were supposed to be reviewed and updated every three years. However, these reviews were never carried out, and the assumed factors remained unchanged until 2014 when they were amended after a lawsuit forced EPA to carry out the review based on actual refinery data. The review demonstrated that the flare emission of VOCs was four times the amount previously assumed (Environmental Integrity Project 2015).

6.2 VOCs

VOCs are organic chemicals that have a high vapour pressure, i.e. they evaporate easily from a liquid (or solid) into a gaseous state in the surrounding air or as a natural gas. VOCs have short atmospheric lifetimes (fractions of a day to months) and limited direct effect on radiative forcing. However, VOCs influence the climate through their production of organic aerosols and their involvement in the production of ozone (O_3) in the presence of NO_X and light. VOCs are the precursors to smog and can be hazardous (i.e. toxic) air pollutants (HAPs). The EPA assessment of the public health costs of VOCs range from US$900 to US$4,000 per ton (2015).

Significant VOC emissions occur from natural gas venting, leakages of oil and gas installations, and poorly operated flares. EPA's 2015 accepted emission factor for VOCs is 0.66 lb/MMBtu (EPA 2018). With a typical heating value of unconditioned flare gas of 1,242 Btu/scf (see Appendix A), the VOC emission factor equates to 0.0131 kg/m^3. Based on GGFR natural gas flaring estimates for the United States, the resulting amount of VOCs emitted based on the EPA emission factor was estimated at 124,730 tonnes in 2017 and 185,120 tonnes in 2018. As mentioned above, the emission factor may overestimate the destruction efficiency of flare combustion, resulting in higher actual VOC emissions from flaring. Nevertheless, flaring will combust a large fraction of VOCs, while vented emissions will emit VOCs directly into the environment. Total VOC emissions in the United States from the oil and gas industry in 2017 was estimated at 2.54 million tons (EPA 2017) (see Table 5).

Table 5: VOC emissions in the US oil and gas industry split by source

2017 VOC Emissions from US Oil and Gas Industry	Amount of VOCs (in tons)[10]	Share of total VOC emissions
Gas Flaring	137,491	5.4%
Gas Venting	2,354,588	92.6%
Subtotal Oil & Gas Production	2,492,079	98%
Refineries	51,718	2%
Total Oil and Gas	2,543,797	100%

Source: authors' calculations based on data from EPA (2017).

The United States follows the global average trend that flaring and venting each contribute about half to natural gas volume emissions.[11] This implies that of the VOCs entering natural gas flares (~2.35 million tons), only 0.137 million tons remain after combustion. This equates to a destruction efficiency of 94.22 per cent instead of 98 per cent.

Based on above-mentioned EPA assessments of public health costs, VOC emissions from US oil and gas operations are therefore estimated to be in the range of US$2.23 billion to US$10.18 billion per year (in 2015 US$). The most commonly emitted VOC compounds (other than alkanes) and their emissions in the United States are presented in Table 6.

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[10] The conversion of tonne (metric ton) to US short ton is based on 1 ton = 0.90718 tonne.

[11] For 2019, IEA estimated US methane emissions from upstream oil and gas operations at 9.117 Mt (excluding downstream gas contribution of 2.225 Mt). Based on a methane density of 0.668 kg/m^3 and the unprocessed natural gas composition in Appendix A, this equates to 17.43 Bcm of natural gas vented. For 2019, the latest figures from Groom and Hiller (2020) indicate a further increase in US flaring from 14.1 Bcm in 2018 to 16.16 Bcm in 2019. The relative contribution from venting and flaring in the United States in Bcm of natural gas is therefore 52 per cent versus 48 per cent, respectively.

Table 6: Overview of some of the non-alkane VOC emissions by US oil and gas production and refineries

2017 Other Emissions from US Oil and Gas Industry	Oil and Gas Production (in tons)	Refineries (in tons)
Formaldehyde (VOC) [12]	23,632	282
Benzene (VOC) [13]	27,371	327
Toluene (VOC)	18,878	659
Styrene (VOC)	8.2	40
Xylene (VOC)	25,916	502

Source: authors' calculations based on data from EPA (2017).

6.3 Organic carbon, NO_X and SO_X, and other emissions

Partial combustion of VOCs and oxidization of VOCs in the air create chemicals known as 'organic carbon'. Organic carbon (OC) generally refers to the mix of compounds containing carbon with another element such as hydrogen or oxygen and are the products of incomplete combustion. Like ozone, OC is an agent that absorbs incoming solar radiation but to a lesser extent than black carbon.

Other than CO_2 and H_2O, flaring of natural gas can create other by-products in the combustion process. Contaminants in the gas, such as compounds of sulphur (H_2S) and nitrogen, can create NO_X and SO_X and other particulate matter (such as black carbon) during flaring.

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[12] Formaldehyde is a toxic, volatile chemical and a known carcinogen. It is an intermediate chemical in the oxidation (or combustion) of methane, as well as of other carbon compounds. When produced in the atmosphere it becomes part of smog.

[13] Benzene, toluene, xylene, and styrene (BTXS) are aromatic VOCs that share common properties. They are used on an industrial scale in the production of petrochemicals (EPA 1998).

Table 7: Overview of NO_X, SO_X, and other emissions from oil and gas production and refineries

2017 Other Emissions from US Oil and Gas Industry	Oil and Gas Production (in short tons)	Refineries (in short tons)
PM10	12,580	20,165
PM2.5	12,237	16,573
Organic Carbon (of PM2.5)	4,020	2,254
Hexane	3,561	756
CO	632,266	57,401
NO_X	617,568	67,943
SO_X	63,830	60,139
H_2S	691	605
NH_3	269	2,598
N_2O (Nitrous Oxide)[14]	14.3	4

Source: authors' calculations based on data from EPA (2017).

6.4 Black carbon

Soot and smoking (BC) occur when a gas flare is insufficiently oxygenated. A partial burn breaks open the carbon bonds of the organic compounds, which then start to form polyaromatic hydrocarbons (PAHs). The higher the content of heavier hydrocarbons, the more likely the occurrence of smoking. Knock-out of liquid hydrocarbons and gas conditioning prior to gas flaring can significantly reduce the risk of smoking. Studies have confirmed the relationship between flare-gas composition (in particular its heating value) and BC emission factors (Huang and Fu 2016). The volume of oxygen supplied to the flare to ensure a clean burn increases from a factor of 9.6 for methane to 38.3 for pentane (EPA 2018). For this reason, primary air is added to the gas before the mixture enters the flame. In addition to insufficient oxygen, smoking also occurs when crosswinds reduce the effective flare height and, therefore, the temperature of the flare combustion zone. Well-operated flares with flame temperatures of 2,500 K produce 0.57 g/m^3 of BC, and poorly operated flares at 700 K and below produce 1.75 g/m^3 of BC (Caseiro et al. 2019).

The PAHs formed are solid-state molecular compounds that can vary from <1μm to 100 μm. PAHs with sizes smaller than 3μm (PM2.5) are particularly harmful to lungs and are a contributing factor in respiratory disease (Rao and Krishna 2012). Soot particles are prone to adsorb toxic organics and metals, further compounding their environmental and health impacts. BC is a known carcinogen. Although BC is short-lived in the atmosphere (with a lifetime ranging from days to months), its impact on climate change is severe. It warms the atmosphere directly by absorbing sunlight and indirectly by reducing the reflectivity (albedo) of clouds and of snow and ice in polar regions, causing these to melt at accelerated rates. Once snow and ice start to melt, BC starts to concentrate, and the melting process accelerates further. Global climate models suggest that the reduction of snow and ice albedo by BC is three times as effective as CO_2 in radiative forcing of global warming (Ramanathan and Carmichael 2008).

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[14] The global warming potential (GWP) for nitrous oxide is a factor 300, which is much higher than methane. See https://insideclimatenews.org/news/11092019/nitrous-oxide-climate-pollutant-explainer-greenhouse-gas-agriculture-livestock

Figure 14: Radiative forcing of black carbon contributes significantly to snow and ice melt

Source: by Pyty / image used under a standard license from Shutterstock.com.

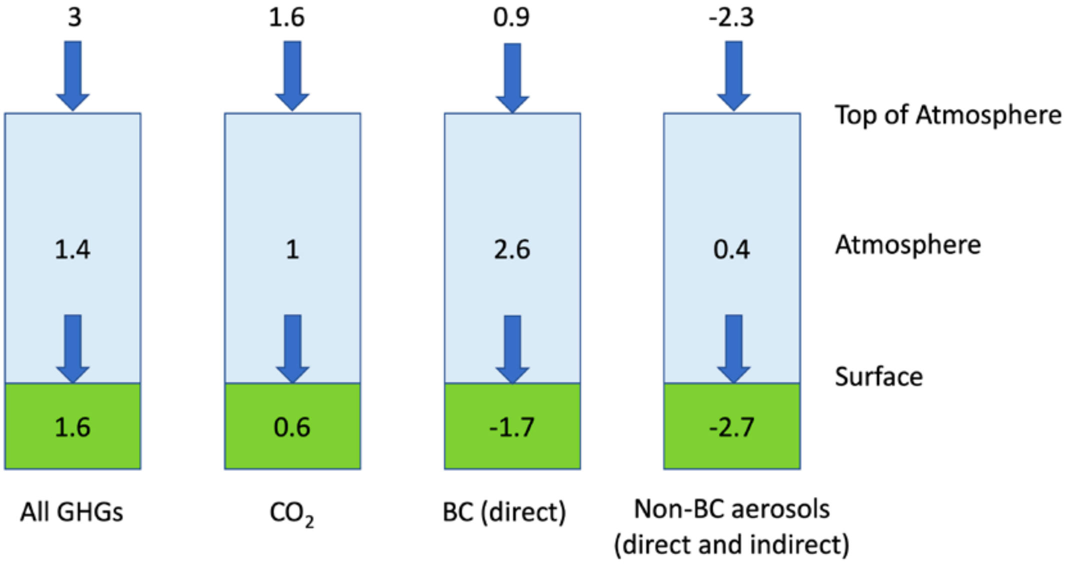
Gas flaring is estimated to contribute 0.27 and 0.21 mtpa of BC emissions in 2005 and 2010, respectively, which is 3 per cent of global BC emissions (Klimont et al. 2017). Although this global percentage may seem small, estimates of the contribution of gas flaring to BC deposits in the Arctic region (where they have a disproportionately large impact) have a highly significant range of 30–42 per cent. A NASA-sponsored study using satellite data to observe gas-flaring emissions was able to reproduce the amount of BC over the Arctic region that had been observed with direct measurements (Gray 2016; Can et al. 2016).

Moreover, benchmark estimates for flare emissions may be biased, as these are based on controlled experiments of laboratory flares and selected field measurements, complemented by modelling. Consequently, the established assumed BC emission rates are 0.57 g/m^3 for well-operated [Organization for Economic Cooperation and Development (OECD)] flares and 1.6 g/m^3 for poorly operated (non-OECD) flares, a factor of 2.8 (Klimont et al. 2017). This approach may have missed contributions from super-emitters because of badly operated flares. GGFR considers that a flare destruction efficiency of 98 per cent is obtained only under ideal conditions, and some flares may combust as little as 60–70 per cent of the gas. Research based on extensive field measurements across multiple countries quantified BC emission rates from flares that spanned four orders of magnitude from 0.003 to 53.7 g/s (i.e. a factor of 18,000) (Conrad and Johnson 2017). Moreover, BC emissions from individual flares can also show large variability over time, with intermittent bursts causing excess emissions. In one flaring example, 10 per cent of the instantaneous flare data was responsible for 56 per cent of the measured emissions. This implies that dense measurement sampling over longer durations is required to obtain accurate BC emission averages. Both observations demonstrate that flaring ‘outliers’, which are easily overlooked, are highly relevant in calculating global flaring emissions, including BC. Contributions from **unstable and super-emitter flares** need to be included in impact assessments of flaring on air pollution and climate.

After carbon dioxide, BC is the second-strongest contributor to global warming. Of the total 3 Wm^{-2} radiative forcing by all GHGs, CO_2 is contributing 1.6 Wm^{-2} (55 per cent) and the direct pathway of BC 0.9 Wm^{-2} (30 per cent). The radiative heating effect of BC in the atmosphere (2.6 Wm^{-2}) is almost twice the contribution of all GHGs (1.4 Wm^{-2}) (Ramanathan and Carmichael 2008) (see Figure 15). However, in contrast to CO_2 and other GHGs, BC has a negative direct radiative effect on the earth's surface (-1.7 Wm^{-2}). This is partially counteracted by the reduction in albedo of precipitated BC on ice and snow. The dimming of the earth's surface caused by BC's direct solar heat absorption contributes to less global water evaporation and reduced rainfall (see Figure 16). As precipitation is a major sink for flushing out BC from the atmosphere, this reduction of rainfall can further have positive feedback on BC concentrations in the atmosphere.

Since the publication by Ramanathan and Carmichael (2008), significant additional research has been done on the climate impact of BC, showing the importance of particle size distributions (Matsui et al. 2018), mixing, and interactions with other aerosols in the forcing pathways. The uncertainty ranges on the climatic effects of BC have consequently been adjusted and enlarged (Zhang and Wang 2011). Mixing with other aerosols doubles the forcing of BC, and this partially explains the larger range in forcing values now reported. Also, the occurrence of BC at elevated levels in the atmosphere strengthens its forcing by absorbing solar radiation reflected from lower clouds. The strong radiative forcing of BC and its short lifetime make reduction of BC a major opportunity to mitigate against the effects of global warming.

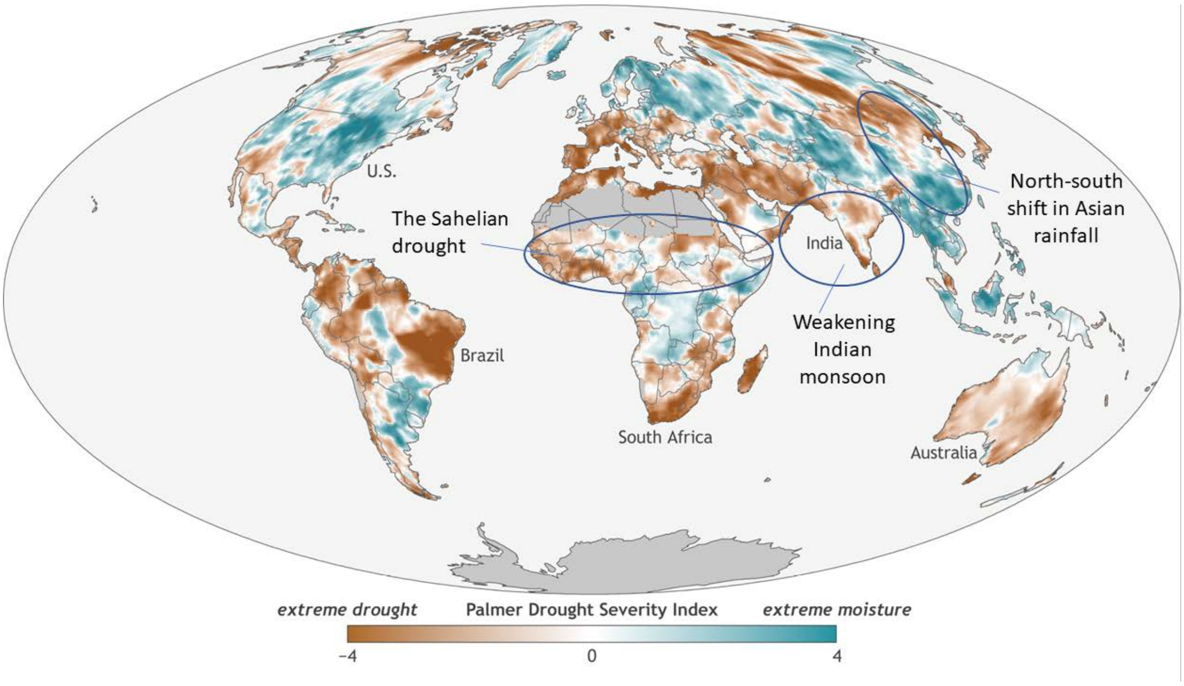
Figure 15: Comparison of global radiative forcing (in Wm^{-2}) caused by GHGs and soot emissions



Note: indirect pathways of radiative forcing by BC, such as albedo reduction, are not included.

Source: authors' illustration based on data from Ramanathan and Carmichael (2008).

Figure 16: Precipitation trend in 2017, with reduced rainfall in global areas where BC concentrations are highest



Note: expressed in the Palmer Drought Severity Index.

Source: reproduced from NOAA Climate.gov (Scott and Lindsey 2018); labelled circles are the authors' addition.

As noted above, while there has been significant additional research on the climate impact of BC and the importance of particle size distributions since the Ramanathan and Carmichael (2008) publication, there has been less analysis of the impact of hydrocarbon flaring and venting on human health.

The World Health Organization (WHO) finds that air pollution, defined as PM—including black carbon (BC), ozone (O_3), nitrogen dioxide (NO_2), and sulphur dioxide (SO_2)—is the leading environmental health risk that humans face. When small particulate matter is inhaled, it penetrates deeply into the lungs. One in eight premature deaths is caused by air pollution, largely a result of increased mortality from stroke, heart disease, lung disease, and cancers. This is particularly significant for people living in low- and middle-income countries. Of the 4.2 million premature deaths in 2016, 91 per cent occurred in low- and middle-income countries. The most affected are the WHO South-East Asia and Western Pacific regions. In follow-up work, we intend to further prioritize the eradication flares on their likelihood of causing disproportionate harm in terms of health to local populations.

In the next section of this paper, we discuss the impact from natural gas flaring, venting, and leakages based on a social cost model approach (see also Appendix B). The social cost methodology enables the consistent integration of various types of damages from atmospheric emissions, including their impact on climate change, health impacts from climate change, health impacts from chemical toxicity, and regional aerosols-induced hydrologic cycle changes (i.e. changes in regional rainfall).

7 The socio-economic impact of gas flaring and venting in oil and gas activities

The 7 per cent of natural gas flared and vented globally causes half of all damages from natural gas

- Most impact assessments for natural gas flaring and venting focus on CO_2 and methane emissions and their impact on climate in terms of US$/tonne CO_2e.
- On a per-unit volume basis, methane emissions from venting have much larger negative climate and health impacts than CO_2 from flaring.
- The impact pathways for methane and other chemicals released by venting and flaring are inherently different from CO_2 and so are their damage functions. Using CO_2e as a proxy to calculate social costs for other atmospheric releases underestimates its impact, particularly if it has toxicity to health.
- The social cost of flaring increases significantly when the quality of the flaring process does not meet its 98 per cent destruction efficiency target, i.e. because of poor design and/or operations.
- Contributions from unstable and super-emitter flares need to be included in impact assessments of flaring on air pollution and climate.
- Recent assessment models integrate social impact assessments of air quality and climate. Shindell's model includes four social cost elements of atmospheric releases (SCAR):
  - the impact of air quality (i.e. pollutant composition) on health;
  - the impact of climate on health;
  - the aerosols-induced impact on the regional climate;
  - the global climate impact.
- A fifth element in the socio-economic assessment of flaring and venting is the opportunity cost to capture, process, and utilize the wasted natural gas and obtain financial-economic benefits.
- Shindell's SCAR estimates (in US$/ton per emitted chemical) are in range with other social cost assessments, except for:
  - NO_X, for which Shindell SCAR exceeded the uncertainty range of other assessments;
  - VOC, for which Shindell does not provide a SCAR estimate;
  - NO_X and VOC, for which SCAR estimates were chosen that are averages from a range of studies.
- Our assessment confirms that the SCAR of flaring and venting significantly exceeds the value of natural gas expressed in gas price. This is not a surprise outcome: the EPA 2016 climate social cost of methane US$1,460/ton ($2019) equates to a value of US$17.42/MMBtu versus a 2019 (Henry Hub) natural gas price of US$2.57/MMBtu.
- With the updated Shindell social cost criteria, the estimated SCAR for US upstream gas flared and vented is US$75/MMBtu, while the SCAR for marketed gas is US$5.29/MMBtu, comprised of downstream fugitive emissions (US$0.36/MMBtu) and full combustion (US$4.93/MMBtu).
- While US natural gas emission intensity in 2017 is 3.7 per cent of produced gas, global emissions are more than double this amount at 7.6 per cent. (US flaring increased significantly in 2018 and 2019.)
  - US split: 1.1 per cent upstream flaring, 2.1 per cent upstream venting, 0.5 per cent downstream venting;
  - global split: 3.7 per cent upstream flaring, 3.1 per cent upstream venting, 0.7 per cent downstream venting.
- The estimated global SCAR of natural gas flared and vented is US$956 billion per annum, exceeding the US$812 billion SCAR of the 92.5 per cent gas marketed and effectively combusted and that has a sales value of approximately US$655 billion (at an assumed global gas price of US$4/MMBtu).
- **The 6.8 per cent of global natural gas flared and vented in oil and gas operations (excluding downstream gas) causes 49 per cent of the total SCAR of global natural gas produced and used.**

- If 75 per cent of the global upstream gas flared and vented could be captured and brought to market, it presents a US$36 billion of additional annual sales (at an average gas price of US$4/MMBtu).
- Despite large uncertainties in SCAR estimates, the quantification of the social cost of flaring and venting on climate and health clearly demonstrate the imperative to reduce these emissions.
- Permissive legislation and regulator practices of routinely issuing permits that condone large cumulative volumes of flaring and venting are not acceptable in light of the damages caused.

The emissions from natural gas flaring and venting have a diverse socio-economic impact at local, national, and global scale. As the Stiglitz, Stern 2017 commission report on carbon prices noted (Carbon Pricing Leadership Coalition 2017): 'assigning a financial value to both emitted and avoided volumes of CO_2 emissions helps reveal the hidden risks and opportunities in a company's operations and supply chain.[15] This is particularly relevant for companies that have to navigate an array of carbon-pricing regulations because their operations span multiple countries'. Furthermore, investors are increasingly demanding comprehensive climate disclosure as funds with an environmental, social, and corporate governance (ESG) mandate increase in size and scope.

In this section we aim to provide an overview of the direct and indirect costs and other consequences on society. The discussions on how to evaluate the social cost of carbon (SC-CO_2) illustrate the complexities of this evaluation process (CarbonBrief 2017). Cost evaluations vary based on different technical (climate) models, different economic assumptions (such as discount rate), and scope (national impact or global impact). Furthermore, each technical model itself has a large uncertainty range based on the uncertainties in input parameters and in the calculation process itself. Despite the wide ranges in assumptions and outcomes, policy makers[16] should not shy away from defining costs for atmospheric releases (AR) as a policy instrument, regardless of the current scientific accuracy behind the numbers. Policy makers can choose a number within the range of values provided by scientists and, over time, adjust these valuations when new information becomes available. This is a better approach than not using the social cost approach as a policy instrument because of political choices and/or difficulties in choosing the 'right' number.[17]

A common issue, acknowledged by scientists and regulators, is that most of the modelling exercises to calculate the social costs of carbon focus on a subset of risks and do not include other potential vitally important impacts of carbon emissions that affect a combination of climate, health, and the economy. Moreover, studies on the social cost of carbon have focused on CO_2 as the dominant source of emissions and convert other types of releases, such as methane, into an equivalent volume of CO_2. However, the impact pathways for these chemicals are inherently different from CO_2 and so are their damage functions. Using CO_2 as a proxy to calculate social costs for other atmospheric releases underestimates their impact, particularly if they have toxicity to health. Increasingly, the importance for improved social cost estimates for specific atmospheric releases

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[15] It further noted that 'the introduction of performance-based… GHG-intensity standards can approach or exceed the efficiency and effectiveness of carbon pricing'.

[16] For example, in France, the UK, and the US, the social cost of carbon is used for policy appraisal and evaluation of public investments, with a provision for updating as the knowledge of science and economics improves with time.

[17] The politicization of science is well illustrated in changes in social cost assessments that can follow a change in government. For example, the US Environmental Protection Agency (EPA) has chosen to no longer value the cost of VOCs, despite earlier assessments in 2006 and despite clear continued recognition, even by EPA, that VOCs are harmful. Similar changes of 'policy-driving science' are highlighted in comments on EPA's reassessment of the cost of methane from oil and gas operations by the Institute for Policy Integrity (2019). See also Office of Management and Budget (2006).

is being recognized. However, to date, few studies exist on assessments of the social cost for methane, the second-largest source of climate change after CO_2.

Another development in the assessment of SCAR is that certain governments only wish to account for the impact in their own country, even if their releases are border crossing. Advances in transportation modelling and observations from satellites increasingly demonstrate the wide-ranging impact of atmospheric releases across geographies. Assessment methodologies that exclude impacts across borders obviously underestimate the social cost. A study by Ricke et al. (2018) concludes that if countries were to price their own carbon emissions at their own country social cost of carbon (CSCC), approximately only 5 per cent of the global climate externality would be internalized (Ricke et al. 2018). Moreover, this approach is short-sighted, as their impacts on other countries ultimately find their way back through, for example, increased global supply chain costs or lower growth of export markets. Climate change disproportionally impacts on the poorest and most vulnerable. In 2019, the IPCC issued a Special Report on Global Warming of 1.5ºC to expand the scope of its work to include sustainable development and efforts to eradicate poverty (Rogelj et al. 2018). Consistent with other studies, Ricke found that the international distribution of SCC is inequitable. This does not mean that climate change does not impact richer countries also substantially. Countries that incur large fractions of the global social cost of carbon (GSCC) consistently include India, China, Saudi Arabia, and the United States. While the US emits about 15 per cent of global emissions, its share of GSCC is 12 per cent. For China, which emits some 31 per cent, its share of GSCC is 6 per cent. Some countries, such as Russia (contributing a 6 per cent share of emissions), are due to receive a net benefit from GSCC. Countries that are disproportionally strongly negatively impacted relative to their share of emissions are India (6 per cent emissions versus 21 per cent GSCC), Saudi Arabia (2 per cent emissions versus 11.5 per cent GSCC), and Brazil (1.5 per cent emissions versus 6 per cent GSCC).

Integrated assessment models (IAMs) that combine the economic costs from a range of impacts in a consistent methodology are preferred over selecting impacts from individual studies. Examples of IAMs for the evaluation of SC-CO_2 are DICE, FUND, and PAGE.[18] Most of the IAMs' scope is on assessing the linkages between climate models and their economic impact. Recently, IAMs are expanding to also include health impacts from the toxicity of AR compounds. This is a very welcomed development, as these efforts build the bridge between climate change impact and air quality impact from AR in a consistent methodology. However, this expansion of IAM scope also results in even further increased uncertainty envelopes.

Given this wide range of impacts, in our assessment of the Social Cost of Atmospheric Releases (SCAR), we have chosen to draw upon the methodology of Drew T. Shindell (2015). In his work, Shindell integrates the economic impact from global climate change, regional aerosols-induced hydrologic cycle changes, health impacts from climate changes, and health impacts from air quality into a single model. The model specifies the SCAR in terms of damages per short ton in 2007 US$ for a wide range of pollutants, including: CO_2, methane (CH_4), nitrous oxide (N_2O), HFC-134a (a hydrofluorocarbon refrigerant with chemical formula 1,1,1,2-Tetrafluoroethane), BC, SO_2, CO, OC, NO_X, and NH_3. Apart from HFC-134a, estimates for US emissions for each of these chemical compounds were provided in Section 6.

We are therefore now in a position to assess the SCAR from US flaring and venting and use this information to scale this outcome to global levels. As part of the evaluation process, we have reviewed Shindell's SCAR assessment against a range of other studies to verify if Shindell's

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[18] DICE (Dynamic Integrated Climate-Economy model), FUND (Framework for Uncertainty, Negotiation and Distribution model), and PAGE (Policy Analysis of the Greenhouse Effect model). See CarbonBrief (2017).

numbers are in range. With the exception of NO_X, for which Shindell provides a high value ($81,600/ton 2019 US$) that is out of range, we have chosen the average of a range of assessments, including Shindell's, that is US$16,064/ton (2019 US$). Shindell does not provide a SCAR for VOCs. Hence, we have taken the average of the range of EPA (2006) and European Commission DG Environment (2002, 2005) estimates. See Appendix B for details on ranges of SCAR estimates.

As part of our assessment, we have selected a discount rate of 3 per cent for the SCAR evaluation. For discussion on the topic of selecting a discount rate for social cost evaluation, we refer to the overview provided by the earlier reference to CarbonBrief (2017) and other literature. A discount rate of 3 per cent is often used as a mid-range evaluation that balances the arguments for and against using a lower discount rate (e.g., 1.4 per cent) or higher discount rate (e.g., 5 per cent or even higher 7 per cent).[19]

Table 8: Social impact in 2019 US$ per short ton of atmospheric releases by pollutant

Impact in 2019 US$/ton	CO_2	CH_4	BC	SO_2	CO	OC	N_2O	HFC-134a	NO_X	NH_3	VOC
Climate	39	1,105	24,295	-1,701	109	-3,401	11,176	43,731	-267	-463	
Regional climate aerosols	0	0	31,583	5,345	0	10,568	0	0	425	1,458	
Climate-health	55	3,401	182,211	6,924	316	13,362	29,154	133,621	36	1,822	
Composition-health	0	814	75,314	40,086	292	61,952	0	0	*15,870*	26,724	
Median[20] total estimate	102	5,588	327,979	51,019	765	82,602	44,945	194,358	*16,064*	30,368	*2,563*

Note: climate-health addresses climate impact on air quality and on vector-borne diseases such as malaria and dengue. Composition-health accounts for toxicity impact on health. Scattering and absorbing aerosols induce stronger regional hydrologic cycle changes than well-mixed GHGs, thus impacting stronger regional changes in precipitation than temperature changes alone.

Source: authors' calculations based on data from Shindell (2015), converted from 2007 US$ to 2019 US$ based on US GDP implicit price deflator https://fred.stlouisfed.org/series/GDPDEF#0. NO_X and VOC estimates are based on averages from multiple assessments. See Appendix B.

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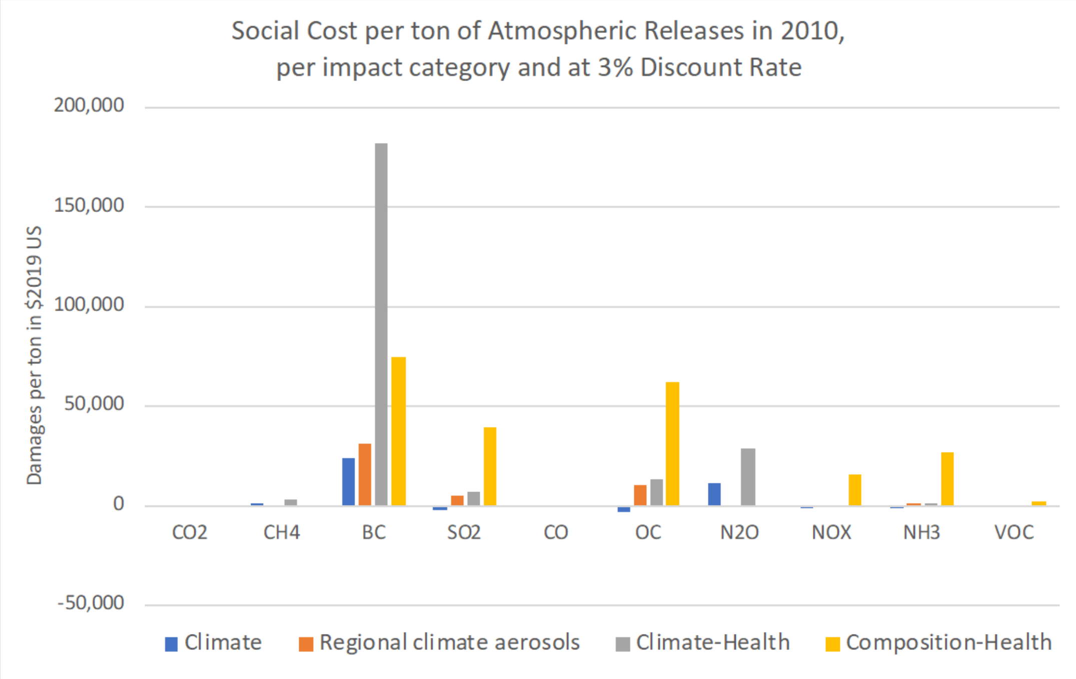
[19] Economic discounting is a calculation mechanism to value future benefits and costs in today's money. A high discount rate preferentially values short-term impacts over long-term impacts, while a low discount rate reduces the discounting of long-term impacts. From a business investment perspective, some argue that climate-related investments should provide a higher rate of return than the market, thereby promoting a high discount rate. Others argue that climate and health impacts are by nature longer term, and a high discount rate would wrongly value a life today much higher than being alive in the future. A discount rate of 3 per cent is in the 'acceptable range' of most countries, institutions, and economists.

[20] Statistical damage functions tend to have a tail of low probability but high impact realizations. In such situations, the median (i.e. middle score) of a ranked data set is generally considered the better representative of the central position within the data set, as it is less affected by outliers and skewed data than the mean (i.e. statistical average). For most statistical populations, the median of the sum is not the same as the sum of the median.

Figure 17: Impact categories' contributions to Shindell social cost for atmospheric releases



Note: individual chemicals of atmospheric releases are presented along the x-axis, while the y-axis shows for each of these chemicals the four contributing categories of damage. Aerosol contributions to atmospheric releases, such as BC, have highly significant damages in terms of cost per ton, with health cost impacts exceeding climate cost impacts. This is true for a range of discount rates, including 1 per cent and 5 per cent (not shown here).

Source: authors' illustration based on data from Shindell (2015), corrected for NOx and VOC added.

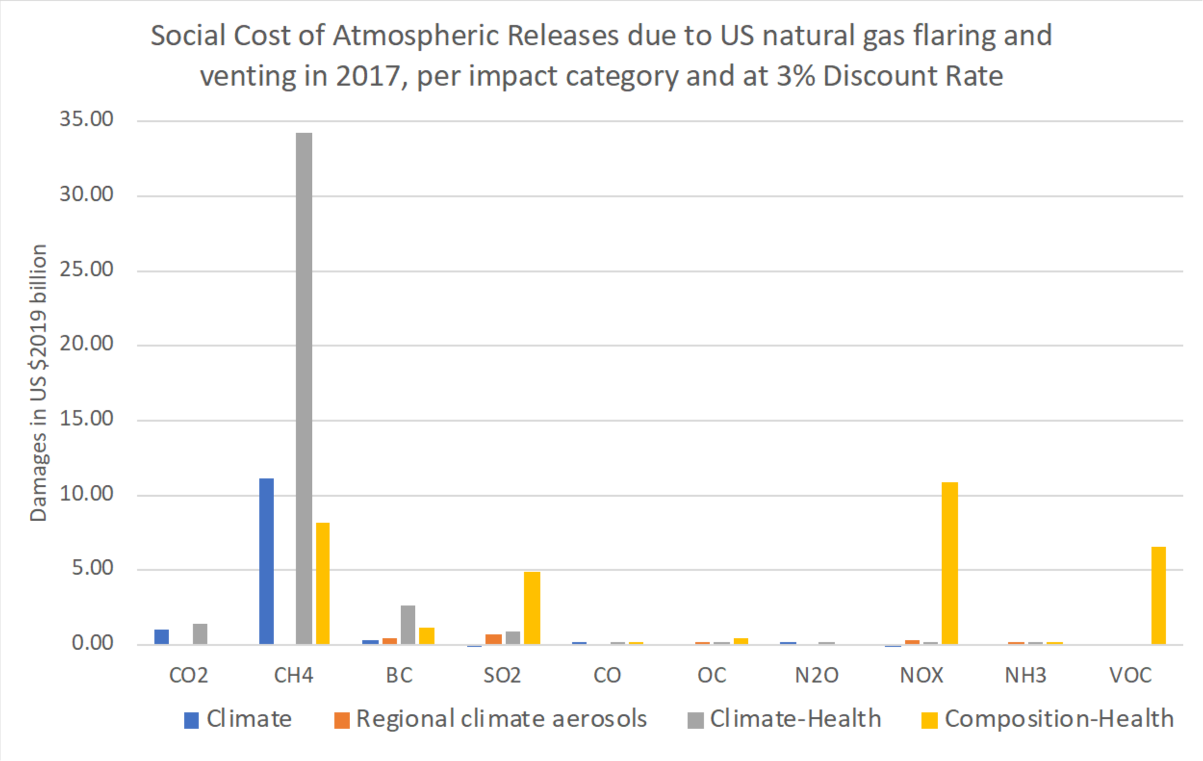
Table 9: Social impact in 2019 US$ for atmospheric releases by the US oil and gas industry in 2017

SCAR of US in 2017	Total	CO_2	CH_4	BC	SO_2	CO	OC	N_2O	NO_x	NH_3	VOC
F&V emissions (kton)	38,411	24,295	10,050	14.456	123.97	689.67	6.247	0.0183	685.51	2.867	2,544
F&V SCAR ($ mln)	88,367	2,479	56,156	4,741	6,325	528	518	0.82	11,012	87	6,520
NG flaring ($ mln)	25,963	2,479		4,741	6,325	528	518	0.82	11,012		359
NG venting ($ mln)	62,404		56,156							87	6,161
NG marketed ($ mln)	189,354	175,649	13,705								
NG produced ($ mln)	277,721	178,128	69,861	4,741	6,325	528	518	0.82	11,012	87	6,520

Note: NEI data for US oil and gas industry does not provide emissions data for HFC-134a. NG=natural gas, F&V=flared and vented.

Source: authors' calculations based on data from Shindell (2015), EPA (2017), IEA (2020c), and GGFR (2020). See Appendix B for further details.

Figure 18: SCAR for flaring and venting of natural gas in the US in 2017 based on Shindell social cost for atmospheric releases



Note: individual chemicals of atmospheric releases are presented along the x-axis, while the y-axis shows for each of these chemicals the four contributing categories of damage.

Source: authors' illustration based on data from Shindell (2015), corrected for NOx and VOC added.

Table 10: SCAR breakdown for the US oil and gas industry in 2017

SCAR of US natural gas in 2017	Total $ mln	CO_2	CH_4	BC	SO_2	CO	OC	N_2O	NO_X	NH_3	VOC
Flaring & venting	88,367	2.81%	63.55%	5.37%	7.16%	0.60%	0.59%	0.00%	12.46%	0.10%	7.38%
Flaring	25,963	9.55%		18.26%	24.36%	2.03%	2.00%	0.00%	42.41%		1.38%
Venting	62,404		89.99%							0.14%	9.87%
NG marketed	189,354	92.76%	7.24%								
NG F&V & used	277,721	64.14%	25.16%	1.71%	2.28%	0.19%	0.19%	0.00%	3.97%	0.03%	2.35%

Note: the rows show SCAR breakdown percentages for each category of release.

Source: authors' calculations based on data from Shindell (2015), EPA (2017), IEA (2020c), and GGFR (2020).

Of the total SCAR US$88.4 billion caused by US oil and gas industry flaring and venting in 2017, flaring accounted for US$26.0 billion (29.4 per cent) and venting for US$62.4 billion (70.6 per cent). For venting, methane and VOC emissions account for 90 per cent and 10 per cent of SCAR contributions, respectively.[21] For flaring, SCAR is distributed across a greater variety of chemicals, particularly NO_X, SO_2, BC, and CO_2.

The emission estimates for US marketed natural gas (i.e. not flared or vented in upstream operations) include downstream gas methane venting of 2.45 million short tons and 1,721 million short tons of CO_2. Table 11 provides a breakdown of US natural gas utilization and emissions. Total gas flared and vented is 3.7 per cent of natural gas produced, of which 1.13 per cent is flared and 2.57 per cent is vented, the latter in upstream (2.07 per cent) and downstream gas (0.5 per cent) operations, respectively.

Table 11: SCAR intensity for the US oil and gas industry in 2017

US natural gas in 2017	Volume (bcm)	% of produced natural gas	SCAR ($ billion)	Share of SCAR (%)	SCAR intensity ($/m^3)
Upstream flaring	9.50	1.13%	25.96	9.3%	2.73
Upstream venting	17.43	2.07%	62.40	22.5%	3.58
Upstream flaring & venting	26.93	3.20%	88.37	31.8%	3.28
Marketed gas vented	4.25	0.5%	13.70	4.9%	3.22
Marketed gas combusted	812	96.3%	175.65	63.3%	0.22
Marketed gas vented & combusted	816	96.8%	189.35	68.2%	0.23
Produced gas	843	100%	277.72	100%	0.33

Note: upstream venting has a higher SCAR intensity than downstream venting because of the presence of VOCs in upstream natural gas.

Source: authors' calculations based on data from Shindell (2015), EPA (2017), IEA (2020c), and GGFR (2020).

The SCAR intensity of upstream venting (in US$/m^3) is a factor almost 16 times higher than the emissions for downstream gas. For flaring, the SCAR intensity is a factor 12 times higher. In 2017, the estimated **3.2 per cent of natural gas flared and vented in oil and gas operations (excluding downstream gas) contributed 32 per cent of the total SCAR of US natural gas**.

Furthermore, in 2019, US natural gas production grew to 1,025 bcm (up 21.6 per cent from 843 bcm in 2017), while natural gas flaring grew disproportionally from 9.5 bcm in 2017 to 17.3 bcm (up 82 per cent). Consequently, in these two years, US flaring grew from 1.1 per cent of produced gas volume to 1.7 per cent, adding an additional US$21.3 billion of SCAR. The SCAR of marketed natural gas increased in this same period by US$41.9 billion, raising US annual oil and gas emissions (including downstream utilization) from US$278 billion to US$341 billion (+23 per cent).

Another way to assess the economic impact of flaring and venting is to compare the SCAR estimates with market prices for natural gas. Gas prices vary with market geographies and over

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[21] Other alkanes, in particular ethane and propane, can account for an additional 3 mol per cent (downstream gas) to 9 mol per cent (upstream conditioned gas) of atmospheric release under venting. Their contributions have not been included in the SCAR assessment here.

time. In the United States, because of excess production of associated natural gas from shale oil, upstream gas prices have been trading in a low-priced range US$2–6/MMBtu during the last 10 years. In Asia, natural gas prices have ranged typically US$10–18/MMBtu in this period but recently much lower, even to US$2/MMBtu, because of global oversupply of LNG. A reasonable long-term range for global gas prices under normal market situations is therefore US$4–12/MMBtu. These natural gas market prices provide an interesting reference point for evaluating the SCAR estimates in Table 12. The SCAR US$5.31 for marketed natural gas in the United States exceeded market prices in 2017 at ~$3/MMBtu, by a factor of almost 2. This implies that even under more controlled conditions in downstream natural gas, where gas compositions, rates, and combustion processes are stable and optimized, the social cost of natural gas significantly exceeds its price. When we include the additional volumes flared and vented in oil and upstream gas operations, the SCAR for produced natural gas increases to US$7.53/MMBtu. However, if we wish to price in the SCAR from flaring and venting in the volume of gas that remains, i.e. the natural gas marketed, the social cost breakeven gas price would have to increase by US$2.47,[22] from US$5.31 to US$7.78/MMBtu.[23]

Table 12: SCAR expressed in US$/MMBtu, for the US oil and gas industry in 2017

SCAR of US natural gas in 2017	$ / MMBtu	CO_2	CH_4	BC	SO_2	CO	OC	N_2O	NO_X	NH_3	VOC
Flaring and venting	74.85	2.10	47.57	4.02	5.36	0.45	0.44	0.00	9.33	0.07	5.52
Flaring	62.31	5.95		11.38	15.18	1.27	1.24	0.00	26.43		0.86
Venting	81.65		73.47							0.11	8.06
NG marketed	5.29	4.93	0.38								
NG F&V & combusted	7.51	4.82	1.89	0.13	0.17	0.01	0.01	0.00	0.30	0.00	0.18

Note: upstream venting SCAR is US$81.85/MMBtu, while downstream venting is US$73.47/MMBtu because of the additional VOCs in the upstream gas content.

Source: authors' calculations based on data from Shindell (2015), EPA (2017), IEA (2020c), and GGFR (2020).

The SCAR intensity values presented in Table 11, now shown in **bold** in Table 13, can be used to scale up the data derived from US oil and gas operations to a global level. For example, in 2019, global natural gas production was 4,058 bcm, of which 150 bcm (3.7 per cent) was flared[24] and 126 bcm (3.1 per cent) was vented in upstream operations. A further 29 bcm (0.72 per cent) was vented in downstream gas operations.[25] Therefore, 7.5 per cent of the produced gas was unutilized and lost as emissions.

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[22] Another way of looking at these price/cost evaluations is that the 2017 US gas price of US$3/MMBtu just about pays for the social cost of the 3 per cent of natural gas flared and vented but not much else (investments, processing and transportation, and the social cost from burning are the remaining 97 per cent).

[23] The total social cost of US$278.5 billion divided by 816 Bcm, i.e. the volume of gas marketed, and then converted into US$/MMBtu based on a gross heating value (GHV) of 1.242 MMBtu/kcf (see Appendix A).

[24] Note that we have assumed the same emission factors for global flaring as those in the United States. This implies that we have not taken account for super-emitter sources of flaring or venting globally. A 1 per cent prevalence of flares that emit 100 times the emission factors assumed, i.e. well within the range observed, would double global flare emissions.

[25] The methane emissions data from IEA (2020c) has been converted to natural gas volumes using a methane density of 0.668 kg/m^3 and a methane mol per cent of 78.32 per cent.

Table 13: SCAR and economic (opportunity) value for global oil and gas industry in 2019

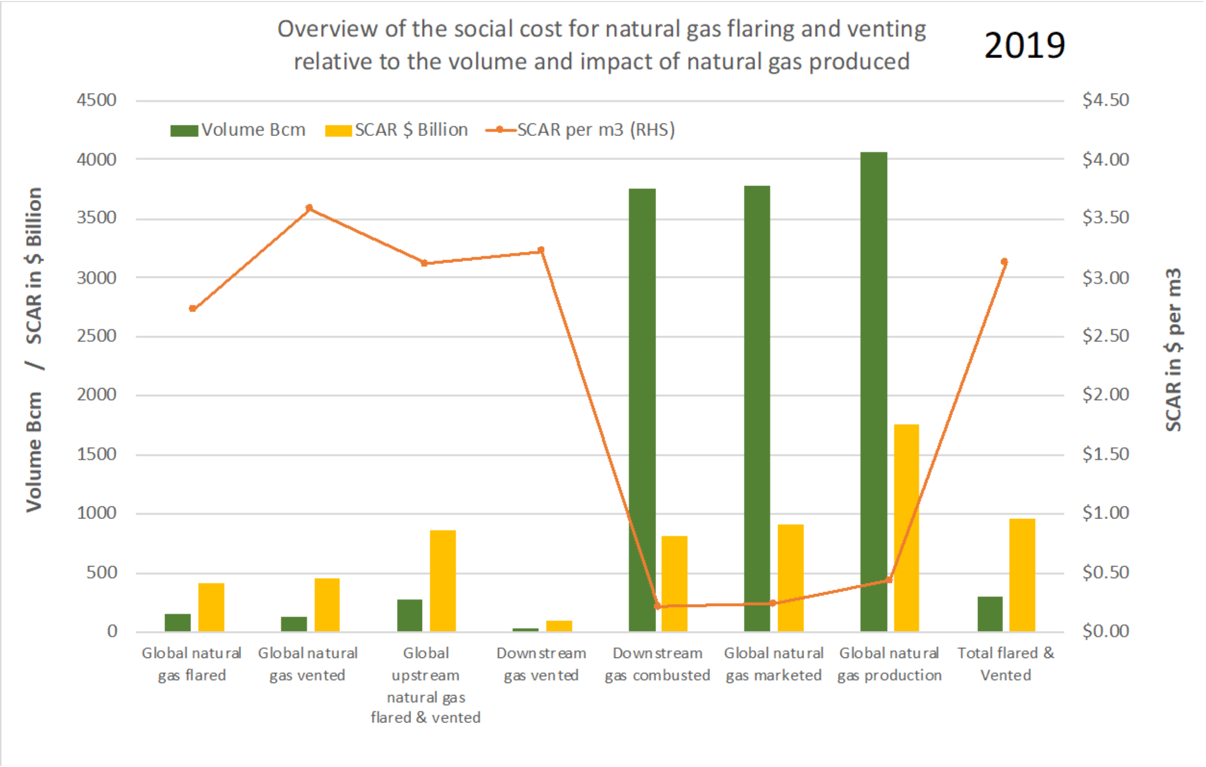
Global natural gas in 2019	SCAR intensity ($/m^3)	Volume (bcm)	% of produced natural gas	SCAR (US$billions)	Share of SCAR (%)	Sales value at gas price: US$4/MMBtu (US$billions)
Upstream flaring	**2.73**	150	3.70%	410	23.2%	26.2
Upstream venting	**3.58**	126	3.11%	452	25.5%	22.0
Total upstream flaring & venting	3.12	276	6.80%	862	48.7%	48.2
Marketed gas vented	**3.22**	29	0.72%	94	5.3%	5.1
Marketed gas combusted	**0.22**	3,753	92.5%	812	45.9%	655
Total marketed gas vented & combusted	0.24	3,782	93.2%	906	51.3%	660
Produced gas	0.44	4,058	100%	1,768	100%	708
Total flared & vented gas	3.13	305	7.53%	956	54.1%	53.3

Note: the economic values shown in green shading are opportunity values, i.e. economic value that could partly be recovered in the absence of flaring and venting. The opportunity value would need to be adjusted for processing and transportation cost of the incremental gas volumes monetized.

Source: authors' calculations based on data from Shindell (2015), EPA (2017), IEA (2020c), and GGFR (2020).

The social cost in 2019 for global volumes of natural gas flared and vented is estimated at US$956 billion. The combustion of the remaining 92.5 per cent of global natural gas produced that was marketed adds a further US$812 billion in social cost. In 2019, the estimated **6.8 per cent of natural gas flared and vented in oil and gas operations (excluding downstream gas) contributed 49 per cent of the total SCAR of global natural gas produced.**

Figure 19: Overview of the social cost of flaring and venting relative to the volume and impact of global natural gas produced



Note: the SCAR from upstream flaring and venting, representing less than 7 per cent of the volume of produced natural gas, exceeds the SCAR from downstream gas combustion (92.5 per cent of produced natural gas).

Source: authors' illustration based on data from Shindell (2015), EPA (2017), IEA (2020c), and GGFR (2020).

In addition to reducing damages (i.e. social cost) from natural gas flaring, venting, and leakages, the capture of natural gas otherwise lost also provides an opportunity for creating economic value. If 75 per cent of natural gas flared and vented globally were to be captured, it would provide additional natural gas sales value of US$40 billion per annum (assuming an average gas price of US$4/MMBtu), with a correspondingly large revenue gain for host country governments. Many governments, however, do not have full overview of the potential opportunities to mobilize additional revenues from hydrocarbon gas being flared and vented.

There are separate global and national databases for flaring, for venting, and for individual chemical releases. In this paper, for the first time, we applied an integrated methodology to show the scope, scale, and impact of hydrocarbon flaring and venting at the country level. The results show that fugitive emissions by three countries (China, Russia, the US) are so far ahead of all other countries that even small percentage reductions in these three would make a disproportionately large impact on climate compared to other individual countries. Over and above global climate considerations, reductions in local emissions also provide significant domestic benefits. For policy makers in low- and middle-income countries who are focused on local resource utilization, energy access, and growth, improving health to increase economic productivity, reductions in flaring, and venting creates a variety of material benefits.

Policy makers are now able to obtain transparent information about fugitive gas opportunities to mobilize domestic revenues from industry activities and to establish a larger tax base. In our second paper, we set out opportunities for action that can generate domestic revenues in a short time period. High-resolution spatial data from satellite measurements enable the rates and locations of individual emission sources (and their owners) to be identified. Flare and vent rates together with distance to market are the two key criteria determining the potential for commercial gas monetization. Costs for small-scale gas monetization have reduced significantly through scalable and modular design optimization, with applications that are containerized and truck-mounted. Fiscal measures, i.e. taxation of volumes flared and vented, will positively influence the commerciality of monetizing these resources. Moreover, regulatory fines for substandard flare operations (i.e. flare quality) play an important role in reducing the SCAR from flaring, while driving investments into gas processing, a key first step in gas monetization. Satellite information can validate compliance with regulatory frameworks. The SCAR evaluation per volume of gas flared and vented, detailed in this paper, enables governments to measure the co-benefits from capturing hydrocarbon gas otherwise lost as fugitive emissions. Because these emissions affect air quality, human health, agriculture, and the climate, there are important implications for decisions on public expenditures. Further work can be done to identify the scale and location of potential investments and prioritize the options to aggregate, process, and utilize natural gas for local economic use that can stimulate further benefits for communities.

8 Overcoming impediments to reduce natural gas flaring and venting

The previous sections have shown the magnitude and trends of flaring and venting in oil and gas operations, as well as their emissions and impact on health and climate. It is important to realize that natural gas is not a waste product, even though generally tolerant attitudes towards flaring and venting may give the impression that it is. Moreover, narrowly focused oil and gas companies may wish to argue that routine flaring and venting is a necessary sacrifice to avoid a greater waste—that is, leaving hydrocarbons behind in the ground if they are not allowed to do so. However, it is worth re-emphasizing that prudent operators will execute development plans and conduct operations that limit climate and environmental impacts and that are sufficiently robust to accommodate the costs of doing so.

The discussion on how stakeholders define ‘waste’ is important, as was illustrated in the introduction section. It is not ‘waste’ to leave hydrocarbons in the ground until the infrastructure is available to process and properly evacuate the production streams. The hydrocarbons are therefore not lost but merely deferred until these conditions are met.

The simplest way to achieve the needed gas infrastructure is to implement oil and gas regulation that makes it mandatory to have a development solution for produced associated gas. However, this is not common practice. Norway is one of the few countries that have policies and regulations that disallow the practice of routine flaring to produce oil.

A second impediment to stop routine flaring practices is the ability to enforce such regulations. Exception permits are too easily handed out. Field observations to monitor local emissions are seldom (if ever) carried out or conducted inadequately. Apart from capacity, this is also a capability issue.

Measurements of fugitive emissions, including flaring and venting, are difficult in the absence of (accurate) metering. Flared and vented associated gas streams are generally not measured. Hence, data are sparse and estimates often unreliable. Remote-sensing technologies are increasingly capable and accurate in monitoring fugitive emissions, particularly those from gas flares. In addition, flow metering of flare and vent gas, as well as regular gas sampling for compositional analysis, should be made mandatory in situations where these practices are approved. The practice of using emission factors should be restricted to their use in comparing actual measured data with what are considered minimum performance criteria. The use of emission factors for estimation purposes is not reliable, as our flare examples in the previous section demonstrated.

Self-reporting of flare and vent data without a validation process currently causes systematic under-reporting of these resource streams. Hence, governments do not have visibility over the true scale of the opportunity and the potential value for the country. There is therefore less incentive to facilitate infrastructure development to capture the natural gas being wasted. Third-party assessment of fugitive emissions is an important mechanism to improve data reliability.

Regulators should not only require measurement of flare and vent streams to assess their volumes, they should also measure flare properties to improve their operational performance and minimize negative environmental impact. Given their disproportionately large environmental impact, the occurrence of super-emitter flares should be avoided and penalties imposed for not meeting flare quality standards. Measurement of air quality should also be part of a mandatory measurement scheme.

As gas flaring is easier to detect and monitor, there is a risk that oil producers dispose of their gas through vents instead of gas flares to avoid detection. Improved methane detection levels and high spatial resolution from satellite sensors are important to ensure improved measurement of methane emissions and to ensure compliance of producers.

In unconventional oil and gas, as well as in other onshore oil and gas provinces, there are many small individual producers. In these oil developments, economies of scale are less critical. However, for the economic development of associated gas utilization, it is often necessary to aggregate the produced gas from multiple producers to get sufficient economies of scale. There is a role for government and regulations to facilitate and incentivize such initiatives.

When local gas markets are lacking, regulations that put ownership of gas produced to the state provide governments and regulators with better options to facilitate the monetization of this resource. For example, the state could sell the gas rights of a large production area to an aggregator to facilitate development.

Governments and regulators should price in the cost of externalities, such as emissions of gases, particulates, produced water, and energy inefficiency, into the fiscal framework for oil and gas taxation. Where development of associated gas may not meet commercial thresholds, such fiscal measures move the economic baseline and incentivize producers to utilize resources that would be wasted otherwise.

Other incentives to reduce flaring and venting could be defined for developing common infrastructure, improving access to markets (transportation and local market development), benchmarking and best practice sharing, and technology development and implementation (e.g., sponsored piloting of technologies).

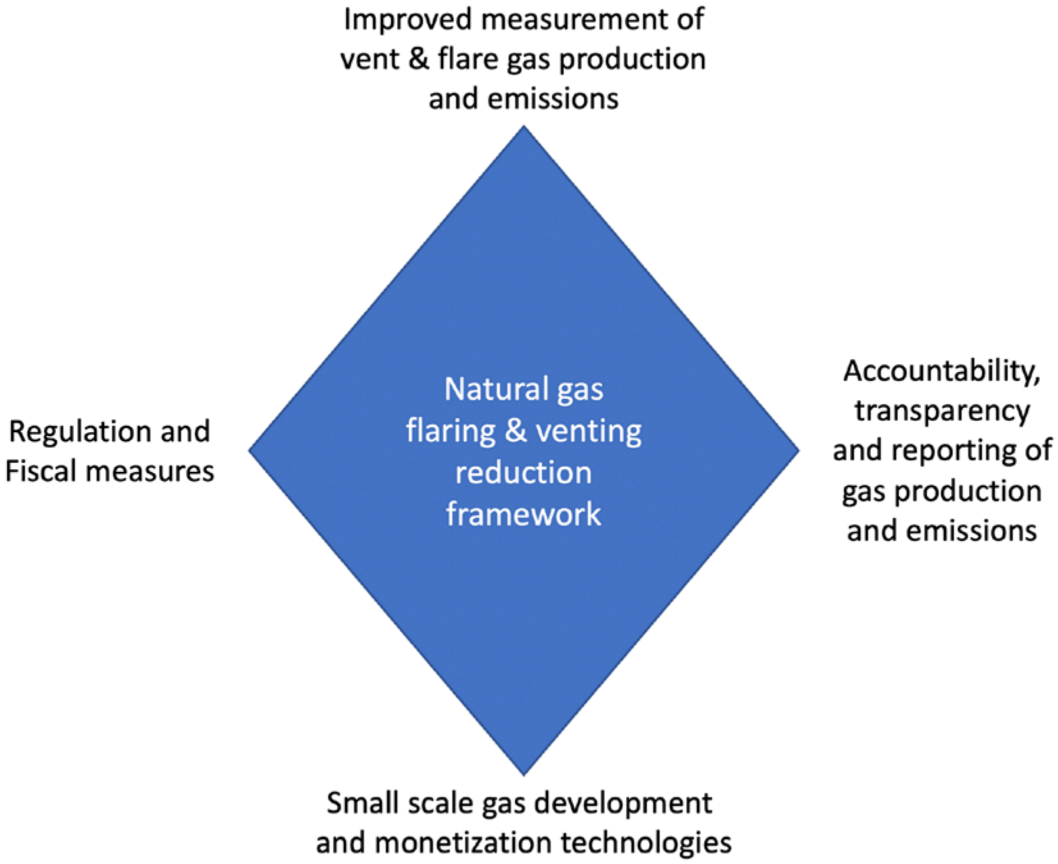
Governments may also reduce barriers to provide tax credits for imports of certain technologies and equipment that could make associated gas developments economic when such equipment cannot be locally fabricated.

Finally, governments could stimulate local gas market development or, in the case of gas-to-wire, stimulate electricity market development by providing gas price guarantees or electricity feed-in tariffs over a limited period of time to stimulate infrastructure development whilst reducing investment risk.

International financiers and organizations that have adopted the UN Sustainable Development Goals as part of their development strategies could provide further resources to facilitate development whilst reducing wasteful emissions. Capturing hydrocarbons by avoiding upstream flaring and venting offers significant opportunities for many UN SDGs: Agriculture (SDG2), Good Health and Wellbeing (SDG3), Gender Equality (SDG5), Sustainable Cities and Communities (SDG11), Energy Access (SDG7), and Climate Action (SDG13).

In conclusion, there are wide-ranging initiatives and solutions to overcome the impediments that currently hinder the utilization of associated gas. The selection of what initiatives are most suited are situation dependent. However, the continuous improvement of gas monetization technologies, in combination with improved measurements, accountability, transparency, and reporting, as well as regulations and fiscal measures, provide the potential for an integrated framework (see Figure 20) to end routine flaring and venting in many oil and gas developments. This is particularly important for low- and middle-income countries, as satellite data since 2005 show that 85 per cent of total gas flared is in developing countries.

Figure 20: Integrated framework to end routine flaring and venting



Source: authors' illustration.

9 Conclusions and recommendations

Routine flaring and venting of natural gas are generally accepted practices and are pervasive in the oil and gas industry. The main purpose of routine flaring and venting is to get rid of associated gas, a by-product in the production of oil. Too often, this valuable energy resource is wasted by letting it go up in smoke, even though technical solutions exist to capture and use this important energy resource and reduce unnecessary emissions. The decision by oil and gas companies to flare or vent natural gas is often based on the criteria as to whether utilizing the gas is diluting the financial rates of return obtained by their primary product: oil production. This is an unacceptably too low bar for deciding to emit significant and avoidable pollution into the atmosphere once the negative externalities are factored in. Oil and gas development plans and operations should only be approved if these do not unnecessarily waste resources and pollute the environment. If the economics of an oil development are not sufficiently robust that they can carry the cost of the utilization of the gas as a valuable by-product, the oil development should be deferred until it can. Contrary to the arguments of some oil companies and regulators, leaving oil in the ground is not 'waste'. The opportunity remains to produce the oil and gas at a future date when the necessary infrastructure, markets, capital, and/or technologies have matured so that the integrated development of the oil and the gas is economic.

Annually, the world flares 3.7 per cent and vents 3.8 per cent of its produced natural gas, a total of 7.5 per cent. Most of these emissions (i.e. 6.8 per cent) occur in upstream oil and gas operations. If all the natural gas flared and vented globally is captured and brought to market, it could supply more than all of South and Central America gas consumption, plus all of Africa's power needs.

The socio-economic impact of atmospheric releases from flaring and venting is generally addressed through studies that investigate individual chemicals, such as carbon dioxide or methane, individual processes (flaring or venting), segments (upstream oil, upstream gas, downstream oil, or downstream gas), or impacts (air quality, climate, or health). Furthermore, different data resources use different variables for emissions (e.g., natural gas, CO_2, methane, CO_2-equivalent), different quantities (volume, mass, or energy), and different units (e.g., ton, tonne, kg, lbs). This makes data comparison and data integration difficult.

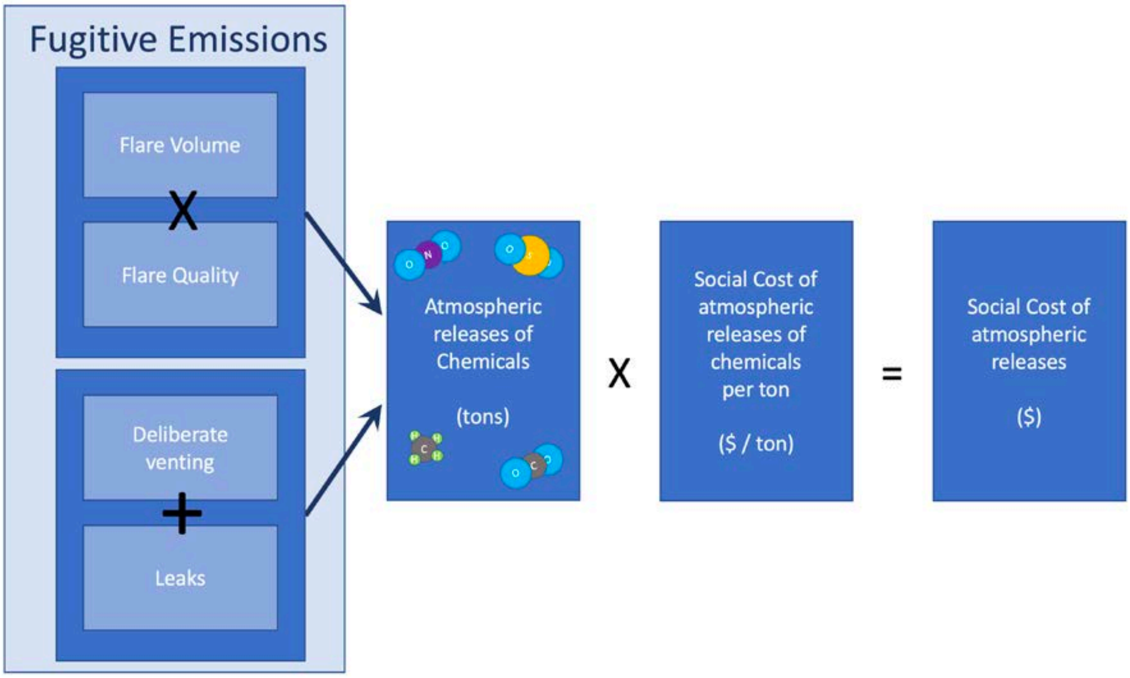
Using Shindell (2015), EPA (2017), IEA (2020c), and GGFR (2020) as our main data sources, we have integrated the available assessments of the volumes of natural gas flared and vented and their impact on amounts of chemicals released into the atmosphere, including specifically CO_2, methane, NO_X, SO_X, black carbon, VOCs, organic carbon, CO, N_2O, and NH_3. Using data from integrated assessment models (particularly Shindell 2015), we have subsequently applied the social costs for each of these chemicals in US$/ton to EPA's estimates of tons emitted by the oil and gas industry in the United States. We have estimated natural gas flared and vented volumes from GGFR estimates of CO_2 emissions and IEA estimates of methane emissions, respectively. This detailed evaluation of social cost factors per volume of natural gas flared and vented has then been scaled to other countries, from which we can assess the issue by sector or globally.

From this analysis, it is possible to conclude that the estimated 6.8 per cent of natural gas flared and vented in global oil and gas operations in 2019 (excluding downstream gas fugitive emissions) was responsible for 49 per cent of the total social cost of global natural gas emissions (54 per cent including downstream gas fugitive emissions). The global social cost of all flaring and venting emissions exceeds the sales value of the global gas marketed by a factor of 1.5, assuming a global average gas price of US$4/MMBtu.

Because of poor flaring operations, the social cost per volume flared is 12.6 times higher than it would be under perfect combustion. Poor flare operations negate most of the benefits that flaring has over venting (SCAR for venting is 16 times higher than for perfect combustion). In addition to continued efforts to put flares out, work to improve the quality of flaring (thus avoiding super-emitter flares) is an obvious low-cost/high-impact opportunity.

The analysis in this paper provides the background to the imperative to reduce and eliminate as far as is practically possible the impact of natural gas flaring and venting. Also, these social cost estimates can guide stepwise solutions, such as the conversion of vents into flares and the conversion from poor-quality flaring to high-quality flaring (i.e. 98 per cent destruction efficiency) and avoiding super-emitter flares.

Figure 21: Schematic model for the calculation of SCAR from fugitive emissions



Note: the social cost of flaring and venting can be calculated from the amount of chemicals emitted as atmospheric release times the SCAR of each chemical. As the pathways for damage creation are different for each chemical, it is incorrect to assume CO_2-equivalents for other emissions than CO_2. As CO_2 (at atmospheric concentrations) has no direct health impact, converting other chemicals into CO_2e obscures the types and costs of damages caused.

Source: authors' Illustration.

Furthermore, the application of natural gas capture technologies for unprocessed natural gas can create significant revenue opportunities. If 75 per cent of natural gas flared and vented globally were to be captured, it would provide additional natural gas sales value of US$40 billion per annum (assuming an average gas price of US$4/MMBtu), with a correspondingly large revenue gain for host country governments. These economic opportunities for domestic resource mobilization are particularly significant for low- and middle-income countries dependent on oil and gas production. Satellite data since 2005 show that 85 per cent of total gas flared is in developing countries. Moreover, improvements in air quality and reduction in regional aerosols-induced hydrologic cycle changes provide benefits to health and other economic activity, such as agriculture, that are expected to significantly increase the added value from these emission reductions. Therefore, capturing upstream hydrocarbon flaring and venting offers significant opportunities for many UN SDGs: Agriculture (SDG2), Good Health and Wellbeing (SDG3), Gender Equality (SDG5), Sustainable Cities and Communities (SDG11), Energy Access (SDG7), and Climate Action (SDG13).

The history of gas flaring and venting has shown that large fugitive emissions and large volumes of flaring are not the inevitable by-products of oil production. Between 1996 and 2010, significant progress was made to reduce gas flaring among the top 30 emitting countries, with Nigeria and

Russia as notable examples. Between 1994 and 2014, overall volumes of fugitive emissions, which include gas flaring, increased. Nevertheless, there are also regions and countries that significantly reduced fugitive emissions, including the EU (-44 per cent), Nigeria (-28 per cent), and Ukraine (-11 per cent). Trends in gas flaring over time show that although there is overlap between large oil-producing countries, countries with high fugitive emissions, and top flaring countries, there are also a number of countries that managed to reduce flaring, even while increasing oil production. Countries such as Angola, China, Kuwait, Russia, Kazakhstan, and Qatar were able to increase oil production or keep it stable while, at the same time, reduce gas flaring. Saudi Arabia and Canada similarly increased oil production while keeping gas flaring stable. Norway, Kuwait, Qatar, UAE, and Saudi Arabia have relatively low flaring in view of the size of their oil production. It is also possible to have large oil production without having large fugitive emissions (Saudi Arabia, UAE, Brazil).

Flaring is not necessarily linked to the stage of oil development, to increasing oil production, or to the overall size of oil production. In the period 2013–19, the 'rest of the world' countries outside the flaring top 30 countries reduced their flaring volumes by 35 per cent. The argument that routine flaring occurs mainly in the early production phase to allow gas infrastructure development to catch up is often not substantiated by the data. This is especially noteworthy, as it is the top five flaring countries that have some of the most developed and mature oil and gas infrastructure.

A second paper that is linked to this set of topics further addresses the integrated framework ('Diamond Model') to end routine flaring and venting. This model combines four elements: 1) improved measurement of vent and flare gas production and emissions, 2) accountability, transparency, and reporting of gas production and emissions, 3) small-scale gas development and monetization technologies, and 4) regulation and fiscal measures. Incorporating the socio-economic cost analysis detailed in this report into the Diamond Model will provide the means to construct an abatement strategy that adds most benefits (financial and social) with sequenced actions that are both effective and practical to capture economic and social value from hydrocarbon gas flaring and venting.

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Abbreviations and units

AR	Atmospheric release
bbl	barrel (1 bbl is 0.159 m^3)
BC	black carbon
bcm	billion (= one thousand million) cubic meter
Btu	British thermal unit—measure of the energy content in fuel (1 Btu = 1.06 J)
BTXS	benzene, toluene, xylene, and styrene
CH_4	methane
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CSCC	country social cost of carbon
DICE	Dynamic Integrated Climate-Economy model (IAM)
ECA	emission control area
EIA	US Energy Information Administration
EMA	Singapore Energy Market Authority
EPA	US Environmental Protection Agency
ESG	environmental, social, and corporate governance
EU	European Union
FLNG	floating LNG (liquefaction facility)
F&V	flaring and venting
FUND	Framework for Uncertainty, Negotiation, and Distribution model (IAM)
GGFR	Global Gas Flaring Reduction Partnership, led by World Bank Group
GHG	greenhouse gas (such as carbon dioxide, methane, and others)
GHV	gross heating value
GSCC	global social cost of carbon
GWP	Global warming potential (relative to carbon dioxide)
HAP	Hazardous Air Pollutants

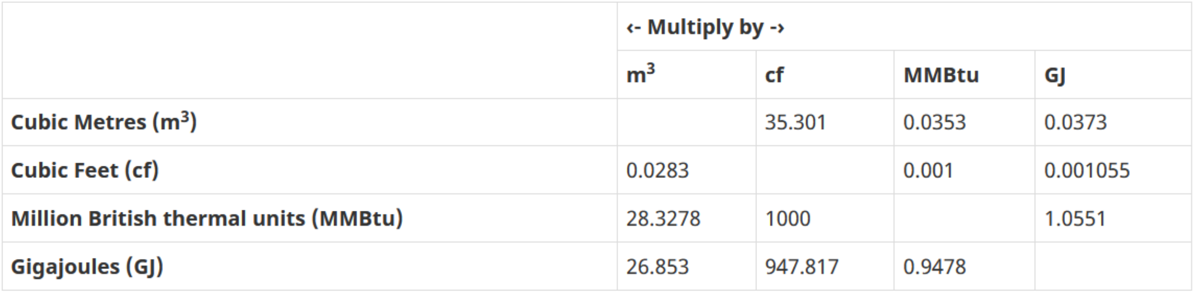
HFC-134a	a hydrofluorocarbon refrigerant with chemical formula 1,1,1,2-Tetrafluoroethane
H_2O	water
H_2S	hydrogen sulfide
IAM	integrated assessment models (to calculate the impact of climate change)
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
J	Joule, measure of the energy (1J = 1N × 1m)
K	Kelvin, a measure for absolute temperature
Kg	kilogram, SI unit of mass
LNG	liquefied natural gas
m	meter, SI unit of distance
m^3	cubic meter
mbopd	million barrels of oil per day
Mln	million
mm	millimeter (one-thousandth of a meter)
MMBtu	million British Thermal Units—measure of the energy content in fuel (1 BTU = 1.06 J)
Mt	megatonne (Mt), a unit of mass equal to one billion kilograms (10^9 kg)
$MtCO_2e$	megatonne of CO_2 equivalent (emissions)
Mtoe	million tonnes of oil equivalent
mtpa	million tonne per annum
N	Newton, SI unit of force ($1N = 1Kg\ m/s^2$)
NASA	US National Aeronautics and Space Administration
NEI	National Emissions Inventory
NG	natural gas
NH_3	ammonia
NOAA	National Oceanic and Atmospheric Administration
NO_x	chemical compounds made from elemental nitrogen and oxygen
NO_2	nitrogen dioxide
OC	organic carbon (partially oxidized VOCs)
OECD	Organization for Economic Cooperation and Development

O_3	ozone
PAGE	Policy Analysis of the Greenhouse Effect model (IAM)
PAH	poly-aromatic hydrocarbons (constituents of black carbon)
PM	particulate matter
s	second, SI unit of time
SCAR	social cost of atmospheric releases
SCC	social cost of carbon
scf	standard cubic foot
$SC\text{-}CO_2$	social cost of carbon dioxide
SDG	Sustainable Development Goal (as defined by the United Nations)
SO_x	chemical compounds made from elemental sulphur and oxygen
SO_2	sulphur dioxide
UN	United Nations
US$	United States dollar
VOC	volatile organic compound
W	Watt, SI unit of power (1W = 1J/1s)
$W\ m^{-2}$	s measure for radiative forcing (the intensity of global warming)
WHO	World Health Organization
°C	degree Celsius, unit of temperature
°F	degree Fahrenheit, unit of temperature

Appendix

A Calculation of CO_2 emissions from unprocessed natural gas

Table A1: Approximate natural gas conversion factors (for 1000 Btu/cf gas)



	‹- Multiply by -›			
	m^3	**cf**	**MMBtu**	**GJ**
Cubic Metres (m^3)		35.301	0.0353	0.0373
Cubic Feet (cf)	0.0283		0.001	0.001055
Million British thermal units (MMBtu)	28.3278	1000		1.0551
Gigajoules (GJ)	26.853	947.817	0.9478	

Note: for example, to convert from 1 Gigajoules to MMBtu, multiply by 0.9478

Source:reproduced from https://www.nrcan.gc.ca/energy/energy-sources-distribution/natural-gas/natural-gas-primer/5641#conversion.

Synopsys

1 Bcm of gas produces under a perfect (100 per cent) burn:

- 35.3 million MMBtu (1000 Btu/scf)
- 0.51 million tonne of Carbon
- 1.868 million tonne of CO_2
- 2.32 million tonne of CO_2 (raw feed gas 1242 Btu/scf)
- 2.09 million tonne of CO_2 (conditioned fuel gas 1121 Btu/scf)

Calculation

1) With a perfect (100 per cent) burn, **natural pipeline gas produces 14.43 kg carbon per MMBtu**[26]
2) Assume normalized calorific value of 1000 Btu / scf $\wedge$ 1 m^3 = 35.31 scf ⇔
3) 1 MMBtu = 28.32 m^3

1+3 ➔ 14.43 kg carbon per 28.32 m^3 ⇔

4) 1 m^3 produces 0.5095 kg carbon
5) Molecular weight of carbon = 12, of CO_2 = 12+16+16 = 44
6) 4+5 ➔ 1 m^3 of 1000 Btu/scf gas produces 44/12 x 0.5095 = 1.868 kg of CO_2

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[26] EPA, https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

Unprocessed natural gas generally has higher calorific value than pipeline gas, due to heavier carbon elements contained in the gas (see table below). The raw feed gas gross calorific value is calculated[27] to be 46.27 MJ / m^3.

7) 46.27 MJ / m^3 x 0.001 x 0.9478 = 0.0439 MMBtu / m^3 = 43855 Btu / m^3 ⇔
8) $\wedge$ 1 m^3 = 35.31 scf ⇔ 1242 Btu / scf

6+8 ➔ 1 m^3 of raw feed gas (1242 Btu / scf) produces 1.868 x 1.242 = **2.32 kg of CO_2**, assuming a perfect (100%) burn.

Note:
Conditioning the raw feed gas into fuel gas (Table A2) changes the calorific value of the gas from 1242 Btu / scf to 1121 Btu / scf (41.75 MJ / m^3), and therefore 1 m^3 of conditioned fuel gas produces **2.09 kg of CO_2** under a perfect burn.

Table A2: Natural gas data for a drilling rig site in Texas

Composition (mol %)	**Raw Feed Gas** (Methane Number: 50) (Propane Knock Index: 24.6) (Weight: 0.888 Kg/m^3)[28]	**Conditioned Fuel Gas** (Methane Number: 69) (Propane Knock Index: 8.3) (Weight: 0.779 Kg/m^3)
Methane (C1)	78.32	87.95
Ethane (C2)	11.48	7.21
Propane (C3)	4.35	2.129
Butanes (C4)	2.71	0.992
Pentanes (C5)	0.91	0.29
N-Hexanes (C6)	0.13	0.04
Hydrogen Sulfide (H_2S)	0.003	0.002
Carbon Dioxide (CO_2)	1.97	1.29
Nitrogen (N_2)	0.08	0.12
Water	0.060	0.001

Source: authors' construction. Gas composition by: https://www.mtrinc.com/wp-content/uploads/2018/09/NG08-MTR-Power-Gen-NG-2015.pdf ; methane number and PKI by Wärtsilä calculator: https://www.wartsila.com/marine/build/gas-solutions/methane-number-calculator.

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[27] See https://www.unitrove.com/engineering/tools/gas/natural-gas-calorific-value

[28] Weight is calculated at NTP (Normal Temperature and Pressure) conditions, defined as 20 °C and 1 atm. https://www.engineeringtoolbox.com/gas-density-d_158.html

B Assessment of social cost for atmospheric releases

The practical use of carbon pricing

In Chapter 2 of the IPCC report 'Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development', an explanation is provided for the different methodologies that can determine the cost of carbon. Cost Effectiveness Analysis (CEA) aims at identifying pathways that achieve a certain GHG or global warming limit while minimizing mitigation costs. Cost Benefit Analysis (CBA) aims to identify pathways that minimize discounted cashflows from mitigation measures and climate damages. A third method, the Social Cost of Carbon (SCC) measures the total net damages of an extra metric ton of CO_2 emissions due to the associated climate change. Each of the methodologies has its own application areas. For example, CEA estimates what we should be willing to pay as the price of carbon to achieve climate goals. CBA determines which investments have the highest impact in mitigating climate change per dollar invested. SCC assesses the climate-induced social damage caused per volume of carbon emitted.

CEA, CBA, and SCC assessments measure different aspects of the cost of climate change and therefore cannot directly be compared, due to the different tools, assumptions, and approaches used in the calculation methods. Despite these differences, SCC literature identifies a range of factors, assumptions, and value judgements that support SCC values above US\$100/CO_2 that are also found as net present values of the shadow price of carbon in 1.5°C pathways (Rogelj et al. 2018). The recognition of tipping points in the climate system, the preference for a low social discount rate, and the avoidance of increased social inequality are all factors that support SCC values that are higher than CEA and CBA, when the objectives of the mitigation actions are aligned with these value statements.

The SCC and the shadow price of carbon are not merely theoretical concepts but used in regulation. As stated in the aforementioned report of the High-Level Commission on Carbon Pricing, 'in the real world there is a distinction to be made between the implementable and efficient explicit carbon prices and the implicit (notional) carbon prices to be retained for policy appraisal and the evaluation of public investments, as is already done in some jurisdictions such as the USA, UK and France' (Carbon Pricing Leadership Coalition 2017).

SCAR climate models and pricing methodologies are in need of further development, with scope extending beyond the price of carbon (i.e. CO_2). Other atmospheric releases, such as methane, black carbon, organic carbon, SO_X, and NO_X, affect global warming through different physical and chemical process than CO_2 does. Moreover, many of these other climate actors also have toxicity that affect health directly (as per Shindell's modelled assumptions), see Table B1. Other than Shindell's assessments, we have to date not found other independent estimates of the social cost of methane, nor black carbon, in the way this is calculated for CO_2. Instead, SCC assessments for 'other carbons' rely on a conversion of an equivalent emission of CO_2 (CO_2e) and then assume the climate forcing of CO_2 to apply on this CO_2e volume. This approach causes the SCARs to be underestimated.

In addition to the differences in carbon pricing methodologies (CEA, CBA, and SCC), social cost assessments of atmospheric emissions show large ranges in estimates and this is due to a variety of reasons:

- Uncertainty in how a certain chemical impacts a certain aspect of economic activity;
- Uncertainty in the transportation of a chemical between its source of release and the target area of impact;
- Variations in value assumptions, e.g., the cost of a human life, discount rate, etc.;

- Variations in the scope, i.e. what types of impacts are included in the impact assessment: direct climate forcing pathways, indirect climate forcing pathways, interactions between emitted chemicals, health impacts due to toxicity, etc.

Despite the large ranges of uncertainty observed, valuations can still have merit. Often, the purpose is not to arrive at an accurate absolute number, but to arrive at relative values. For example:

1. What is the relative impact between upstream gas venting, upstream oil venting, downstream gas venting, and downstream oil venting?
2. What is the relative impact between venting and poor operational flaring?
3. What is the relative impact between poor operational flaring and high-quality flaring (i.e. with 98 per cent destruction efficiency)?
4. What is the relative impact in terms of social cost of flaring on climate versus health?
5. What is the relative impact in terms of social cost of venting on climate versus health?

To account for the impact of emissions and to set policy, one can question if it is really necessary to have scientifically accurate cost estimates, or whether accounting practices (i.e. assumed cost impacts) can be used as valid instruments to balance financial economic returns with socioeconomic costs (cost externalities). Specifically, it can be justified to define a 'reasonable' CO_2 tax rate, without having to derive this number directly from science. It is with this mindset that we have derived the social cost estimates for flaring and venting in this paper.

We have reviewed Shindell's cost estimates against a range of other social costs studies on atmospheric releases. We have summarized these here in this appendix, as well as the basis for the social cost estimate for VOCs that was not included in Shindell's assessment. Table B1 shows that Shindell's estimates are in range of the other assessments, apart from NO_X for which Shindell's health estimate exceeds every other estimate. This could be due to Shindell using a more comprehensive scope than other studies for health-impact assessment of NO_X (see also note below Table B1).

Institutions and organizations, including the EPA, remark that their impact assessments may not include the full set of pathways and effects that affect climate and/or health. Hence, in addition to best mean estimates, they also suggest using the 95 per cent confidence interval of the impact function as a proxy for the effects not modelled. The 'best' estimate is therefore somewhere in between the mean and the high (i.e. P95) estimate.

Table B1: Overview of social cost estimates in 2019 US$ per short ton, 3% discount rate (where available)

SCAR	Impact	CO_2	CH_4	BC	SO_2	CO	OC PM2.5	N_2O	NO_X	NH_3	VOC
Shindell	Global Climate	39	1,109	24,365	-1,706	110	-3,411	11,208	-268	-463	
Shindell	Regional Climate	0	0	31,675	5,360	0	10,599	0	426	1,462	
Shindell	Climate-Health	55	3,411	182,739	6,944	317	13,401	29,238	37	1,827	
Shindell	Composition-Health	0	816	75,532	40,203	292	62,131	0	81,623	26,802	N.A.
Shindell	Median total estimate	**102**	**5,604**	**328,930**	**51,167**	**768**	**82,842**	**45,076**	**81,623**	**30,457**	
AP2	Ground				47,720		74,230		6,787	40,297	
AP2	Elevated				23,330		38,176		4,030	39,236	
EASIUR	Ground				22,269		127,252		10,392	51,961	
EASIUR	Elevated				21,209		73,170		6,681	33,934	
InMAP	Ground				31,813		106,044		13,786	41,357	
InMAP	Elevated				37,115		116,648		11,665	54,082	
Fann et al	Ground				49,894		898,100		12,099	47,400	2,994
Fann et al	Elevated				73,594		573,789		18,710		
BeTa	Rural low				1,352		1,952		2,091		683
BeTa	Rural high				11,015		30,675		11,433		10,039
BeTa	Rural average				7,250		19,521		5,856		2,928
CAFE’05	Average				22,309		104,574		16,732	43,224	3,904
Defra’19	Low				1,797		27,224		764	1,366	66
Defra’19	Central				7,561		127,559		7,471	7,287	123
Defra’19	High				21,527		395,235		27,905	22,739	247
IWG/EPA	Low/Central	46	1,325		36,640		160,300	17,015	10,305		845
IWG/EPA	High	137	3,567		81,295		354,950	44,238	37,556		3,802
Average		95	3,500		29,883		182,862	33,900	**15,870**	34,140	**2,563**

Legend:	Shindell reference estimate	Estimate < 20% below Shindell	Estimate deviates < 20% from Shindell	Estimate >20% above Shindell

Note:

1. EPA estimates for social benefits from NO_X and SO_X reduction (as per National Emission Standards for Hazardous Air Pollutants, NESHAP) include the health impacts from conversion from precursor emissions to ambient fine particles (PM2.5) and ozone. However, EPA costs do not include reduced health effects from direct exposure to NO_2, SO_2, ecosystem effects, or visibility impairment. All fine particles are assumed to have equivalent health effects, regardless of composition. Social cost of

directly emitted PM2.5 are estimated for OC. Social cost estimates for VOC are based on 2006 EPA documentation. EPA no longer calculates social costs for VOCs due to uncertainties in geographic distribution of VOCs.

2. See references for social cost estimates at the end of this appendix. Costs have been adjusted from the financial year of modelling to 2019 using local GDP deflation factors and converted from native currency to US$ using the average currency exchange rate in 2019, and if applicable, unit assumed have been converted to short tons.

Source: authors' elaboration.

Social impact assessment of CO_2

Table B2: 2020 social cost assessments for CO_2 from integrated assessment models (IAMs)

CO_2 2019 US$ / ton 3% disc. rate	**FUND**	**DICE**	**PAGE**	**USG**	**Average**
Low (P5)	3	18	6		9
Mean (μ)	23	43	78	46	48
High (P95)	65	84	327	137	153
Average	31	48	137	91	75

🟦 Estimate < 20% below Shindell

🟩 Estimate deviates < 20% from Shindell

🟧 Estimate >20% above Shindell

Note: FUND (Framework for Uncertainty, Negotiation and Distribution model), DICE (Dynamic Integrated Climate-Economy model), PAGE (Policy Analysis of the Greenhouse Effect model), USG (US Government model, a mix of DICE, FUND and PAGE).

Source: authors' elaboration based on references listed at the end of this appendix.

Shindell valuation of 2010 emissions for CO_2 (at 2019 US$, 3% discount rate) at US$102/short ton is based on the damage function in the DICE model with reference temperature changes following a business-as-usual-trend.

Social impact assessment of methane

Many approaches to calculate the social impact of methane use the difference in radiative forcing between methane and CO_2 to convert amounts of methane emissions into CO_2-equivalent (e.g. $mtCO_2e$). Using the IAMs for CO_2 discussed above, estimates for the social cost of methane expressed in CO_2e are obtained. However, the pathways for methane that impact climate and health are substantially different than those of CO_2. Hence, methane valuations that include climate and air quality show impacts that are substantially larger than climate alone (CO2e). Moreover, the climate impact function of methane not only shows different radiative forcing; the decline rate of methane due to chemical processes that break it down is much faster than CO_2.

Box B1: Natural methane sinks

The most common oxidization process that acts as a methane sink in the atmosphere is through its initial reaction with hydroxyl radical (·OH) to create the (·CH_3) radical. Thereafter, two key reaction mechanisms occur, one that creates ozone (O_3) and one that doesn't. Both reaction processes result in the creation of formaldehyde (HCHO) and water. This reaction in the troposphere gives methane a mean life time of 9.6 years. Another major sink for methane is through bacterial reactions in the soil. Forest areas are most effective as a methane sink, because the moist content of the soil is optimum for methanotrophic bacteria and methane diffuses less easily into the atmosphere as it does in wetland soils. Methanotrophic bacteria oxidize methane as a source of energy into CO_2 and water.

In comparison, CO_2 is chemically inert and is removed from the atmosphere by dissolving into oceans and conversion through biological photosynthesis.

Hence, nearer term methane impacts (0–20 years) are even much more severe than long term impacts (100+ years). Compared to CO_2, methane releases have a stronger negative impact on global warming in the short term, but methane also has a shorter half-life and therefore the degree of negative impact versus CO_2 reduces faster with time. Depending on the time horizon, methane has a Global Warming Potential (GWP) of 72 and 25 for a 20-year and 100-year time horizon, respectively.[29]

EPA uses a social cost of methane of US$1,300/metric ton in 2020 and US$1,500/metric ton in 2025 (based on a 3 per cent discount rate and rounding from IWG 2016) (EPA 2016[30]). However, estimates are subject to change due to evolvement of science, as well as politics (Krupnick et al. 2018[31]).

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